CONTINUED CONSIDERATIONS ON HYDROGEN PIPELINE PROJECTS IN EUROPE

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ABSTRACT

In the presentation of the previous year, the authors had been focusing on issues related to admixture of hydrogen into the European gas grid. This year's presentation focuses on design aspects of hydrogen pipelines in Europe. Generally, the design of a pipeline system need to follow rules and regulations, among other to provide a framework for authorities to grant the construction permits. One of the challenges for hydrogen pipeline projects in Europe is, that there are currently no harmonized standards available. The paper addresses several aspects of the design of hydrogen pipelines, among other process and safety considerations, material aspects but as well welding considerations.

The ignition and combustion properties of Hydrogen are very different to natural gas. In this respect the emergency blow down and heat radiation calculations will be presented and it will be discussed whether the technical solutions are indeed similar to the solutions known from natural gas.

Adequate material selection and the definition of the welding process are relevant to ensure resistance to stress corrosion cracking and hydrogen embrittlement. Generally, the risk of failure is increased at higher temperatures and pressures and is mitigated by low stress levels. Therefore, material selection, fabrication processes, design and material thicknesses should be chosen with a view towards achieving low residual stresses. The paper summarizes approaches taken for the specification of equipment such as valves and vessels.

Last not least, the welding process for hydrogen pipeline is considered as critical. It is important that hardness levels in the weld and the weld heat affected zone are controlled to avoid hard spots. Some relevant aspects of a welding specification for construction of a hydrogen pipeline will be presented in the paper.

1 INTRODUCTION

Whenever a new gas (natural gas) pipeline has to be built, the engineering companies can reach to pre-established standards that set the regulatory and safety basis for its design. This is hardly the case for new hydrogen pipelines in Europe, where there is still a lack of standardized framework within Europe. So what to do while there is no specific baseline to design and construct H_2-Pipelines?

American standard ASME B31.12 seems to be one step ahead and defines clear rules and is broadly used in Europe as well. Other industry recommended practices (but not standards) such as EIGA 121/14 are also referred and basis. Nonetheless, any design of a new H_2-Pipeline based on ASME B31.12 will still need the endorsement of each country's regulatory bodies.

The paper addresses several aspects of the design of hydrogen pipelines, among other process and safety considerations, material aspects but as well welding considerations. An engineering approach is provided, e.g. by using similar approaches as conducted for natural gas and adapting to the specific parameters and properties of hydrogen.

The findings presented in this paper are results of studies and projects which have been conducted by ILF in the last year for clients in serval European countries.

2 PROCESS CONSIDERATIONS

The first part of the paper refers to process considerations for depressurisation of compressor station and of a pipeline section.

2.1 Emergency shutdown in compressor station

For transport systems of natural gas, automatic depressurisation of a compressor station in an emergency case is one of the safety requirements, refer ISO 23251, which basically refers to API 521. Formally these standards may not be considered to be applicable for hydrogen. From a technical perspective a depressurization of compressor station in an emergency status is evident and it has been considered that similar rules shall be followed for a hydrogen compressor station.

The standard states that in case of an emergency situation the compressor station shall be depressurized within 15 minutes to a pressure level of < 6.9 barg. The depressurization is usually via a vent stack, which is installed at an isolated location within the compressor station. The location, height of the vent stack and the control of the flow are designed in a way to protect operator personnel against a defined heat radiation level (considered < 6.31 kW/m² at ground level).

Respective process calculations have been performed, where the depressurization of a compressor station have been compared for the cases of natural gas and H2. The following initial parameters have been considered:

Table 1 Parameters for calculation

Height of vent stack	m	20
Diameter of vent stack	DN	250
Mach number at tip of vent stack at maximal mass flow	Ma	0.7
Pressure level	barg	73.2
Volume to be depressurized	m^3	20
Thermodynamic Model used		Peng-Robinson

Two typical weather conditions have been considered:

Table 2 Weather conditions

Wind-velocity in m/s	Pasquill-stability	Name Scenario
1	F	1/F
10	C	10/C

In case of natural gas, a composition with 90% methane has been considered, whilst for the hydrogen case 100% of H2 is used. In case of hydrogen, 3 scenarios have been considered:

- Same depressurization time as natural gas
- Same piping geometry as natural gas
- Same maximum mass flow

The following charts show the size of the ex-zones resulting from dispersion calculation for the weather scenario 10/C and the result of the radiation study considering an ignition of the gases during the venting operation, e.g. caused by lightning stroke.

Figure 1 Ex-zones resulting from dispersion calculation for the weather scenario 10/C

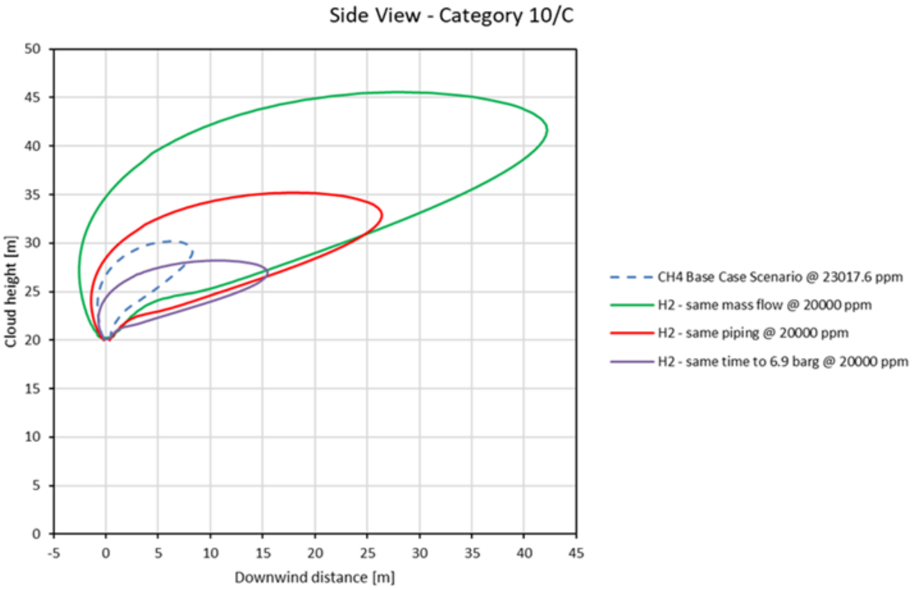
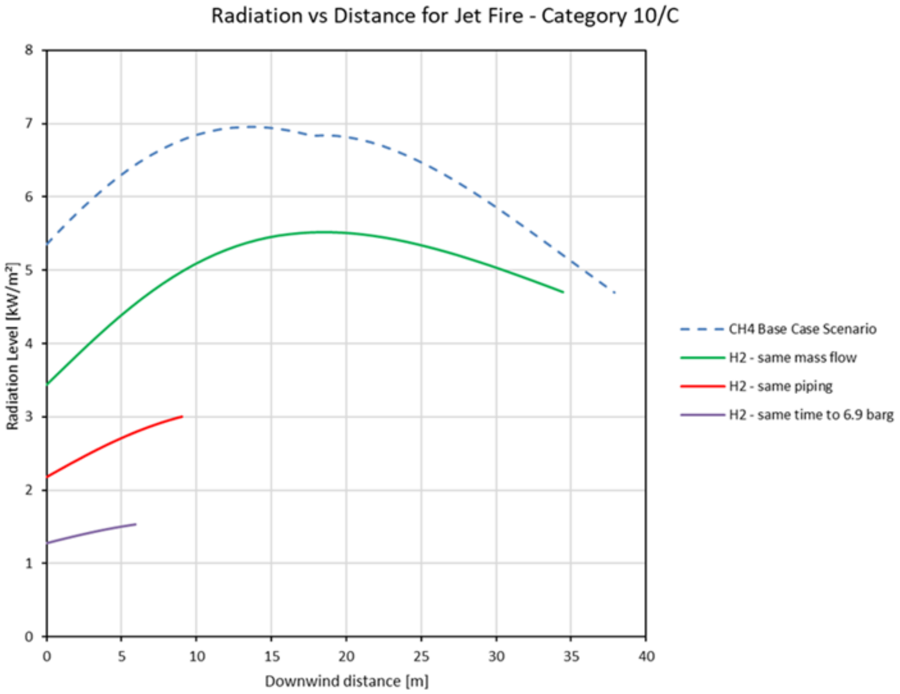


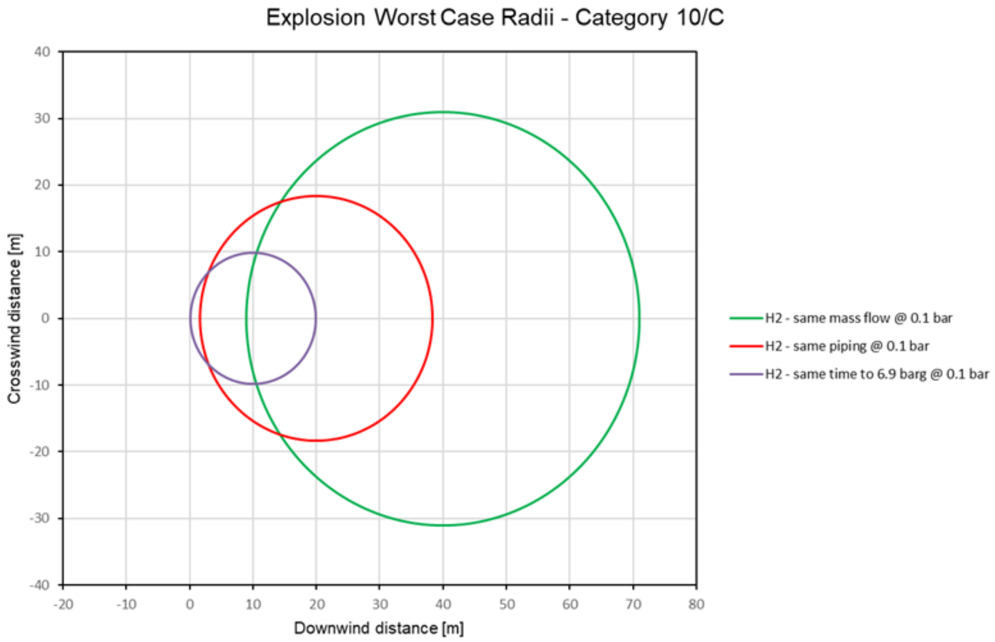
Figure 2 Heat Radiation calculation for the weather scenario 10/C



Above results show that the ex-zones for the hydrogen cases are significant larger for the cases of “same mass flow” and “same geometry”. For the case of “same depressurization time” the size of the ex-zones are however similar. Due to the lower molecular weight, the depressurization is faster for hydrogen. There are substantial differences related to diffusivity in air between natural gas and hydrogen. In case of an ignition during the venting operation, the radiation levels for hydrogen are significantly smaller. As a consequence, the size of the sterile area may in principle be reduced for the case of hydrogen, in particular in case for the scenario "same depressurization time".

The minimum ignition energy for hydrogen is significantly lower compared to natural gas (0.017 mJ against 0.25 mJ) and in addition the flame speed for hydrogen is by an order of magnitude larger. In this respect pressure waves from explosion type scenarios should be assessed for the hydrogen cases. The figure below show contour lines at 0.1 bar, a value which often is used within Quantitative Risk Assessments to distinguish zones with and without lethal effects. It is noted that the explosion type pressure waves are occurring only for the cases of hydrogen.

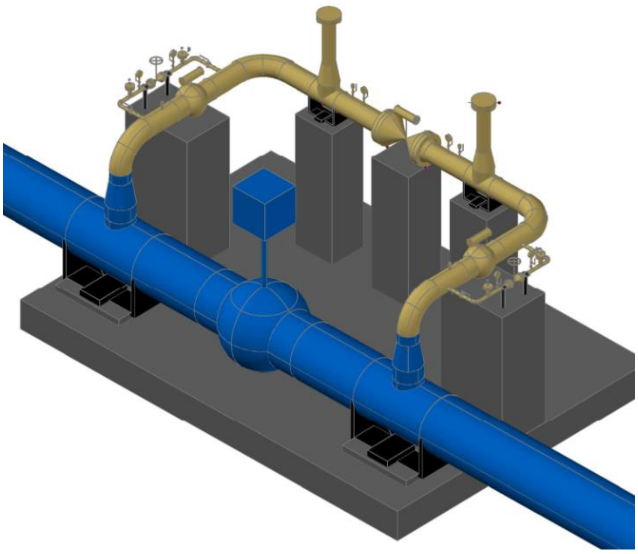
Figure 3 Contour Lines for pressure waves at 0.1 bar in case of Explosion type scenarios



2.2 Depressurization of pipeline

A similar assessment has been conducted for the case of depressurization of a pipeline section. Such activity – of course – is never in the interest of a pipeline operator, due to the negative impact to climate and the economic losses, however may become required during operation of the pipeline. Pipeline sections are usually depressurized at block valve stations, where the operation is not an automatic safety function from the ESD system but performed during maintenance. The piping arrangement for a typical block valve station is shown in the figure below. It was considered that the pipeline section shall be depressurized from 50 bar to 1 bar within 24 hours.

Figure 4 Arrangement for typical block valve station



A 10 km pipeline section, pipeline diameter DN 500 and vent size DN 150 has been assumed. The vent tip shall have a height of 2 m, during depressurization the max speed shall be again limited to Mach 0.7. Again the following calculations have been performed:

- Dispersion calculations for different weather scenarios
- Radiation from jet fire considering ignition during the venting operation
- Explosion type, pressure wave calculations in case of hydrogen

The results are shown in Figure 5, 6 and 7.

Figure 5 Ex-zones resulting from dispersion calculation for the weather scenario 10/c

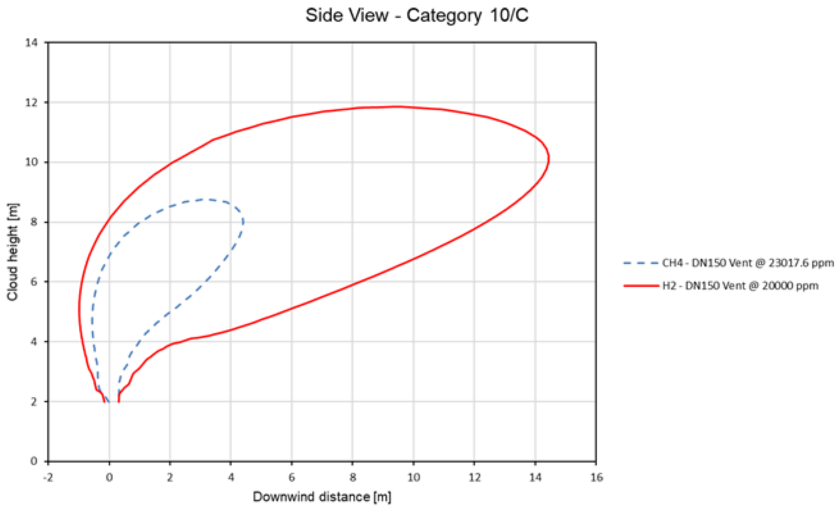


Figure 6 Heat Radiation calculation for the weather scenario 10/C

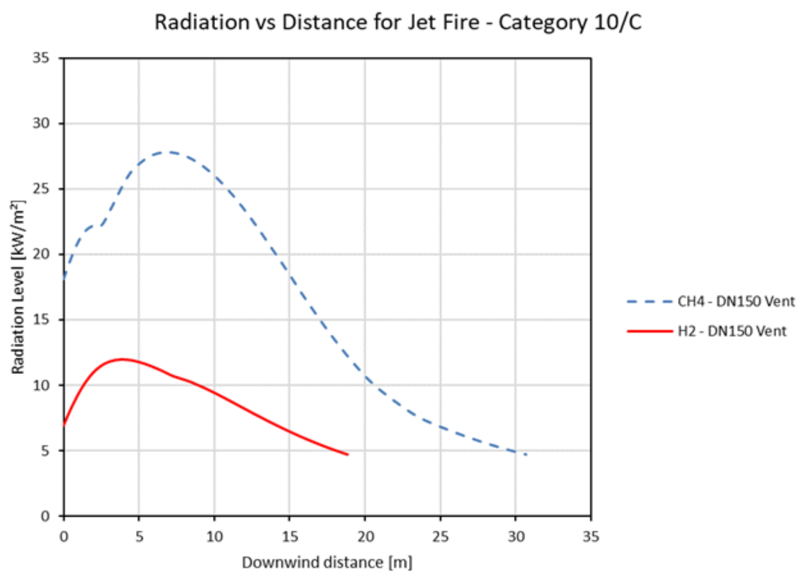
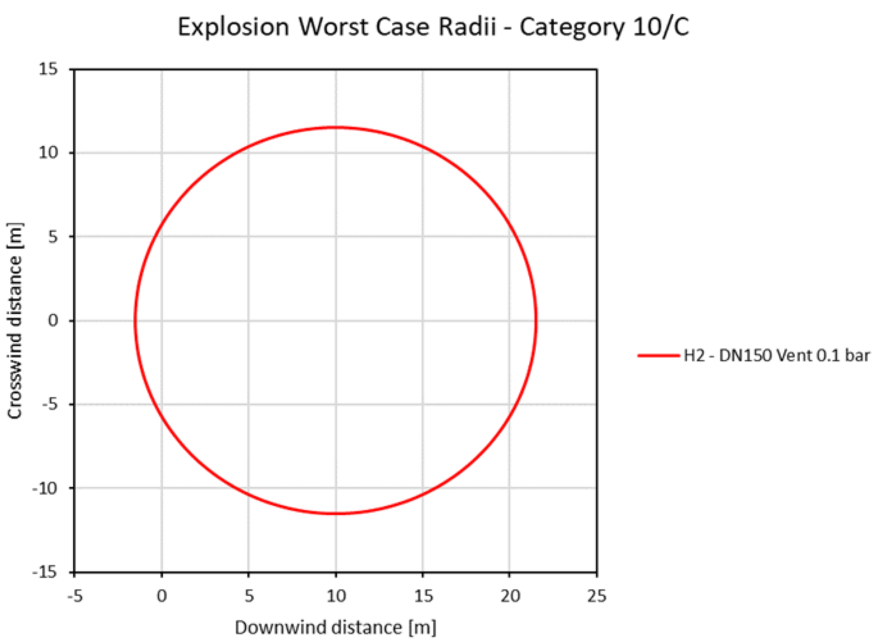


Figure 7 Contour Lines for pressure waves at 0.1 bar in case of Explosion type scenario



The dispersion calculation show significantly larger ex-zones for the case of hydrogen compared to natural gas. It is noted that the depressurization time of a 10 km pipeline section takes significantly longer compared to the depressurization of a compressor station (see above), the ex-zones for dispersion would therefore be available for several hours, which increases the likelihood of an ignition. It shall be noted that in case of natural gas the venting requirements are heavily discussed between the operators and the design engineers: Whilst engineering state that radiation levels in case of ignition during the venting are very high and may cause serious accidents with fatalities, operators often state the operation is avoided as far as possible and if conducted only during stable weather conditions. In case of a depressurization of hydrogen the radiation levels are lower compared to natural gas, but again significantly above 6.31 kW/m2 which could lead to serious injuries for personnel in the vicinity of the block valve stations. Due to the very low ignition energy and the long time required for such operation, the probability of such a case however is significantly higher. In addition to radiation there might be as well an explosion type phenomenon. The pressure rise within the centre of the explosion may have several bars amplitude, in case operators would stay with the contour lines shown this may lead to fatalities. Equipment would be severely damaged, if not completed destroyed. It is therefore strongly recommended that any venting of hydrogen should be conducted in a sterile area within sufficient safety distance to permanent installed equipment. A mobile type vent stack may be used, which may be connected to flanges at the vent tips as per Figure 4.

2.3 Summary of process considerations

In summary, the standards may not provide clear rules for depressurisation for hydrogen, however the rules applied for natural gas are considered as good engineering practice and should be used as well. From technical perspective the ignition and combustion properties of Hydrogen are very different to natural gas. Ignition of hydrogen (at a stoichiometric mixture with oxygen) requires a very low minimum ignition energy – which, as a consequence, makes hydrogen far more sensitive to ignition than natural gas. The heat radiation of a hydrogen flame is lower when compared to natural gas. In case of ignition the heat radiation effects due to jet fire may become a safety risk as well.

In addition for venting of hydrogen, there is risk of explosion pressure waves. Any venting operation shall therefore be conducted in a sterile area. Alternatively, a controlled flaring (i.e. with use of pilot burners) may be used for depressurization of compressor stations and or pipeline sections.

3 CONSIDERATIONS IN RESPECT TO MATERIALS AND EQUIPMENT

The main technical concerns and challenges which have to be resolved when selecting materials and equipment for Hydrogen pipeline transmission system are:

- Selection of reliable and durable hydrogen compression technology
- Potential degradation of the mechanical properties of materials which compromises the structural integrity
- Permeation of hydrogen through materials, resulting in an effective leak through the structure

3.1 Compressors

Two common compressor types used for compression of hydrogen are reciprocating (piston) and centrifugal (turbo) compressors. The design criteria specific to hydrogen compression in hydrogen transmission pipeline operation in addition to those for natural gas operations are generally:

- Compression power required for hydrogen is approximately three times higher compared to compression power required for natural gas (consequently higher number of compressors).
- For hydrogen compression, the compressor's materials also have to withstand the hydrogen embrittlement.
- Blade tip velocities for turbo compressors shall be 600-700 m/s, much higher than for compression of natural gas.
- Reciprocating compressors still have pretty low reliability and durability, to be used in large capacity hydrogen transmission pipelines (according to Siemens Energy the state-of-the art piston compressors are economical solution for transport capacities up to 750,000 Nm^3/h).

The larger scale development is expected until 2030 in positive displacement (reliability and durability) and centrifugal (efficiency and capacity) hydrogen compression technologies for transmission pipeline operations.

3.2 Pipeline Materials

As stated in the introduction, the technical standard framework in EU does not provide the specific requirements (yet) to specify materials and equipment for hydrogen pipeline transmission systems. EIGA IGC 121/14 Hydrogen Pipeline Systems prepared by the European Industrial Gas Association is considered a baseline for Hydrogen design in Europe, however is not mandatory but an industry recommended practice. For the specification of pipeline materials in many case therefore the ASME 31.12 is referred to. The code specifies two options for the design of new H2 pipelines:

- Option A (prescriptive design method) using a design factor F (location class) of at least 0.5 instead of 0.72 in Location Class 1, div. 2.
- Option B (performance-based design method) evaluating the material for hydrogen resistance and using design factor F as usual by ASME B31.8 (0.72 for Loc. Class 1, div.2). Option B define a series of requirements for new pipeline material, additionally to API 5L PSL2. This includes among other:
  - » Phosphorus content ≤ 0.015% wt
  - » Ultimate Tensile Strength (UTS) ≤ 110ksi (max. 755 MPa)
  - » Specified Minimum Yield Strength (SMYS) ≤ 70ksi (max. 485 MPa or X70)

» Fracture toughness shall be evaluated using the ASME BPVC Sec. VIII, Div. 3. Article KD-10

» Other optional/additional requirements in App. G might be considered useful to increase fracture toughness of the material:

- Carbon content ≤ 0.07% wt
- Carbon Equivalent (Pcm) ≤ 0.17% wt.
- Microalloyed steel
- TMCP shall be used in steel making

Option A leads up to 70% higher wall thickness and in this respect to an overdesign, which is not considered an economical solution for long pipelines. Option B allows to define and specify pipeline materials, which can be procured from the market in Europe with a “ready for H2” certificate.

For a pipeline project in the European Union with Design Pressure of 80 barg and Diameters of DN 700 and DN 300, taking steel material in grade L415ME (X60ME) and L360ME (X52ME) respectively, and design factors “F” for Location classes as per Table 3, the wall thickness calculation results in values as per Table 4 below. Such line pipes in material grades L415ME (X60ME) and L360ME (X52ME) are already available on the European market, including adequate certificates from the pipe suppliers.

Table 3 Design Factors

Location Class	ASME B31.12 Option A	ASME B31.12 Option B	ASME B31.8 (Natural Gas)
1	0.5	0.72	0.72 (Div. 2)
2	0.5	0.6	0.6
3	0.5	0.5	0.5
4	0.4	0.4	0.4

Table 4 Wall thickness calculation

Nominal Size	Material Grade	Location Class	ASME B31.12 Option A	ASME B31.12 Option B	Difference
DN 700	L415ME	1	17.48	10.31	69.5%
		2	17.48	12.70	37.6%
		3	17.48	15.88	10.1%
		4	22.23	19.05	16.7%
DN 300	L360NE	1	7.92	5.56	42.4%
		2	7.92	7.14	10.9%
		3	7.92	7.92	0.0%
		4	9.53	9.53	0.0%

3.3 Valves

A pipeline system, i.e. pipeline and compressor station(s), requires a large number of valve types for with different purposes (isolation, safety shut-off, control etc). Generally those valves are designed in accordance with API 6D standard or equivalent European standard EN 13942. It is not expected that valves for hydrogen pipeline shall differ, in their essential form, from valves for natural gas pipelines.

The design criteria for valves in high pressure hydrogen transmission pipeline systems to be considered in addition to natural gas operations, based on engineering experience and best practices, are generally:

- Production of valve components by forging is preferred over casting
- Carbon steel materials shall be selected from the grades with hardness lower than 230 HB and SMYS lower than 360 MPa
- Valves made from cast iron or ductile iron shall not be used in hydrogen service
- Martensitic stainless steel, nickel and nickel alloys are not recommended for valve components in hydrogen service
- Valves shall be pressure tested with helium as test medium (as required by AMSE B31.12)
- In order to prevent the potential for hydrogen leakage, it is recommended to provide:
  - Double seals or sealing packs for stem sealing and valve body flanges
  - Leak test for each individual housing
  - Preferably welded valve housing
- Actuator type shall be electric or electro-hydraulic
- Valves should be provided with fugitive emission type test certificates in accordance with EN ISO 15848-1

3.4 Pressure Vessels (Filter-separators, Pig Traps)

The reputable manufacturers of pressure vessels for gas transmission pipelines (such as filter separators, suction scrubber vessels and pig traps) are generally familiar with hydrogen effects on materials for manufacturing vessels and weldments. Their experience with hydrogen effects and possible damage is coming either from pipelines in sour service (HIC and SOHIC) or pressure vessels in hydrogen operations in refineries (HTHA). The design criteria for pressure vessels in high pressure hydrogen transmission pipeline systems to be considered in addition to natural gas operations are generally:

- Materials for construction of pressure vessels have to be qualified for hydrogen service in accordance with ASME BPVC Section VIII Division 3 Article KD-10

- Hardness of carbon steels shall not exceed 22 HRC. The same is valid for welds (weld materials and heat affected zone)
- Nozzles shall be integral reinforced type

4 WELDING CONSIDERATIONS

4.1 General Aspects

The following sections refer specifically to the requirements of field welding, i.e. production welding of the pipeline and the station piping. Generally, the welding process for a new H2 pipeline system is not far from those processes used in natural gas pipelines. It is advisable to consider a semi-automatic welding process in order to have more control over the final weld quality and prevent hard spots. Quality assurance and NDT procedures should include the test of 100% of <u>all</u> weld (either by automatic UT or RT). Additional welding requirements to the conventional natural gas pipeline would include the following:

- Shielding gas containing hydrogen shall not be used for the welding process
- Electrodes shall be used which limits the hydrogen deposition to the weld (e.g. 4 mL/100g (H4) mentioned in ASME B31.12 as a limit)
- Welding process shall ensure low residual stresses, e.g. by selecting and controlling the steel composition. Additional post-weld heat treatment should be avoided whenever possible for pipeline construction.
- Measurement of the hardness on the weld area, the Heat Affected Zone (HAZ) and the parent metal is already part of the WPS qualification. Hardness measurement on field welds with portable testers in the surface should be added as part of the QA/QC. Limits of 250 HV10 for field welds, 235 HV10 for factory welds and 200 HV10 for station ping are considered in ASME B31.12 and may be used as starting point.

Above requirements may have a direct impact on costs and the time schedule of a new pipeline construction, in particular:

- Costs: welding processes require more expensive electrodes and more expensive welding processes. Semi-automatic and automatic welding methods are more complex and performed only by experienced EPC contractors (keyword availability).
- Time schedule: there is limited impact to the time schedule to the welding itself. However, adding hardness tests to the QA/QC of the field welds might add more time to the NDT inspection of each weld due to surface preparation requirements for this test. Reducing the frequency of the hardness test might possibly be discussed. However, whenever hardness tests fails to meet the requirements, this may have a strong impact to the further pipeline construction.

4.2 Special qualification of WPS

A higher complexity is added to the prequalification of the WPS. The requirement in principle is to control fracture toughness and therefore destructive testing of the qualification welds shall include certain tests as defined in Option B of ASME B31.12.

One important point is to be mentioned: ASME B31.12 specify fracture toughness tests for the welds in main pipeline material (Sec. PL-3.7.1-(b)(2)). However, it does not clearly state if the material toughness shall also be part of the qualification of WPS for field welding. Since the suitability to transport hydrogen shall be demonstrated to the authorities, it is however strongly recommended to perform the fracture toughness tests as in ASME B31.12 also for the qualification of the WPS for the field construction of a new pipeline.

For the evaluation of the fracture toughness under hydrogen service, the K_{IH}, test procedure as per ASTM E1681 is requested in ASME B31.12 Option B (BPVC Sec. VIII, Div. 3, Art. KD-10). Acceptance criteria is set at 55 MPa(m)$^{1/2}$ for all materials.

Experience tells that tests according to ASTM E1681 in constant load will not show any crack propagation at the end of the testing period. In this case however the direct impact is, that K_{IH}(actual) cannot be calculated. It should therefore be considered to use ASTM E1820 under H_2-conditions instead. The advantage of this procedure is, that direct stress intensity factor can be calculated by measuring the elastic-plastic fracture curve, instead of the mentioned ASTM E1681.

In respect to the time impact of these tests the following can be stated: On the one hand, additional testing as per ASTM B31.12 for Option B pipelines (fracture toughness test) should be considered in the lead time of pipe material purchase. Pipe mills with in-house testing facilities (for hydrogen) are capable on reducing the testing for ASME B31.12 certification to a couple of weeks. Pre-qualified pipe manufacturing routes (e.g. X70 at a specific maximum wall thickness) can be used for the certification of H2-ready pipes and reduce cost and time to the purchaser as well. In case such in-house testing facilities are not available from the pipe supplier/mill, an external lab has to be engaged for these tests and a certification timeline of 3 to 6 months should be considered before start of pipe production. Due to a high demand on these type of tests, additional 1 to 5 months may need to be added as “waiting list”.

For the qualification of WPS by a construction company, this will always require the engagement of an external laboratory capable to perform the tests under hydrogen environment. A similar timeframe can be expected: 1 to 5 months in the waiting list plus additionally 3 to 6 months for the tests itself. It is noted that currently there is a very limited number of laboratories which can make such qualifications of the WPS. The WPS qualification need to commence immediately after an award to a construction company, due to the relative large additional time requirements.

5 CONCLUSIONS

As mentioned in the paper, in many aspects there are no applicable and/ or no harmonized norms and standards available for the development of H2 Pipeline system projects.

The task "plan a new H_2-Pipeline" can be tackled from an engineering perspective, e.g. by using similar approaches as conducted for natural gas and adapting to the specific parameters and properties of hydrogen.

The paper has presented examples on process considerations, such as depressurisation of a compressor station and a pipeline section. It was shown that care need to be taken when adapting such approach, as additional phenomena may need to be considered in case of hydrogen.

For the specification of pipeline materials the ASME 31.12 is often applied. The standard provides two options, i.e. a prescriptive design method leading to conservative and in many cases non-economical results and a performance based approach, which requires significant more effort for testing and quality control.

A similar statement can be made for the specification of valves and pressure vessels where again rules from AMSE B31.12 and ASME BPVC may be applied from engineering perspective.

The field welding process has additional requirements compared to conventional natural gas pipeline, in particular extensive measurements of hardness and the prequalification route of the WPS, which may have significant impact on the realisation time of pipeline construction.

Whilst an engineering approach may be considered from a technical perspective as adequate, the issue becomes substantially more complicated during the certification processes. In fact, this certification process has less to do with proofing sound engineering which can be achieved without the use of standards, but with limiting the liability of the planer, certifier and operator. Without specific H_2-specific requirements mentioned on EN-Standards, this leaves it open to each single EU member country (even each federal state) to ask for different certification procedures for a new pipeline. With 27 member states and pipelines crossing borders everywhere, this does not specially easy-up the work of the engineers.

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