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Assessment of Requirements for OCTG Connections in Hydrogen Storage Wells

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Abstract

Storage safety, especially ensuring the gas sealability of hydrogen storage wells, needs to be carefully managed. Premium OCTG connections are used to connect casing and tubing pipes in these wells. Vallourec Research and Development department has investigated a new qualification testing protocol for hydrogen storage to properly validate connections for such application.

The existing qualification standard for gas well was designed for the oil and gas industry and does not consider the specificities of hydrogen storage. The lifecycle of hydrogen storage is also expected to be different from standard gas underground storage. The approach is based on two main steps. In theory, hydrogen presents a higher capacity to leak through seals compared to methane or helium. In the first step, several gases are investigated to assess the sealability capacity of a connection with a metal-to-metal seal.

Leaks detections devices by vacuum and accumulation with spectrometry were compared and assessed during this phase. For the second step, a dedicated connection test flow-chart is elaborated to consider the specific lifecycle of the hydrogen storage.

The first test program involves several gas mixtures including different concentrations of hydrogen. The purpose of these tests is to determine which kind of gas mixture could be used for the future connection tests to assess 100% hydrogen gas content with the lowest representative hydrogen content to facilitate testing. It was demonstrated that the accumulation leak detection method allowed a better sensibility for the leak detection up to 10-7 mbar.L/s. The conclusion of this first phase is that up to 470 bars the metal-to-metal seal behavior is the same for the different hydrogen concentration studied. In the second phase, storage lifecycle was studied. A connection test protocol was created to reflect the storage with a seasonal cycle and a daily cycle of loading and unloading when the storage well helps to cope with intermittencies of hydrogen production from renewables. This second test program was performed in full-scale in 9-5/8" 47.00 ppf L80 on our latest generation of advanced premium T&C connections to assess the hydrogen sealability performance with positive results. These two test programs have demonstrated a significant improvement in the performance assessment of connections with metal-to-metal seal in these hydrogen storage wells.

Large scale underground storage of hydrogen will be instrumental in global decarbonization. As hydrogen is a flammable, greenhouse gas, and more prone to leak, all the well completion and production equipment

will need a specific validation. The current accepted standard used to assess connection performance is API RP 5C5, which is not fully relevant for hydrogen storage applications.

Introduction

In underground storage, the hydrogen is injected through a tubing composed of steel pipes and connections.

The OCTG connection is a major component able to ensure the structural integrity between the pipes of the casing and the tubing in the well. One connection is doing the junction between 2 pipes. API SPEC 5B discloses the design of API connections either with round thread shape or trapezoidal thread shape. These connection design have a limited performance in tension and especially in sealability as the tightness is only carried out with the thread compound inside the connection (Bollfrass, 1985). Therefore, these API connections will not be covered in this paper. There is a second category of connection, so called proprietary connection or premium connection (Figure 1). Each design is unique, and the performances of these connections are assessed through the API RP 5C5 for wells in oil and gas applications. The design of these connections presents at least one metal to metal seal providing better sealability performances than API connections (Sugino, et al., 2010).

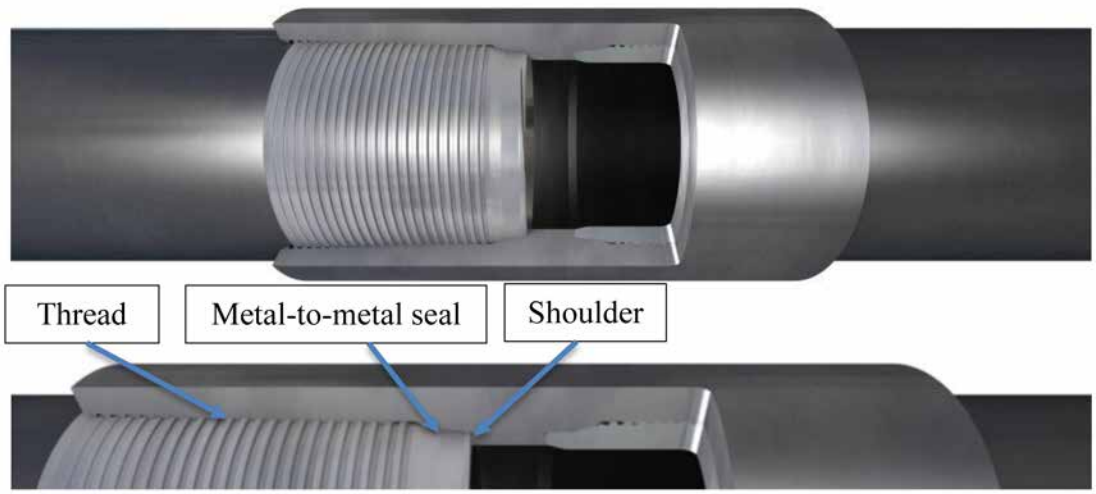

Figure 1—Example of premium OCTG connection

The API RP 5C5 gas tracer used in the test protocol are most of the time helium or nitrogen or a mixture of these 2 gases. However, for hydrogen storage this leak detection methodology cannot be sufficient as this molecule can be more prone to leak. As demonstrated, hydrogen exhibits higher leak ratio than helium at 98atm (Mak, Gleason, Smith, & Karagozian, 2009). The hydrogen, as a gas tracer, seems necessary to assess the connection performance for hydrogen storage application in the well. For safety reason, it can be also difficult to perform high pressure test at 100% hydrogen. In this paper different hydrogen contents are investigated to determine if the leak ratio is the same with different percentage of hydrogen.

Different types of flow leaks

There are different types of flow to determine the leak rate. The 2 main flows are the laminar flow and the molecular flow. They are driven by two different models and equations. The leak rate in laminar flow is described through the Poiseuille Law. This flow is driven by the dynamic viscosity of the gas. Molecular flow is described by the Knudsen law and here mainly driven by the mass of the molecule.

Then, at the same temperature and pressure, it is possible to compare leak rate of gases between each other by using these 2 formulae (NASA & Jet Propulsion Laboratory, 1969). The leak could be generated by a main leak path in the seal or by multiple small leak paths in the seal. In case of a main leak path, Poiseuille equation and dynamic viscosity should be used for leak conversion between the gases (Eq. 1). Whereas for multiple small leak paths, Knudsen equation and molecular mass should be preferred for the conversion (Eq. 2).

Laminar flow leak rate conversion:

$$q2 = \frac{\eta 1}{\eta 2} q1 \tag{1}$$

Molecular flow leak rate conversion:

$$q2 = \sqrt{\frac{\mu 1}{\mu 2}}\, q1 \tag{2}$$

In these equation q1 is the gas leak flowrate of reference and q2 the gas leak flowrate to convert. In premium connection with metal-to-metal seal, leak behavior is not known. No data nor studies are available to determine if, in case of leaks, the seal will behave in laminar or molecular flows. In absence of such knowledge the leak conversion should be performed both for laminar and molecular flows.

Comparison with other gases

The gas leak ratio comparison is carried out on:

- Helium, as it is the refence of most of leak detection test
- Hydrogen, the gas to evaluate
- Methane, as it is the most critical gas application validated through the API RP 5C5
- Nitrogen, as it is also used as a reference gas or also combined with helium

The reference used in the comparison of the different gases is helium. Indeed, it is the most used gas to detect leak in many laboratories. The leak ratios have been calculated with the values of the Table 1.

Table 1—Dynamic viscosity and molecular mass values used for the leak rate conversion

Gas	Dynamic viscosity at 25°C (Po)	Molar mass (g/mol)
Helium (He)	$1.9846.10^{-4}$	4.003
Hydrogen (H_2)	$0.89154.10^{-4}$	2.016
Methane (CH_4)	$1.1067.10^{-4}$	16.043
Nitrogen (N_2)	$1.7805.10^{-4}$	28.013

In Figure 2 the helium leak ratio is set at 1 as it is the reference.

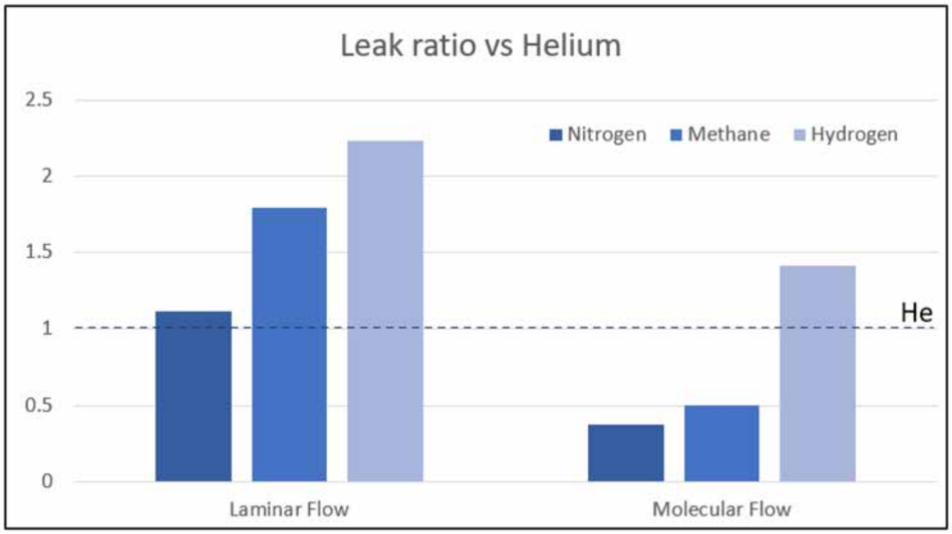

Figure 2—Leak ratio comparison of nitrogen, methane, and hydrogen vs. Helium

In laminar flow the hydrogen is likely 2.2 times more prone to leak compared to helium. For instance, it means that at the same conditions of pressure and temperature, a helium leak at 1 cm3/h would be at 2.2 cm3/h with hydrogen.

In molecular flow the difference is less important. The hydrogen is likely 1.4 times more prone to leak vs. helium. However, with this flow the difference with nitrogen and methane is more important.

As a first conclusion the hydrogen is the gas with the highest leak sensitivity among the gases evaluated. Using helium and/or nitrogen as gas tracer cannot be suitable to assess premium connection performances for hydrogen storage: a dedicated evaluation is required.

Hydrogen content experimental data

Given flammability and explosivity profile or pure hydrogen, a representative fluid has been studied: the aim is to combine relevant leak evaluation and easier conditions for demanding tests in the laboratory. Theoretically, the leak rate should be higher at 100% hydrogen, but sealability tests have been performed to assess if the gas test used for the future hydrogen storage protocol could be lower than 100% hydrogen and even better in a nonflammable area. For instance, hydrogen is not flammable below 5% when it is mix with 95% nitrogen.

A proprietary premium connection in 9-5/8" 47.00 ppf in L80 has been tested at 470 bar with different hydrogen contents:

- 100% hydrogen
- 50% hydrogen / 50% nitrogen
- 5% hydrogen / 95% nitrogen

The accumulation method was chosen as leak detection method to have enough sensitivity for helium, nitrogen and hydrogen gasses (Lejeune & Cougnon, 2012).

The following sequence has been followed for accumulation test method (Figure 3):

Figure 3—Test of the connection at 470 bars with leak detection by accumulation method

- Each side of the connection is covered with a tarp sealed with double-taped joint
- Two sniffers connected to a spectrometer are placed in these two tarps to measure the leak flow rate
- The specimen is filled with test gas pressurized up to 470 bars of internal pressure at ambient temperature
- Gas leak flowrate is measured on each side of the connection by the sniffers at T0 (when the 470 bars pressure is reached) and the second one is taken after two hours of holding time

The results presented in the Figure 4 shows the leak flow rate through the premium connection. The leak flow rate is calculated according to EN 1779 (European Standard, 1999).

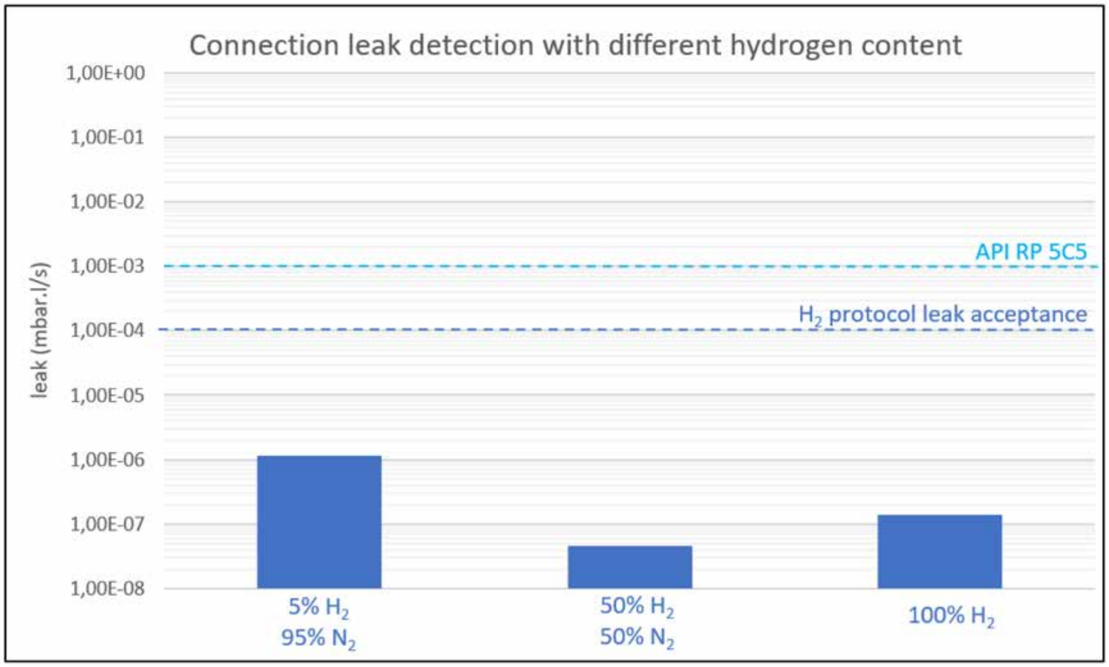

Figure 4—Leak measurement at 470 bars of internal pressure with 5%, 50% and 100% hydrogen

The results demonstrates that the detected flow rate is almost one thousand time smaller than the API RP 5C5 leak acceptance criteria (0.9 cm^3/15 min corresponding to 1.0 x10^{-3} mbar.L/s). Surprisingly the gas with 5% hydrogen and 95% nitrogen seems to have a bigger leak rate than with 100% hydrogen. However, these results are close to the leak sensitivity detection due to the presence of air in the tarp with naturally around 5.10^{-5}mbar.L/s of hydrogen. Therefore, the detected values, and differences between the gases, are deemed non-significant.

These results exhibits that the hydrogen content does not significantly change the leak rate for test at high pressure. Then the gas content for the hydrogen test protocol with combined load will be 5% hydrogen and 95% nitrogen. As hydrogen storage application is more severe, the proposed targeted leak acceptance criteria have been decreased to 10^{-4} mbar.L/s, ten times lower than API RP 5C5 criteria.

Hydrogen storage wells life cycles

The life cycle of the hydrogen underground storage needs to be fully understood to adapt the test protocol as close as possible to the actual application. The main parameters to consider are the tension and compression levels, temperature, pressure range, bending level and the number of cycles.

Daily and seasonal cycling

After discussions with several operators, two different potential usages have been identified. The first one is linked to the renewable energies producing energy daily. For instance, when the windmills produce too much, and the energy consumption demand is low. The over production of electricity can be used to generate hydrogen with electrolyzers and store this hydrogen underground. The storage can be also more seasonal when the solar resources are more important in summer (Parra, Valverde, Javier Pino, & Patel, 2019).

For daily storage, the temperature is quite stable, and the pressure variation limited. The underground storage will not be empty and then full in one day. The number of pressure cycles is high (about 5500 cycles representing one cycle per day for 15 years), but with shallower variations of pressure around the seasonal trend. The tubing will remain in tension.

For seasonal storage, the pressure range will change significantly, typically between minimum and maximum pressure, and the temperature will also change. The number of cycles is limited (we performed 30 cycles representing 2 cycles per year for 15 years). Due to the temperature change the tubing can be either in tension or compression in the most demanding case.

In the pilot salt cavern hydrogen storage of Etrez (France), the pressure range was between 60 and 190 bars (Pique, Thoraval, Lahaie, & Sarriquet, 2021). In salt cavern the temperature range is also evolving, the minimum temperature could reach about 5°C and above to 55°C as the maximum temperature in the well (Bérest & Louvet, 2020). The hydrogen protocol should at least cover these pressure and temperature ranges to suit for underground storage.

Loads in the well

A fit for purpose hydrogen protocol for premium connection was created to represent the different loadings in a hydrogen underground storage (Figure 5). This protocol is composed of 4 phases:

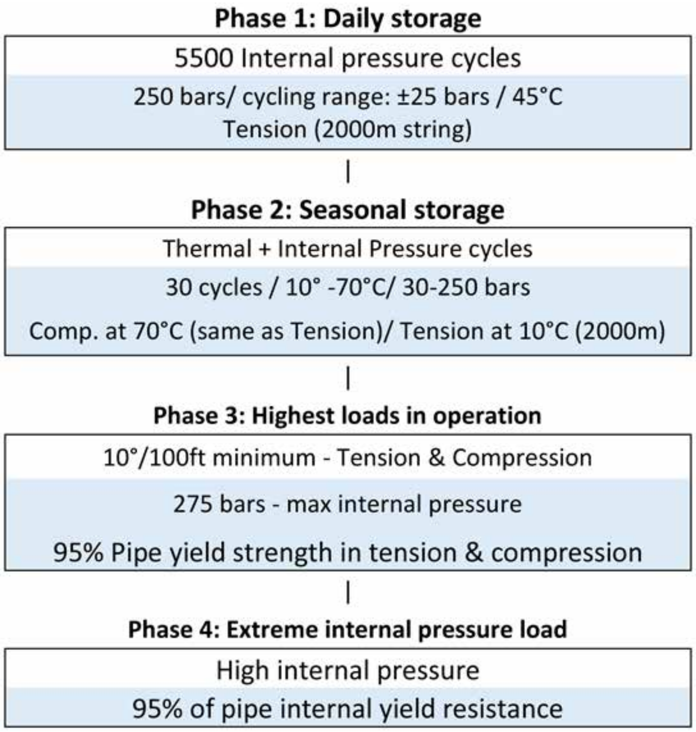

Figure 5—Hydrogen test protocol for premium connection flow-chart

- Phase 1: 5500 internal pressure cycles at 250 bars with a variation of +/- 25 bars. Tension applied corresponding at 2000m of string
- Phase 2: 30 cycles with temperature variation of 10°C-70°C. Pressure range 30 – 250 bars (Figure 6)
- Phase 3: Internal pressure with the highest combined load of tension and compression with bending following the loading points (LP) from API RP 5C5 in series B.
- Phase 4: Internal pressure loading up to 95% of the pipe yield strength

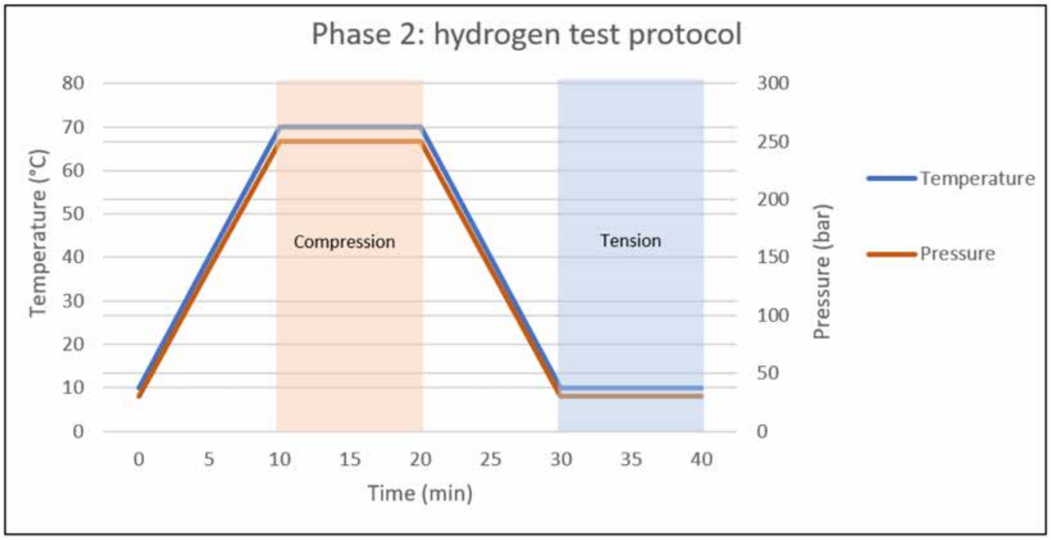

Figure 6—Phase 2 test protocol cycle x30

Full-scale tests

As explained above, the connection in the well is subjected to several loadings working simultaneously. Up to now the assessment of premium connection is not possible by simple laboratory test (i.e., non full-scale test). The digital simulation, the combined loads, the interaction with the thread compound and the metal-to-metal seal behavior cannot be fully captured without carrying out a full-scale test. This is a test with final product at scale 1. Before launching these costly and time-consuming tests, several finite element analyses are conducted to determine the most critical seal and thread interferences. Then, the connection is going to be specifically machined with tight tolerances to the worst tolerance configuration.

Furthermore, the maximum loads to apply during this full-scale test are important. The maximum loadings point to be applied on the proprietary premium connection 9-5/8" 47.00ppf L80 are:

- 62.0 MPa of internal pressure
- 5,000 kN of tension and compression
- Bending up to 11°/100ft

To perform the hydrogen protocol a load frame able to pass combined load in tension, compression, bending and with different temperature has been used.

Test setup

In all situations, pressures are measured using calibrated transducers. For internal pressure tests, the pressure is generated by a gas mix of 95% Nitrogen + 5% Hydrogen. Tensions are measured using calibrated load cells or strain gauges applied on the frame cylinder rod (Figure 7). These devices are calibrated and certified.

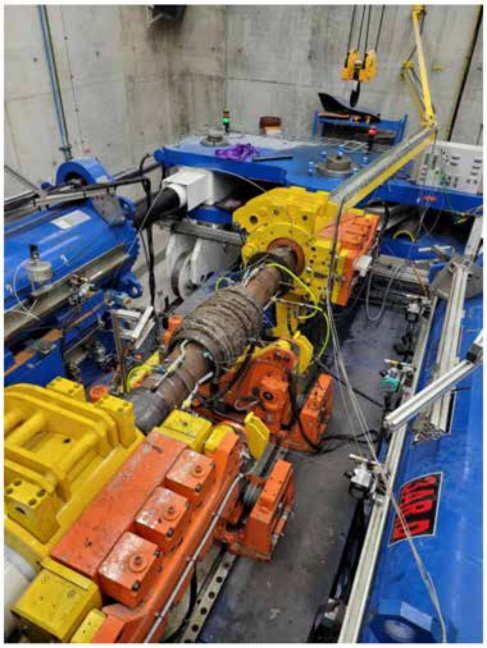

Figure 7—Load frame during hydrogen test protocol

Before the test, the leak detection device is set up and calibrated to measure Hydrogen mass instead of Helium mass. The leak detection is checked through bubble method detection and the analysis, with the mass spectrometer, of the gas present in the container allows to check the presence of hydrogen.

Full scale test results

In general, the performance of a premium connection is represented with a VME. The x-axis represents the tension with the positive value and the compression in the negative value. On the y-axis, the positive value represents the internal pressure and the negative value the external pressure (no external pressure test then not represented here in Figure 8)

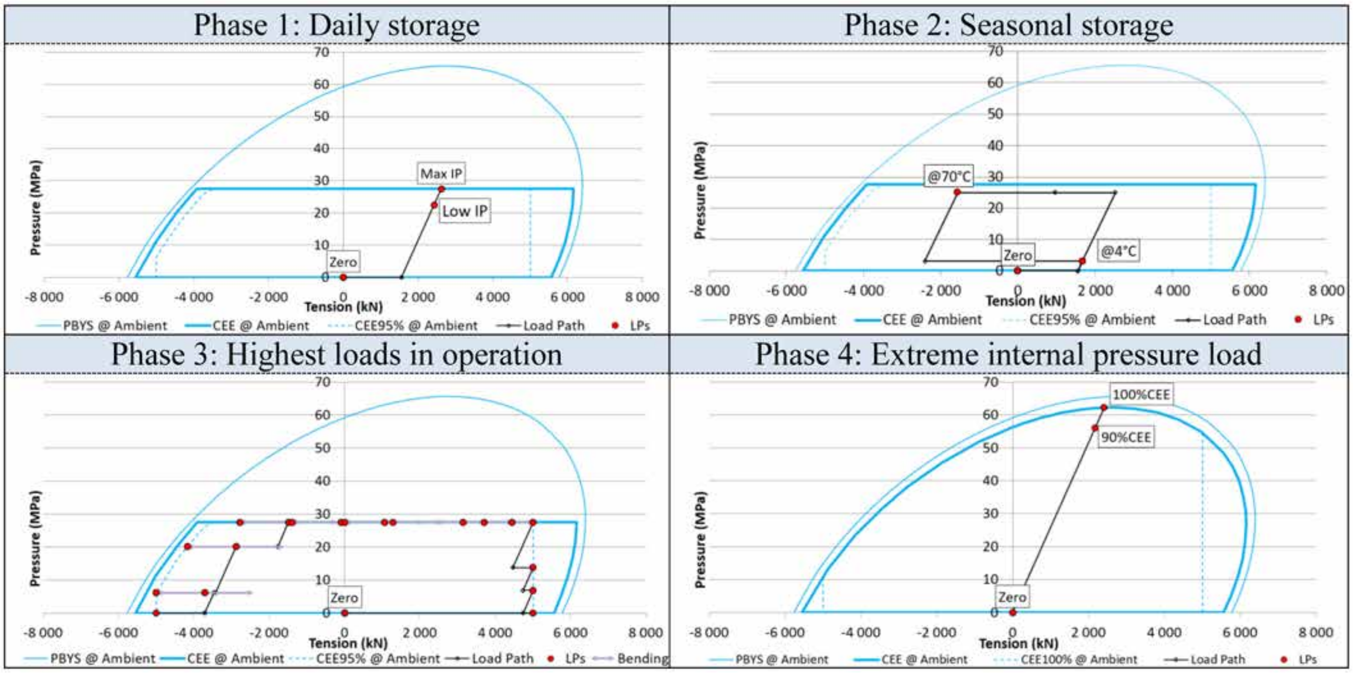

Figure 8—Von Mises Envelope of hydrogen test protocol with 5% H_2 and 95% N_2

The test performed demonstrates the feasibility of such full-scale test. For each phase, the leak detection was below the 10^{-4}mbar.L/s threshold defined previously, and also well below the 10^{-3} mbar.L/s threshold of API RP 5C5 standard. The proprietary premium connection 9-5/8″ 47.00 ppf L80 successfully passed the hydrogen test protocol without any leakage.

Conclusions

The need to develop a specific test protocol for threaded connection for hydrogen storage has been identified. This paper details also the need to use hydrogen as gas tracer for this kind of application because this molecule is more prone to leak compared to other gases.

For safety reason, it is difficult to perform high pressure test with a high hydrogen content. It has been also demonstrated that it is not necessary to use a gas with 100% hydrogen to perform this test protocol. A lower content of hydrogen, for instance 5%, is enough to measure the leak rate with the same efficiency and then allowing to perform test at high pressure in a safe manner.

Once the gas mixture and the test protocol are defined, a full-scale test has been carried out successfully on a 9-5/8″ 47.00# L80 on our latest generation of advanced premium T&C connections to confirm the feasibility of the hydrogen protocol and to validate the improvement in connection assessment with metal-to-metal seal for underground hydrogen storage applications.

More tests and Finite-Element Analyses are being carried out on selected dimensions and configurations, to validate the product line for hydrogen underground storages and feed future standardization work on the sealability tests of premium connections in hydrogen gas.

Nomenclature

API = American Petroleum Institute
CEE = Connection Evaluated Envelope
Hydrogen = Dihydrogen (H_2)
LP = Loading Point
OCTG = Oil Country Tubular Goods
Po = Poise
ppf = pound per feet
PBYS = Pipe Body Yield Strength
q = Leak flowrate
T&C = Threaded and coupled
VME = Von Mises Envelope
η = Dynamic viscosity
µ = Molar Mass

Metric

atm	x10^5	= Pa
bar	x10^5	= Pa
ft	x0.3048	= m
kN	x1000	= N
mbar.L/sec	x10	= Pa.m^3/s
MPa	x1000000	= Pa
Po	x0.1	= Pa.s

References

Bérest, P., & Louvet, F. (2020, September 11). Aspects of the thermodynamic behavior of salt caverns used for gas storage. *Oil & Gas Science and Technology*, **75** (57). doi:https://doi.org/10.2516/ogst/2020040

Bollfrass, C. (1985, June 1). Sealing Tubular Connections. *Society of Petroleum Engineers*. doi:https://doi.org/10.2118/14040-PA

European Standard. (1999). EN 1779. Non-destructive testing - Leak testing - Criteria for method and technique selection.

Lejeune, H., & Cougnon, L. (2012). Alternative Tracing Gas Mixtures for Valve Fugitive Emission Measurements. ASME Pressure Vessel and Piping Division Conference. Toronto.

Mak, C., Gleason, L., Smith, O., & Karagozian, A. (2009, May). Hydrogen-Helium Leak Detection at Elevated Pressures and Low Temperatures. *AIAA Journal*, **47**(5). doi:https://doi.org/10.2514/1.39952

NASA, & Jet Propulsion Laboratory. (1969). *Leakage Testing Handbook* (Revised ed.).

Parra, D., Valverde, L., Javier Pino, F., & Patel, K. (2019). *A review on the role, cost and value of hydrogen energy systems for deep decarbonation* (Vol. **101**). (M. 2019, Ed.) Renewable and Sustainable Energy Reviews. doi:https://doi.org/10.1016/j.rser.2018.11.010

Pique, S., Thoraval, A., Lahaie, F., & Sarriquet, A. (2021). Preliminary risk assessment for tests planned in a pilot salt cavern hydrogen storage in the frame of the French project STOPIL-H2. International Conference on Hydrogen Safety. Edinburgh.

Sugino, M., Nakamura, K., Yamaguchi, S., Daly, D., Briquet, G., & Verger, E. (2010). Development of an innovative high-performance premium threaded connection for OCTG. Offshore Technology Conference. Houston. doi:https://doi.org/10.4043/20734-MS