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## Innovative Solutions for Enhanced Safety of Onsite Hydrogen Storage

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## ABSTRACT

The decarbonization of heavy industries and mobility—such as refineries, green ammonia, e-fuels, and steelmaking—relies increasingly on low-carbon hydrogen, often produced via electrolysis. This introduces variability in supply, making reliable hydrogen storage essential. Where large-scale underground storage (e.g., salt caverns) is unavailable, onsite storage becomes critical, typically requiring capacities from a few to several tens of tons.

This paper presents the development, qualification, and safety validation of a novel onsite underground compressed hydrogen storage solution. The system features vertically oriented subsurface pressure vessels designed for large capacity, enhanced safety and minimal space requirement.

The research details the validation for hydrogen service of the materials and connections used in this solution. It introduced the full technology qualification process based on DNV RP-A203, including results from a demonstration project in France. Safety performance is assessed through Computational Fluid Dynamics (CFD) and Quantitative Risk Assessment (QRA), comparing this solution with conventional above-ground systems.

The paper synthesizes lessons learned from design, testing, and risk modeling, and evaluates the technology's applicability to hydrogen and derivative production. It demonstrates how this compact, modular, and safer storage option supports project integration and accelerates permitting in the hydrogen economy.

Key words: hydrogen storage, hydrogen embrittlement, materials, tight connections, safety, Quantitative risk assessment (QRA).

## INTRODUCTION

The transition to a low-carbon economy necessitates the deployment of hydrogen as a clean energy carrier. Hydrogen can be produced from renewable sources via electrolysis, but its intermittent production profile requires robust storage solutions to ensure a steady supply to downstream applications such as green ammonia, e-fuels, and steelmaking. Onsite hydrogen storage becomes essential in locations where underground salt caverns or pipeline networks are not available.

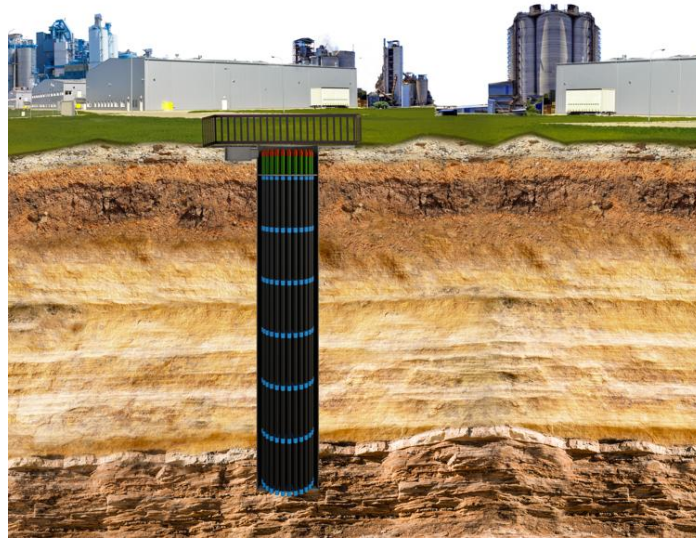
However, hydrogen's physical and chemical properties pose significant challenges. Its low molecular weight leads to high diffusivity and leakage potential. Hydrogen embrittlement (HE) is a critical concern for metallic materials, especially steels, as it can lead to premature failure. Additionally, hydrogen's flammability and explosivity require stringent safety measures. These challenges complicate permitting processes and necessitate innovative storage solutions that are compact, safe, and compliant with regulatory standards.

This paper will explore innovative designs to ensure such large-scale (1-100 tons), onsite, hydrogen storage, while keeping it safe and compact, and will detail the technical basis to validate such approach, looking at the material selection, tightness assessment and overall compliance and safety evaluation.

In particular, given the low volumetric density of hydrogen (c. 20 kg/m<sup>3</sup> at 280 bar and 20°C), large storage volumes are required. One way to increase the volumes from pre-existing type I cylinders<sup>1</sup> is to extend the length of seamless pressure vessels, by connecting several seamless pipes using hydrogen-tight metal-to-metal seals.

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<sup>1</sup> “Type I” cylinders refer to entirely metallic (usually made of steel or aluminum), monolithic (single material throughout, no composite reinforcement), pressure vessels. Under this classification, “type II” refers to cylinders made of a metal liner with composite wrap on cylinder hoop; “type III” refers to cylinders with an aluminum liner and full composite reinforcement and “type IV” are made of a thermoplastic liner with a composite wrap.



**Figure 1: Illustrative side view of the innovative Hydrogen storage architecture for onsite storage in an industrial environment.**

The proposed storage solution features a vertical subsurface architecture comprising an inert containment cavity up to 100 meters deep and a shallow service cavity 2–3 meters deep. The containment cavity eliminates ignition risks, while the open-top service cavity ensures natural ventilation and prevents hydrogen accumulation. This design significantly reduces the risk of vapor cloud explosions, as quantitative risk assessment will confirm.

## **TECHNICAL BASIS AND EXPERIMENTAL PROCEDURE**

### **Technical Basis: Materials Selection for Hydrogen Storage**

Steel-based vessels have been used for hydrogen storage, up to high pressures (500 bar and above), for decades: storage tanks are manufactured out of special carbon alloys (for instance, 34CrMo4 grade) and then properly heat treated to obtain the appropriate microstructure and mechanical properties.

Similarly, the design of large-scale pressure vessels for hydrogen storage requires careful selection of materials and manufacturing. The focus has been on metallurgies commonly used with threaded connections in the oil and gas industry for “OCTG products” – while offering expected high performance in hydrogen service. In addition, the aim has been to validate high yield strength (YS) materials, up to 110/120 ksi, to reduce the amount of steel required in the solution: assessment of performance with hydrogen is even more needed, as materials with higher YS may be more susceptible to hydrogen embrittlement.

Therefore, Vallourec has conducted extensive research on the hydrogen stress cracking resistance of seamless pipes, as documented in [1] and [2]. The studies evaluated fracture toughness and fatigue crack growth rates of various steel grades under 100 bar hydrogen gas. Fracture toughness tests were performed in two laboratories (A & B) in accordance with ASTM E1681 standard. All tested materials exceeded the ASME B31.12 Option B threshold of  $55 \text{ MPa}\sqrt{\text{m}}$  for KIH, confirming their suitability for hydrogen service.

Material	Lab	Number of specimens	$K_{Iapplied}$ (MPa. $\sqrt{m}$ )	Crack growth	$K_{IH}$ (MPa. $\sqrt{m}$ )
K55	A	4	129 132 136 159	Yes	106.3 105.8 116.5 125.6
	B	3	174-176	No	>87.0
L80 Type 1 Thickness : 21.2 mm	A	5	140-165	No	>70.0
	B	3	156-157	No	>78.0
L80 Type 1 Thickness : 65 mm	B	3	175-180	No	>87.5
T95	B	3	136-138	No	>68.5
C110	B	3	136-138	No	>68.5
P110	B	3	136-137	Yes	94.2 94.7 101.9
34CrMo4	A	4	140-143	No	>70.0
	B	3	117-118	No	>58.5

**Table 1: Fracture toughness values with constant displacement of a selection of steel grades, under 100 bar of H<sub>2</sub>.**

The constant displacement testing method described in ASME B31.12 is, however, not providing an accurate enough view of the respective performances of the materials, as explained in [2]. Therefore, Vallourec carried out additional tests with rising load methodology. These tests have been performed according to ASTM E1820, at 400 bar of hydrogen gas. Several materials with a yield strength ranging between 110 and 140 ksi were tested, of which the selected materials for the proposed hydrogen storage solution. 2 specimens were tested for each material.

Table 2 details the results of these fracture toughness tests and shows that the selected material comes with very high fracture toughness values, with  $K_{IH}$  typically in the range of 110-150 MPa $\sqrt{m}$ . It also shows much higher values for this special grade than the ones obtained for alternative P110 materials that were tested under the same conditions.

Material Grade	Actual Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	$K_{IH}(J0,2)$ (MPa.m <sup>0.5</sup> )
Selected C110 proprietary grade A	796	871	158
			110
Selected C110 proprietary grade B	803	880	121
			102
Alternative material A 110 ksi (P110)	862	930	70
			71
Alternative material B 110 ksi (P110)	923	990	46
			50

**Table 2: Fracture toughness values with rising load of a selection of steel grades under 400 bar of H<sub>2</sub>**

The targeted application is storage, which comes with significant fluctuations of pressure, depending on end-user application: for instance, in the case of hydrogen production by electrolysis, supplied by solar power, a day/night filling/emptying pattern would be expected. Thus, assessment of potential fatigue of the material under such cyclic stresses (and in hydrogen gas) is a key question to address.

The fatigue crack growth rate (FCGR) tests reveal that hydrogen accelerates crack propagation, especially at low load ratios and frequencies. However, the tested tempered martensitic steels