Risk-based inspection planning for hydrogen technologies: review of currents standards and suggestions for modification

IOP Conf. Series: Materials Science and Engineering 1193 (2021) 012075 doi:10.1088/1757-899X/1193/1/012075

Risk-based inspection planning for hydrogen technologies: review of currents standards and suggestions for modification

F Ustolin[1], D Wan[1], A Alvaro[1,2] and N Paltrinieri[1*]

[1] Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology NTNU, Richard Birkelands vei 2B, 7034 Trondheim, Norway
[2] SINTEF Industry, SINTEF, Richard Birkelands vei 2B, 7034 Trondheim, Norway

*Corresponding author: nicola.paltrinieri@ntnu.no

Abstract: The research addressing loss of integrity (LOI) for hydrogen containment technologies requires a multidisciplinary perspective. However, lack of collaboration between materials and process safety engineers is reflected in the theory addressing the LOI phenomena. Even though the potential degrading mechanisms related to hydrogen-metals interaction are being extensively studied, they are not explicitly considered by standards and recommended practices in relation to plant inspection planning. This inevitably introduces additional uncertainties while planning for inspections and predictive maintenance and leads to the necessity to address and consider generic mechanisms of material degradation within the framework of LOI development prediction. A review of the available standards and recommended practices for inspection planning is here conducted to identify how metal-hydrogen interactions are currently considered in terms of degradation mechanisms. Focus is given to risk-based approaches, which include the assessment of potential accident scenarios as consequence of LOI. In particular, the association of metal-hydrogen mechanisms with damage factors influencing the predicted LOI frequency is studied to understand their impact both on the risk and the inspection typology. Appropriate knowledge of material degradation mechanisms for hydrogen containment is of paramount importance as it allows not only for a correct design of the equipment of interest, but also for a suitable inspection and maintenance planning so to guarantee its integrity through an effective and informed risk-based approach. A few modifications to the current standards are suggested as a result of this work.

Keywords: Hydrogen containment, Risk-based inspection, Loss of integrity, Hydrogen damage, Standards.

1. Introduction

After the outbreak of the COVID-19 pandemic, the interest in renewable energy systems (RESs) for the energy transition skyrocketed [1]. One of the main drawbacks of the RES is its intermittence. This limitation may be surmounted by employing hydrogen as energy carrier in the solar and wind parks [2]. Although hydrogen has very peculiar properties that make it suitable for several applications, it is also a hazardous substance and different accident scenarios might arise if not properly handled. On the one hand, it is the most abundant element in the universe, potentially clean and renewable, non-toxic and with a high gravimetric energy content compared with the hydrocarbon fuels (lower heating value: 120 MJ kg^{-1} [3]). On the other hand, some few hydrogen characteristics raise the safety concern about its application in different processes and technologies. In particular, it is highly flammable and the size of its molecule is the smallest one when compared to the other existing elements. Therefore, it can escape from containment creating flammable jets or explosive clouds and diffuse in the materials due to its atomic and molecular size [4]. Depending on different parameters such as the operative conditions, several types of hydrogen damages (HDs) can manifest [5]. The material (often metal) in contact with hydrogen is then subjected to a degradation that is time dependent and that may lead to the loss of integrity (LOI) of the piece of equipment at a certain point.

Ustolin et al. [5] demonstrated that there is a lack of collaboration between materials and process safety researchers, suggesting that the LOI investigation for hydrogen technologies based on a multidisciplinary approach would be more suitable. This inadequate cooperation reflects in the theoretical knowledge on the LOI phenomena. Moreover, the outcomes of different studies on metal-hydrogen interaction mechanisms [6,7] are not yet included in the main standards and recommended practices for plant inspection planning despite being highly relevant with respect to LOI characterization and prediction. In fact, these documents consider only the generic degradation mechanisms for almost all the interactions between different substances and materials, introducing uncertainties during the planning for inspections and predictive maintenance activities.

The risk-based inspection (RBI) is the decision-making technique for inspection planning based on risk [8]. During the inspection phase of the RBI approach, the risk is evaluated. Both the probability and the consequence of failure are necessary to assess the risk level. The calculation of the probability of failure for hydrogen technologies is a challenging task. For this reason, different accident databases for hydrogen were created as, for instance, the hydrogen incident and accident database (HIAD) which was recently updated by the Fuel Cells and Hydrogen Joint Undertaking 2 – Joint Research Centre (FCH 2 JU JRC) [9]. However, the traditional risk assessment tools cannot be employed due to the limited amount of statistics available on faults and failure modes [9]. The understanding of the LOI phenomena for hydrogen technology might aid the evaluation of the loss of containment (LOC) frequency.

The aim of this contribution is to comprehend which degradation mechanisms should be considered for hydrogen technologies. Hence, appropriate suggestions on modification of the current RBI standards are provided as well as proposition for future studies. In section 2, the H2 CoopStorage project in which the hydrogen degradation mechanisms will be investigated, is briefly described, while in section 3 the RBI methodology is presented. The methodology adopted in this analysis, and the results and discussion are provided in section 4 and 5, respectively.

2. H2 CoopStorage project description

This study is part of the "Development of tools enabling the deployment and management of a multi-energy Renewable Energy Community with hybrid storage (H2 CoopStorage)" project [10]. The aim of this project, funded within the framework of the Smart Energy Systems ERA-Net [11], is to promote the deployment and management of a multi-energy (electric and heat) community by integrating hybrid energy storage (electrochemical and hydrogen) able to satisfy the daily and seasonal energy demands, and through the development of methodological tools and software. Part of the project focuses on the safety aspects of the hydrogen handled and stored within the energy community. The motivation is to cover the lack of knowledge on the safety issues associated with the widespread deployment of hydrogen technology that represents a major bottleneck for industry, authorities, end users and the social acceptance. In this context, the development and validation of risk assessment models and the dissemination of knowledge and guidelines concerning the hydrogen safety, for use by the general public, are of paramount importance. In particular, a predictive methodology for the dispersion of hydrogen gas in its environment will be developed so to allow the determination of the risks related to events of a leak or explosion. This innovative and validated risk assessment tool for the hydrogen value chain will support critical decision making in terms of safe design, inspection and maintenance operations. In order to achieve these audacious goals, it is essential to investigate the metal-hydrogen interactions and thus fully comprehend the physical and chemical phenomena that may lead to a LOI of the hydrogen equipment.

IOP Conf. Series: Materials Science and Engineering 1193 (2021) 012075 doi:10.1088/1757-899X/1193/1/012075

3. Risk based inspection (RBI)

The first RBI methodology was developed by the American Petroleum Institute (API) in 1994. For this reason, most of the current RBI standards are based on the API methodologies (mainly API RP 580 and 581 [4, 5]). Generally, RBI is an approach that aims to achieve different targets related to health, safety, business and environment criteria [14]. Usually, a multidisciplinary engineering analysis is applied to meet these targets. In particular, optimized inspection, monitoring and maintenance programs based on a risk-based methodology are implemented in the analysis. As previously mentioned, the evaluation of risk follows the procedure describe in figure 1, thus both the probability and consequence of failure must be estimated.

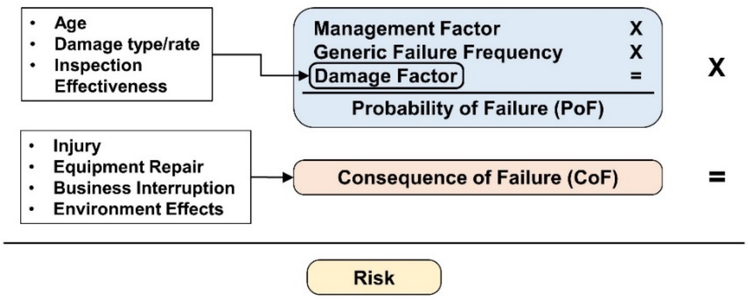

Figure 1. Risk evaluation approach.

The calculated risk can be decreased or confirmed by the inspection results. The effectiveness of the RBI methodology is depicted in figure 2 where the predicted risk, which exponentially increases in time due to several factors, can be reduced after each inspection and be kept below a relatively safe risk target.

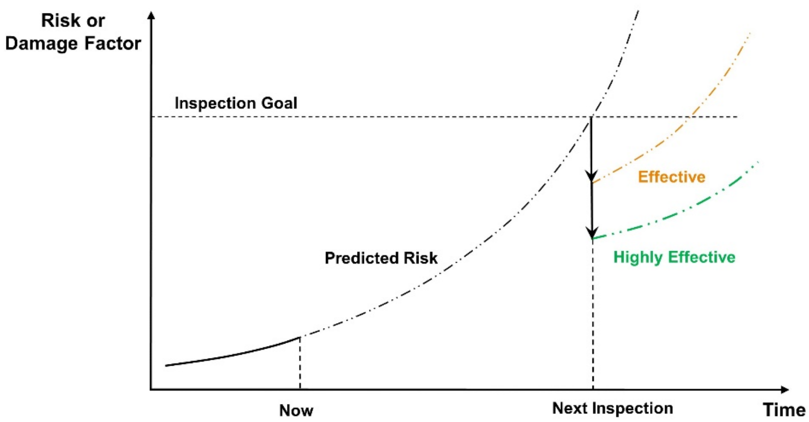

Figure 2. Risk target and inspection planning.

The definition of the RBI framework (RBIF) constitutes the core of the analysis, after the planning of the primary work products of RBI assessment and management which aids the prioritization of system and/or equipment inspection based on risk. Finally, the methodology must comply with applicable legal or normative regulations and guidelines. Different requirements must be met by the RBIF: plant and process documentation, personnel requirements, requirements for performing probability of failure (PoF) and consequence of failure (CoF) analyses and risk assessment [14]. Therefore, the RBIF process is divided in different steps which are displayed in the schematic of figure 3. These steps create a loop that should ensure the continuous improvement of the analysis and suggest modifications of the management. It can be concluded that RBI is a decision-making management tool applied to the issue of inspection planning which aims to increase reliability by lowering cost and risk (likelihood and consequence) [8].

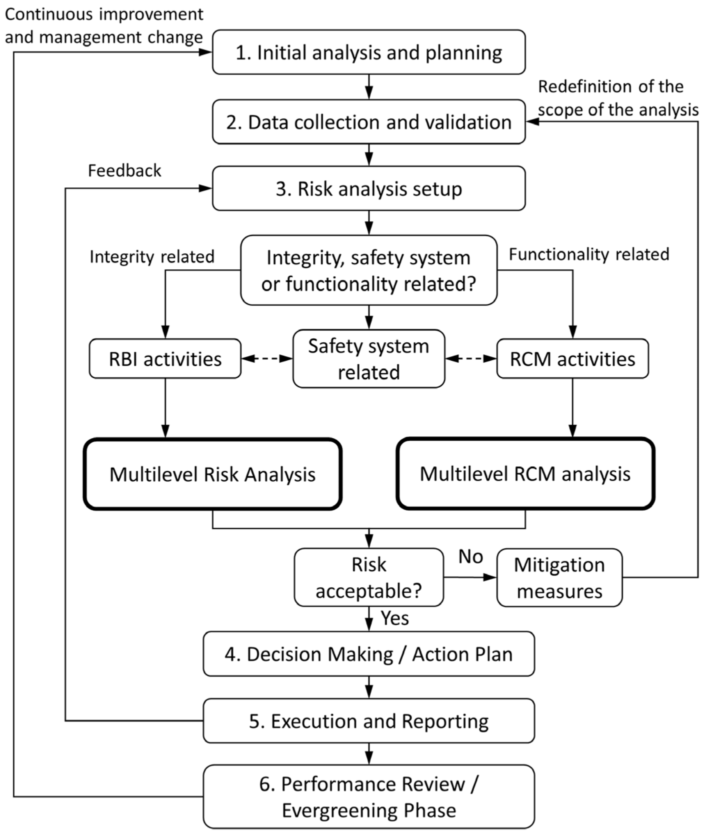

Figure 3. Framework of RBIM procedure within the overall management system (adapted from [14]).

4. Methodology
Firstly, a brief review of the available standards and recommended practices on RBI planning was conducted. Secondly, the most recent standard was selected, and the reported types of damage generated by different degradation mechanisms were investigated. Therefore, the focus was placed on the metal-hydrogen interactions and the phenomena that may lead to a LOI of the containment. A comparison between the main LOI phenomena for hydrogen technologies and the types of damage considered by the standard was conducted. Since the types of damage differently influence the predicted LOI frequency and thus the risk and the inspection method, appropriate recommendations for the modification of the RBI standard were provided.

5. Results and discussion
In this section, the results of the review of the available standards and recommended practises for inspection planning are presented. Furthermore, the outcomes of the comparison between the damages considered by the standards and the LOI phenomena related to hydrogen are reported.

5.1. RBI standards and recommended practices
The main available standards and recommended practices for RBI planning are listed in table 1. Only the most recent version of each standard is presented. All the standards suggest inspection once the predicted risk of a piece of equipment reaches a predetermined risk value. As previously mentioned, both the PoF and CoF analyses must be conducted to estimate the risk level. Although the RBI

methodologies proposed by these documents have several aspects in common, they differ in the definition of the damages. For instance, the DNVGL-RP-G101 considers the damage mechanisms while the EN16991 provides examples of types of in-service damage. Moreover, few damage types are not included in all the standards listed in table 1.

Table 1. Risk-based inspection standards in literature.

Standard	Ref.	Title	Year
API 580	[12]	Risk Based Inspection	2016
API 581	[13]	Risk Based Inspection methodology	2016
ASME PCC-3	[15]	Inspection Planning Using Risk-Based Methods	2017
DNVGL-RP-G101	[8]	Risk based inspection of offshore topsides static mechanical equipment	2017
EN16991	[14]	Risk-based inspection framework	2018

Table 2. Comparison between examples of damages provided by the EN16991 standard [14], and the loss of integrity (LOI) phenomena for hydrogen technologies [5].

LOI phenomena	EN16991
Hydrogen damages (HD):	
o Hydrogen embrittlement (H_2 environment embrittlement, H2 stress cracking, loss in tensile ductility)	Embrittlement incl. hardening, strain aging, temper embrittlement, liquid metal embrittlement, etc. (general)
o Hydrogen attack (HA)	High temp. HA (H_2 induced damage)
o Blistering	Blistering (H_2 induced damage)
o Shatter cracks, flakes, fisheyes	Cracking, mainly on surface (general)
o Microperforation	Micro-cracking (general)
o Degradation in flow properties	Fluid flow disturbance (general)
o Metal hydride formation	Dealloying (general)
Low temp. embrittlement	Embrittlement (general)
Thermal contraction, stresses caused by: o dimensional change o thermal gradients	Dimensional changes, thermal fatigue (general)

5.2. Loss of integrity phenomena and their mechanisms

A thorough review of the main physical and chemical phenomena that may lead to a LOI of hydrogen technologies together with their mechanisms can be found in [5]. The LOI phenomena that are provoked by the metal-hydrogen interaction at molecular level are categorized as hydrogen damage (HD). It must be mentioned that the HD might happen even in equipment in which hydrogen is not directly employed. On the other hand, the low temperature embrittlement (LTE) and the thermal contraction are LOI phenomena that develop due to the extremely low temperature of liquid hydrogen (-253°C at atmospheric pressure [16]). During the thermal contraction the stresses in the material can be generated by the dimensional change or the high thermal gradient between different parts of the liquid hydrogen (LH_2) equipment such as a tank or a pipe. However, these two phenomena are usually not considered as HD but can manifest together with one or more HDs, and thus increase the risk level of the piece of equipment. Since the last standard listed in table 1 (EN16991) is the most recent one as well as the result of previous RBI methodologies, it was selected for a more detailed investigation on the interested LOI phenomena. A comparison between these latter and the damages considered by the EN16991 standard is presented in table 2.

It can be noticed that only two types of damages are related to hydrogen: the high temperature (200 ÷ 595°C) hydrogen attack (HTHA) and the blistering. Even though different LOI phenomena are taken into account by the selected RBI methodology these are generalized for all the types of interactions between metals and different substances. The damage mechanisms that lead to the LOI phenomena are different for hydrogen compared to most of the substances due to the large difference in chemical and physical properties. One of the most studied and well-known LOI phenomena is the hydrogen embrittlement which includes three different phenomena: hydrogen environment embrittlement, hydrogen stress cracking and loss in tensile ductility. Hydrogen embrittlement phenomena are very peculiar and frequent in the process industry. However, the magnitude of the degrading effects of hydrogen uptake into materials is highly material-dependent and therefore, HE can be "managed" and even avoided with an appropriate selection of materials during the design phase and/or by refraining processing techniques that might generate hydrogen, such as electroplating [17], during both the design and maintenance phases. However, this type of damage is generalized in the standard and hydrogen is not even mentioned. This is the case also for the micro-cracking, fluid flow disturbance and dealloying. Furthermore, flakes and fisheyes, which are similar to blistering but manifest during forging, weldment and casting, were not reported in the document. Finally, metal-hydrogen interactions can drastically vary depending on the materials systems and the operating conditions. Therefore, the damage mechanisms may lead to significant different LOI, thus LOC and CoF. An inappropriate risk assessment might be carried out by generalizing or neglecting the types of damage.

As previously mentioned, the LTE as well as the thermal contraction may occur due to the extremely low temperature of the LH_2 or cold hydrogen gas. The boiling points of the cryogenic fluids usually employed in the process and chemical industries are quite higher than the temperature of LH_2 at atmospheric pressure. For instance, liquid nitrogen, adopted in several applications and processes, has a temperature of -195.8°C (77.35 K) [16] at atmospheric pressure, i.e. more than 56°C above the LH_2 boiling point. Therefore, the stresses generated in the materials which contains the LH_2 are greater than the ones for the other cryogens with exception for liquid helium which has a boiling point of -268.9°C (4.25 K) [16] at atmospheric pressure. In addition, the LH_2 boiling point is lower than the ductile-brittle transition temperatures of most of the metals commonly employed in the chemical industry. This aspect reduces the range of suitable materials choice for hydrogen storage and might increase the PoF. The fatigue life of the components subjected to either pressure or temperature cycles must also be carefully evaluated. Different studies conducted by Murakami et al. [18], Nakamura et al. [19] and San Marchi et al. [20, 21] demonstrated the need for further investigations on the behaviour during fatigue cycles for the materials selected for hydrogen applications. Finally, the cryo-compressed hydrogen storage is one of the most suitable solutions to increase the hydrogen density (up to 80 kg m^{-3} at 300 bar and -235°C [22]). In this case, the HD can manifest together with other physical phenomena such as LTE and thermal contraction, and the fatigue cycles are of thermomechanical nature. It must be highlighted that nearly each HD has different mechanisms and a unifying universal theory able to encompass all the reported HDs does not exist yet. The understanding of the HD mechanisms might greatly aid the probability evaluation during the risk assessment particularly if allows for the prediction of failure modes inherent to the material of interest for the given application. This seems to be currently impeded due to the lack of fault and failure modes for hydrogen [9].

For all the reasons heretofore described, it is suggested to update the current standards and recommended practices. In particular, few LOI phenomena related to hydrogen such as flakes and fisheyes must be included among the damages considered by the EN16991 standard. In addition, it should be specified that the damage mechanisms and failure modes may differ greatly when hydrogen enters into play when compared to more inert environments. Furthermore, a dearth of knowledge on metal-hydrogen interaction still exists in the literature. Nevertheless, it is critical to comprehend which are parameters and operational conditions affecting the LOI occurrence the most in order to prevent and/or mitigate any LOI occurrences during the design, inspection and maintenance phases.

IOP Conf. Series: Materials Science and Engineering 1193 (2021) 012075 doi:10.1088/1757-899X/1193/1/012075

6. Conclusions

The RBI methodology was described in this study and a brief review of the available RBI standards and recommended practices was provided together with a comparison between the main HDs and the types of damage considered by the RBI standards. It was highlighted that most of the HDs are not included in these documents. Therefore, few modifications to the standards are suggested. Moreover, it is critical to improve the knowledge on material degradation mechanisms for hydrogen equipment especially in the case of new applications and thus emerging technologies. Future studies on the HD mechanisms must be conducted to understand which are the parameters that influence more the formation of the phenomena. In this manner, it would be possible to optimise the inspection planning of the hydrogen containment.

Acknowledgements

This work was undertaken as part of the research project "Development of tools enabling the deployment and management of a multi-energy Renewable Energy Community with hybrid storage (H2 CoopStorage)", and the authors would like to acknowledge the financial support of the Nordic Energy Research within the programme "ERA-Net Smart Energy Systems" (Grant No. 106291).

References

[1] DNV-GL 2021 *The impact of COVID-19 on the energy transition* (https://www.dnvgl.com/energy-transition/impact-of-covid19-on-the-energy-transition.html) accessed 18 February 2021
[2] Widera B. 2020 Renewable hydrogen implementations for combined energy storage, transportation and stationary applications *Thermal Science and Engineering Progress* **16** p 100460
[3] Argonne National Laboratory 2010 The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) 1.8d1
[4] Libert J F and Waterworth G 2016 Cable technology *Undersea Fiber Communication Systems* (Academic Press) pp 465–508
[5] Ustolin F, Paltrinieri N and Berto F 2020 Loss of integrity of hydrogen technologies: A critical review *International Journal of Hydrogen Energy* **45** (43) pp 23809–23840
[6] Wan D, Alvaro A, Olden V and Barnoush A 2019 Hydrogen-enhanced fatigue crack growth behaviors in a ferritic Fe-3 wt% Si steel studied by fractography and dislocation structure analysis *International Journal of Hydrogen Energy* **44** (10) pp 5030–5042
[7] Alvaro A, Wan D, Olden V and Barnoush A 2019 Hydrogen enhanced fatigue crack growth rates in a ferritic Fe-3 wt% Si alloy and a X70 pipeline steel *Engineering Fracture Mechanics* **219** p 106641
[8] DNV-RP-G101 2009 *Risk based inspection of offshore topsides static mechanical equipment* (Det Norske Veritas) (https://rules.dnv.com/docs/pdf/dnvpm/codes/docs/2009-10/RP-G101.pdf) accessed 17 February 2021
[9] Melideo D, Wen J and Moretto P 2019 HIAD 2.0 - Hydrogen Incident and Accident Database *Proc. Int. Conf. on Hydrogen Safety (Adelaide)*
[10] European Union 2021 *H2CoopStorage* (https://h2coopstorage.eu/) accessed 17 February 2021
[11] Smart Energy Systems ERA-Net 2021 *Innovation for Smart Energy Systems in Europe* (https://www.eranet-smartenergysystems.eu/) accessed 17 February 2021
[12] American Petroleum Institute 2016 API 580 - Risk Based Inspection
[13] American Petroleum Institute 2016 API 581 - Risk Based Inspection methodology
[14] European Committee for Standardization (CEN) 2018 EN16991 - Risk-based Inspection Framework
[15] American Society of Mechanical Engineers 2017 ASME PCC-3 - Inspection Planning Using Risk-Based Methods
[16] NIST 2019 *NIST Chemistry WebBook* (http://webbook.nist.gov/) accessed 19 March 2019

[17] Edeskuty F and Stewart W 1996 *Safety in the Handling of Cryogenic Fluids* (New York: Springer Science+Business Media, LLC)
[18] Murakami Y, Kanezaki T, Mine Y and Matsuoka S 2008 Hydrogen embrittlement mechanism in fatigue of austenitic stainless steels *Metallurgical and Materials Transactions A* **39** pp 1327–1339
[19] Nakamura J, Miyahara M, Omura T, Semba H, Wakita M and Otome Y 2010 Degradation of fatigue properties in high pressure gaseous hydrogen environment evaluated by cyclic pressurization tests *Procedia Engineering* **2** (1) pp 1235–1241
[20] San Marchi C, Hecht E S, Ekoto I W, Groth K M, LaFleur C, Somerday B P, Mukundan R, Rockward T, Keller J and James C W 2017 Overview of the DOE hydrogen safety, codes and standards program, part 3: Advances in research and development to enhance the scientific basis for hydrogen regulations, codes and standards *International Journal of Hydrogen Energy* **42** (11) pp 7263–7274
[21] San Marchi C, Yamabe J, Schwarz M, Matsunaga H, Zickler S, Matsuoka S and Kobayashi H 2018 Global Harmonization of Fatigue Life Testing in Gaseous Hydrogen *Proc. ASME 2018 - Pressure Vessels and Piping Conference (Prague)* vol 6 (The American Society of Mechanical Engineering) pp 1–10
[22] Ahluwalia R K, Peng J-K and Hua T Q 2015 *Compendium of Hydrogen Energy - Cryo-compressed hydrogen storage* (Woodhead Publishing) pp 119–145