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Comparing Inspection Strategies For Hydrogen Refuelling Stations: Time Based And Risk Based Approaches

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Abstract

Hydrogen is a clean and versatile energy carrier with the potential to usher in a new era of sustainable road transport. The global adoption of fuel cell-powered vehicles is rapidly rising, and 814 refueling stations were already in operation worldwide at the end of 2022. However, the highly flammable nature of hydrogen gas and the capacity to permeate and embrittle most metallic materials pose significant challenges to its safe containment. The risk is particularly pronounced in hydrogen refueling stations, where a leak can swiftly escalate into an accident if not promptly detected. From this perspective, robust safety protocols become essential to unlock hydrogen's full potential while ensuring a safe and sustainable future for road transport. Inspection activities have a prominent role in preventive maintenance strategies. Time-based inspection planning is a consolidated approach in which component integrity assessments are carried out with predetermined schedules. On the other hand, the risk-based approach involves a meticulous evaluation of potential hazards and allows for a targeted examination of high-risk components. Even if an RBI approach would provide a dynamic perspective on safety that responds to the specific characteristics of each refueling station, it has never been adopted for any hydrogen technology. This study directly compares time-based and risk-based inspection of a hydrogen refueling station. In addition, a new methodology to calculate the probabilities of failure of components exposed to compressed gaseous hydrogen is proposed. The results show how a risk-based approach can provide a comprehensive and adaptive inspection framework for hydrogen refueling stations.

Keywords: hydrogen refueling station, predictive maintenance, time based inspection, risk based inspection, hydrogen-induced damage

1. Introduction

Hydrogen was indicated by the European Commission as a promising and sustainable energy carrier with the potential to decarbonize the mobility sector and mitigate the environmental impact of road transport. This fuel can be produced from renewable energy by water electrolysis and used in fuel-cell systems or internal combustion engines with elevated efficiencies and near-zero pollutant emissions (European Commission, 2018). The global adoption of hydrogen-fueled vehicles is rapidly gaining momentum, but the infrastructure for H_2 transport and distribution is still under development. At the end of 2022, 814 hydrogen refueling stations (HRS) were already operative worldwide, and concrete plans for 315 additional stations are in place. On the other hand, the number of fuel-cell electric vehicles on the world's roads increased by 40% in 2022, compared to 2021, accounting for more than 72,000 vehicles (IEA, 2023). These numbers are expected to rise in the forthcoming years due to the extensive investment campaigns of regional and national governments.

Despite its environmental advantages, hydrogen is considered a hazardous substance due to its high flammability (flammability range from 4% to 74% in the air) and low ignition energy (0.019 mJ). The small atomic dimensions of hydrogen make its containment challenging and prone to leaks from joints and sealings. In addition, it can permeate and embrittle most structural materials, degrading their mechanical properties to an extent that could result in component failures (Kotchourko and Jordan, 2022). Unintended hydrogen releases in congested spaces, such as hydrogen refueling stations, are critical and can escalate to accidents with severe consequences. Since 2013, at least three undesired events involved HRSs in Norway. In June 2019, a hydrogen release from a high-pressure storage unit provoked a fire and caused extensive economic damage to the refueling station in Kjørbo (Campari et al., 2023a).

From this perspective, inspection activities are a fundamental part of preventive maintenance strategies and allow one to guarantee the safety and fitness-for-service of the facilities. Over the years, several inspection planning approaches have been proposed. The optimal strategy should minimize the costs and complexity of the inspections and downtimes of the plant while guaranteeing safety and reliability (Rachman and Ratnayake, 2019). Time-based inspection (TBI) is a state-of-the-art methodology, well-established and standardized, which lies in assessing the component integrity with predetermined schedules. TBI is easy to implement and requires minimal training for the personnel, but results in too frequent inspections since it ignores the actual operating conditions and working life of the facilities (Ahmad and Kamaruddin, 2012). On the other hand, risk-based inspection (RBI) assumes that the risk is not equally distributed among the plant's components, and a limited amount of equipment items is responsible for a high share of the total risk. Therefore, RBI involves a rigorous assessment of the probabilities and consequences of failures for each piece of equipment, allowing for a targeted inspection of the high-risk components to minimize the overall risk. The risk assessment can be continuously updated with new information obtained from previous inspections; therefore, the RBI approach provides a dynamic perspective on safety that can be adapted to specific characteristics and service life of each facility (Bhatia et al., 2019). Despite its advantages, implementing risk-based inspection planning for hydrogen technologies represents a challenge since the existing RBI standards do not account for most hydrogen-induced material damages, particularly for hydrogen embrittlement (HE). Hence, the probability of failure of components exposed to pressurized gaseous hydrogen is affected by high uncertainty, making the risk evaluation unreliable (Campari et al., 2022).

Given this background, this study compares the time-based and risk-based inspection strategies for a hydrogen refueling station. The RBI methodology is applied in compliance with the standard API 581 (API, 2019). A new methodology allows quantifying the impact of hydrogen embrittlement on the probability of failure of the components, depending on their working conditions, structural material, and inspection history. On the other hand, TBI is used as a reference inspection planning methodology. The following section summarizes the principles of TBI and RBI and illustrates the adapted risk-based methodology for hydrogen technologies. The authors selected a hydrogen refueling station supplied by a gaseous hydrogen tube trailer and capable of dispensing 300 kg of fuel daily as a case study. Finally, the results are presented and extensively discussed to highlight the advantages of a dynamic and adaptive risk assessment from safety and financial perspectives.

2. Inspection strategies: time-based vs risk-based

Preventive maintenance requires that the components are checked to prevent breakdowns and unexpected failures, thus maintaining their physical integrity and fitness for service. Inspection activities allow one to determine if the degradation of the equipment reached a critical point and if corrective actions are required. The inspection does not reduce the risk but limits the uncertainty and allows one to carry out maintenance activities before the predicted failure date (API, 2016a). Ideally, a valuable inspection strategy should reduce the cost, frequency, and complexity of inspections while guaranteeing the maximum availability and reliability of the facilities under safe conditions. Two inspection planning approaches are presented in the following: time- and risk-based inspection.

2.1. Time-based inspection

Time-based inspection is a consolidated strategy in which inspection and maintenance are carried out at predetermined schedules, most likely at regular frequency. TBI assumes that the probability of failure exclusively depends on the age of the equipment, thus implying that two components of the same type and age have the same failure rate, regardless of the working conditions and events they experienced during their service life. TBI starts by collecting failure data and performing statistical analysis to estimate the failure trends of the plant’s components. In general, the failure rate tends to decrease in the first part of the equipment's working life, and then it remains constant during the normal operating life. Then, approaching the decommissioning date, the failure rate tends to increase again due to the aging effect. The decision-making process, which involves the operational cost assessment and equipment mechanism assessment, aims to evaluate the most convenient option between accepting a potential failure and repairing or replacing the component. Finally, the most strategic policy is put into action (Ahmad and Kamaruddin, 2012).

This methodology is easy to implement since it requires minimal training for the operators and has a predictable schedule. Nevertheless, only 15-20% of the total industrial failures can be considered age-related, while the rest is due to events that occur randomly during the component’s life. In addition, TBI assumes that the operating conditions remain unchanged, which is highly unrealistic. A time-based inspection schedule is often overconservative and imposes too frequent maintenance. This is problematic not only for the higher maintenance costs but also for the additional risk introduced by the excessive downtime of the plant (Campari et al., 2023c).

In this case, the time-based inspection schedule is implemented according to the standard ISO 19880 (ISO, 2020). It establishes the minimum inspection and maintenance requirements for hydrogen refueling stations. In general, detailed inspections to detect any structural damage to the HRS components should be conducted every five years.

2.2. Risk-based inspection

Risk-based inspection focuses on minimizing the risk associated with equipment failures and unintended releases of hazardous substances. If properly implemented, it allows the adoption of preventive measures to reduce the likelihood of failure and mitigation strategies to limit the release consequences. Ideally, RBI aims to focus the inspection efforts on high-risk components, monitoring less frequently low-risk equipment (API, 2016a). The first step is the data collection and validation. Given the technical specifications and the plant's operating conditions, all the damages likely to occur are identified and quantified to calculate the failure probability of each component. Then, the consequences of failure are evaluated in terms of financial consequences and impact area. The equipment items are ranked based on the risk level, and the inspection and maintenance activities are planned accordingly (API, 2019).

The probability of failure can be calculated as the product of three factors:

$$P_f\ (t, I_E) = gff \cdot D_f\ (t, I_E) \cdot F_{SM} \quad (1)$$

where gff represents the generic failure frequency, D_f is the damage factor, F_{SM} is the management system factor, t and I_E are the time and effectiveness of previous inspections, respectively. The former coefficient indicates the probability of failure of a certain type of component, which is based on historical data. It is tabulated for four different hole sizes. The damage factor accounts for the operating conditions and structural materials of the component, the associated damage mechanisms, and the history of previous inspections. The damages can be broadly divided into six categories: thinning, stress corrosion cracking, external damage, mechanical fatigue, brittle fracture, and high-temperature hydrogen attack. The management system factor indicates the effectiveness of the management in maintaining the mechanical integrity of process equipment. It is applied equally to each component and does not influence the risk-based ranking (API, 2019).

The definition of the damage mechanisms in the current RBI standards does not include most hydrogen-induced damages. Hydrogen embrittlement is a material damage resulting from the hydrogen-metal interaction that depends on three synergistic factors: H_2-containing environment, susceptible material, and applied or residual stress field. This material damage tends to degrade several mechanical properties and facilitate the brittle fracture of otherwise high-performance materials. It can affect storage tanks, cylinders, and pipes and represents a primary concern for most hydrogen handling and storage equipment (Campari et al., 2023c). The inaccurate evaluation of HE introduces additional uncertainty in the calculation of the failure probability of components exposed to compressed hydrogen gas, thus limiting the applicability of the RBI methodology to hydrogen technologies.

Hence, a new methodology for determining the damage factor associated with HE is presented in Fig. 1. In this flowchart, the environmental severity is determined based on the component's working environment (i.e., hydrogen partial pressure and temperature). The material susceptibility depends on the structural material used and is influenced by its microstructure and chemical composition, the presence of post-weld heat treatments (PWHT) and coatings. The severity index is calculated from the environmental severity and the material susceptibility and divided into five classes. Then, the base damage factor can be corrected, depending on the age of the component, the time since the last inspection, and the presence of online monitoring equipment:

$$D_f^{HE} = min\left[\frac{D_{fB}^{HE} \cdot (max[age, 1.0])^{1.1}}{F_{OM}}, 5000\right] \quad (2)$$

where D_{fB}^{HE} represents the base damage factor for hydrogen embrittlement, age is the age of the component (in years), and F_{OM} is a coefficient accounting for the on-line monitoring equipment (Campari et al., 2023b).

The consequences of releasing hazardous fluids are evaluated for each substance based on its chemical and physical properties. A set of hole sizes is considered, and theoretical release rates are calculated for each hole. The type of release, either instantaneous or continuous, influences the method used for modeling the consequences and is evaluated based on the total amount of fluid available for release. Detection and isolation systems have an impact on the release magnitude. From these bases, masses and release rates are calculated, and the flammable or explosive consequence areas are estimated (in the case of flammable fluids):

$$CA_f^{flam} = \frac{\sum_{n=1}^{4} gff_n \cdot CA_{f,n}^{flam}}{\sum_{n=1}^{4} gff_n} \quad (3)$$

where gff_n indicates the generic failure frequency and $CA_{f,n}^{flam}$ is the consequence area of a flammable release for a certain hole size n (small, medium, large, or rupture). Finally, the financial consequences are calculated by adding all the costs associated with the equipment failure:

$$FC_f = FC_{f,cd} + FC_{f,affa} + FC_{f,prod} + FC_{f,inj} + FC_{f,env} \quad (4)$$

where $FC_{f,cd}$ represents the financial consequence of the component damage, $FC_{f,affa}$ is the cost of the damage to surrounding equipment, $FC_{f,prod}$ is the financial consequence of lost production, $FC_{f,inj}$ accounts for the cost of serious injuries to the personnel, and $FC_{f,env}$ indicates the cost of environmental clean-up (API, 2019).
The quantitative RBI requires specialized software to manage the vast amount of information regarding the design, operating conditions, and service life of the equipment. In this case, the software *Synergi Plant – RBI Onshore* (DNV, 2022) was used and complemented with additional damage factors to account for the time-dependent effects of hydrogen embrittlement.

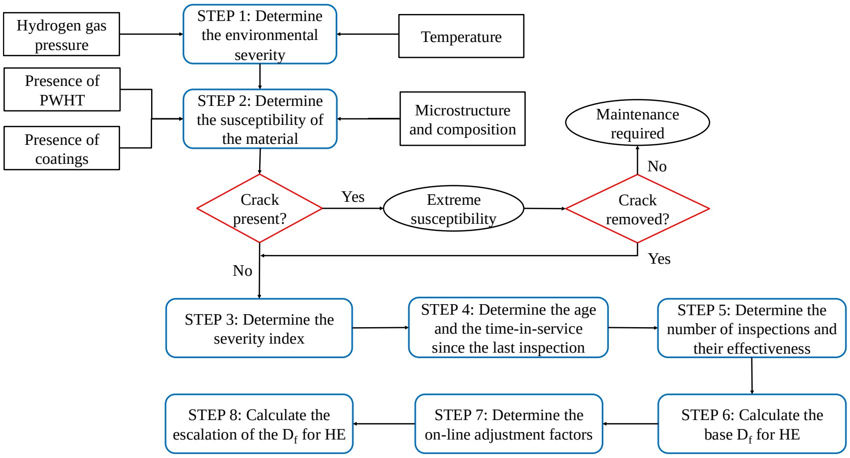

Fig. 1. Methodology for the determination of the damage factor for hydrogen embrittlement (Campari et al., 2023b).

3. Case study

A typical hydrogen refueling station with off-site production consists of a multistage inter-cooled compressor, several hydrogen storage tanks, a pre-cooling system, and dual pressure dispensers (at 350 and 700 bar), depending on the type of vehicle being refueled. In addition, safety equipment, such as safety valves, gas leak detectors, and fire extinguishing systems, are conveniently located near each component. An HRS supplied with hydrogen by a tube trailer and cascade fill is used as a case study and schematically shown in Fig. 2 (Pratt et al., 2015).

Approximately 500 kg of gaseous hydrogen is transported through tube trailers at around 200 bar. Hydrogen is compressed by a multistage compressor, which increases the volumetric energy density and allows the storage of a greater amount of fuel. Then, the pressurized gas passes through a heat exchanger where its temperature is lowered to guarantee that the storage tanks do not exceed 85 °C. Several compression stages allow to reach the highest storage pressures of approximately 900 bar. Medium and low-pressure storage tanks operate at around 600 and 300 bar, respectively. The on-site storage is controlled by valves, fittings, and electrical controls specifically designed to regulate pressure and interact with the dispenser during refueling. All these components are realized with specific hydrogen-compatible materials to avoid any hydrogen-assisted cracking (Genovese et al., 2023).

The high-pressure storage tank must operate at pressures above the target pressure of the fuel-cell vehicle's tank (i.e., up to 700 bar) due to the pressure losses during the refueling process. In the cascade fill, several storage tanks at different pressure levels operate in coordination with one another. When a vehicle is refueled, depending on the maximum pressure of the onboard storage tank, cascade management ensures that hydrogen is drawn from the low-pressure storage tank during the first phase. When the pressure difference between the HRS storage and the onboard tank falls below a certain level, the refueling switches to the medium-pressure tank and finally to the high-pressure tank (Genovese and Fragiacomo, 2023).

The cascade fill maximizes the energy efficiency and minimizes the gas compression costs. Before dispensing the fuel to the vehicles, hydrogen is cooled to -40 °C to ensure a fast and efficient filling and comply with the safety protocols. The dispenser has two hoses operating at selected pressures to refuel different vehicle types (i.e., 700 and 350 bar). The nozzles are controlled by specifically designed valves which regulate the flow rate required to fill the vehicle up to its design pressure. This facility can dispense 300 kg of high-purity hydrogen gas per day (Pratt et al., 2015).

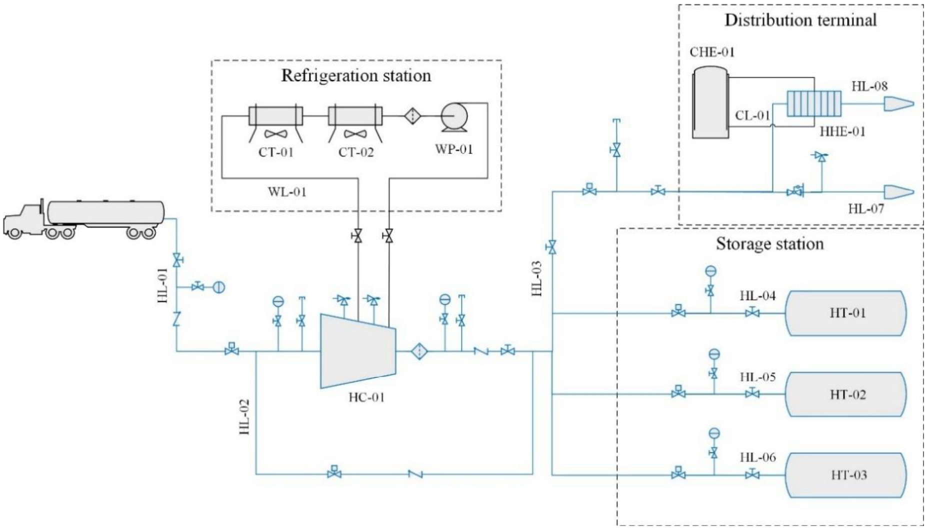

Fig. 2. Simplified P&ID for the hydrogen refueling station with cascade fill and capacity of 300 kg/day (adapted from Pratt et al., 2015).

The technical specifications and operating conditions for each component of the HRS are summarized in Table 1. Dimensions, structural materials, operating pressures and temperatures, and costs are specified for each component and used to calculate the probabilities and consequences of failure. Ancillary equipment, such as valves, filters, and pressure transducers, are not included. Components that are not exposed to compressed hydrogen gas, such as the refrigeration station for the compressor, the gas control cabinet, and the infrared flame detector, were also excluded since a potential failure could only result in the interruption of the operations, without any additional risk for the operators or the surrounding equipment.

Table 1. Technical specifications and operating conditions of the components and piping of the hydrogen refueling station.

Component	ID	Diameter [mm]	Length [m]	Thickness [mm]	Material	Pressure [bar]	Temperature [°C]	Cost [USD]
Hydrogen compressor	HC-01	800	4	140	AISI 4130	1034	45	150,000
High-pressure tank	HT-01	600	20	15	GRP + liner	944	10	40,000
Medium-pressure tank	HT-02	600	20	15	GRP + liner	613	10	40,000
Low pressure tank	HT-03	600	20	15	GRP + liner	330	10	40,000
Hydrogen pipe	HL-01	21.3	7	2.6	AISI 316	207	10	7,400
Hydrogen pipe	HL-02	21.3	6	2.6	AISI 316	345	10	6,500
Hydrogen pipe	HL-03	13.5	30	7.1	AISI 316	1034	45	28,000
Hydrogen pipe	HL-04	13.5	2	6.3	AISI 316	944	10	2,900
Hydrogen pipe	HL-05	13.5	2	6.3	AISI 316	802	10	2,900
Hydrogen pipe	HL-06	13.5	2	6.3	AISI 316	613	10	2,900
Hydrogen pipe	HL-07	10.2	4	2	AISI 316	350	10	1,700
Hydrogen pipe	HL-08	10.2	10	2	AISI 316	700	-40	4,200
Hydrogen cooling block	HHE-01	10.2	20	3.2	AISI 316	700	-40	350,000

Even if the risk associated to several ancillary components is not evaluated due to the insignificant consequences of a potential release, they can be affected by the loss of integrity of other equipment in the surrounding area. Hence, their cost is considered for the evaluation of the financial consequences. The assumptions are summarized in Table 2.

Table 2. Summary of the financial consequences of a release..

Cost	Value	Reason for the assumption
Injury cost	10,000,000 USD	The cost of a serious injury is a fixed value for most RBI applications
Outage cost	700,000 USD/year	The cost of hydrogen is 6-7 USD/kg and the maximum capacity of the HRS is 300 kg/day
Environment clean-up cost	100 USD/m^3	The environmental clean-up cost associated with a hydrogen release is limited due to the high buoyancy and low environmental impact of the gas
Equipment cost	1,400 USD/m^2	The equipment cost is the total cost of the facility (i.e., 1,500,000 USD) divided by the total surface of the HRS (i.e., 1,100 m^2)
Population density	0.0036 pers/m^2	Four persons are permanently at the HRS
Worst-case fatality count	12	Three operators work at the HRS, the driver of the supply truck can be in the surrounding area, and two vehicles (with four passengers each) can be fueled at the same time
Worst-case equipment damage cost	1,500,000 USD	The cost of the facility considers all the components and the ancillary equipment, such as control systems, flame detectors, and pneumatic systems

4. Results and discussion

The evaluation date for the risk-based inspection is the 31st of December 2020, five years after the opening of the refueling station. The future evaluation date was set on the 31st of December 2025. The HRS is outdoors, and most equipment items are exposed to rain and atmospheric agents. Therefore, they are protected with coatings against atmospheric corrosion. Only the hydrogen compressor and storage tanks are indoors and, therefore, are not subjected to external thinning damage. In addition, most of the HRS's components are exposed to high-pressure H_2 gas and are prone to hydrogen embrittlement damage, depending on their operating conditions. Since the Type IV tanks of the storage station are made of glass-reinforced plastic (GRP) and plastic liners, they are susceptible to liner failure but cannot be affected by HE. Moreover, the hydrogen compressor and the pipes downstream of rotating equipment or pressure-reducing valves can be subjected to vibration fatigue, while the hydrogen cooling block can be prone to thermal fatigue. Table 3 summarizes the damage factors for the damage mechanisms that can affect each component and the probabilities of failure calculated at t_0 and after five years.

Table 3. Damage factors for the active damage mechanisms and probabilities of failure.

ID	External thinning		Hydrogen embrittlement		Liner failure		Vibration fatigue	Thermal fatigue	$P_f(t_0)$	$P_f(t)$
	$D_f(t_0)$	$D_f(t)$	$D_f(t_0)$	$D_f(t)$	$D_f(t_0)$	$D_f(t)$	D_f	D_f		
HC-01	-	-	100	587.3	-	-	475	-	0.01760	0.03251
HT-01	-	-	-	-	2.0	26.0	55	-	0.04115	0.05851
HT-02	-	-	-	-	2.0	26.0	35	-	0.02671	0.04407
HT-03	-	-	-	-	2.0	26.0	35	-	0.02671	0.04407
HL-01	2.0	2.0	10	58.7	-	-	100	-	0.00343	0.00492
HL-02	57.6	57.6	10	58.7	-	-	-	-	0.00207	0.00356
HL-03	111.9	111.9	100	587.3	-	-	200	-	0.01260	0.02752
HL-04	137.0	1345.8	100	587.3	-	-	-	-	0.00725	0.02217
HL-05	43.0	43.0	100	587.3	-	-	-	-	0.00438	0.01929
HL-06	6.9	6.9	10	58.7	-	-	-	-	0.00052	0.00201
HL-07	18.1	18.1	10	58.7	-	-	-	-	0.00392	0.00541
HL-08	87.2	87.2	100	587.3	-	-	-	-	0.00573	0.02064
HHE-01	61.4	61.4	100	587.3	-	-	-	55	0.00662	0.02153

The probability of failure is almost the same for each component, and external thinning and hydrogen embrittlement represent two dominant damage mechanisms for most of the equipment items. In general, the stretch of pipe connecting the supply truck with the compressor manifests a low failure probability at the first evaluation date, but this value tends to rise sharply due to the increased HE degradation over time.

In addition, the dispenser at 700 bar has a low P_f at the first evaluation date, but the combination of atmospheric corrosion and hydrogen embrittlement tends to increase significantly this value in five years. The H_2 storage tanks have a probability of failure that depends on the operating pressure (i.e., 944, 613, and 330 bar, respectively) since they are all designed to store gas compressed up to 944 bar. Finally, the compressor and the hydrogen pre-cooling system manifest a relatively low P_f despite the complexity of the component.

The consequences of failure were evaluated based on the safety area and the total failure cost. The safety areas were calculated through integral models for each credible scenario and hole size and weighted on the event probability and the hole size distribution. On the other hand, the financial consequences are quantified based on the cost of the damaged component and surrounding equipment, the downtime of the facility and the costs of lost production, environmental clean-up, and the cost of any serious injury. This last term accounts for the highest fraction of the financial consequences, considering that an HRS can temporarily host the operators, car drivers and passengers, and the driver of the supply truck. The C_f for each equipment item is shown in Fig. 3.

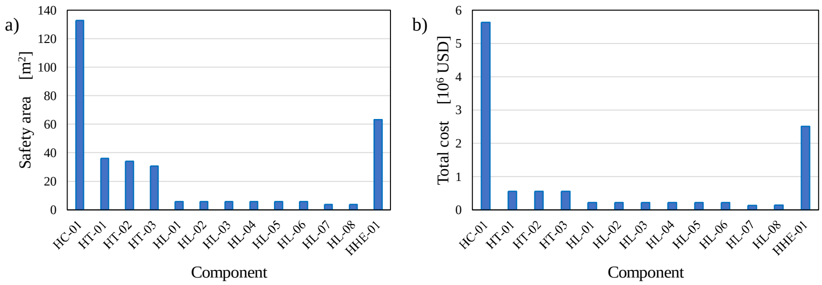

Fig. 3. Consequences in terms of (a) safety areas and (b) total failure cost.

The hydrogen compressor and pre-cooling block have the most severe consequences of failure in terms of cost and safety area. The compressor operates the largest gas flow rate at the highest pressure level. In addition, both the rupture and the large hole are credible scenarios for this type of equipment. Similar considerations apply also to the pre-cooling block which operates at 700 bar and -40 °C. In addition, this plate heat exchanger is the component with the highest cost in the HRS. Type IV storage tanks have relatively high consequences due to the large amount of flammable fuel stored. The consequences depend entirely on the operating pressure since all the tanks have the same dimensions and design pressure but store different amounts of compressed gaseous hydrogen (at 330, 613, and 944 bar, respectively). A significant difference between area-based and financial-based consequences can be observed due to the limited cost of these equipment items. Finally, all the piping has low consequences both in terms of safety area and failure cost. The highest financial consequence is associated with the injury cost for all the equipment. More specifically, the rupture of the storage tanks and the compressor is expected to result in 12 fatalities (i.e., the worst-case fatality count). In contrast, the rupture of a pipe is very unlikely to cause even a single serious injury.

Fig. 4 and Fig. 5 show the risk associated with the equipment items of the hydrogen refueling station in terms of consequence area and cost of failure, respectively. While the consequence of failure remains constant, the probability is time-dependent and, therefore, is evaluated after five years. Fig. 4 (a) shows the position of each component on the iso-risk plot. At the evaluation date, most items are classified as medium-risk, two pipes are low-risk components, and the hydrogen compressor and the high-pressure storage tank are ranked as medium-high risk. This is reflected by the risk matrix in Fig. 3 (b). After five years, the distribution of the equipment on the iso-risk plot changes significantly; each item is shifted along the P_f-axis, depending on the updated probability of failure. In this case, eight components of the refueling station are classified as medium risk and four as medium-high risk, as shown in Fig. 4 (c). A single equipment item is still classified as low-risk. The increased likelihood of failure of the metallic components is due to the higher damage factor for hydrogen embrittlement. In addition, the Type IV storage tanks manifest a higher probability of failure of the polymeric liner. Similar considerations apply also to the financial-based iso-risk plot in Fig. 5 (a). At the evaluation date, most components are classified as medium-high risk, and the two distribution terminals are medium-risk. After five years, the probability of failure of each equipment item is expected to rise sharply, and each point on the iso-risk plot shifts up on the P_f-axis. Hence, the risk associated with the hydrogen compressor escalates, reaching the critical value shown in Fig. 5 (c).

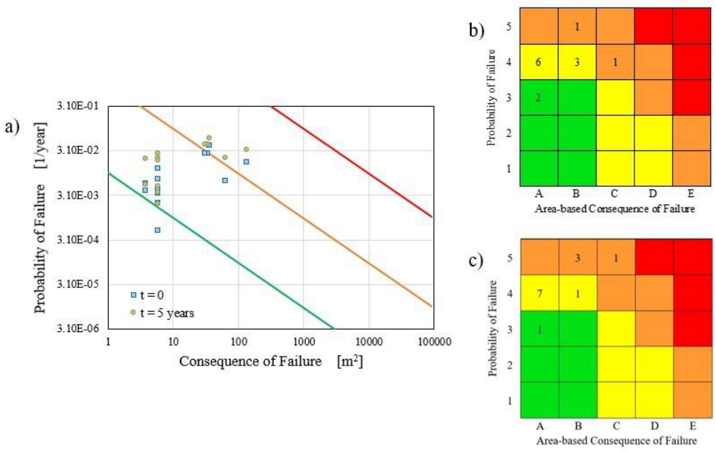

Fig. 4. (a) Iso-risk plot for area-based consequence of failure of the components of the HRS. Risk matrices at the evaluation date (b) and after five years (c).

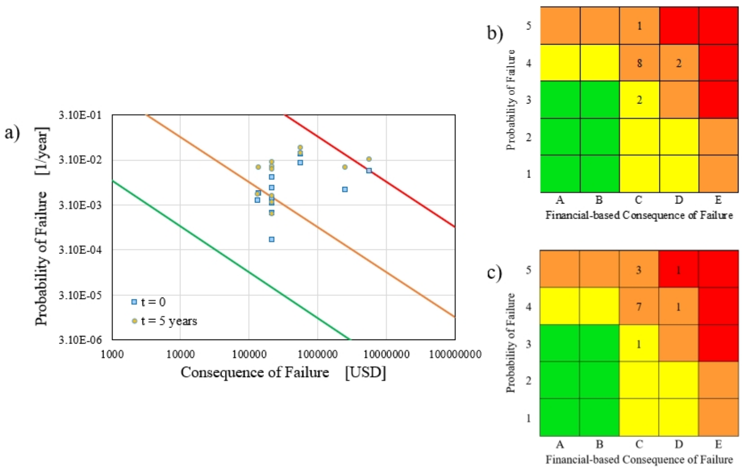

Fig. 5. (a) Iso-risk plot for financial-based consequence of failure of the components of the HRS. Risk matrices at the evaluation date (b) and after five years (c).

Fig. 6 shows the time dependence of risk over a five-year period. As expected, the hydrogen compressor is the most critical component since has the highest risk at t = 0 and the highest slope of the risk curve. This trend is driven by the severe consequences of a loss of integrity. The high-pressure storage tank is ranked second in terms of risk, and the medium and low-pressure tanks are ranked third and fourth, respectively. All the piping is classified as low-risk despite the high probability of failure of such components exposed to atmospheric corrosion, hydrogen embrittlement, and eventually vibration fatigue. In contrast, the plate heat exchanger is ranked fifth at the first evaluation date due to the limited impact of corrosion under insulation and thermal fatigue.
Despite this, the hydrogen-induced degradation of the component exposed to high pressure and low temperature (i.e., the most severe operating conditions for austenitic steels in hydrogenated environments) tends to rise sharply over time. As a result, this component overcomes the low-pressure storage tank in terms of risk and is expected to overcome the medium-pressure one. This trend proves unequivocally the significant effect of hydrogen-induced damages on the probability of failure of hydrogen technologies.

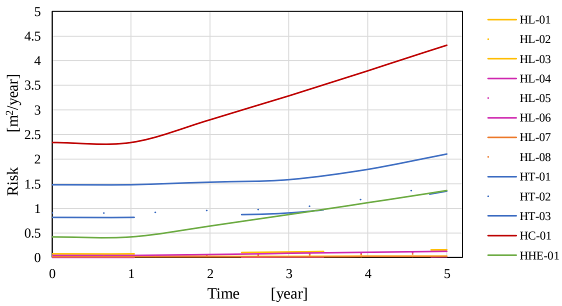

Fig. 6. Time-dependent risk of the compressor (red line), storage tanks (blue lines), pre-cooling system (green line), supply terminal pipes (yellow lines), tanks' pipes (purple lines), and distribution terminal pipes (orang lines) over five years.

Fig. 7 shows how a limited number of equipment items are responsible for a high percentage of the overall risk of the HRS. More specifically, three components (i.e., hydrogen compressor, high- and medium-pressure storage tanks) account for 80% of the total risk. Two additional components (i.e., the low-pressure storage tank and the pre-cooling block) account for another 16% of the HRS overall risk. In contrast, the remaining eight components have a negligible influence on the risk of failure of the entire facility (less than 4%). Hence, the optimal inspection strategy lies in focusing all the efforts on these equipment items.

Magnetic particle testing (MT), liquid penetrant testing (PT), and wet fluorescent magnetic particle testing (WFMT) are useful for detecting surface cracks. Surface preparation by high-pressure water blasting, grit blasting, or flapper wheel cleaning is usually necessary for these types of non-destructive testing (NDT). As an alternative, alternating current field measurement (ACFM) and eddy current testing (ECT) can be used since they do not require surface preparation. Ultrasonic testing, such as shear wave and phased array ultrasonic testing (SWUT and PAUT), can find and size subsurface hydrogen-induced cracks. In addition, acoustic emission testing (AET) can be used to locate cracks and continuously monitor crack growth (API, 2020). Nevertheless, in high cycle fatigue, the time required for a crack to reach a size identifiable by NDT is most of the component's fatigue life. Hence, detecting a crack before failure is inherently challenging, and relying on NDT for global routine inspections is impractical. Hence, more frequent inspections can be focused on specific areas (e.g., welds and heat-affected zones) that are known to be highly susceptible to fatigue failures. In addition, vibration monitoring of dynamic components may provide early detection of severe operating conditions that could lead to future failures.

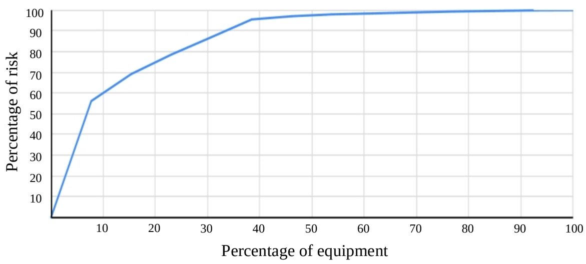

Fig. 7. Percentage of equipment vs percentage of risk

Hydrogen refueling stations are often inspected at regular intervals. The minimal inspection frequency is established for each component. Internal inspections are scheduled every ten years for pressurized storage tanks, while external inspections are carried out every five years, according to the standard API 510 (API, 2022). In this case, this inspection schedule is highly conservative since the hydrogen storage tanks are not subjected to HE, and the liner failure is the only damage that could affect the inner surface of these components. In addition, the standard API 570 (API, 2016b) lays down that pipes and valves for flammable gases should be inspected every five years. This inspection interval sounds reasonable due to the rapid increase of the damage factor for hydrogen embrittlement and atmospheric corrosion. Both internal inspections to detect cracks and external inspections for thinning damage should be carried out. In contrast, the standard API 628 for reciprocating compressors does not establish inspection intervals and relies on the manufacturer's instructions.

The only HRS specific standard (i.e., ISO 19880) is still under development and, at this stage, provides general recommendations for the inspection and maintenance of valves (ISO 19880-3), pipes, and flexible hoses (ISO 19880-5).

However, the sections for compressors (ISO 19880-5) and dispensers (ISO 19880-2) are not published yet and the development of additional sections for storage tanks and pre-cooling systems is not even planned (ISO, 2020). Therefore, the TBI approach strongly relies on expert judgment, operators' experience, and manufacturers' recommendations. The lack of a unified regulatory framework tends to result in too frequent inspections, increasing the downtime of the plant and the preventive maintenance costs.

5. Conclusion

This study applies the RBI methodology on a hydrogen refueling station. An accurate and reliable evaluation of the probability of failure of hydrogen handling and storage equipment was not possible since most H_2-induced degradations are not considered by the existing RBI standards. Therefore, a new methodology was developed to account for the hydrogen embrittlement effects. The RBI approach was compared with the time-based inspection guidelines for HRSs. The outcomes show how the overall risk can be significantly reduced by focusing the inspection effort on the hydrogen compressor and storage tanks. Several material degradations, such as atmospheric corrosion and hydrogen embrittlement, can reduce the facility lifetime and increase the failure probability of the components. In general, RBI can provide a dynamically adaptive inspection framework for hydrogen refueling stations with the potential to reduce the inspection frequency, while guaranteeing the safety and reliability.

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