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Time-Dependent Risk Drivers of the Onboard High-Pressure Hydrogen Tank

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Abstract

Hydrogen-powered vehicles are an excellent solution for controlling air pollution in large cities. During the last decade, rapid growth has been observed in hydrogen storage technologies for onboard applications. However, there is limited experience in using these technologies in the vehicle industry, and accordingly, the associated risks have not been fully identified. Risk assessment processes are typically performed based on qualitative, semi-quantitative, and quantitative approaches. Several researchers have investigated the risk analysis of potential random events during the lifecycle of hydrogen tanks. However, time-dependent risks such as hydrogen embrittlement, cracking, and metallurgical failures have not yet been studied. This study uses a fully quantitative risk assessment process for risk analysis of the onboard high-pressure hydrogen vessels. Through this risk assessment process, the potential damage mechanisms, probabilities of failures, and the consequences of failures for hydrogen vessels are determined. According to the results from quantitative risk analysis, the likely failures may affect $32m^2$ around the failure location.

1. Introduction

In order to control global warming and air pollution in large cities, fossil fuel vehicles are being replaced with fuel cell hydrogen vehicles (FCHV), which are used throughout the world [1]. Two significant challenges in using hydrogen are the safety and storage problems [2, 3]. It is known that FCHVs have already hit the roads [4]. However, the safety issues of using FCHVs have not yet been studied sufficiently [5]. Hydrogen can be stored in three different methods for use by fuel cells in cars [6]: (1) high-pressure gas phase [7], (2) liquid phase [8], and (3) solid-state storage [9]. Researchers continuously develop hydrogen storage techniques based on the abovementioned methods. Cost and safety play the primary role in the selection of the final choice for onboard hydrogen storage [10]. Most solid-state hydrogen storage methods require a thermal system to enable the hydrogen absorption and desorption process. In addition, they require costly materials such as reactive hydride composites to chemically store the hydrogen. Also, liquid-phase hydrogen storage requires cryogenic materials and equipment, which increases the cost of the storage. At present, it appears that hydrogen storage in high-pressure tanks is more practical. However, there are safety concerns in using composite onboard hydrogen storage tanks operating at pressures between 70 and 90 bars in a vehicle. A quantitative risk assessment of onboard hydrogen storage exposed to a fire is discussed in a study by Dadashzadeh et al. [11]. They have considered

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fatality and financial risk types. They reported the risk of about 3.14×10ˆ(-3) fatality per accident, which is higher than the acceptable risk level for hydrogen tanks (1.00×10ˆ(-5)). Safety components such as thermal pressure relief devices, fittings, and connections may fail and put the hydrogen system at risk. The risk of such components is also discussed by Dadashzadeh et al. [11, 12]. Sun and Li [13] analyzed typical accident progressions of hydrogen fuel cell vehicles in a road collision event. A review of the literature shows that the risks associated with random events such as tank fires, road accidents, safety device failures, and poor connections and fitting problems were studied by different researchers. However, the time-dependent risk drivers of hydrogen vessels, such as hydrogen embrittlement of tank components, risks associated with regular operation, and the aging of the high-pressure hydrogen system, have not yet been studied. This study employs a quantitative risk assessment process for evaluating the time-dependent risks of high-pressure hydrogen tanks. Unlike previous studies that mainly focused on random or external failures such as collision-induced rupture or thermal events, the present work provides a quantitative framework for evaluating time-dependent risks, such as progressive thinning, cracking, and metallurgical degradation over time. By utilizing the API RP 581 standard in combination with actual design and operational data, this study uniquely integrates risk modeling with practical inspection planning for onboard hydrogen systems. This approach offers a more comprehensive risk profile and addresses a critical gap in the hydrogen safety literature. The analysis result of the explosion-affected area has been compared with other studies and found good conformity. The results of the present study can help designers develop inspection and test plans for hydrogen vessels.

2. Methodology

The risk assessment procedure used in this study has been presented in Fig. 1. The risk assessment procedure of pressurized hydrogen tanks used in the present study is in conformity with API-RP-581 recommended practice [1]. Risk in this context is defined as the combination of the probability of failure (PoF) and consequence of failure (CoF) as shown in Eq. (1) [14].

$$Risk = PoF \times CoF \quad (1)$$

Where PoF is usually defined based on failures per year, and CoF is defined based on dollars per failure or affected area per failure. The value of PoF changes with change in type and severity of active damage mechanisms, the material of construction, corrosive content of the fluid service, operating temperature, operating pressure, and inspection methods and frequencies. The general equation for the calculation of PoF is [15]:

$$PoF = gff \times D_f(t) \times F_{ms} \quad (2)$$

where gff is the total general failure frequency which is estimated from previous failure reports. $D_f(t)$ represents the effects of active time-dependent damage mechanisms. Both internal and external failure mechanisms can be considered.

Failures occur due to damage mechanisms. Object impacts, corrosion, and overpressurized conditions are examples of failure mechanisms. F_{ms} considers the effectiveness of failure management methods in a vehicle, which depends on the suitability of tank placement and protection inside a vehicle. This parameter is estimated using a questionnaire and scoring method and depends on the tank and vehicle brand and manufacturer. During failure, a tank can fail with holes of different sizes. Experiences in the petrochemical industry showed that the holes produced in most failures of pressurized tanks are medium-sized. However, failures with small or large holes ,and even ruptures, were reported. In this study, the weighted average of general failure frequencies for all failure modes of a hydrogen tank is considered as gff=3.06E-05 failures per year based on experiences in using hydrogen vessels in petrochemical industries [1]. This value is above the acceptable risk level for the vehicle industry and should be reduced by managing the effective parameters, as discussed in Eq. (2).

It should be noted that the general failure frequency (GFF) value of 3.06×10^{-5} failures/year used in this study is based on historical data from petrochemical applications. While this offers a practical starting point for risk estimation, we acknowledge that onboard hydrogen tanks in vehicles may experience additional dynamic stresses such as vibration, cyclic mechanical loading, and thermal fluctuations. These operational differences could influence the actual failure rate. Therefore, the current value is used as a conservative approximation, and refinement using vehicle-specific data is suggested for future work.

Generally, for hazardous fluids, three types of consequences are calculated: 1) flammable and explosive consequence, 2) toxic consequence, and 3) nonflammable, nontoxic releases. Given the inherent properties of hydrogen, including nontoxic and flammable characteristics, only the first category, meaning the flammable and explosive consequence, should be considered in the risk assessment of a hydrogen tank. It is known that in a failure scenario of a pressurized vessel, the significant consequences are associated with pool fires for liquid releases and vapor cloud explosions (VCEs) for vapor releases. Neither pool fires nor VCEs are anticipated for hydrogen releases, as hydrogen is generally in gas form with a huge buoyancy effect. In this assessment scenario, the consequence areas can be determined based on serious personnel injuries and component damage from thermal radiation and explosions. Financial losses are determined based on the area affected by the release. In order to show the affecting parameters in a fully quantitative risk assessment process for time-dependent threats, the properties and operating conditions of an example hydrogen vessel in a typical FCHV are considered. Table 1 presents the design and operational parameters used for the risk assessment case study in this work. These values are not based on a specific proprietary system but represent a typical high-pressure onboard hydrogen tank configuration used in fuel cell vehicles. The data are synthesized from publicly available literature [7, 11, 19], default input suggestions from RBLX software, and standard industry practices. The goal is to simulate a realistic scenario under standard design conditions to demonstrate the applicability of the API RP 581-based risk assessment methodology.

For the goal of consequence analysis, the hydrogen release rate from the likely failure hole is calculated using Eq. (3). This equation is based on discharges of gases and vapors at sonic velocity through an orifice [16].

$$\chi=\frac{C_d}{1000}.A_n.P_s.\sqrt{\left(\left(\frac{k.MW.g_c}{R.T_s}\right)\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}\right)} \quad (3)$$

Where P_s(kPa) is the storage or normal operating pressure. The discharge coefficient, C_d, for fully turbulent gas or vapor flow from sharp-edged orifices is typically in the range of $0.85 \leq C_d \leq 1.0$. A conservative value of C_d=0.90 is used in this study. Also, the release hole size area, A_n is calculated using Eq. (4).

$$A_n=\frac{\pi d_n^2}{4} \quad (4)$$

Considering continuous hydrogen release without the chance of auto-ignition, the flammable consequence area for the hydrogen tank can be calculated using Eq. (5).

$$C_f= 64.5.X^{0.992} \quad (5)$$

Where X is the release rate. This equation was adapted from empirical dispersion and flammable consequence models reported by Crowl and Louvar [16], where X is the hydrogen release rate in kg/s. This power-law relationship reflects the scaling behavior of thermal impact radius versus release magnitude for buoyant gases like hydrogen.

It is noted that the component life is estimated at 47.7 years, which exceeds the design life of 40 years. This value represents a practical case study. According to API RP 581 and associated risk-based inspection (RBI) methodologies, such estimates are valid outputs of damage rate extrapolation. However, operation beyond the design life should always be accompanied by a fitness-for-service (FFS) assessment in line with API 579, and may require engineering justification or regulatory approval in practice.

Table 1
Parameters for risk analysis of a compressed hydrogen tank and values for the case study of the present work.

Design / Installation		Operating & Process	
Component type	Vessel	Operating temp. (°C)	0
Component shape	Cylinder	or below the MDMT or MAT	False
Design Life (years)	40	Equipment design allows water to pool	True
Component life (years)	47.7	Fluid name	Hydrogen
External coating quality	Medium coating quality	Component fluid mass (kg)	60
Material	A-285 GR.C	Inventory component group fluid mass (kg)	0.33
Material specification no	A 285	Operational fluid phase	gas
Design pressure (bar)	8.2	pH	7
Design temp. (°C)	-240.2	Hydrogen	True
MDMT/MAT (°C)	-29	Water	True
Tensile strength (MPa)	379	Oil	False
SMYS (Yield)(MPa)	207	HF	False
Size diameter (inches)	21	Oxygen	False
NT (mm)	20.64	HCl	False
Joint efficiency (0 to 1)	0.85	Atmosphere corrosivity	Frequently
Design corrosion allowance (mm)	3.2	Insulated	True
MAWT (mm)	14.53	Insulation contains chloride	False
PWHT	True		
Stress relieved	True		

3. Results and Discussion

Fig. 2 shows the process flow diagram of a typical high pressure hydrogen system of a vehicle fuel cell. It can be seen from Fig. 2 that the failures can occur in (1) the hydrogen vessel, (2) valves and connections, and (3) the fuel cell. The causes of failure can be categorized, as shown in Fig. 3, into three parts: human errors, natural events, and technological problems. Regardless of the risk source, the damage drivers can be divided into time-dependent and time-independent damage evolution types. Fig. 3 shows the subcategories of each group. It is possible to develop growth estimation equations for time-dependent damage types. However, time-independent damage types cannot be anticipated. Therefore, this study focuses on time-dependent damage types to predict the failure occurrence date. The time-dependent damage types considered in this study include thinning, metallurgical damage, cracking/mechanical damage, and external damage.

The first step in the risk assessment process is to identify potential damage mechanisms. This step is carried out using the screening method to assess which are relevant to the under-investigated problem. In this study, the screening process is performed automatically by the RBLX software. This commercial software conducts the screening based on API-RP-571 recommended practices using design and operation data as input. The output of the software-CoF values for each potential damage mechanism-is presented in Table 3. Eq. (5) was used to calculate the consequences of the likely damages. Table 4 shows the results of the CoF analysis.

PoF scores in Table 3 are derived using the RBLX software which performs complex calculations based on the screening logic of API RP 571. PoF follows a semi-quantitative scale ranging from 0 to 5, based on API RP 581 (2016). Table 2 summarizes the meaning of each score.

Table 2
Semi-quantitative PoF scoring scale according to API RP 581.

PoF Score	Description
0	Not applicable
1	Rare
2	Moderate likelihood
3	Likely
4	Very likely
5	Almost certain

For example, a PoF score of “2” for cracking and mechanical damage reflects the presence of pressure cycling, moderate material strength (SMYS=207MPa), and post-weld heat treatment, which moderately reduces residual stresses. These parameters were entered into the software as part of the case study and influenced the PoF rating outcome.

It is worth noting that both the tank material and wall thickness play significant roles in determining the risk profile of hydrogen storage systems. Stronger materials with higher yield and tensile strengths can increase burst pressure and reduce the likelihood of mechanical failure. However, materials with higher strength may exhibit increased susceptibility to hydrogen embrittlement, particularly in high-pressure environments. Similarly, increasing wall thickness enhances structural integrity and corrosion tolerance, thereby reducing PoF, although it may add to weight and cost. These trade-offs should be considered in design optimization, and a sensitivity analysis is recommended for future studies to quantify these effects on overall risk levels.

Table 3
Probabilities of potential damage mechanisms for onboard Hydrogen tank

Damage mechanism	PoF
Thinning	1
Cracking and mechanical	2
Metallurgical	0
External corrosion	1
Overall	2

It is noted that the PoF value for “Metallurgical” damage in Table 3 is zero. This outcome was generated by the RBLX software based on the vessel’s material (A-285 Gr. C), its post-weld heat treatment (PWHT), stress-relief condition, and operating temperature. These parameters reduce the susceptibility to hydrogen-induced cracking, carbide precipitation, and other metallurgical degradation modes. As per API RP 571, such mechanisms typically activate under high-temperature service or in harder alloy steels. While metallurgical degradation is generally a valid time-dependent risk driver, it is not active under the current case conditions. This does not preclude its significance in other designs or service environments; threfore, it should be reassessed if design or service parameters change.

Table 4
Affected area consequence calculation for onboard hydrogen tank

Consequence Criteria	Affected area	CoF score
Safety (m^2)	32.7	B

Additionally, from a safety perspective, exposure to thermal radiation above 12.5kW/m^2 is recognized as a fatal threshold, capable of causing second-degree burns within one second. Based on API RP 581 (Part 3), the affected area is calculated to correspond to this level of radiation intensity for the hydrogen mass flow considered. Thus, the consequence analysis result is realistic and aligns with published risk thresholds and simulation-based studies.

According to API RP 581, the Consequence of Failure (CoF) score can be influenced by mitigation strategies such as fireproofing, insulation, and protective system layout [19]. These measures are intended to reduce the impact of thermal events (e.g., jet fires or external pool fires) by shielding the tank and slowing the rate of pressure rise. While CoF calculation in this study did not explicitly include a mitigation factor, the addition of thermal protection layers could potentially reduce the affected area or damage intensity, thereby shifting the CoF score from category B to A.

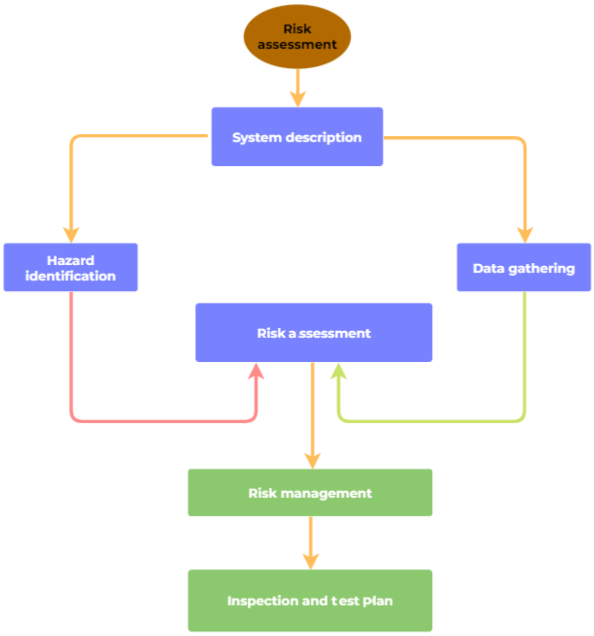

Fig. 1. Risk assessment process for the onboard high-pressure Hydrogen tank [17].

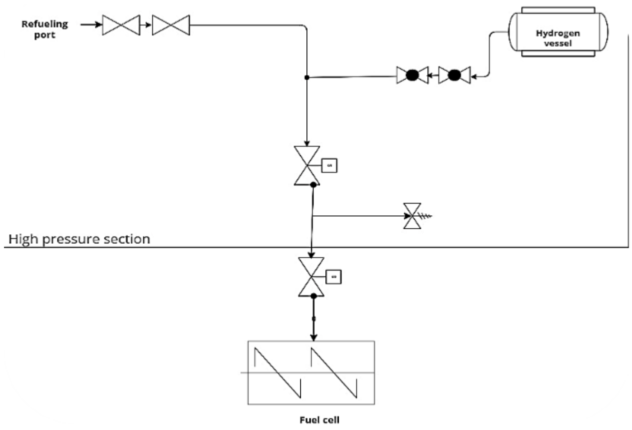

Fig. 2. Schematic of onboard high-pressure Hydrogen system [13].

These options are especially important for vehicles operating in high-risk environments or subject to external fire threats.

Considering the obtained PoF and CoF values, the risk of the tank can be estimated using the API risk matrix, as shown in Fig. 4. It should be noted that the risk level of the tank may change due to aging and variations in operating conditions. In order to ensure safe operation, the risk of the tank should be maintained at a low level.

Based on risk category of the hydrogen vessel, inspection intervals can be adjusted-either shortened or extended. For the case study presented in this work, as the total risk of the equipment is classified as low, the inspection plan as Table 6 is recommended.

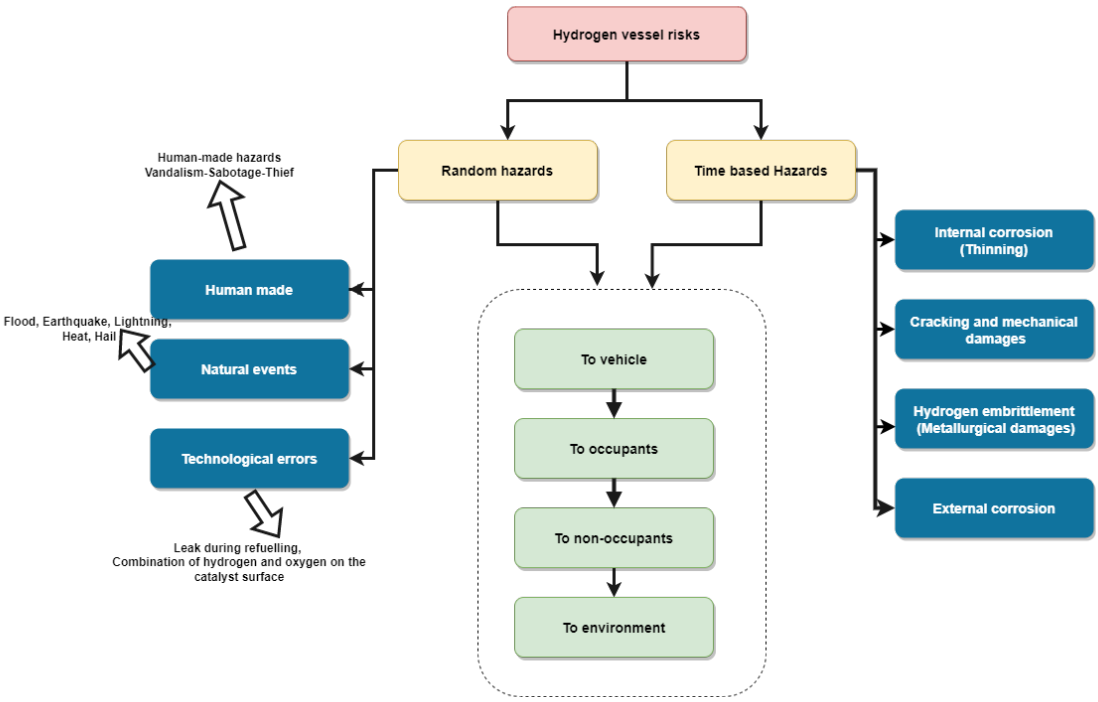

Fig. 3. Hydrogen vessel-related risks.

The inspection intervals proposed in Table 6 are based on the RBI framework defined by API RP 581. According to this standard, the inspection interval is determined by the risk category resulting from the combination of PoF and CoF. The hydrogen tank evaluated in this study was categorized as 'Low Risk' in the API risk matrix (Fig. 4), which justifies the recommendation of a 5-year inspection interval. Table 5 shows a typical mapping of risk category to inspection interval based on API RP 581.

These intervals are subject to adjustment based on operational changes, inspection history, and degradation mechanisms observed.

Given the low-risk classification of the hydrogen tank (Fig. 4), a risk-based inspection plan is proposed. The plan aligns with the guidance of API RP 581 as well as hydrogen system standards such as ISO 16111 and SAE J2579. The selected methods and intervals are designed to detect the onset of damage mechanisms, including thinning, cracking, or leak points, before failure occurs.

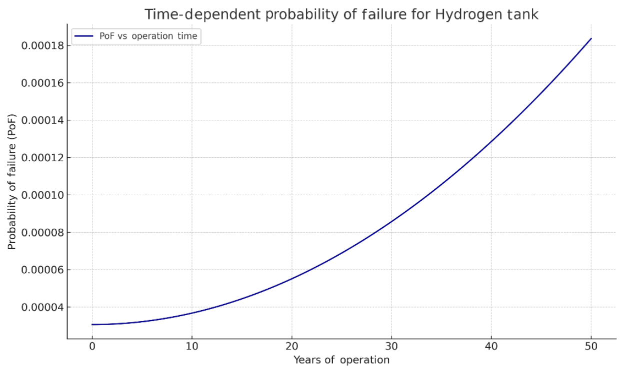

Fig. 4. Time-dependent PoF curve for Hydrogen tank

The proposed methods are non-destructive and tailored to detect the expected damage mechanisms in composite or steel hydrogen tanks. For example, acoustic emission (AE) testing is effective in identifying micro-cracking and fiber breakage in Type III tanks and is increasingly used in periodic safety verification. Leak detection is especially critical due to hydrogen's high diffusivity and low ignition energy.

Fig. 5 illustrates the time-dependent growth in the PoF for the hydrogen storage tank used in the case study. The illustrated curve reflects a simplified degradation model where PoF grows quadratically with operational time due to cumulative damage mechanisms such as thinning and fatigue. This visualization emphasizes the importance of early inspection and condition monitoring during the mid-to-late service life of the equipment.

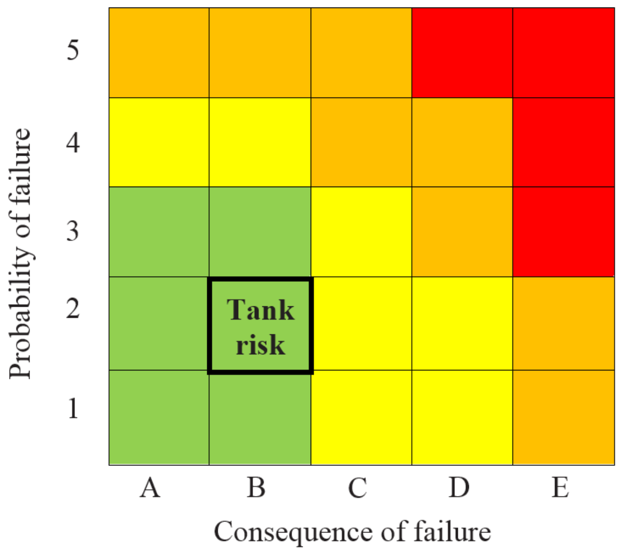

Fig. 5. Risk level of Hydrogen storage tank [18]

Table 5
Recommended inspection intervals based on risk categories [1].

Risk category	Typical inspection interval
High risk	1-2 years
Medium risk	3 years
Low risk	Up to 5 years

Table 6
Recommended inspection plan for Hydrogen cessel in the study.

Component type	Inspection method	Inspection interval	Purpose
Hydrogen vessel	Hydrostatic pressure test (per ISO 19881)	Every 5 years	Assess structural integrity and leakage under pressure
	Visual inspection (external/internal if possible)	Annually	Detect coating failure, corrosion, deformation
	Acoustic emission (AE) monitoring	Every 5 years or during pressure test	Detect active crack growth or delamination in composite tanks
Valves & connections	Hydrogen leak detection (soap solution or H2 detector)	Every 6 At joints and fittings	at joints and fittings
	Operational function check (e.g., relief valve lift)	Every 6 months	Ensure valves respond correctly under overpressure
	Tightness test during fueling cycles	Every 3 months	Check for ongoing integrity of seal interfaces

Compared to qualitative or semi-quantitative risk assessment techniques (e.g., failure modes and effects analysis (FMEA), risk ranking matrices), the API RP 581-based quantitative risk assessment approach used in this study offers several advantages. It provides numerical outputs for botj PoF and CoF, allows for objective comparison between different equipment, and directly feeds into inspection interval planning.

Additionally, while advanced methods such as CFD-based modeling (e.g. [19]) offer detailed simulations of explosion or leak scenarios, they are often limited to specific case studies and require high computational resources. Bt contrast, the API RP 581 methodology is faster and more scalable, making it suitable for widespread use in RBI programs across the hydrogen fuel infrastructure.

A hybrid approach combining CFD-based consequence validation with API-style risk quantification could offer a balanced methodology in future work.

3.1. Mechanical Integrity Considerations

In line with API RP 581 recommendations for assessing time-dependent degradation mechanisms, the mechanical behavior of the tank structure under pressure plays a critical role in determining its PoF. The material strength properties used in the analysis (see Table 1) include specified minimum yield strength (SMYS)=207MPa and tensile strength=379MPa. A simplified estimation of the tank's burst pressure can be calculated using the classical thin-walled cylinder approximation (Eq. (6)).

$$\mathrm{P} = \frac{2tS_{act}}{D} \tag{6}$$

Where t is the minimum wall thickness, S_{act} is the reported actual tensile strength, and D is the outside diameter of the pressure vessel. For the case under study, the calculated burst pressure is approximately 64.8 bar, which is significantly higher than the design pressure (8.2 bar), ensuring a substantial safety margin.

In addition, potential crack initiation sites and the resulting stress concentration effects (SCF) contribute to time-dependent damage mechanisms [20]. While a full finite element analysis is beyond the scope of this study, the risk model implicitly incorporates these effects through damage mechanisms like cracking and metallurgical degradation. Weld joints, geometry transitions, and cyclic loading conditions can amplify localized stress levels and should be addressed in future work using detailed stress analysis and fracture mechanics modeling.

4. Convlusion

A quantitative risk assessment of hydrogen storage tank was conducted. Potential damage mechanisms are categorized, and the failure risks associated with time-dependent damage mechanisms were studied in detail. The analysis showed that the risk of thinning, cracking, mechanical, and metallurgical damage types fall into the low-risk category. It was found that the likely failures will affect $32m^2$ around the failure location. Based on the risk category of the hydrogen system, the corresponding inspection plans with inspection intervals were proposed. The use of fireproof materials, thermal protection insulation, and properly calibrated thermal pressure relief devices can significantly reduce the CoF, especially in scenarios involving external heat exposure. These strategies are consistent with mitigation recommendations outlined in API RP 581 and can lead to improved safety margins and longer inspection intervals. It is emphasized that the risk of the hydrogen tank can change due to aging and variations in operating conditions. Therefore, the risks should be revised whenever influencing parameters are modified.

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