

Assessment of the Remaining Life of Liquefied Petroleum Gas Pressure Vessels Located in Coastal Areas

Evaluación de la vida remanente de recipientes a presión de Gas Licuado del Petróleo ubicados en zonas costeras

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Abstract: Pressure vessels for liquefied petroleum gas (LPG) located in coastal areas are exposed to accelerated external corrosion due to environmental factors such as marine aerosols and humidity, which limits their service life and poses operational safety risks. The objective of this study was to determine the corrosion rate and assess the remaining life of vessel number 4 (5 m³, SA516Gr70 steel) from the LPG battery at Hotel Brisas Guardalavaca (Holguín, Cuba), through inspection following API 510 standards. Ultrasonic thickness measurements (DMS Go+ equipment, DA512 transducer) were performed at pre-identified critical points (CMLs), and direct pitting depth measurements were taken with a gauge in the most affected areas of the heads and cylindrical shell, calculating short-term corrosion rates (2022-2024) and remaining life. The results show that the dominant damage mechanism is pitting corrosion, with global ultrasonic rates of 0–0.04 mm/year (remaining life ≈ 80 years) but localized pitting rates of 0.4–1.0 mm/year (remaining life ≈ 1 year in critical zones), demonstrating that vessel integrity is controlled by localized defects. It is concluded that evaluations of coastal LPG vessels

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must prioritize localized corrosion to establish conservative inspection intervals and mitigation actions.

Keywords: Fuel resources, gas resources, gas feul

Resumen: Los recipientes a presión de gas licuado del petróleo (GLP) ubicados en zonas costeras están expuestos a corrosión externa acelerada por aerosoles marinos y humedad, lo que compromete su vida útil y seguridad operativa. El objetivo de este trabajo fue determinar la velocidad de corrosión y evaluar la vida remanente del recipiente No. 4 (5 m³, acero SA516Gr70) de la batería de GLP del Hotel Brisas Guardalavaca, Holguín, Cuba, mediante inspección conforme a la norma API 510. Se realizaron mediciones de espesores por ultrasonido en puntos críticos y medición directa de profundidad de *pitting* en las zonas más afectadas. Los resultados muestran un contraste significativo entre ambos métodos: el ultrasonido indicó tasas globales de corrosión de 0–0,04 mm/año y una vida remanente aproximada de 80 años, mientras que el *pitting* reveló tasas localizadas de 0,4–1,0 mm/año y una vida remanente cercana a 1 año en áreas críticas. Esto confirma que la integridad del recipiente está gobernada por corrosión localizada y no por pérdida uniforme de espesor. Se recomienda priorizar el control de las picaduras profundas e implementar medidas de intervención o retiro oportuno en recipientes con proyección de pérdida crítica de vida útil, para proteger la integridad de la instalación y la seguridad de las personas.

Palabras claves: recursos combustibles, industria del gas, combustible gaseoso

1. Introduction

Liquefied petroleum gas (LPG) pressure vessels are designed to store gases or liquids at pressures above the atmosphere pressure, under strict regulations and technical standards to ensure the safety and structural integrity of the equipment (Venegas-Vásquez *et al.*, 2026). These vessels' remaining life is the estimated time they can continue operating safely, considering the deterioration mechanisms they are exposed to (API 2022). Timely withdrawal from service of a pressure vessel with damage that is inadmissible under inspection codes, standards, or regulations can prevent major incidents that could lead to the loss of human lives and significant material and economic losses (Venegas-Vásquez *et al.*, 2024; Molina *et al.*, 2025)

LPG is mainly stored in low-alloy carbon steel vessels. Its main damage mechanism is pitting corrosion on the external surface (Frankel, 1998; Szklarska-Smialowska, 2005). This type of corrosion's morphology difficults the accurate assessment of its dimensions, mainly the greatest depth, which corresponds to the smallest remaining thickness (Sun *et al.*, 2024; Shekari, 2017; Moreira & Borges, 2022). Determining the damage caused by corrosion on the external surface is important for comparing the remaining thickness values with the retirement limit values and, based on the corrosion rate calculation, determining the vessel's remaining service life (Gómez, 2022; Melchers & Tan, 2023; Ginting *et al.*, 2023).

Technical studies have developed models and procedures for evaluating pressure components, including the calculation of remaining service life, corrosion rate and acceptance or rejection criteria, by applying traditional methods and technological innovations (Jarić *et al.*, 2021; Gómez & López, 2022; Silva, 2023; Tai *et al.*, 2025). However, in coastal LPG vessels, it is necessary to compare ultrasound (average thicknesses) and direct pitting measurement to estimate the actual remaining life (Abdulameer *et al.*, 2024; Rosenberger, 2024).

LPG pressure vessels located near the sea, such as those in the hotel zone of Guardalavaca tourist destination, tend to suffer thickness losses on the pressure body's external surface due to environmental corrosion processes. Although characterization studies on these corrosive aggressiveness processes in nearby areas have been carried out (Castañeda *et al.*, 2015), no corrosion rate value has been found in the literature that allows for evaluating the remaining life of LPG pressure vessels located in coastal areas.

Therefore, this work is aimed at determining the corrosion rate and evaluate the remaining life of vessel number 4 from the LPG battery at Hotel Brisas Guardalavaca (Holguín, Cuba), through inspection following the API 510 (2022) standard.

2. Materials and methods

2.1. Materials

2.1.1. LPG vessel

Figure 1 shows a panoramic view of the LPG vessel battery, where the relative arrangement of tanks and the location of vessel 4, selected for the study, can be seen.

Vessels 1, 2 and 3 were replaced in 2024; at the time of inspection, they showed no evident damage. Vessel 4 has been in operation since the hotel was built.



Figure 1. General view of LPG vessel battery at Hotel Brisas Guardalavaca, indicating vessel 4 position.

The object of study was vessel number 4 (5 m³, SA516Gr70 steel), built at Quintín Banderas factory, which is located in the Plaza de la Revolución municipality, in Havana city. The prevailing criterion in the vessel selection was: existing damage on the external surface (Figure 2).

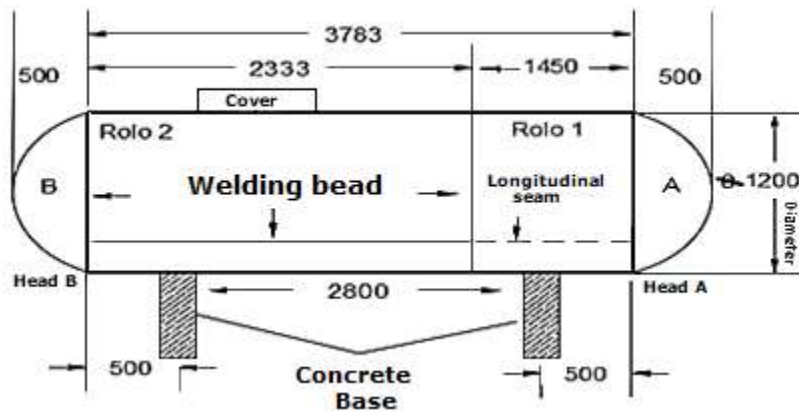


Figure 2. Design characteristics of vessel 4 from LPG battery at Hotel Brisas Guardalavaca.

Figure 2 shows LPG vessel 4 diagram indicating its main geometric dimensions (diameter, cylindrical shell length, head geometry). The most relevant design data (operating pressure, test pressure and manufacturing material) provided by the manufacturer's nameplate are shown in Table 1.

Table 1. Vessel design data

Identification key	Vessel No. 4
Origin	Cuba
Manufacturer	SIME Quintin Banderas
Capacity (c)	5000 liters
Minimum head thickness (tc)	10 mm
Minimum Shell thickness (te)	10 mm
Working pressure (Pt)	2.5 MPa
Test pressure (Pp)	1.7 MPa
Head type	Semi-elliptical
Vessel type	Horizontal cylindrical
Manufacturing material	SA516gr70

2.1.2. Ultrasound equipment

Thickness measurements were performed using a General Electric ultrasound device model DMS Go, with A-Scan representation and multiple-echo measurement method. The DMS Go+ equipment offers high measurement stability and reliability thanks to its zero-return procedure, automatic amplification adjustment for better reproducibility in corrosion checks, configuration and optimal device performance, and high measurement precision especially due to stored diffraction error correction data. It works with a transducer measuring on the echo flank or the echo peak Dual-Multi for measuring through the coating. Its measuring range is 0.25 to 14000 mm (steel), depending on the probe, material and surface, and digital resolution 0.01 mm or 0.1 mm (eligible) over the entire measuring range (DMS Go+ operating manual).

2.1.3. DA512 transducer

To generate and receive the ultrasonic wave, the DA512 dual-crystal transducer with 7.5 MHz sound pulse frequency, from the Krautkramer brand, was used. The DA512 probe is designed for fine-grain materials, has high sensitivity, a 7.5 MHz frequency, 7.5 mm of contact diameter and a measuring range from 0,80 mm to 75 mm (Brammertz, 2026)

2.1.4. Staircase pattern

The equipment was adjusted using a step wedge from 1 to 10 mm with 1-mm steps as shown in Figure 3.



Figure 3. Step wedge from 1 to 10 mm with 1 mm steps.

2.1.5. Gauge

The depth measurements of the pits/pitting located on the external surface were performed using a GAL GAGE CO: 269-465-5750 gauge.

2.2. Methods

2.2.1. Scientific observation

A visual inspection of the vessel's external part was performed to locate damage on the external surface and identify the damage mechanism(s).

2.2.2. Thickness measurement

The calculation procedure implemented in this work is based on API 510 standard, which establishes that the evaluation of in-service pressure vessels must be based on the determination of short-term and long-term corrosion rates, as well as the calculation of remaining life based on the minimum required thickness and the component's actual thickness. The selected expressions allow for quantifying material loss in relation to time, and conservatively estimating the vessel's safe operating range. When localized corrosion is present, it is necessary to use the rate associated to the most severe damage, as the structural behavior is determined by the zones with smaller remaining thickness and not by global averages.

Uncertainty estimation was performed on the base of instrumental resolution, calibration via staircase pattern, measurements repeatability, and access conditions to the inspected surface. Consequently, an expanded uncertainty of 0.13 mm for ultrasound and 0.16 mm for gauge measurement was adopted. These values were considered into the thickness temporal variation analysis. Additionally, a cross-validation between both techniques was performed, comparing the global thicknesses measured by ultrasound

with the maximum pitting depths obtained in the critical zones, in order to verify the result consistency and evaluate each method representativeness against the predominant damage mechanism.

The long-term corrosion rate was determined using expression 1. This equation is used to estimate a global thickness loss trend when the available measurements span an interval greater than two years, according to the procedure recommended by API 510.

$$TC_{LT} = \frac{e_i - e_A}{t_i - t_A} \quad [1]$$

Where

e_i : initially measured thickness

e_A : current thickness

t_i : initial time

t_A : time elapsed until current measurement.

The short-term corrosion rate was calculated using equation 2. This expression is used when the compared measurements correspond to an interval no greater than two years, and allows to reflect the recent damage evolution with greater sensitivity.

$$TC_{LT} = \frac{e_p - e_A}{t_p - t_A} \quad [2]$$

Where

e_p : thickness measured on a date prior to the current measurement

e_A : current thickness

t_p y t_A : times corresponding to both readings.

The vessel's remaining life was estimated using equation 3, which relates the available thickness reserve to the deterioration rate, allowing the estimation of the time the equipment can continue operating before reaching the minimum permissible limit.

$$\text{Remaining life} = \frac{e_p - e_R}{TC} \quad [3]$$

Where

e_p : previous thickness

e_R : required thickness

TC: corrosion rate or speed.

2.2.3. Statistical treatment of corrosion data

Thickness and pitting depth values were processed using basic descriptive statistics. The minimum, maximum, average values and measurement dispersion were determined for each zone under evaluation, which allowed to appreciate the degree of damage's spatial variability. This statistical treatment provides information on deterioration heterogeneity, particularly on the difference between the average thicknesses measured by ultrasound and the maximum pitting depths. Interpretation of results should be based on the extreme values observed in the critical zones, which condition the equipment's structural behavior.

3. Results

3.1. Localized corrosion spatial distribution

The visual inspection carried out on the vessel revealed that pitting corrosion is not distributed homogeneously over the external surface, but rather concentrates in specific regions of the cylindrical shell, the heads and the lower zones near the base. This distribution confirms that the predominant damage mechanism is localized in nature and, therefore, the severity of the deterioration cannot be adequately represented by average thickness values.

Areas with different affectation degrees were identified during the vessel's global assessment, comprising from incipient pits up to deeper cavities. Although the points of greatest severity in each section were selected for quantitative analysis, the comprehensive observation of the equipment verified the existence of other zones with less intense localized corrosion. In this sense, the points analyzed represent the most critical conditions observed within each sector, however they do not characterize the entire vessel shell.

Particular attention should be paid to the base area in contact with support surfaces, where accumulation of moisture and surface deposition were detected, favoring contaminants retention and localized corrosion appearance. This behavior is consistent with contact areas tendency to have less ventilation, poor drainage and favorable conditions to develop accelerated degradation mechanisms. Therefore, the base should be considered as a relevant region in the vessel's integrity assessment, even though the main measurements were concentrated on the heads and cylindrical shell.

Statistical analysis identified the stability or variability of the corrosive process in each sector. In zones where dispersion is low, material loss tends to be more uniform; however, in those with high dispersion, the presence of isolated deeper pits is confirmed. This fact is particularly important for future inspection planning, as it suggests the need to increase monitoring frequency in areas where the greatest contrasts between average and maximum values are concentrated.

From the inspections performed, damage was identified on the external part of the vessel, on the cylindrical shell, the base, the lower part of the shell, the upper part and the heads. Table 2 shows the affectations on the heads (high dispersion zones). Figure 4 shows the areas affected by corrosion on heads A and B of vessel 4, where specific areas (Zones 1-4) with pitting on the external surface are identified; these were later on selected for a detailed measurement of thicknesses and pit depths.

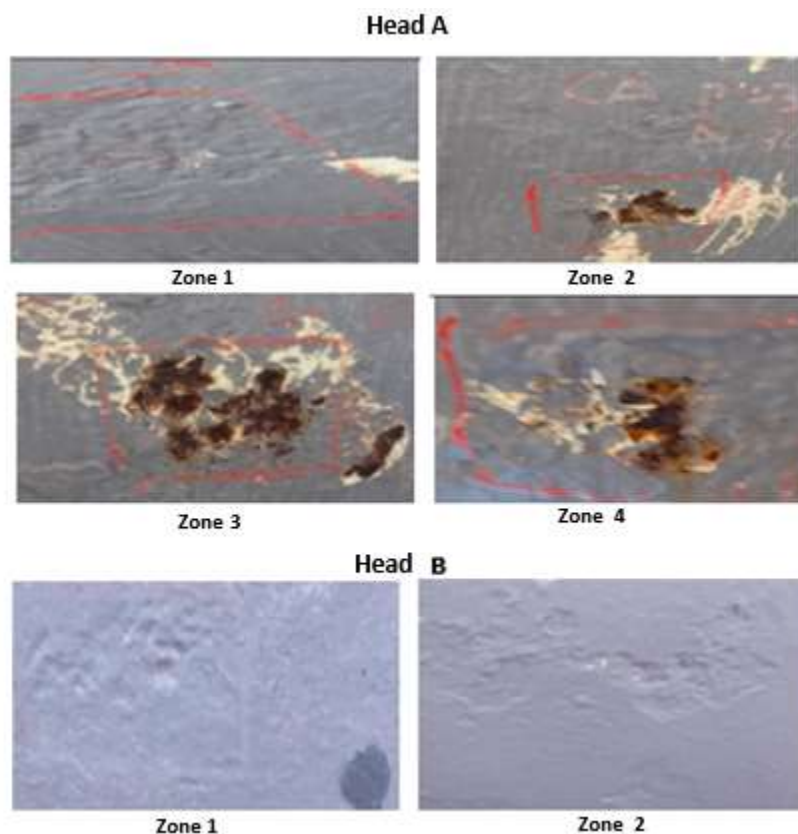


Figure 4. Evidence of damage on the vessel heads.

The type of damage identified was pitting corrosion (Figure 5). Pits of different morphology and size are observed, which concentrate material loss at specific points

and comprise the critical zones considered in the corrosion rate and remaining life analysis.



Figure 5. Area affected by pitting corrosion (lower part of the vessel).

3.1.1. Thicknesses determined by ultrasound method

Table 2 shows minimum thickness average values for each component of the pressure vessel shell taken during inspections carried out between 2022 and 2024. The estimated measurement uncertainty was 0.13 mm.

Table 2. Minimum thickness average values

Element	Thickness (mm)	
	Year 2022	Year 2024
Head A	9,92	9,90
Head B	9,83	9,82
Shell course 1	9,90	9,90
	9,83	9,82

From the thickness values taken by ultrasound, thickness profiles in the form of a cross-section cut of the vessel wall were obtained. Figure 6 shows the thickness profiles measured by ultrasound on the different elements of vessel 4 (heads and shell courses), representing the minimum values recorded between 2022 and 2024 along the cross-section of the wall, showing the thickness loss spatial distribution on the external surface.

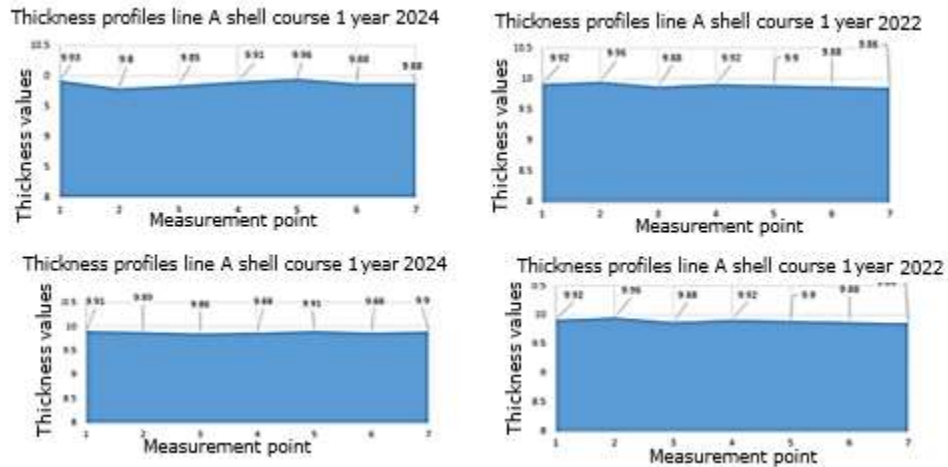


Figure 6. Thickness profiles measured by ultrasound.

3.1.2. Pitting depth measurement with gauge

Table 3 shows the average pitting depth values obtained and the remaining thickness at the deepest points in the damaged areas. The estimated measurement uncertainty was 0.16 mm.

Table 3. Average maximum pitting depth and remaining thickness value

Element	Zone	Inspectin 2022		Inspection 2024	
		Avg. max. depth	Remaining thickness	Avg. max. depth	Remaining thickness
Head A	1	0,70	9,3	1,7	8,30
	2	0,60	9,40	2,6	7,40
	3	0,70	9,30	1,7	8,30
	4	0,70	9,30	1,7	8,30
Head B	1	0,80	9,20	1,6	8,40
	2	0,60	9,40	1,8	8,20

3.1.3. Corrosion rate

The short-term corrosion rate results considering the ultrasound method are shown in Table 4.

Table 4. Short-term corrosion rate with data from the ultrasound method

Element	Corrosion rate (mm/Año)
Head A	0
Head B	0,04
Shell course 1	0
Shell course 2	0,04

The short-term corrosion rate results considering pitting depth using gauges are shown in Table 5.

Table 5. Corrosion rate by pitting depth

Elemento	Corrosion rate (mm/Año)
Head A Zone 1	0,5
Head A Zone 2	1,0
Head A Zone 3	0,5
Head A Zone 4	0,5
Head B Zone 1	0,4
Head B Zone 2	0,6

3.1.4. Withdrawal limit

The withdrawal limit obtained is shown in Table 6.

Table 6. Withdrawal limit

Element	Minimum required thickness (mm)
For the ellipsoidal head	6,66
For the cylindrical shell	6,68

3.1.5. Remaining life

The determined remaining life values due to corrosion are shown in Table 7.

Table 7. Remaining life

Method	Remaining life (years)
According to ultrasound measurement	80
According to gauge measurement	1

4. Discussion

The LPG storage battery at Hotel Brisas Guardalavaca comprises several 5 m³ vessels parallelly arranged to guarantee continuous supply to the hotel. Vessel 4 was selected because it presented the most evident external damage during the preliminary inspection, so it can be considered representative of the worst-case scenario within the battery (Rosenberger, 2024). In future inspection campaigns, the methodology applied in this work can be extended to the rest of the vessels, providing a comprehensive characterization of the corrosion behavior throughout the facility.

The selection of equations (1), (2) and (3) responds to their standard use in the evaluation of in-service pressure vessels, since they allow to transform thickness measurements into operational integrity parameters comparable to API 510 inspection

criteria (American Petroleum Institute, 2022). In the presence of pitting, their application must be complemented with local pit depth measurement, because the average thickness can underestimate component's real condition (Tai *et al.*, 2025; Romero Lara & Brito Moncayo, 2023).

The results evidence the damage to the vessel does not respond to a uniform thickness loss, but to a localized pitting corrosion process, concentrated in specific areas of the cylindrical shell, heads and base (Viña-Rodríguez *et al.*, 2021). This distribution explains the marked difference between the remaining life estimated by ultrasound (80 years) and the one calculated on the pit depth basis (1 year). This confirms that the integrity of the equipment is governed by localized defects and not by average thicknesses (Ginting *et al.*, 2023; Abdulameer *et al.*, 2024).

The comparison between methods highlights the limitation of conventional ultrasound when applied in isolation to localized corrosion. While it recorded global rates of 0–0.04 mm/year, direct pitting measurement yielded values of 0.4–1.0 mm/year (Tai *et al.*, 2025). This gap demonstrates that average thicknesses underestimate the real severity of damage in coastal environments, where marine aerosols and moisture retention favor deep pits (O'Keeffe, 2024).

The comprehensive inspection identified affectations on the base and areas in contact with support surfaces, which is consistent with localized corrosion in areas with poor drainage reported by studies on marine environments (Castañeda *et al.*, 2015; Viña-Rodríguez *et al.*, 2021). The selected points represent the most severe conditions within the vessel's comprehensive evaluation (Rosenberger, 2024).

The values obtained should be interpreted in a conservative way, prioritizing the deepest defect. The gap between global and local remaining life confirms the need to integrate ultrasound with direct pitting measurements and complete visual assessment, in order to support safe maintenance or withdrawal decisions (API, 2022; Jarić *et al.*, 2021; Shekari, 2017).

The 1-year remaining life estimated for the critical pitting zones implies that the vessel will reach the minimum required thickness (6.66 mm on heads, 6.68 mm on cylindrical shell) within a critical period, considering a 0.4–1.0 mm/year localized corrosion rate. This condition significantly increases the risk of containment loss, especially on the lower generatrixes and areas near nozzles, where stresses are maximum.

In a battery of parallelly connected vessels, the catastrophic failure of one of them can propagate fires in a knock-on effect, compromising hotel facilities and endangering workers and guests lives (Ardila-Suarez *et al.*, 2025). Preventive withdrawal of vessel 4 or immediate application of local repairs is recommended before the remaining thickness falls below the allowable limit, prioritizing human safety over projected service life (API, 2022).

The results obtained not only confirm the critical importance of differentiating between generalized and localized corrosion in coastal LPG vessels, but also provide practical evidence for technical decision-making in real operational environments. The marked discrepancy between the remaining life estimated by global methods and the one determined by specific defects underscores the need for comprehensive inspection approaches that prioritize structural safety over optimistic estimates. Based on this methodological and technical contribution, the main conclusions and actionable recommendations for storage battery integral management in areas of high environmental aggressiveness are presented.

4.1. Engineering recommendations

Inspection: to extend the methodology to vessels 1, 2 and 3 of the battery within the next 3 months, prioritizing direct pitting measurement on the base, heads and lower generatrices.

Maintenance: to apply local repair by welding on >2 mm-depth pits or epoxy coating in areas with <2 years remaining life, according to API 510.

Mitigation: to implement physical separation systems between vessels (firewalls) and improve base drainage to reduce moisture retention.

Withdrawal: to preventively withdraw vessel 4 from service, replacing it with a new or workshop-repaired unit, given its critical remaining life of 1 year and the risk of propagation in the battery.

5. Conclusions

The LPG vessel located in a coastal area presents pitting corrosion on the external surface as the dominant mechanism, concentrated on the heads, cylindrical shell and base, with heterogeneous spatial distribution.

Ultrasound measurements (2022-2024) indicate global corrosion rates between 0–0.04 mm/year and a remaining life of ≈ 80 years, while direct pitting measurement reveals localized rates of 0.4–1.0 mm/year and a critical remaining life of ≈ 1 year in the most affected zones.

Structural integrity is governed by localized corrosion and not by uniform thickness loss, which limits the representativeness of average thicknesses to assess the equipment's real condition.

A breakdown event due to pitting in vessel 4 could trigger a knock-on BLEVE in adjacent vessels by radioactive thermal effect, compromising the entire hotel facility.

Having localized rates of 1.0 mm/year and minimum remaining thicknesses of 7.4–8.3 mm (2024), the vessel will reach the minimum required thickness (6.66–6.68 mm) in 7–16 months, depending on the most critical zone.

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Author's Contribution according to CRediT Taxonomy

Julio Cesar Rizo Pérez: Conceptualization/Supervision/Formal analysis

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