CHAPTER 33

Oil storage tank bottom corrosion evaluation using acoustic emission testing

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ABSTRACT
The condition of mechanical integrity and the reliability of interconnected storage tanks in the oil export logistics chain in the Brazilian maritime terminals gains in importance in the continuity and operational safety in the coming years. These tanks have large diameters and characteristics that make it difficult to inspect in operation and monitor corrosion damage of the bottom plates. In this scenario, the concern arose with the exhaustion of the installed capacity, which may lead to consequent failures due to loss of containment, compromising not only people, facilities and the environment, but the sustainability of the business itself. Acoustic emission tests were carried out in two oil storage tanks of the marine terminal aiming at the detection and location of regions with corrosive process in the bottom plates. After evaluating the results, it was verified: (1) the relationship between the results found and the expected benefits; (2) the motivations for the use of the technique as an auxiliary tool for monitoring the integrity of the bottom of the tanks in operation; and (3) more assertive planning of shutdowns for general maintenance and internal inspection.

Keywords: Integrity, Oil storage tank, Inspection non-intrusive, Acoustic emission testing, Corrosion, Bottom plate.

1 INTRODUCTION

The failure of an oil storage tank can lead to a condition of great risk with potential leakage of huge volumes, reaching the environment and, with significant risks to people, industrial facilities and their surroundings. Oil storage and transfer activities in marine terminals require enormous logistics capacity, use of technologies and control of considerable risks [1,2].

In the scenario of Brazilian oil, production and export volumes have been breaking records every year significantly since 2013, when national production showed sharp growth due to the discovery of large offshore reserves in the Pre-salt layer in the Southeast Region. According to data from the "Dynamic Panel of Oil and Natural Gas Production" of the National Agency of Petroleum and Natural Gas, all Brazilian oil production reached at the beginning of 2020 the mark of 3 million barrels per day [3]. The export volumes of Brazilian oil follow, proportionally, the increase of this national production and in April 2020, the export reached the volume of 1 million barrels. For the future, the production projection is 4.2 million by 2030, maintaining the trend in exports [3].

Given this history, the availability of storage tanks for larger campaigns has been increasingly required by the operators of these terminals. In addition, marine terminals need to have good predictability of the planning of scheduled shutdown interventions for general maintenance with internal inspection and aim at an optimized management of asset integrity.

In this way, industrial asset integrity programs are required that must be properly implemented in the face of the high risk inherent in the tank. These programs should establish an operational condition for the terminals so that the equipment is structurally safe and properly operated, inspected and maintained. These studies should be based on the evaluation and immersion of the mechanisms of deterioration acting and the main modes of failures in order to support the decisions necessary for operational continuity, definition of scheduled shutdown for internal inspection and/or monitoring through advanced non-intrusive inspection techniques.

Among the main processes that lead to failures by loss of containment by the bottom of storage tanks in operation are the corrosive chemical and electrochemical processes. According to Telles [4] the most causative agent of internal corrosion problems is the stored product itself. The external corrosion of the bottom plate is caused by the atmosphere, by contact with water or soil. The isolated or combined action of these factors affects the health condition of the equipment [4].

Periodic external inspections are provided that are carried out during the operation of the tanks, with the back and ceiling components visible externally and accessible for monitoring with inspection techniques by the direct method. The bottom of the tanks, being supported on the ground, demands greater challenge in monitoring corrosion damage during operation due to the lack of access for a detailed inspection. However, at the end of the campaign, the tank must be taken out of operation, drained and cleaned internally for detailed inspection of all components.

An unscheduled shutdown of an oil storage tank of 550,000 barrel or approximately 87,500 m^3 can cause unavailability of up to 12 months or more, high maintenance costs and loss of profits. According to Telles [4], process equipment is generally the largest size, relevant and unit cost items in the oil industry.

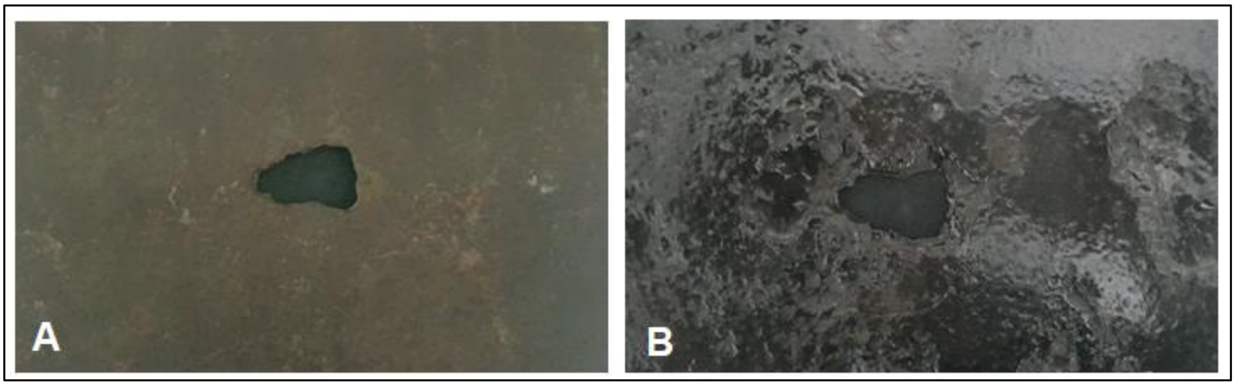
To obtain a longer interval between internal inspections and thus increase to the maximum the campaigns of the storage tanks in operation without prejudice to the safety of the facilities and the environment, terminal operators have been adopting inspection techniques based on non-intrusive methods.

The acoustic emission test for tank bottom is a non-intrusive technique whose purpose is to detect and locate areas with corrosive processes in activity during the execution of the monitoring, producing results that can be auxiliary to risk-based studies, and brings as an advantage the possibility of more frequent monitoring of the tanks in operation. Other non-destructive scanning testing techniques, such as ultrasonic, magnetic flux leakage (MFL) or the use of robotics are applicable in the background, however they can only be performed at scheduled maintenance and inspection shutdowns of tanks when opened.

In this scenario, the acoustic emission technique has been applied for some time as an inspection tool for the monitoring of the bottom plates of the storage tanks in operation [5]. After almost a decade of evolution in the world industry of the application of the acoustic emission test in tank bottoms, in Brazil, it is still questioned as to its effectiveness for the detection of corrosion damage.

In this chapter the central objective is focused on the acoustic emission technique applied in the evaluation of the bottom of oil storage tanks as shown by the localized and intense corrosion of the tank bottom presented in Figure 1. Figure 1A represents the internal part in contact with the oil where there is widespread corrosion of the plate, however, in Figure 1B, on the outside of the bottom where there is contact with the soil and moisture there is an intense corrosive action with penetration of the plate from the outside in.

Figure 1- Carbon steel plate of an oil storage tank bottom, where A represents the internal part and B the external part with intense corrosive action.



2 OIL STORAGE TERMINALS AND TANKS

Currently, there are in Brazil in operation 124 terminals and bases for the movement of oil and its derivatives (gasoline, diesel oil, fuel oil, naphtha, among other hydrocarbon, chemical and petrochemical compounds), being 69 waterway terminals (maritime, fluvial or lacustrine) and 55 land terminals. Within the logistics process necessary to efficiently flow the oil produced in deep waters, the transfer and storage terminals store the production and direct it through ships for export or to the domestic market [3,6].

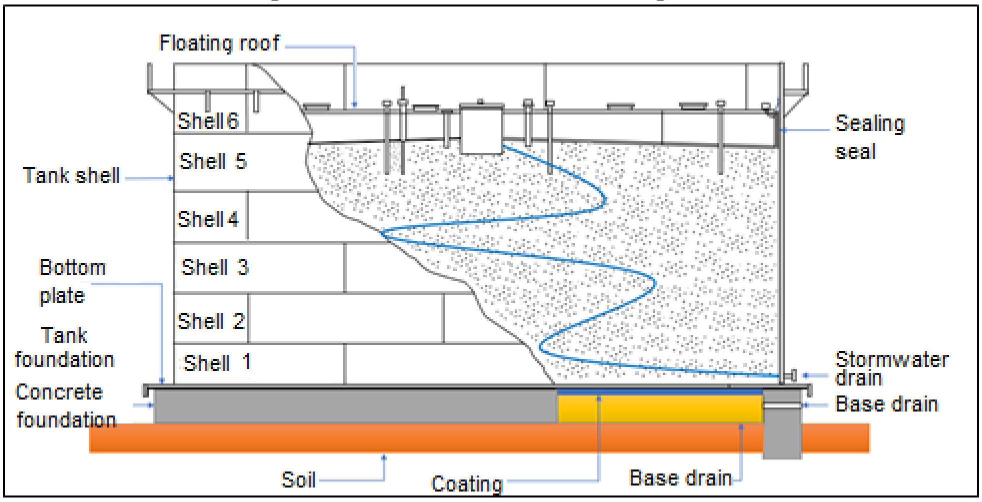
The large existing offshore oil terminals in Brazil were built more than 50 years ago with the design of a project to internalize oil from other producing countries, especially from the Middle East. In August 2020, the ANP, through Authorization No. 582, authorized the construction of an oil terminal located at the Port of Açu, in São João da Barra, RJ. The project foresees the construction of up to 12 oil storage tanks, with a total capacity of 5.7 million barrels and two pipelines that will interconnect to the Cabiúnas Terminal located in Macaé, RJ. This is important news for the logistics of oil flow between oil terminals, a sector that has not received investment in infrastructure to increase capacity for more than 30 years [3].

2.1 STORAGE TANKS

The oil storage tanks, objects of this study, are atmospheric, that is, they operate with approximately atmospheric internal pressure, manufactured in carbon steel, cylindrical, vertical, have a floating roof of double type, are supported on the ground and are intended for oil storage as shown in the scheme presented in Figure 2.

Tanks intended for oil storage are usually sized for large volume capacities. According to Barros [7], storage tanks can be built in a wide range of capacities, from the simplest with 100 barrels to the most complex, whose constructions are special with more elaborate designs, materials with higher mechanical properties that allow to build storage tanks with a capacity ofup to 1 million barrels (159,000 m^3).

Figure 2 – Schematic view of oil storage tank



Oil storage tanks of large dimensions (D > 30 m), large heights (H ≥ 14 m) and floating ceilings, must have a direct foundation under a concrete ring, ensuring better stability and leveling of the side in the movements of the ceiling [7]. One of the constructive advantages of the tanks studied experimentally in this work is the base that consists of a concrete slab with piling, that is, the bottom plates are not in direct contact with the ground, which rules out the occurrence of setbacks.

3 ACOUSTIC EMISSION TEST APPLIED IN OIL STORAGE TANKS

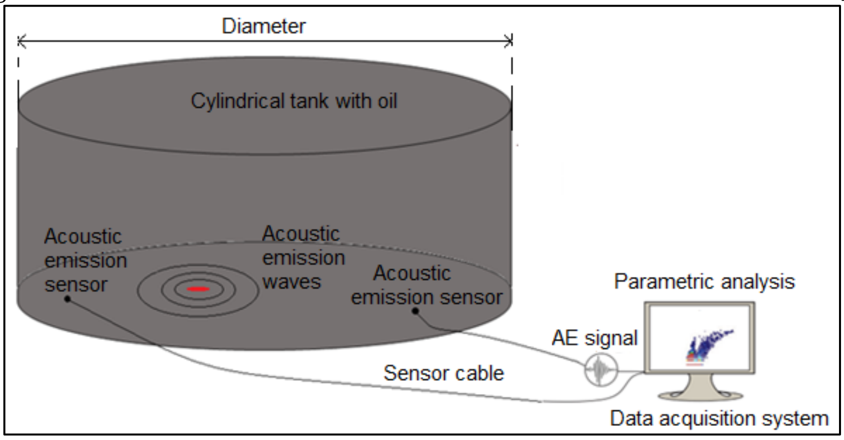
The first experimental test associated with instrumentation for the detection, amplification and storage of signals from acoustic emission was presented by F. Kishinoue in 1933 at a meeting of the Earthquake Research Institute of the University of Tokyo [5, 8] In this experiment acoustic emission was used in seismic studies for the detection of fractures in the Earth's crust [5].

The principle of this inspection technique consists in the detection of mechanical waves generated due to a rapid release of accumulated energy. This energy is released, for example, by the corrosion process of the material, when there is the formation of an oxide layer on the material, which has different properties from the base material formed, having as characteristics the fact of being brittle and forming in plates or layers. In plates where corrosion is advanced, a significant increase in the speed of the deterioration process is observed. Sources of acoustic emission include the mechanisms of deformation and fracture, and leaks from pressurized containers such as pressure vessels and storage tanks also generate signals detected and classified as acoustic emission [8, 9].

According to Filippin *et al.* [8], the energy when released propagates from the source throughout the material as a spherical wave and is captured by transducers positioned on the surface of the equipment to be tested. The signals are processed to be analyzed and located together with the sources of acoustic emission, as shown in Figure 3.

The acoustic emission waves, being mechanical in nature, require a medium so that they can propagate, having some of their characteristics common to any type of wave, including electromagnetic ones. The definition of acoustic wave used in acoustic emission is a disturbance in a medium in which sequential pulses, with a velocity well defined by a wave in question, propagate through the medium itself. The measurement system has high frequency, high resolution and high channel density. These characteristics, according to Filippin *et al.* [8], make complex the hardware and software necessary for the analysis of signals used for propagation of mechanical waves.

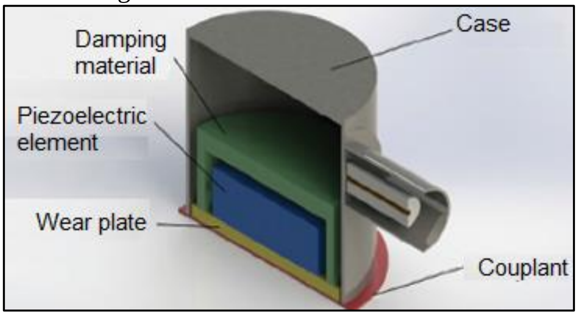
Figure 3 – Schematic of the acoustic emission test in an oil tank and its detection [8]



The basic structure for acoustic emission data acquisition is separated into three essential parts: signal conditioning, digital analog conversion , and processing. Other features are also available, such as: audible and visual alarms, reading of parametric signals and inputs for synchronization.

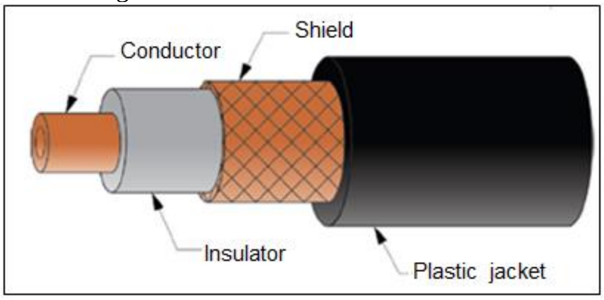
Acoustic emission sensors are of various types, purposes and applications. The main features in a sensor are bandwidth, sensitivity and maximum working temperatures. The sensor is composed of a piezoelectric element mounted on a dielectric and rigid surface, encapsulated by metallic or polymeric material, as illustrated in Figure 4 [8].

Figure 4 – Acoustic emission sensor



Preamplifiers and amplifiers are active circuits made up of transistors called charge amplifiers. They have the function of maximizing the signals captured from the piezoelectric sensors in order to increase the signal-to-noise ratio and reduce unwanted signals. The signal propagates through the cables to the signal capture modules in the tank, which pass through digital filters that eliminate unwanted noise and signals for analysis. Transmission cables between sensors and preamplifiers are of the coaxial type with a voltage of 28 volts, which has good insulation capacity to the external environment. The cable consists of four parts as shown in Figure 5.

Figure 5 – Coaxial Transmission Cable



The coupling of the acoustic emission sensors to the surface of the side of the tank consists of fixing by means of magnetic fasteners or adhesive tapes, and the application of coupling material. The coupling materials can be glues, adhesives or greases that must fill the space between the sensors and the surface of the tank to be analyzed and to eliminate the air that can interfere with the results [8].

According to Soares [9], the typical problems of mounting installation devices and accessories in the field include insufficient sensitivity and the most common causes include: rough surface, dirty surface, air bubbles in the coupler, insufficient, weak sensor, loss of contact force, measurement circuit out of calibration and non-adhesion below the coating layer.

Acoustic emission inspection technology shall pay attention to the quality of the coupling and the particular method of assembly, including the following points [10]:

- Stability of the coupling, especially in relation to the environment;
- Mechanical stability of the fixation;
- Electrical insulation between the sensor and the surface;
- Susceptibility of the coupler to run the structure and/or sensor;
- Prevention of overload on the sensor by the signal cable;
- Proper cleaning of the coupling region before sensor installation.

Insufficient assembly/coupling problems may be associated with consistency between channels, as measured by graphite breakdown [9].

Compared to other Non-Destructive Testing techniques, an advantage of the acoustic emission method is the test execution time that is considered relatively fast, of a large area (as in the case of storage tanks) concentrated in the presence of active corrosive process, and may indicate regions that require complementary inspection.

Other significant benefits can be obtained, such as:

- Prevent people from entering the tanks and exposing themselves to dangerous products;
- Plan tank stops;
- Reduce tank interventions.

This non-intrusive inspection, briefly, provides for corrosion risk assessments and detailing of all the damage mechanisms acting on the tank, which must be inspected and monitored during its operation.

On the other hand, a disadvantage of acoustic emission compared to other Non-Destructive Testing techniques is that it will only detect active discontinuities during the time of monitoring and data acquisition. In the case of storage tanks, the analyses focus on the changes in the bottom when there is the formation of the oxide layer. In this way, when one layer appears on top of the other, the upper layer breaks down, generating mechanical waves that can be detected by acoustic emission sensors [8].

4 MATERIALS AND METHODS

To analyze the application of the acoustic emission test in the evaluation of corrosion in bottom plates of oil storage tanks, field tests were carried out in two tanks, as an experimental part of this study.

4.1 MARINE TERMINAL AND STORAGE TANKS USED FOR ACOUSTIC EMISSION TESTS

The oil storage tanks proposed in this study are part of the Maritime Terminal located on the south coast of Rio de Janeiro, as shown in Figure 6 below. One of the tanks used in the acoustic emission test is presented in Figure 7 and the main operational and constructive characteristics of the selected storage tanks are listed in Table 1.

Figure 6 – Location of the tanks studied at the Maritime Terminal (Google Map)

Figure 7 – Overview of the oil tank used in the acoustic emission test

The surveyed tanks have been operating for more than 45 years, where the first inspection was carried out in 1977 on the occasion of their manufacture. The inspection and maintenance plans have been complied with regularly, according to the applicable technical standards and regulations in force and Table 2 presents the main data related to the history of the internal inspection and the operational condition of the tanks.

Table 1 – Profile of oil tanks

Identification	TQ-07 e TQ-09
Design Standard	API STD 650, Appendix D
Construction year	1975
Operational commencement year	1977
Plate material	Carbon steel
Nominal diameter	85 m
Total height	14 m
Useful capacity height	13 m
Volume	87500 m^3 (550000 bbl.)
Design pressure	Atmospheric
Design temperature	40 / 60 ºC
Maximum operating temperature	60 ºC
Annular plate thickness	11.11 mm
Bottom plate thickness	6.35 mm

Table 2 – History of internal inspections of oil tanks

Oil storage tanks	Average interval between internal inspections	Next internal inspection	Operating condition
TQ-07	11 years and 3 months	2024	In operation without restrictions.
TQ-09	11 years and 6 months	2023	In operation without restrictions.

4.2 METHODOLOGY OF THE ACOUSTIC EMISSION TEST APPLIED IN OIL STORAGE TANKS

This item describes the procedure used in the execution of the acoustic emission test applied to the storage tanks TQ-07 and TQ-09, in 2022, as an experimental part of this study.

4.2.1 Acoustic emission system

In this study we used an acoustic emission system with a capacity of up to 24 channels, manufactured by Physical Acoustics Corporation (PAC), MicroDisp model and shown in Figure 8.

Figure 8 – Acoustic emission system

Acoustic emission data were collected using low-frequency piezoelectric sensors, manufactured by Qing Chang GI40, 40/100 kHz, adjusted for the detection and evaluation of the corrosion process at the bottom of the tanks.

The detection of the signals was stored in an electronic file by the AEWin software and converted for use by universal data reading software. The tank bottom location chart was elaborated from the Visual-AE/Vallen software, through the "*Tank bootom"* tool. The selection of the number of channels/sensors was established based on the area of the bottom of the tank and the type of location used, according to the criteria presented in Table 3.

Table 3 – Definition of the number of channels

Tank diameter	Number of channels	
	Planar location (2D)	Zonal location
Under 8	4	Not evaluated
8 to 15	6	
15 to 30	10	
30 to 40	12	
55	16	16
50 to 70	20	20
Over 70	More than 20	More than 20

Source: Moura [11]

The following additional procedural requirements have been adopted:

- Positioning of the sensors: horizontal – spacing between 2.5 and 11.5 meters for planar location, and less than 15 meters for zonal location. Vertical (height) – The first row of sensors (odd) should be at a height of 100 mm to 300 mm above the bottom of the tank. In cases of solid sedimentation (sludge) accumulated at the bottom of the tank, the sensor line should be at a height just above the level of this sediment. The second line of sensors (pairs) should be at a height of 300 mm to 600 mm above the bottom of the tank;

- The sensors that coincided in the positions of manholes, pipes, drains, overlapping plates, among others, were repositioned;
- The product level in the tank was maintained between 50% and 100% of the maximum operating height (note: level below 50% would impair the evaluation regarding leak detection);
- The minimum rest time of the oil tank before the test is carried out is set at 12 hours;
- All inlet and outlet valves were completely closed. Other noise sources connected to the tank or in the vicinity of the tank have been eliminated or minimized and recorded, such as mixers, drains, heating systems and pumps;
- The test was carried out in the morning and afternoon with reduced oscillation of the ambient temperature and absence of strong winds.

4.2.2 Test preparation

Based on Table 3 and the established horizontal and vertical spacing limits, 24 signal capture sensors were prepared. A visual inspection was performed throughout the basin, around and on the roof of the tank in order to observe and confirm whether the tank was isolated from the system, that is, without flow of filling or emptying fluid and in a resting state for more than 12 hours.

The cables were prepared with connectors and splices, in varied lengths, identified with the corresponding sensor and launched so that the distribution was 12 channels for each side of the side, from the reference point (zero point), where the monitoring data were collected throughout the test.

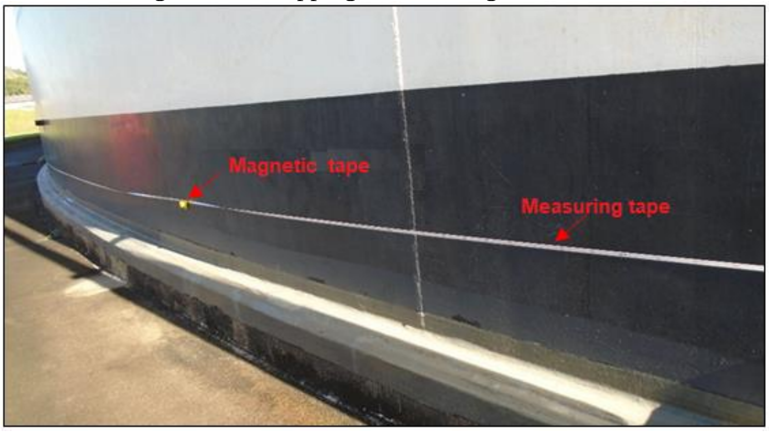
According to Soares [9], the connectors are the most vulnerable points in the handling and assembly of the cables. He then highlights the following points of attention:

- Do not leave the weight of the cable on the connector;
- Do not leave the connector grabbed or protruding while it is being retracted;
- Cable problems due to wear and damage, poor handling and inadequate handling facilities are the main causes of delay problems in the field, such as: open circuit (central conductor and/or ground); short circuit; intermittent connection and loss of protection;
- The faulty cable found should be discarded.

The sequential numbering of the sensors allowed the installation of the same arrangement in the two tanks tested, with the TQ-07 being the first tank to be executed. After the completion of the first tank, these assemblies were disconnected and rolled up with organization, which facilitated the reinstallation in the TQ-09 tank. The zero point and the data acquisition base were fixed next to the helical ladder of the tanks shown in Figure 9. The 24 channels were mapped with tape and magnetic fasteners for the markings on the side and identification of the sensors to be installed (figure 10).

Figure 9 – Reference location and monitoring point for data acquisition

Figure 10 – Mapping and markings on the back



Then, the 24 points were cleaned with dry cloth and on them were fixed the magnetic bases, support with the piezoelectric sensors installed and tested (figure 11). Industrial grease was used as a coupler for the sensor interface with the tank side.

Figure 11 – Installation of piezoelectric sensors

The signal capture sensors were distributed in two rows along the circumference, with alternating heights of 300 mm and 600 mm in relation to the bottom, equally spaced. The first row

(H1) was composed of the odd channels and the second row (H2) of the even channels, as seen in Figure 12.

Figure 12 – Typical location where the sensors were installed odd (H1) and even (H2) positions

4.2.3 System calibration

After installing the sensors and preamplifiers on the side of the tank, the cables were launched and connected for a total of approximately 1716 meters. The system was calibrated and each sensor tested for the quality of communication and electrical supply.

The sources of external noise were identified, controlled and filtered during data collection and treatment. These noise sources have been identified as being:

(a) noise of the flow of the fluid through the outlet of the drains on the slope;

b) Wind noise during the monitoring period.

A reference work published by Li *et al.* [12] showed several types of environmental noise signals collected during the bottom inspection of oil tanks. Li *et al*. [12] collected signals of bird movement on the roof of a storage tank of 61 meters in diameter and also signals from the action of strong winds in two other storage tanks with diameters greater than 80 meters, whose speed was correlated with the rate of acoustic emission signals of events.

4.2.4 System Configuration

In the individual channels of the measurement system, the signal collection and measurement process uses three time parameter operation settings: peak definition time (PDT), signal definition time (HDT), and signal locking time (HLT). In this study, the collection of the main parameters of an acoustic emission signal was enabled: ascent time, count, energy, duration and amplitude.

4.2.5 Data acquisition

Before the start of the data acquisition, a final check was made in order to determine that all channels are enabled and adjusted, as well as the time parameters. In addition, it is also essential to monitor external noises (wind, rain, drive of pumps connected to pipes common to the tanks, steam leakage, etc.) that may interfere with data acquisition.

4.2.6 Data analysis

According to Soares [9] the simplest method of localization consists of zonal location, where the exact coordinates of the source are not determined. The sensor that registers the first acoustic emission signal is considered the closest signal to the source and the amount or intensity of the detected signals will indicate the most active region. According to Filippin *et al.* [8], planar localization is used to detect sources of acoustic emission in two dimensions, and for its execution, non-aligned sensors are required. The methods of zonal localization and planar localization were used, called Method I and II, respectively.

4.2.6.1 Method I – zonal localization (and$_Z$)

Calculate the amount of signals detected per hour in each channel.

Procedures:

1. The stored data is processed in the recorded file during the test. In these data, filters were applied to separate the genuine corrosion signals from possible recorded noises;
2. Through graphs or data tables, information on the amount of genuine signals per channel normalized for 1 full hour of assay was found;
3. Calculated the signal detection rate/hour for each channel using the following formula:

$$E_Z = \frac{N_Z}{2} \quad (1)$$

Where:

Ez - Rate of signals (*hits*) detected in the zone (channel) Z.

Nz - Total number of signals detected in zone Z.

Note: The division by factor 2 in the denominator is due to the 2 hours of data acquisition.

4. The value of E_Z obtained was used as a parameter for classification of the bottom of the tank, following the criteria established in Table 4, for the channel with the highest record ofthe activity, as shown in Figure 13.

Figure 13 – Zonal Location

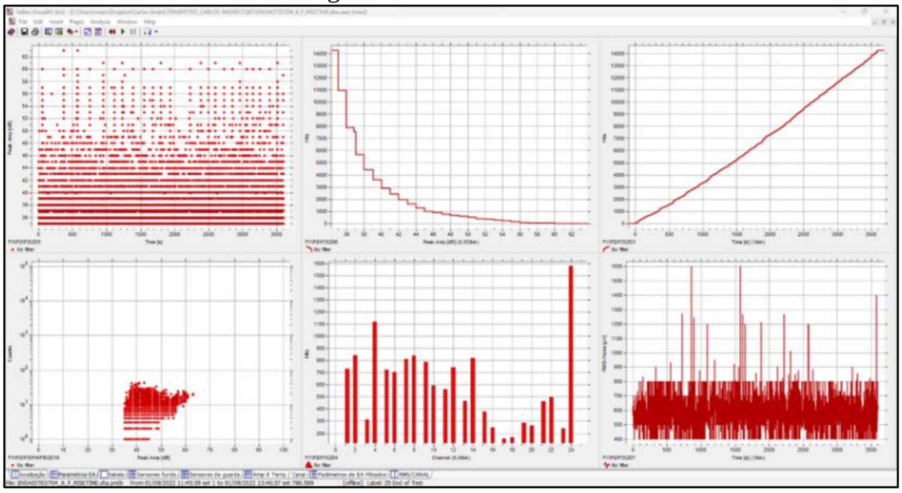


Table 4 – Zonal evaluation based on the number of signals collected (hits)

		Number of signals/h		
		Tank storage capacity (m³)		
Classification	Description	< 5000	5000 a 10000	> 20000
I	None	$E_Z \leq 16$	$E_Z \leq 20$	$E_Z \leq 25$
II	Faint	$16 < E_Z \leq 160$	$20 < E_Z \leq 200$	$25 < E_Z \leq 250$
III	Moderate	$160 < E_Z \leq 1600$	$200 < E_Z \leq 2000$	$250 < E_Z \leq 2500$
IV	Serious	$1600 < E_Z \leq 16000$	$2000 < E_Z \leq 20000$	$2500 < E_Z \leq 25000$
V	Very serious	$E_Z > 16000$	$E_Z > 20000$	$E_Z > 25000$

* Indication of the presence of corrosion a specific region or zone (Assessment of corrosion level);
E_z = total events AE / Number of channels for a period of 1 hour; Source: Procedure MF-005 [11]

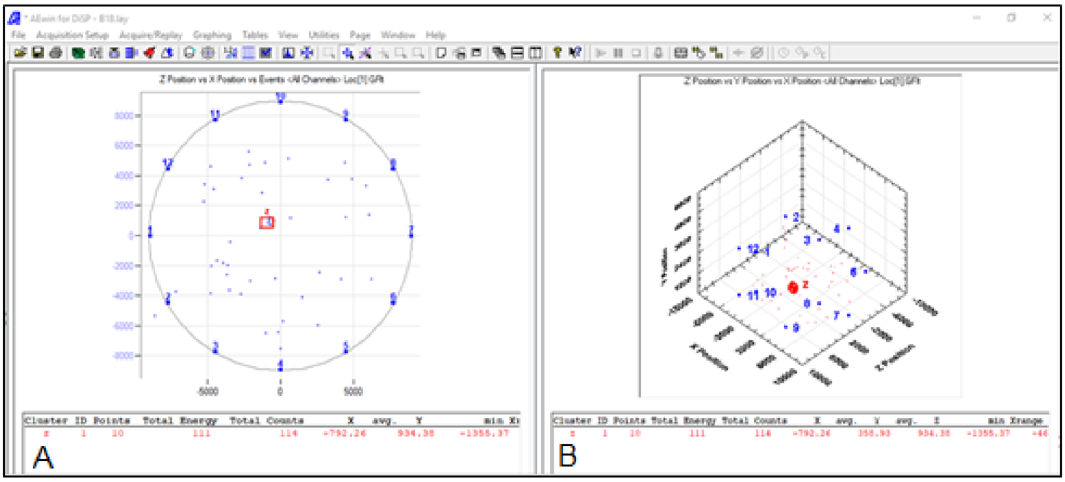
4.2.6.2 Method II – Planar location (andP)

To analyze the regions of interest based on a delimited size of the areas with significant agglomeration of events, called "*clusters*", to calculate the location rate, that is, the number of events detected per unit of time.

Procedures:

1. The stored data is processed in the recorded file during the test;
2. Expanded the location chart of the bottom of the tank;
3. A complete pre-analysis of the graph was performed, noting all the areas with a high concentration of events, as shown in Figure 14.
4. Open the "*cluster*" size adjustment screen by clicking on the "*Display &* Analysis" menu and selecting the first option, "*Hit-Data Analysis*";
5. Adjusted the diameter of the *"cluster*" so that it is equal to 5% of the diameter of the tank. The adjustment should be the radius of the "cluster" and not the diameter;

Figure 14 – (A) Planar location graph of the bottom of the 2D expanded tank; (B) 3D Chart



6. Enabled the analysis by "*cluster*", right-clicking (in the right-handed case) on top of the expanded graph;
7. Performed scan of all areas of interest, that is, all regions with high density of events, by dragging the "*cluster*" with the mouse. The data associated with the events circumscribed by the cluster will appear in numerical form in the data table;
8. Accessed the right mouse button in the data table and selected the option of converting/sending the numeric data, "*Export Data* to Excel", to convert the data presented in the table to the .csv formatting, compatible with the Excel program. Calculated the rate of events (events/hour) using the formula:

$$E_P = \frac{E}{2N} \qquad (2)$$

Where:

E_P = rate of events in a specific "*cluster*"

E = total number of elements contained in the Excel worksheet

N = number of channels belonging to the group.

Note: The division by factor 2 in the denominator is due to the 2 hours of data acquisition.

9. Repeated steps 6, 7 and 8 for all areas of interest;
10. The value of E_P obtained was used as a parameter for classification of the bottom of the tank, following the criteriaestablished in Table 5.

The probability of leakage is given as a function of the agglomeration of acoustic emission events in regions identified by the "*clusters*" on the bottom location map, regions defined as being 5% of the measurement of the diameter of the tank. According to API 575 [13] if a leak is detected during testing, the equipment engineer must investigate the cause and location of the corrosion. The leak must be mitigated and the tank removed from operation for maintenance and inspection.

Table 5 – Evaluation of the probability of leakage

		Number of events/h		
		Tank storage capacity (m^3)		
Classification	Description *	< 5000	5000 a 10000	> 20000
I	None	$E_P \leq 13$	$E_P \leq 18$	$E_P \leq 22$
II	Faint	$13 < E_P \leq 130$	$18 < E_P \leq 180$	$22 < E_P \leq 220$
III	Moderate	$130 < E_P \leq 1300$	$180 < E_P \leq 1800$	$220 < E_P \leq 2200$
IV	Severe	$1300 < E_P \leq 13000$	$1800 < E_P \leq 18000$	$2200 < E_P \leq 22000$
V	Critical	$E_P > 13000$	$E_P > 18000$	$E_P > 22000$

* Indication of the presence of localized corrosion (Evaluation of the probability of leakage); E_P = total cluster events for 1 hour of monitoring. Source: Procedure MF-005 [11]

4.2.7 Obtaining results

The general classification of the bottom of the tank composed of the zonal (E_Z) and planar (E_P) localization methods was defined according to table 6. This matrix defines a periodicity of maintenance intervention in the tank or a deadline for the execution of a new acoustic emission test.

Table 6 – Maintenance intervention periodicity matrix (in years)

		Corrosion classification				
		I (A)	II (B)	III (C)	IV (D)	V (E)
Classification as to the probability of leakage	I (A)	4 years	3 years	2 years	1 year	*PM
	II (B)	3 years	3 years	2 years	1 year	*PM
	III (C)	2 years	2 years	2 year	1 year	*PM
	IV (D)	1 year	1 year	1 year	1 year	*PM
	V (E)	*PM	*PM	*PM	*PM	*PM

*PM – Plan and execute Maintenance. Source: Procedure MF-005 [11]

In the event that both classification methods are used, the higher classification shall prevail as the general classification of the tank. A recommendation action regarding the planning for maintenance execution and internal inspection can be obtained based on the general classification of thetanks, as shown in table 7.

Table 7 – Classification and recommendations for the bottom of the tank

Classification	Degree of corrosion	Recommendation
I	None	No maintenance required.
II	Hypoactive	No immediate maintenance required.
III	Moderate	Consider a schedule for maintenance.
IV	Active	Prioritize shutdown scheduling for maintenance
V	Hyperactive	Schedule immediate shutdown for maintenance.

Source: Procedure MF-005 [11]

4.2.8 Standards used in the acoustic emission test

These tests have been carried out on the basis of the following standards:

- NBR 16997 (ABNT, 2021) – Non-destructive testing – Acoustic emission – Corrosion detection in the bottoms of metal storage tanks.
- JB/T 10764 - Chart 10.2 (CHINESE STANDARD, 2007) – Nondestructive Testing – Acoustic emission testing and evaluation of atmospheric pressure metal storage tanks.
- NBR 16178 (ABNT, 2013) – Non-destructive tests – Acoustic emission – Verification of the performance of acoustic emission sensors.
- NBR 15360 (ABNT, 2013) – Non-destructive tests – Acoustic emission – Characterization of the measurement system.
- NBR 15361 (ABNT, 2015) – Non-destructive tests – Acoustic emission test – Determination of the reproducibility of the acoustic emission sensor response.
- NBR NM 326 (ABNT, 2014) – Non-destructive testing – Assembly of piezoelectric contact sensors for AE.
- NBR NM 341 (ABNT, 2015) – Non-destructive tests – Acoustic emission test (AE) – verification of sensors.
- ISO 9712 (ISO, 2012) – Non-destructive testing, qualification and certification of personal.
- ISO/IEC 17024 (ISO, 2012) – Conformity assessment – General requirements for bodies operating certification of persons.
- NBR NM 302 (ABNT, 2012) – Non-destructive testing. Acoustic Emission Test (AE). Terminology.
- NBR NM 333 (ABNT, 2012) – Non-destructive tests – Continuous monitoring by acoustic emission – Procedure (Reference).

5 RESULTS AND DISCUSSION

5.1 ANALYSIS OF THE HISTORY OF STORAGE TANKS

The result of the analysis of the history of the storage tanks, TQ-07 and TQ-09, was based on the design documents and the maintenance and inspection records of the terminal. The TQ-07 and TQ-09 tanks have a history of two acoustic emission tests in a 1-year interval, carried out in 2020 and 202 1. The methodology of these tests classified the moderate risk as to the probability of leakage of the two tanks. A new inspection was recommended in 2 years to monitor the evolution of acoustic emission signals and operational continuity of oil tanks.

5.2 EXECUTION OF THE FIELD TEST: EVALUATION OF CORROSION IN THE BOTTOM OF AN OIL STORAGE TANK BY THE ACOUSTIC EMISSION METHOD

The execution of the field tests by the acoustic emission method to evaluate the corrosion of the storage tanks TQ-07 and TQ-09 was performed as previously described. Next, items 5.2.1 and 5.2.2 present the results of the tests performed in this work.

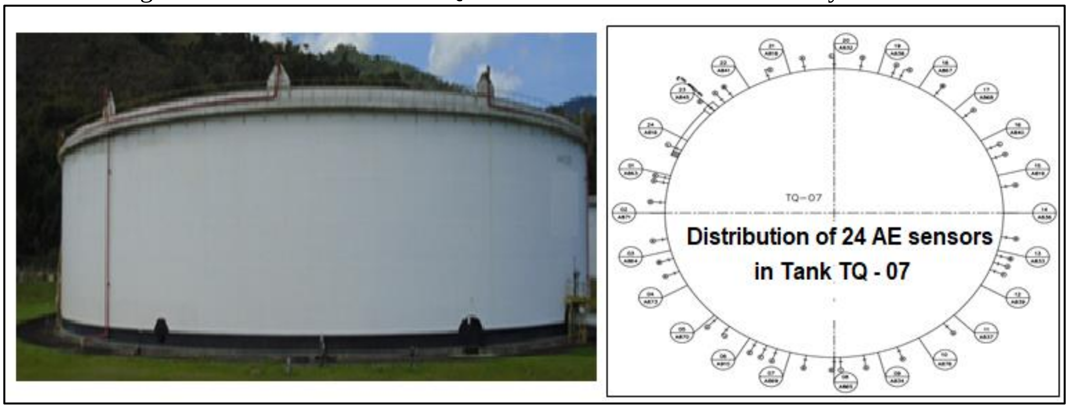
5.2.1 Results of the acoustic emission tests with tank TQ-07

The conditions for the test on tank TQ-07 are described below:

- Test Fluid : Petroleum
- Test fluid temperature: 26°C
- Tested area: 5.805 m^2
- Rest time: 24 hours
- Monitoring time: 02 hours
- Number of sensors: 24
- Level during test: 6.9 m (52.5 %)

The 24 signal capture sensors were distributed along the circumference of the side, spaced equidistantly at angles of 15°, with the first row (H1-300 mm) composed of the odd channels and the second row (H2-600 mm) by the even channels as shown in Figure 15.

Figure 15 – Overview of the TQ-07 tank with 24 sensors on the day of the test



The verification of the assembly was performed before, during and after the test, as directed by ABNT NBR 16178 [14], based on the ASTM E2374 standard [15]. After installing the piezoelectric sensors and preamplifiers on the side of the tank, launching and connecting the cables, the system was calibrated and each sensor tested according to "*Check up*" shown in Table 8.

According to ABNT NBR 15361 [16], the sensors in use should not present difference in amplitude values between one check and another greater than 3 dB. Variations equal to or greater than 4 dB indicate that the sensor has suffered some damage or is in degradation and, if above 6 dB, should be discarded [8].

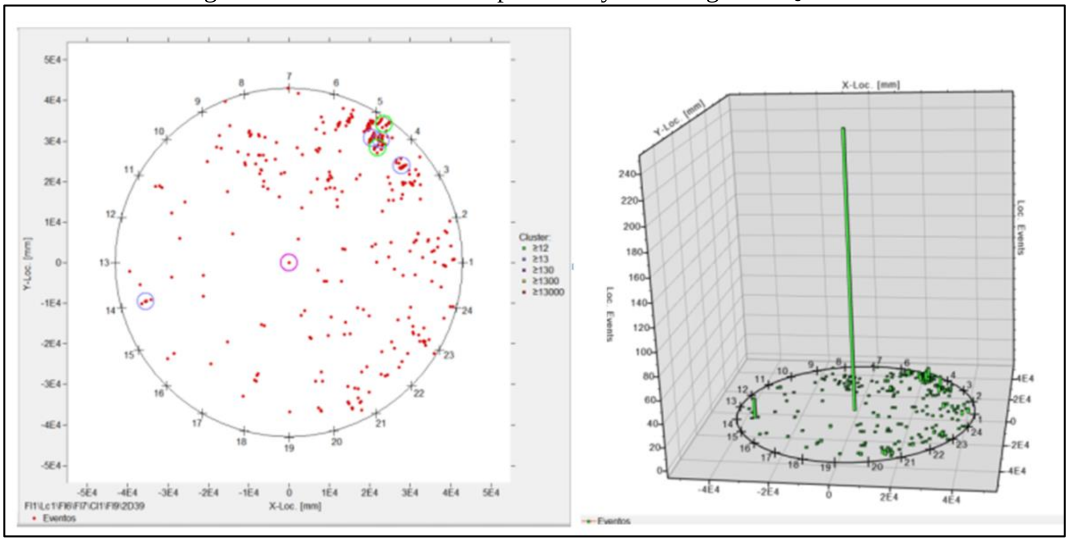
Table 8 – "Check up" of assembly and sensitivity of the channels in the tank TQ-07

CHANNEL	AMPLITUDE (dB)			AVERAGE	SENSORS
1	99	99	99	99	A863
2	98	98	98	98	A871
3	96	96	96	96	A864
4	99	98	98	98	A873
5	99	99	99	99	A870
6	98	98	98	98	A910
7	97	97	98	97	A869
8	99	98	98	98	A865
9	97	96	96	96	A834
10	95	95	97	96	A876
11	99	99	99	99	A837
12	96	97	98	97	A839
13	95	96	96	96	A833
14	97	97	96	97	A836
15	97	97	97	97	A819
16	96	96	95	96	A840
17	96	96	97	96	A868
18	98	98	98	98	A867
19	95	97	97	96	A838
20	99	99	99	99	A832
21	98	97	96	97	A818
22	98	98	98	98	A841
23	98	99	98	98	A845
24	98	98	98	98	A816
TOTAL AVERAGE:				98	

5.2.1.1 Distribution of events in TQ-07

In Figure 16, the map shows the distribution and the number of events. The representations of the views of exact location in the plan of the plates of the bottom of the tank are present.

Figure 16 - Evaluation of the probability of leakage in TQ-07 tank



The region with the highest number of events (magenta color) is located in the center of the bottom of the tank three "clusters" in lower intensity (blue color) conforme shows the detail of Figure 17 and n Figure 18 where the location quotas, the record of the total of events, the averages of the counting and energy parameters for each of the "*clusters*" are presented . For this tank the probability of leakage is level III (magenta color).

Figure 17- Detail showing the region with the highest number of events (magenta color)

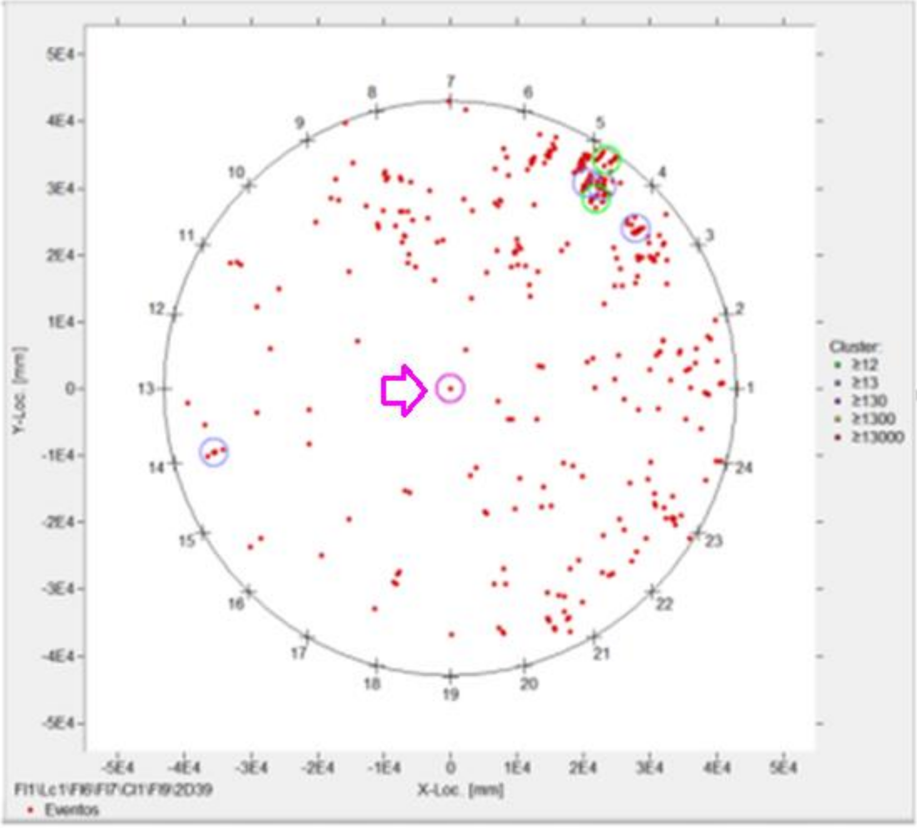
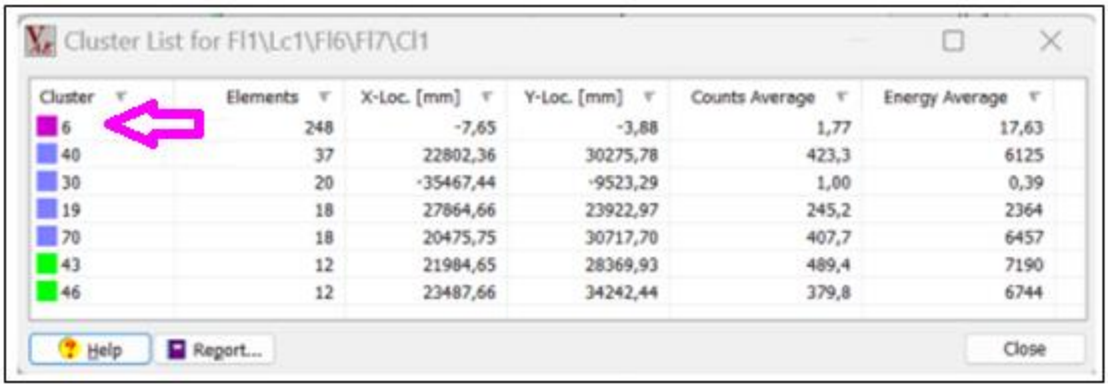


Figure 18 - Location quotas of the "clusters" in the TQ-07 tank


Cluster List for Fl1\Lc1\Fl6\Fl7\Cl1

Cluster	Elements	X-Loc. [mm]	Y-Loc. [mm]	Counts Average	Energy Average
6	248	-7,65	-3,88	1,77	17,63
40	37	22802,36	30275,78	423,3	6125
30	20	-35467,44	-9523,29	1,00	0,39
19	18	27864,66	23922,97	245,2	2364
70	18	20475,75	30717,70	407,7	6457
43	12	21984,65	28369,93	489,4	7190
46	12	23487,66	34242,44	379,8	6744

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5.2.2 Results of acoustic emission tests with tank TQ-09

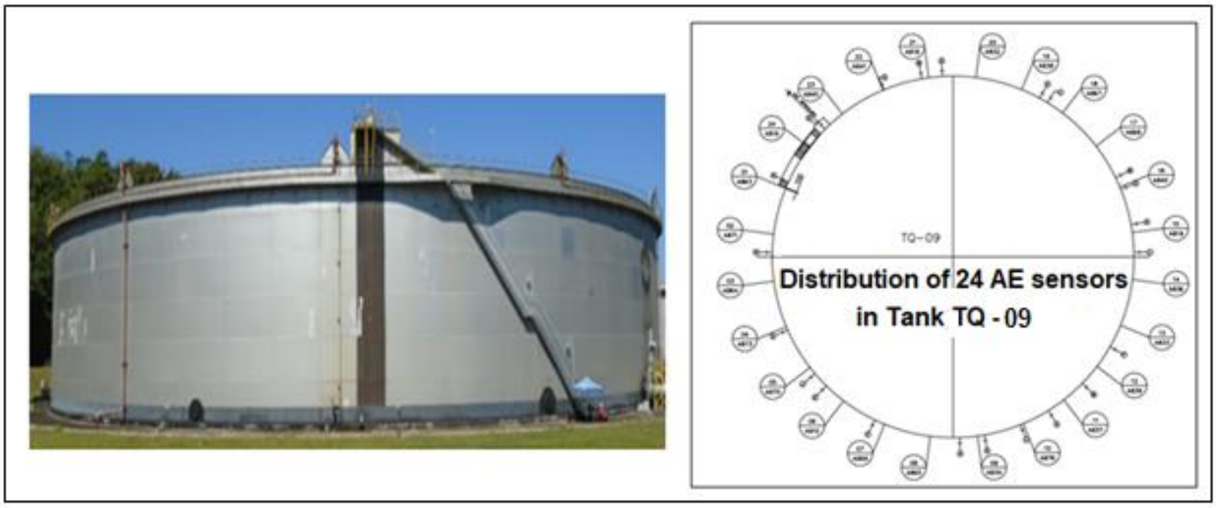
The conditions for the test in tank TQ-09 (Figure 23) are described below:

- Test Fluid : Formation water
- Test fluid temperature: 26°C
- Tested area: 5.805 m^2
- Rest time: 24 hours
- Monitoring time: 02 hours
- Number of sensors: 24

- Level during test: 12.3 m (93.5 %)

Thes 24 signal capture sensors were distributed along the circumference of the side, spaced equidistantly at angles of 15°, with the first row (H1-300 mm) composed of the odd channels and the second row (H2-600 mm) by the even channels as shown in Figure 19.

Figure 19 – Overview of the TQ-09 tank on the day of the acoustic emission test with 24 sensors



As done in the test of the tank TQ-07 was carried out before, during and after the test, as directed by ABNT NBR 16178 [14], based on the ASTM E2374 standard [15] an evaluation of the sensor mounts on the side tank TQ-09. After installing the piezoelectric sensors and preamplifiers on the side of the tank, launching and connecting the cables, the system was calibrated and each sensor tested as "*Check up*" shown in Table 9.

Table 9 – "Check up" of assembly and sensitivity of the channels in the TQ-09 tank

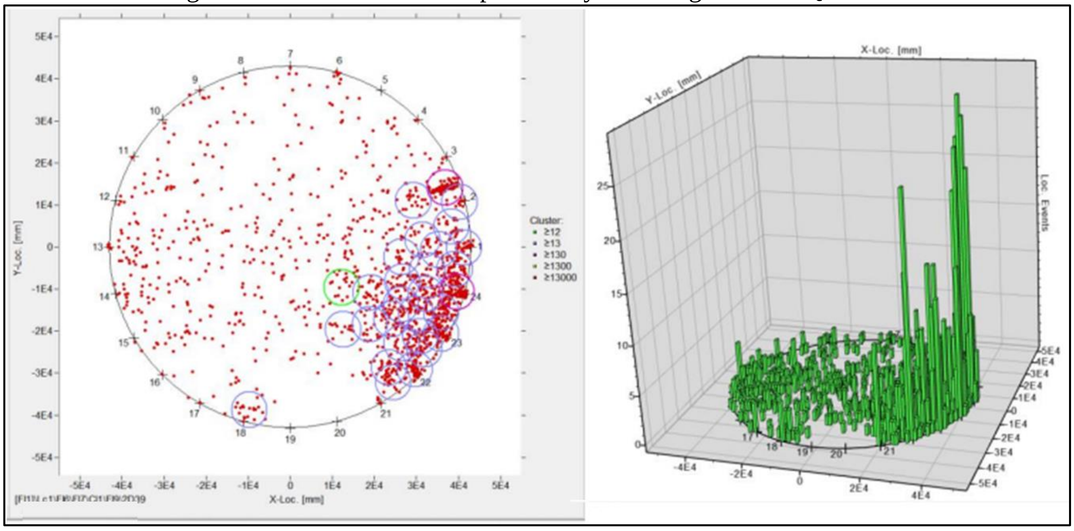
CHANNEL	AMPLITUDE (dB)			AVERAGE	SENSORS,
1	98	99	98	98	A863
2	97	97	98	97	A871
3	99	99	99	99	A864
4	96	97	97	97	A873
5	99	99	99	99	A870
6	99	99	99	99	A910
7	98	98	98	98	A869
8	98	98	99	98	A865
9	96	96	96	96	A834
10	98	98	97	98	A876
11	97	97	97	97	A837
12	97	97	97	97	A839
13	97	96	96	96	A833
14	97	96	96	96	A836
15	98	98	98	98	A819
16	97	96	97	97	A840
17	97	96	97	97	A868
18	98	98	97	98	A867
19	97	97	97	97	A838
20	--	--	--	--	A832
21	97	97	96	97	A818
22	99	98	98	98	A841
23	98	98	98	98	A845
24	98	98	98	98	A816
TOTAL AVERAGE:				98	

According to ABNT NBR 15361 [16], the sensors in use should not present difference in amplitude values between one check and another greater than 3 dB. Variations equal to or greater than 4 dB indicate that the sensor has suffered some damage or is in degradation and, if above 6 dB, should be discarded [8].

5.2.2.1 Distribution of events in the TQ-09 tank

The representations of the exact location views on the plan of the bottom plates of the tank and the three-dimensional view indicate that the "*clusters*" closest to the bottom plates are composed of276 events. In Figure 20, the map shows the distribution of events and the regions with the highest number of events.

Figure 20 - Evaluation of the probability of leakage in the TQ-09 tank



In Figure 21, below, it represents a detailed planar evaluation of the regions where the greatest number of events occur (magenta color). The events are located next to the back of the tank, between sensors 2 and 3, and also on sensor 24. Figure 22 shows the location quotas, the record of the total number of events, the averages of the counting and energy parameters for each "*cluster*". A sum of 276 events are related to magenta color in cluster 2 and 18, which leads to be considered as Level III.

Figure 21 - Detail showing the region of greatest number of events (magenta color) located along the side of the tank, between sensors 2 and 3, and also on sensor 24.

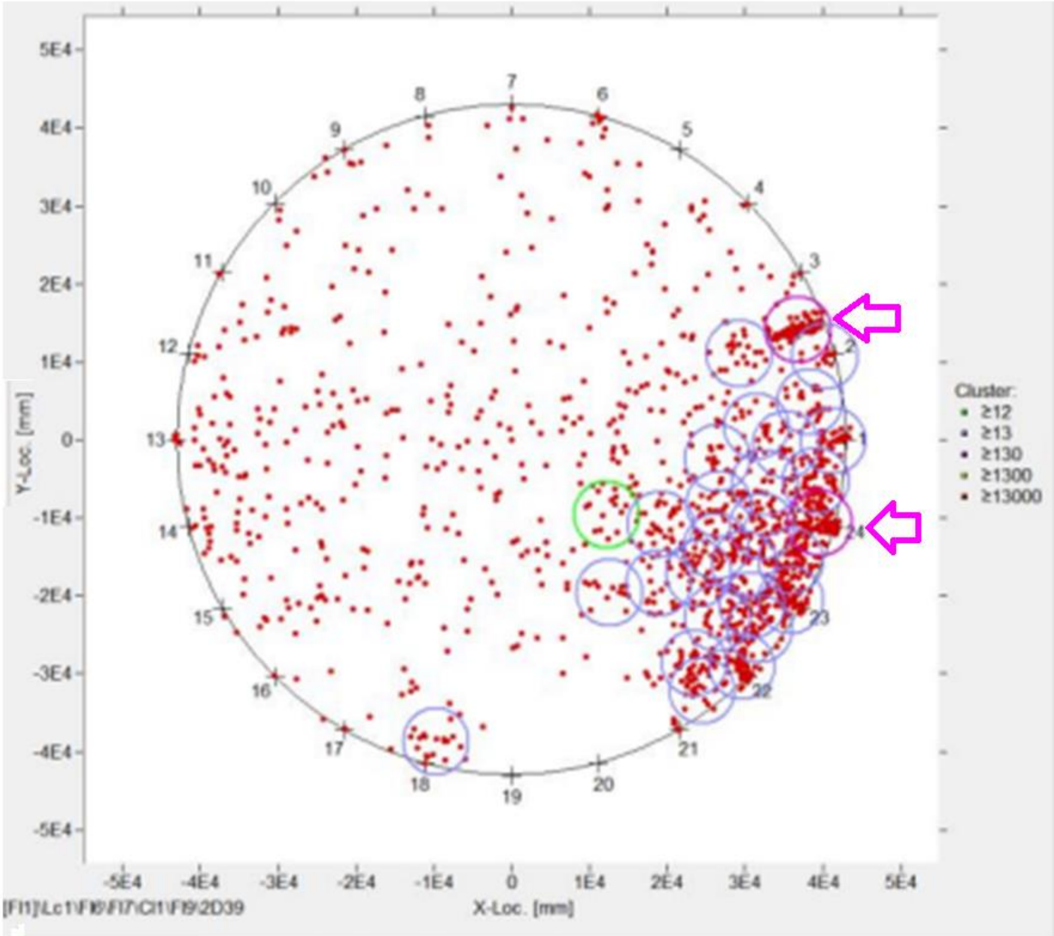


Figure 22 - Location quotas of the "clusters" in the TQ-09 tank

Cluster List for [Fl1]\Lc1\Fl6\Fl7\Cl1

Cluster	Elements	X-Loc. [mm]	Y-Loc. [mm]	Counts Average	Energy eu
2	141	39665,72	-10652,59	3,74	28,10
18	135	36847,48	14148,17	46,30	286,2
25	89	35893,66	-20603,59	3,61	13,59
31	81	29607,95	-29074,39	3,94	16,21
3	75	35966,35	-15574,00	2,40	17,12
17	54	39157,61	-5237,31	6,96	570,3
20	52	30939,38	-21290,37	4,29	21,65
30	49	32250,52	-11092,61	12,02	86,13
41	39	23511,96	-28632,84	14,46	86,99
13	37	26343,89	-13714,82	13,84	104,0
36	36	41328,48	-142,69	6,86	92,33
16	30	19183,84	-10806,01	32,47	407,9
59	29	24066,93	-17181,77	36,07	440,7
27	26	26690,41	-8286,72	25,81	186,8
38	24	26476,72	-22867,60	8,54	41,37
51	23	32592,73	-5569,92	1,96	4,86
70	23	29959,17	-15992,79	3,83	8,94
40	22	38372,19	4872,72	7,32	91,59
9	20	-9717,93	-38731,99	5,45	18,45
33	20	29305,27	11038,55	19,90	102,9
15	18	35279,74	-639,47	16,00	553,0
81	17	24481,09	-32194,85	3,76	9,64
71	17	31913,40	-24324,89	3,35	10,67
49	16	12599,16	-19611,05	23,31	117,6
12	16	26558,54	-2332,78	66,00	613,9
56	16	18958,77	-18398,65	1,94	4,38
54	13	31497,50	1743,39	49,54	28348
65	13	40293,23	10721,68	8,92	22,53
61	12	12293,09	-9601,75	56,75	3970

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5.2.3 Overall assessment of tanks TQ-07 and TQ-09

Table 10 below presents a summary table of the results of the acoustic emission tests performed in tanks TQ-07 and TQ-09.

Table 10 – Summary of AE results performed in oils tanks

Tank	Number of Events	Zonal Location E_Z	Corrosion Level Classification (Table 4)	Planar Location E_P	Classification as to the probability of leakage (Table 5)	Recommendation (Tables 6 and 7)
TQ-07	58440 (554 hits)	2435	III – Moderate ($250 < E_Z \leq 2500$)	Cluster 6 (248 events)	III – Moderate ($220 < E_P \leq 2200$)	III – Moderate (Consider a schedule for maintenance in 2 years)
TQ-09	312758 (10637 hits)	13598	IV – Serious ($2500 < E_Z \leq 25000$)	Clusters 2 and 18 (276 events)	III – Clear ($220 < E_P \leq 2200$)	IV – Active (Prioritize scheduled maintenance in 1 year)

The results of the mapping of the acoustic activities in these two tanks, considering the entire history of the terminal, including the tests performed in this work, that is, between the years 2020 and 2022 demonstrate that:

1. The corrosive process of the TQ-07 plates became less active in the passage from 2021 (157866 events) to 2022 (58440 events);
2. The corrosive process of the TQ-09 plates had a significant increase in the passage from 2021 (170185 events) to 2022 (312758 events) in the order of 80%.

The experiment of Van de Loo and Herrmann [17] who analyzed the results of acoustic emission in the same tank for three consecutive years, concluded that divergent results can be explained by a change in the stored fluid or by a deficiency in the application of the test procedure. In this sense, the significant increase in corrosion activity verified in TQ-09 in 2022 is related to the change of stored product, which occurred from mid-2020, when the tank began to operate exclusively with formation water for the treatment plant of the terminal. As mentioned earlier, the forming water has high salinity, accumulates at the bottom of the tank and contains organic compounds, often with the presence of sulfate-reducing bacteria, which potentiate the corrosive process in the tanks [18].

Finally, it is verified in the results that the general condition of the TQ-07 tank is superior in relation to the TQ-09 tank and are compatible with the scheduled stop plan of these tanks.

In subsequent years and, after the maintenance and inspection shutdowns of the TQ-07 and TQ-09 tanks, the application of the acoustic emission test is presented as a good tool to evaluate the repair services performed of boilermaking and painting on the bottom plates. In this perspective, the results related to the degree free of deterioration would indicate a good protection of the paint and cathodic protection and, on the contrary, the results related to active corrosion activity would indicate failures in the painting and/or cathodic protection [19]. These results in the application of acoustic emission after the maintenance shutdown can also contribute to the history of tests accumulated in the database of the tanks. This track record will provide complementary support in the future to risk-based studies, such as those applied in accordance with API *Recommended Practice* 581 [20] which documents a methodology for risk-based inspection for equipment, such as in storage tanks.

6 CONCLUSIONS

Based on the evaluations and tests of acoustic emission applied to the bottoms of oil storage tanks, it is concluded that:

- The general condition of the tanks evaluated for the level of accumulated damage activities is compatible with the deadlines provided for in the planned shutdown plans for internal maintenance and inspection in force;
- The acoustic emission technique allows a global evaluation of all the tanks of a terminal, within the same operational campaign and, in this way, separate the tanks with advanced corrosion process from the uncorroded tanks or with the corrosion process in initial formation;
- More frequent and in-service monitoring provides fast results (often in real time) that can optimize shutdown preparation and execution resources and the most assertive planning for internal inspection;
- Environmental and process noise may hinder the performance of the test and must be adequately filtered and eliminated during data interpretation (separation of relevant and non-relevant indications);
- The acoustic emission test in a large structure, as in the case of oil storage tanks, with a diameter of more than 80m, requires extremely detailed technical attention during the assembly and disassembly of the cables, sensors and connectors, in addition to all the infrastructure necessary for the execution of the test. The loss of signal by the failure of any of the components can generate great rework and compromise the results of the test;
- The prior planning of the day of the test between the inspecting company and the terminal operator is of paramount importance to ensure the minimum rest time of the tank and the interruption of product handling operations, whether pumping or agitation. Although the test is performed without emptying the tank, noise filtering is fundamental for the acquisition and analysis of the results. In addition, monitoring in the morning and afternoon is recommended.

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