CASE study: Tank and pipes monitoring by Acoustic Emission

2025/09/15

Agenda

1. Business needs and gaps
2. Corrosion - Physical phenomenon
3. Literature review
4. Acoustic emission features
5. Acoustic emission techniques
6. International standards
7. e-siam® corrosion and leak detection
8. e-siam® technology development
9. e-siam® technology results
10. Q&A

Tank farms for storage of liquid substances

Liquid substances are often stored in large quantity in storage tanks, grouped in tank farms. Networks of interconnecting piping are needed to move the substances between tanks and origin and destination of substance

Business gap & need

Storage tanks get corroded, typically inside, and need periodic maintenance
Extent and degree of corrosion is unknown before emptying and internal inspection

FOTO 43: Ossidazione lamiera fondo

FOTO 44: Ossidazione PDU

FOTO 45: Mantello

FOTO 46: Lamiera 14

FOTO 47: Lamiera 4

FOTO 48: Lamiera 6

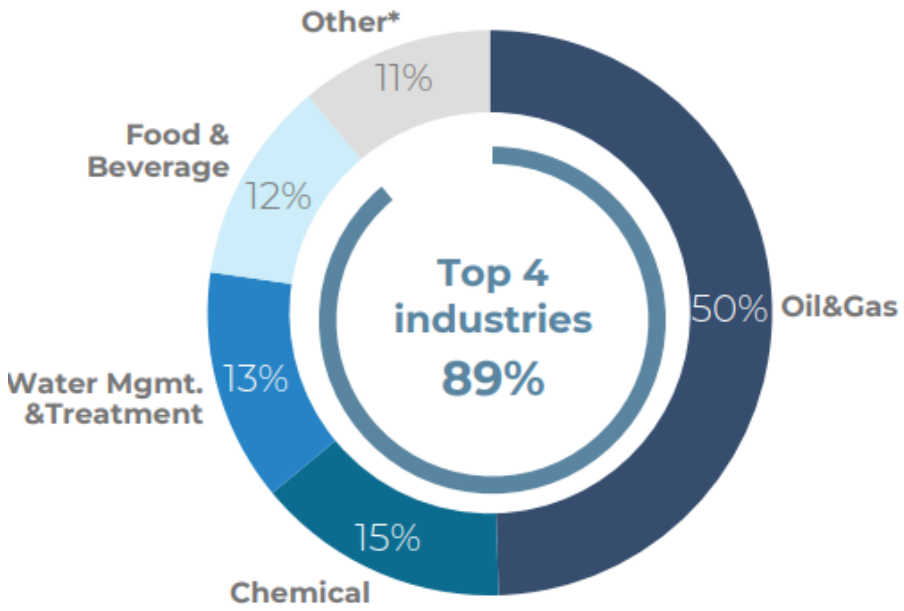
Business gap & need

Pipes can get corroded as well

Metal loss
Thickness reduction

4 industries accouting for 89% of global expenses on tank integrity monitoring

Remote Tank integrity monitoring expense by Industry[1]



Industries in scope with the analysis

- Oil & Gas
- Chemical
- Water mgmt. & Treatment
- Food & Beverage

Industries further refined based on :

- Use case relevance - Leak criticality
- Use case availability (storage tank volumes)
- Asset fit
- Market solution industry coverage

Source: Accenture elaboration on Mordor Intelligence data

Note: 1) Market is still limited due to low presence of solution meeting customers' requirements – see Phase one analysis

O&G emerges as the primary target market

Deep dive in backup

KEY RATIONALES			OIL&GAS[1]	CHEMICAL[2]	WATER MGMT	FOOD & BEVERAGE
	Prioritization		**1°**	**2°**	Low relevance	Low relevance
	Use case relevance	**Criticality and impact** of a potential **leak**	**High** *Prevalence of hazardous material*	**Medium-High** *Mix of hazardous material and not*	**Low** *Stored liquid is in general not hazardous and valuable*	**Low** *Criticality of stored liquid is highly diversified*
	Use case availability and volumes share *(2023)*	Global share of **storage tank that could be potentially targeted** and **presence along the value chain**	**~75%** Along the **entire value** chain, with biggest volumes in **midstream & downstream Upstream - limited number and sizes**	**~20%** Both in **productive plants** and somehow in **tank farms** (big companies)	**<5%** Especially in **midstream phases** where water and wastewater could be **stocked before and after processing**	**<5%** Inside **industrial productive plants,** stocking ingredients
	Asset fit	Average **tank dimensions** (and **material compatibility**) justifying e-siam® application **in relation to possible installation layout**	Big tanks reaching **>100.000 m³** with up to **100 mt** diameters generally made of **steel**	Small-Medium tanks with an average diameter of **10 mt** and up to **2.000 m³** of capacity, generally made of **steel**	**Few large tanks** but **not necessarily** made of **steel**	**Few small** storage tanks both made of **steel and plastics**
	Market solutions industry coverage	Percentage of **companies offering corrosion monitoring solution** targeting a specific industry segment	80%	45% *(if petrochemical)* 20% *(if chemical)*	10%	10%

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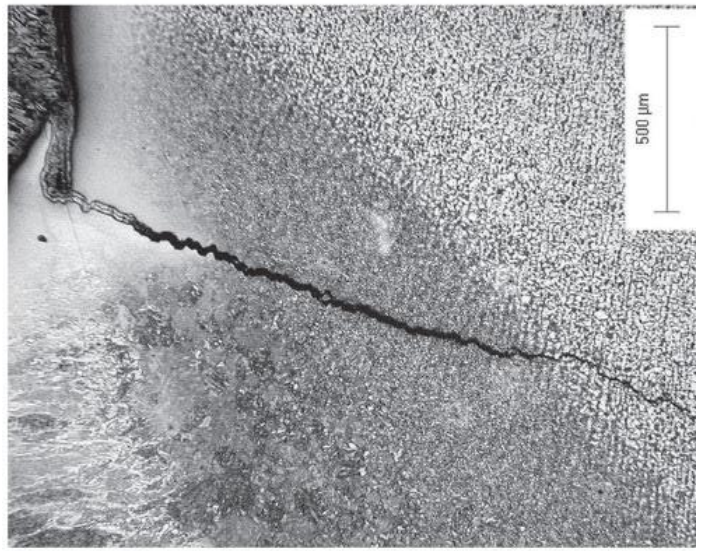
Note: 1) Interview with TotalEnergies Plant Manager 2)Interview with BASF Plant Manager 3) Market solutions coverage total is above 100% due to the presence of solution simultaneously targeting more than one industry

Metal Fatigue and Crack Formation

Repeated deformation in metals causes them to break and crack

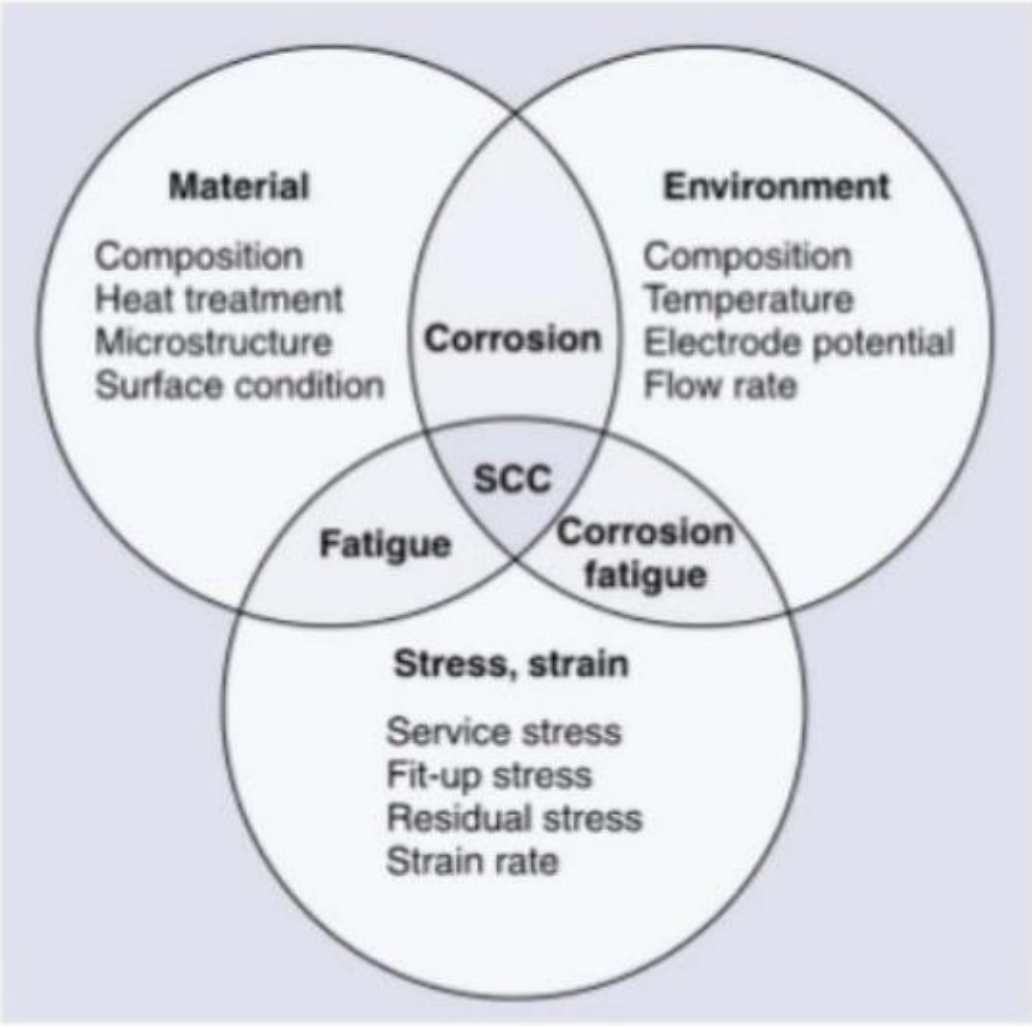
Crack life cycle

Stage	Size
Discontinuity in the material	nm
Micro-crack	µm
Visible crack	mm



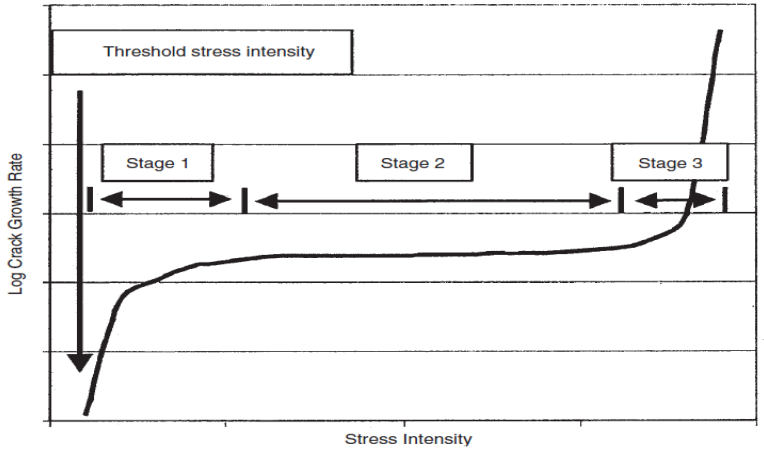
Visible crack occurred in the pipeline (picture provided by Eni SpA, all rights reserved)

Stress-Corrosion-Cracking



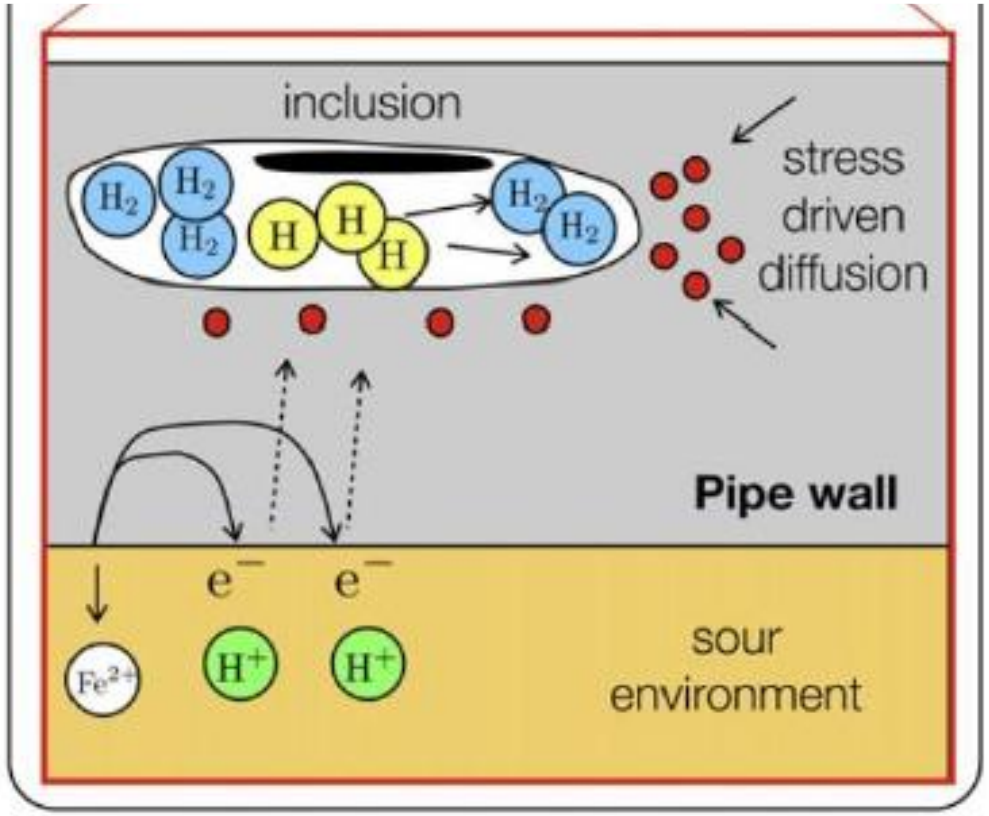
Preconditions for the existence of Stress-Corrosion-Cracking:

- Environment conditions favourable to corrosion
- The presence of a metal imperfection/damage initiates the SCC phenomenon
- The presence of stress amplifies the phenomenon and gives birth to Stress Corrosion Cracking (SCC).



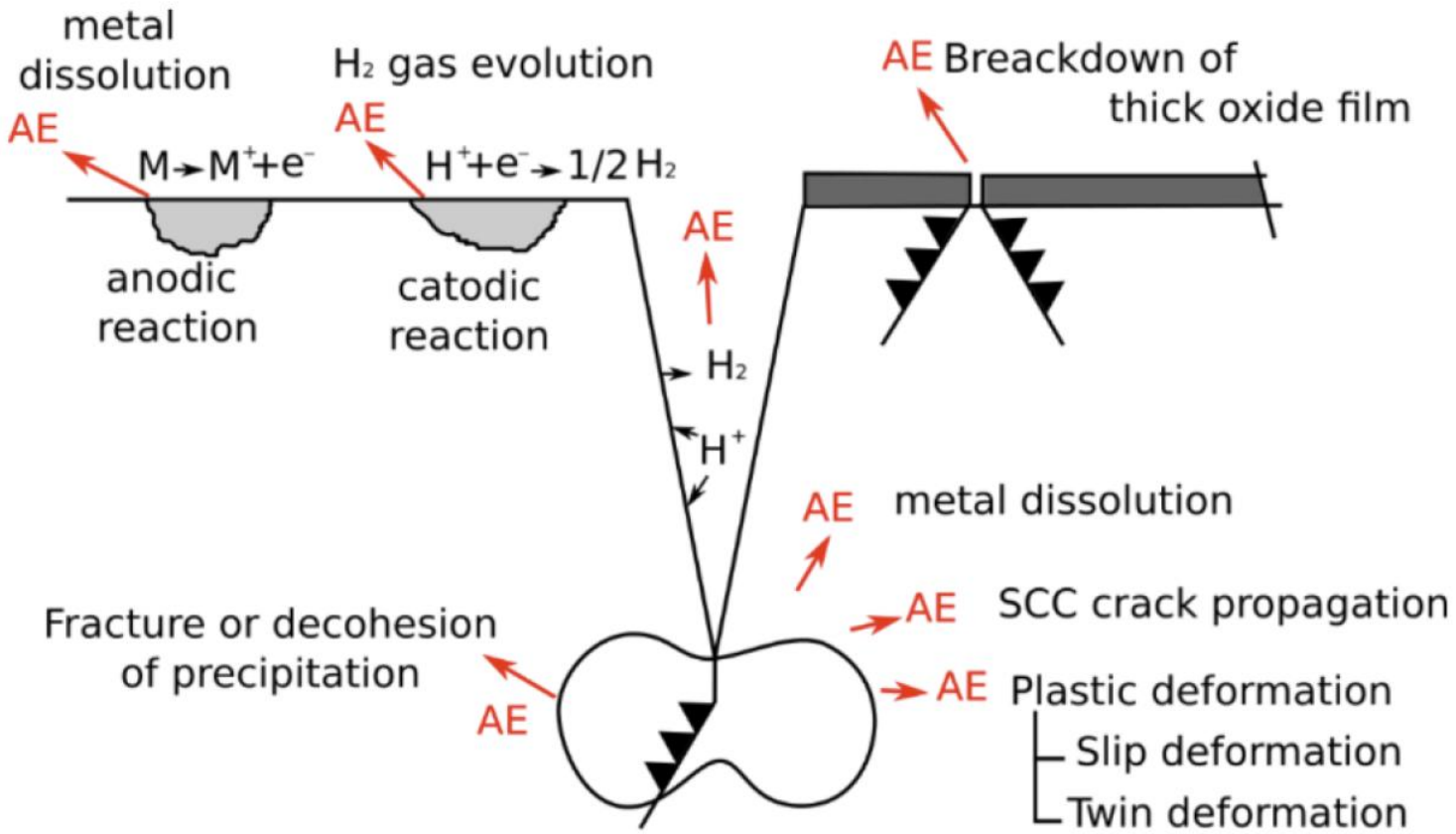
Hydrogen Induced Cracking

- Corrosive reactions with H2S produce hydrogen ions
- mono-atomic hydrogen diffuses into the metal lattice
- A crack occurs when the atomic hydrogen migrates to a trap site and then becomes “trapped.”



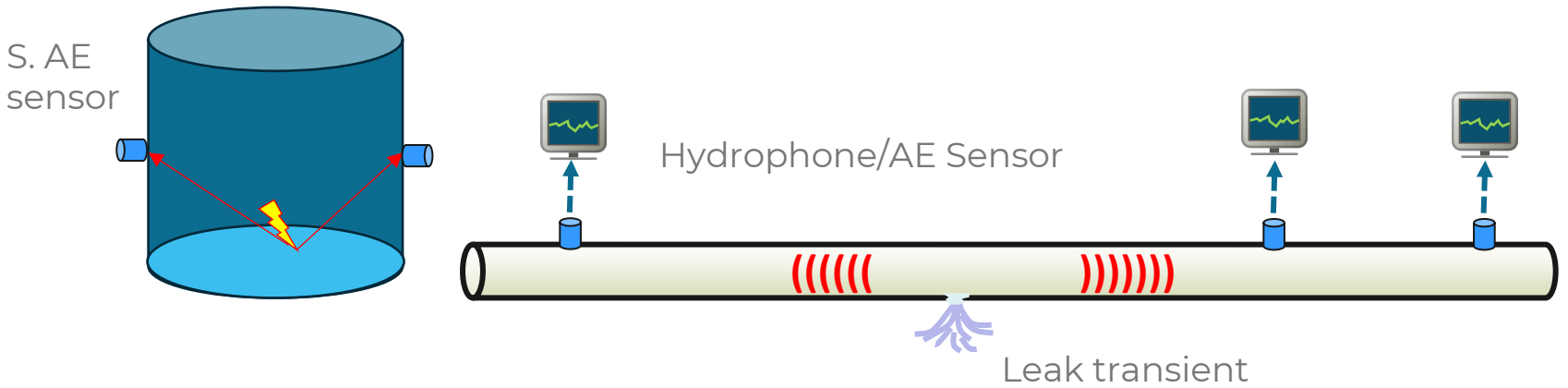
Corrosion – Acoustic Emission

Several corrosion-related phenomena generate **acoustic emissions**



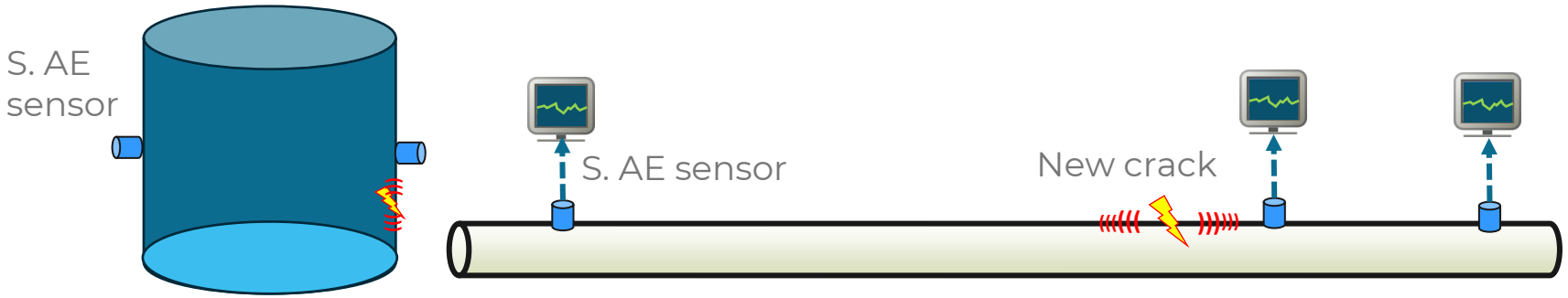
Fluid-borne vs Structure-borne Acoustic Emission

Fluid-borne AE



- Propagation in internal fluid
- Long distance (tens of meters to kms, depending on frequency)
- Hydrophones (low frequency)
- AE sensors (PZT, high frequency)

Structure-borne AE



- Propagation in pipe or tank shell
- Short distance (meters)
- AE sensors (PZT)

Corrosion detection methods

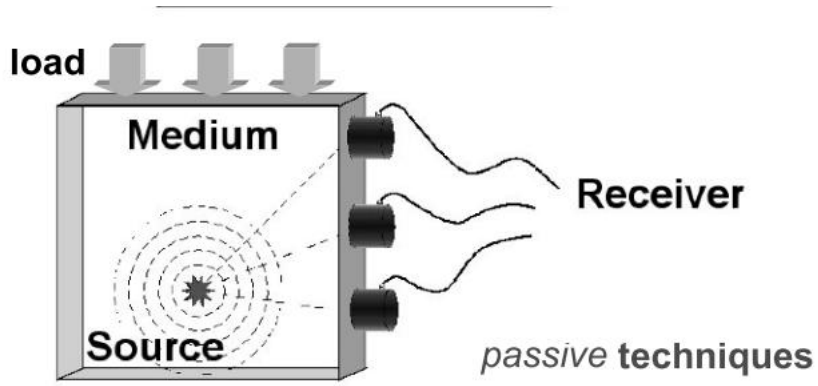
Method name	Detectability of SCC	Detectability of HB	Applicability to SHM of storage tanks	Applicability to SHM of buried pipelines	Notes/comments
Visual Testing (remote visual inspection)	Yes	Yes	Yes	No	Application for SHM is currently difficult due to camera magnification, lighting, and human factors
Ultrasonic Testing & Phased array ultrasonic	Yes	Yes	No	No	Based on off-line evaluation, equipment effective only for local inspection
Guided ultrasonic waves (GUW)	Yes	Not found in literature	Yes	Yes	An effective method that is often seen as promising in SHM, however it is difficult to implement when inspecting large storage tanks (by virtue of their design)
Potential Drop	Yes	No	No	Yes	May be considered as an auxiliary method but only for buried pipelines
Acoustic Emission Testing (passive and active)	**Yes**	**Yes**	**Yes**	**Yes**	Adaptive for SHM and universal. The disadvantages include the difficulty in interpreting the results.
Eddy Current Techniques	No	Yes	No	No	In the literature, a weak sensitivity of the method is often noted.
Magnetic particle inspection	Yes	Yes	No	No	An effective method for on-site inspection to confirm defects, but cannot be used for SHM because it is completely performed by humans
Digital radiography	Yes	Yes	No	No	Based on off-line evaluation, traditional equipment effective only for local inspection
Neutron tomography	No	Yes	No	No	Highly specialized approach

Acoustic Emission Technique (AET)

Reference:
«Acoustic Emission Testing»
Christian U. Grosse, Masayasu Ohtsu,
2008

- Non-Destructive Technique (NDT)
- Passive technique (No active sources)
- Applied during **loading**
- Requires few sensors compared to other NDT (e.g. tomography)
- AE detects the formation of **new cracks** and the **progression of existing cracks** or friction processes.

- AE waves are elastic waves
  - neither ultrasonic nor acoustic.
- AE can be:
  - P-wave (longitudinal wave or volumetric),
  - S-wave (transverse wave or shear),
  - Surface/Guided waves
  - Mode conversion!!



Sensors and Instruments

- AE instrumentation:
  - Sensors to convert elastic wave into electric signal
  - Preamplifier and bandpass filter to increase the maximum cable length and remove background noise.
  - Acquisition (DAC) and storage
  - Elaboration software to performs the detection and localization of the source that generates the event.

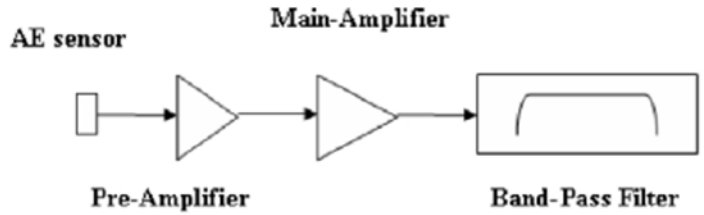
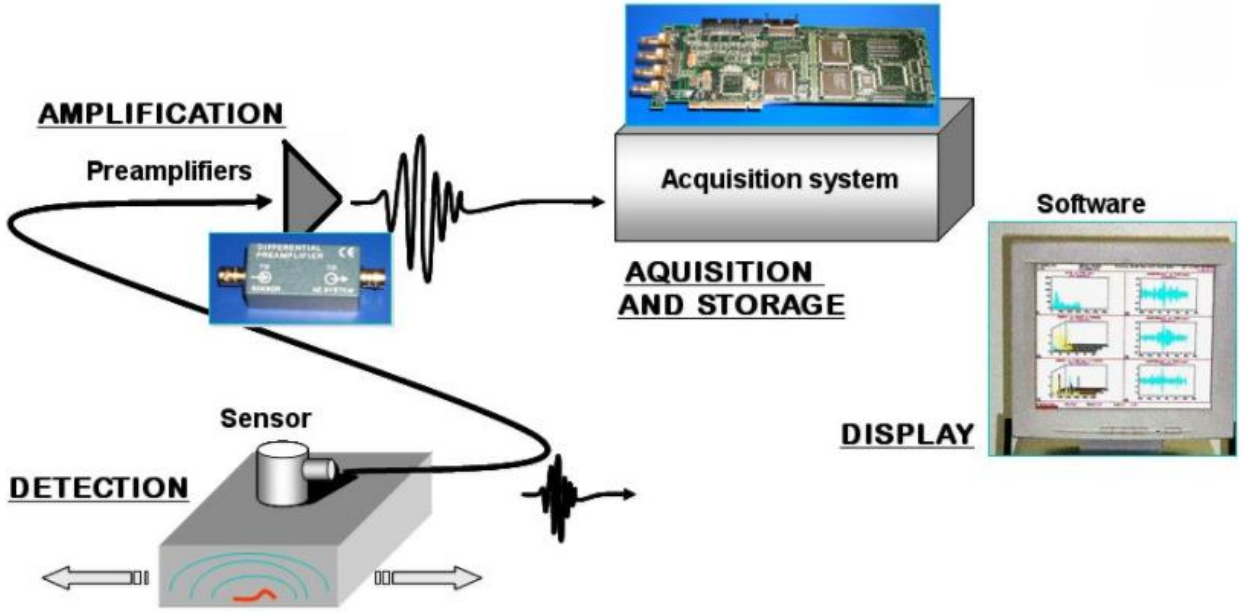


Fig. 2.8. AE detection system.



AE Sensor Selection

- **AE sensors** must be chosen according to the **specific application**:
  - **Environmental conditions** such as temperature, hazardous areas or presence of water and oil. Select sensors suitable to the operating conditions.
  - **Research and feasibility study**, applications when the elastic response of the medium under investigation is unknown. Broadband sensor.
  - **Modal analysis of the structure**, the widest range of frequency must be detected. Broadband sensor.
  - **Structural integrity monitoring**, in some cases it's not important the frequency content of the signals, but only the classical time domain parameter such as Amplitude, Duration, Rise time, Energy. Resonant sensor.

Acoustic emission sensors

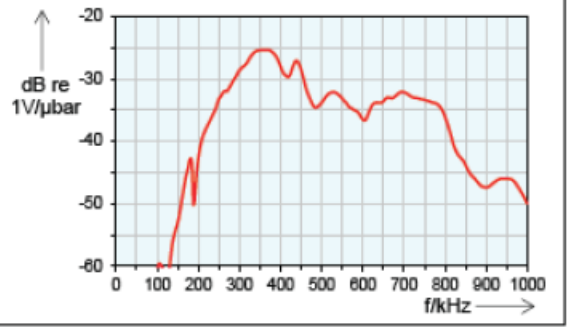
1.6.6.3 AE Softland Times Sensor

Type	Diameter	Height	Port	Shell Material	Contact Surface Material	Frequency Range	Center frequency	Operating Temperature
RS-13A	23.5mm	36mm	M5-KY	stainless steel	Ceramics	16-60KHz	40KHz	-20-130°C
RS-14A	23.5mm	32mm	M5-KY	stainless steel	Ceramics	20-90KHz	50KHz	-20-130°C
RS-15A	18.8mm	22mm	M5-KY	stainless steel	Ceramics	40-150KHz	70KHz	-20-130°C
RS-2A	18.8mm	15mm	M5-KY	stainless steel	Ceramics	50-400KHz	150KHz	-20-130°C
RS-23A	18.8mm	15mm	M5-KY	stainless steel	Ceramics	80-450KHz	200KHz	-20-130°C
RS-24A	13.5mm	14mm	M5-KY	stainless steel	Ceramics	100-500KHz	250KHz	-20-130°C
RS-25A	13.5mm	11mm	M5-KY	stainless steel	Ceramics	100-600KHz	300KHz	-20-130°C
RS-5A	18.8mm	15mm	M5-KY	stainless steel	Ceramics	50-800KHz	Broadband	-20-130°C
RS-53A	13.5mm	11mm	M5-KY	stainless steel	Ceramics	50-800KHz	Broadband	-20-130°C
RS-54A	8mm	7mm	Straight Lead	stainless steel	Ceramics	100-900KHz	Broadband	-20-130°C
RS-35C Integrated Preamplifie Sensor40dB	30.4mm	38.6mm	BNC	stainless steel	Ceramics	50-400KHz	150KHz	-20-70°C

VS275-RIC

VS375-RIC

The VS375-RIC is a piezoelectric AE-sensor with integrated preamplifier. Its frequency response is characterized by a peak at 375 kHz where it exhibits a resonance. Its frequency response bridges the gap between standard frequency range and high frequency range.
The integrated preamplifier has 34 dB gain and supports pulse through for automatic sensor testing.



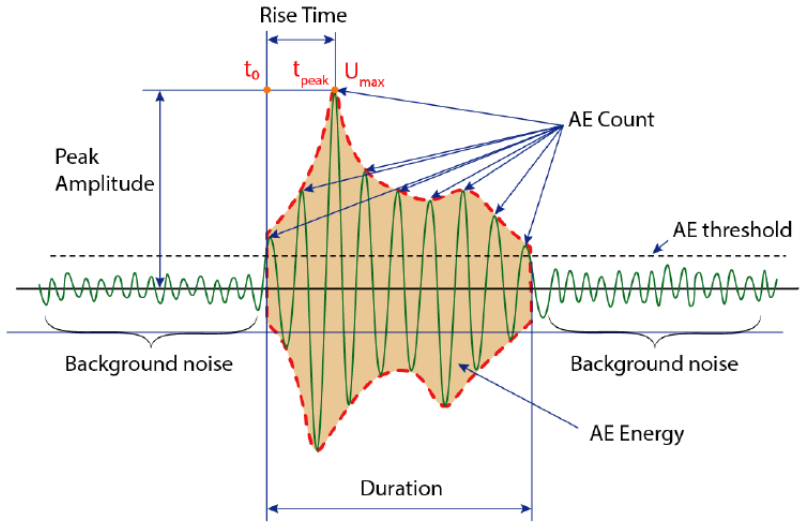
Technical Specification			
Frequency Range (f_{Peak}) [kHz]	250 to 700 (375)	Size (D x H) [mm]	28.6 x 31.5
Power Supply [V_{DC}]	28 ± 2	Weight [g]	80
Typ. Power [W]	0.56 / 2.5 @ Signal 0% / 100%	Case Material	Stainless Steel (1.4571/ 1.4404)
Integrated Preamplifier	Yes	Wear Plate	Ceramics
Preamplifier Gain [dB]	34	Connector	BNC
Pulse Through	Yes	Shield Cross-Talk [dB]	< -80
Operating Temperature [°C]	-40 to +85	Typ. Noise (max. 1/s) [$dB_{AE\ Peak}$]	28.0 @ 95 - 850 kHz
Vibration – Sinus Sweep	2 Oct/Min, 5 to 50 Hz, 20 g	Typ. Noise [μV_{RMS}]	4.5 @ 95 - 850 kHz
Ingress Protection Rating	IP40		

Accessories			
Mounting Holder	MAG4R	Sensor Cable	BNC-xM

AE parametric analysis

- **Identification of AE signal**
  - Voltage threshold excess
- **AE signal parameters - Conventional parameters**
  - Hit (a signal that exceeds the threshold)
  - Count (nr. of times within the duration, where one signal (waveform) exceeds a given threshold
  - Amplitude
  - Duration
  - Rise time
  - Energy
- **Other parameters**
  - RA value (a calculated feature derived from ”Rise time” divided by “Amplitude”, showing the reciprocal of gradient
- **Frequency parameters**
  - Average frequency
  - Initial frequency
  - Reverberation frequency
  - Frequency centroid
  - Peak frequency

Signal acquired by a sensor: Mechanical wave field impulsive waveform

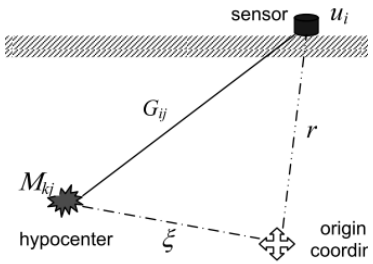


AE signal-based analysis

Localization techniques

- **Zonal and planar localization**
  - Source located within the sensitivity range of one sensor
- **2D/3D localization**
  - Arrival times are used to invert for the source coordinates and the time of origin
- **Moment Tensor Inversion (MTI)**
  - Measurement of displacements
  - Assumed model of medium
  - Methods
    - Absolute inversion (Green's function from theory)
    - Relative inversion (Green's function from reference event)

$$C_{xy}(\nu) = \frac{|\Gamma_{xy}(\nu)|^2}{\Gamma_{xx}(\nu) \cdot \Gamma_{yy}(\nu)}$$



Applications of AE - fields

- AE in Concrete
- AE in the Study of Rock Stability
- AE in Wood
- AE in Superstructures (aboveground)
  - Bridges and buildings
  - Concrete structures
  - Steel structures
- AE in Substructures (underground)
  - Footing, pile, and pier
- AE in Steel pipelines
  - Giunta and Budano
- AE in Storage Tanks
  - IIS Service (Italian Institute of the Welding)

Literature Review

Amplitude and frequency of AE

- This analysis seems to be confirmed if we look at the amplitude distribution (Fig. 14a). It consists of a deformed gauss curve essentially situated between **42 and 52 dB**.
- The mean frequency is centered around the resonance frequency of the sensors that were used. It can be noted that the majority of frequencies is comprised between **130 and 150 kHz.**

Ferrer R., et al. 2002

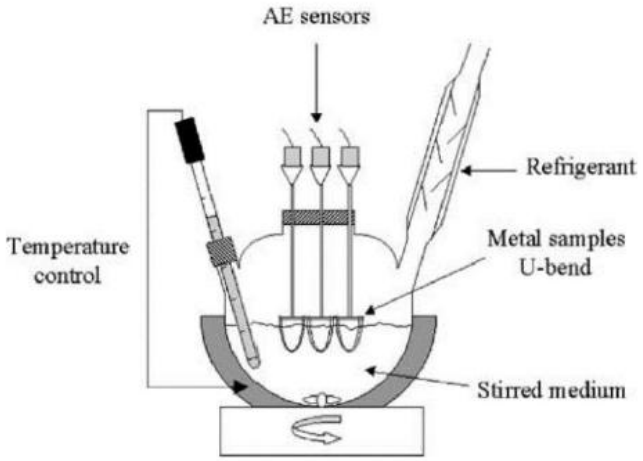


Figure 13: Experimental setup [Ferrer R., et al, 2002].

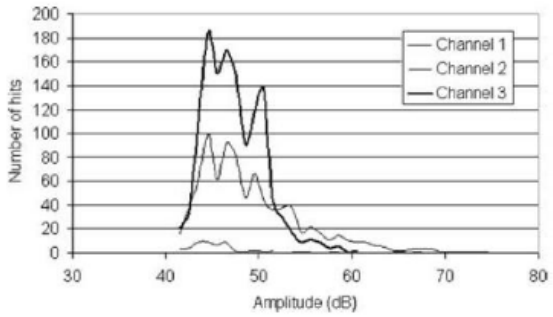


Figure 14a: Amplitude distribution of the signals. Channel 1=stress relieved sample. Channel 2=stressed sample. Channel 3=hyper stressed sample.

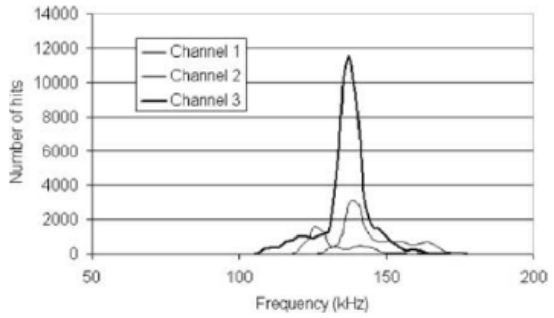


Figure 14b: Frequency distribution of the signals. Channel 1 = stress relieved sample. Channel 2=stressed sample. Channel 3=hyper stressed sample.

Literature Review

Waveforms of AE by corrosion-related phenomena

- Calabrese, L.; Proverbio, E. A Review on the Applications of Acoustic Emission Technique in the Study of Stress Corrosion Cracking. Corros. Mater. Degrad. 2021, 2, 1–30.

https://doi.org/10.3390/ cmd2010001

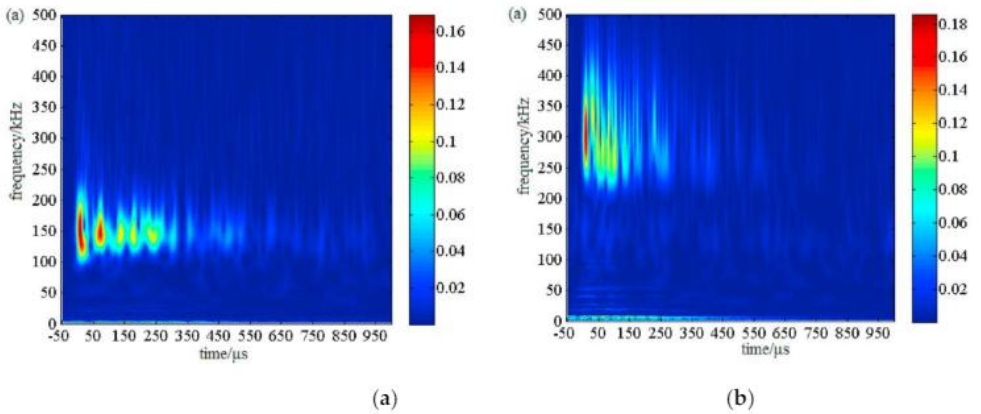


Figure 15. Time-frequency Wavelet 2D diagrams of (**a**) micro-cracks and (**b**) macro-crack AE signals for stress corrosion cracking on aboveground storage tank floor steel [80] (Copyright 2020, with permission from Elsevier).

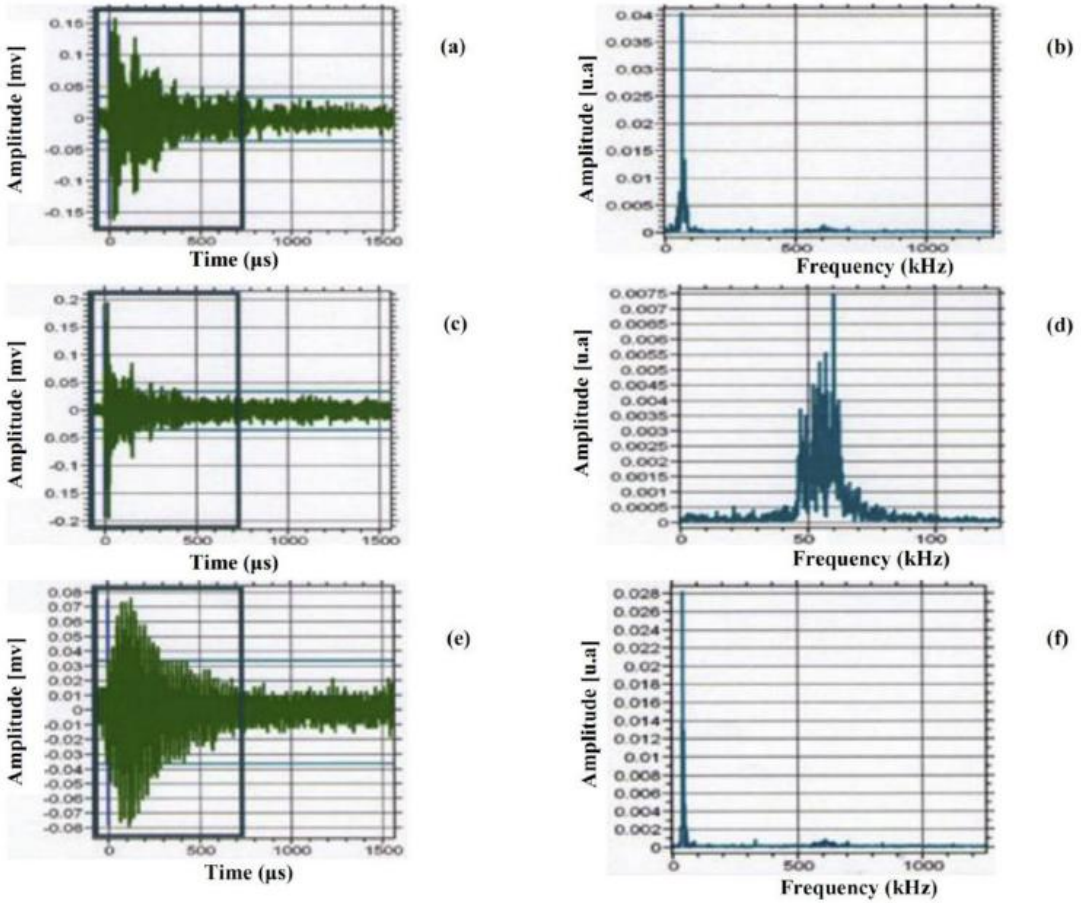
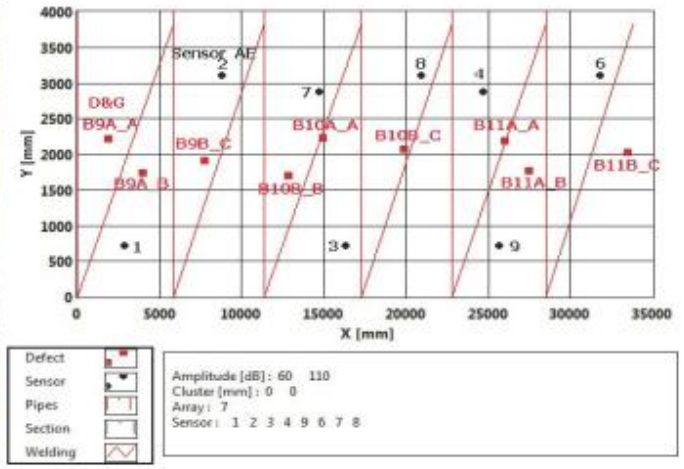
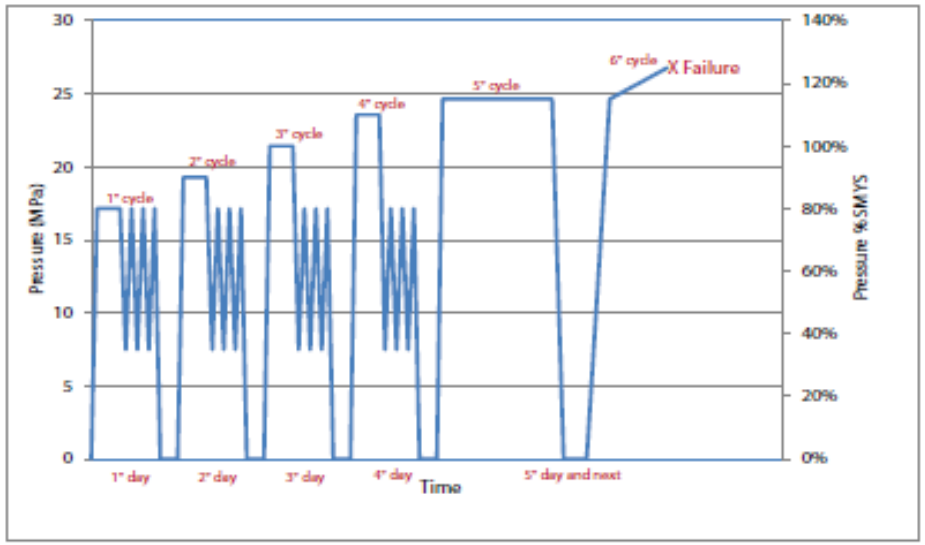


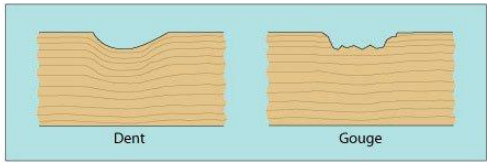
Figure 4: Typical AE waveforms are reported along their spectral content. (a) observed during hydrogen gas evolution, (b) Frequency spectrum of AE signal during hydrogen gas evolution, (c) Typical AE waveform observed during rupture of the passive film, (d) Frequency spectrum of AE signal during passivation, (e) Typical AE waveform observed during metal dissolution, (f) Frequency spectrum of AE signal during metal dissolution.

“Acoustic Emission Technique for Damage Assessment of Gas Pipeline in Hydraulic Test”, A. Lucci et al.

- **Two pilot pipeline sections** were built with pipes made of steel 48 in. OD, HDPE coated.
- A **hydraulic test** until failure was carried out, monitoring the pipeline by using the **AE technique**







International Standard ISO 24489

Non-destructive testing — Acoustic emission testing — Detection of corrosion at atmospheric and low-pressure metallic **storage tank floors**

Table A.2 — Evaluation of AT results by time-difference location

AE source level	Number of located events per hour in the assessed area E	Number of AE location clusters detected	Evaluation of corrosion class of the tank floor in the assessment area
I	$E \leq 10$	Area except level II, III and IV	I
II	$10 < E \leq 50$	9	II
III	$50 < E \leq 300$	2	III
IV	$E > 300$	0	IV

NOTE 1 The source area is circular and its diameter is 8 % of the tank diameter.

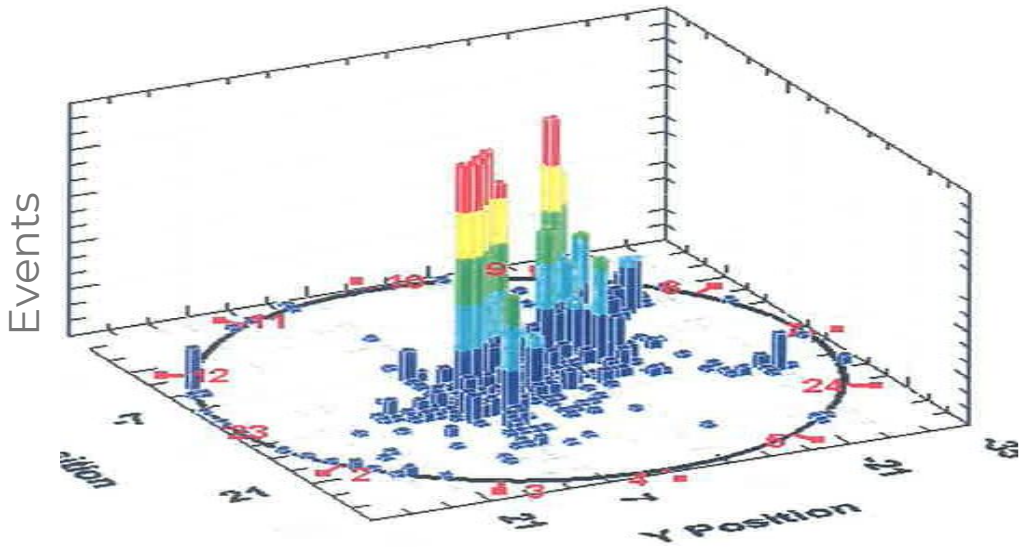
NOTE 2 According to the AT results of 36 atmospheric storage tanks with a volume greater than or equal to 50 000 m^3, the magnetic flux leakage testing results of the bottom plate after opening the tank and the plate cutting verification of the severely corroded parts, the values of a, b and c are determined to be 10, 50 and 300, respectively.

Table B.1 — Evaluation and classification of AE sources based on overall floor condition analysis

AE source level	Normalized number of hits H	Evaluation of AE source	Evaluation of corrosion status of the tank floor
A	$H \leq$ d	None or minor	No corrosion
B	d $< H \leq$ e	Few	Slight corrosion
C	e $< H \leq$ f	Medium	Medium corrosion
D	f $< H \leq$ g	Large	Serious corrosion
E	$H >$ g	Huge	Critical corrosion

The values of d, e, f and g in Table B.1 should be obtained by AT and independent verification on a series of storage tanks with the same specifications and operating conditions. The AT results should be verified by opening the tank, performing other NDT or cutting severely-corroded parts of the tank floor and testing the parts visually (VT) or by other methods.

Example of tank inspection with AE



- The control is carried out by installing **two rows of sensors** directly on the external surface of the shell: The highest row of sensors has a "guard" function,
- The data collected are then analyzed and compared with a database to qualitatively evaluate the active corrosion.
- The system is also able to diagnose the **presence of active leaks** at the time of testing.

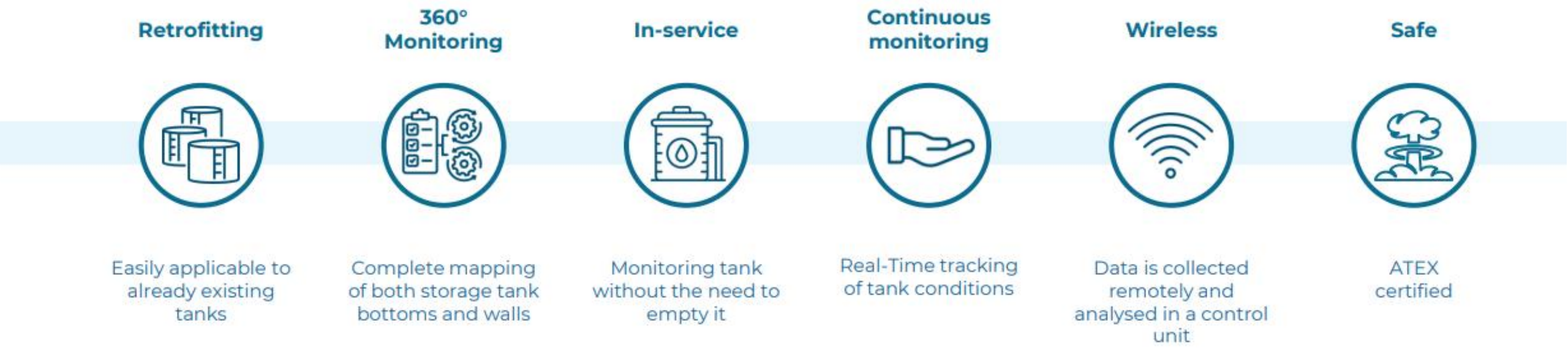
- The control is carried out with a 24-channel Physical Acoustics acoustic emission system and with probes with integrated gain preamplifier

Tank	Judgement	Suggestions
TK 6	Mid-high activity	Repeat test in 1 year
TK 49	Mid-low activity associated to clusters	Repeat test in 2 year
TK 53	Important acoustic activity	Repeat test in 3 months
TK 55	Mid-high activity	Repeat test in 1 year

e-siam™ – eni structural integrity acoustic monitoring

VALUE PROPOSITION

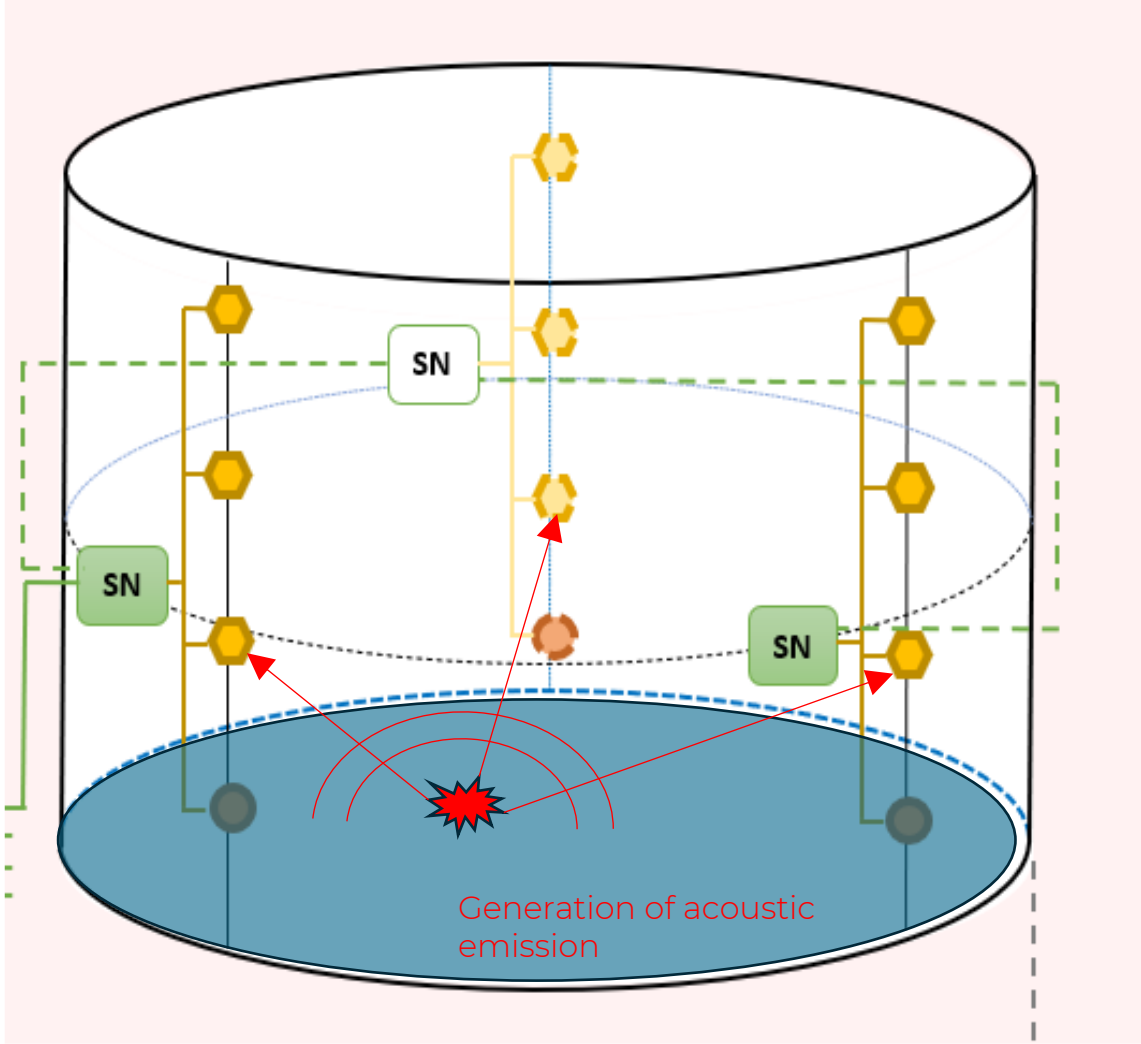
- Eni patented technology provides an early warning system based on **Acoustic Emission and Vibration technology** enabling **continuous 360° corrosion monitoring of storage tanks** and **interconnecting pipes**, to **minimize the probability of leaks** and related financial risk beyond potential visual inspection optimization.



Owner: Eni spa

Licensee: Enivibes

e-siam® corrosion detection – Working principles

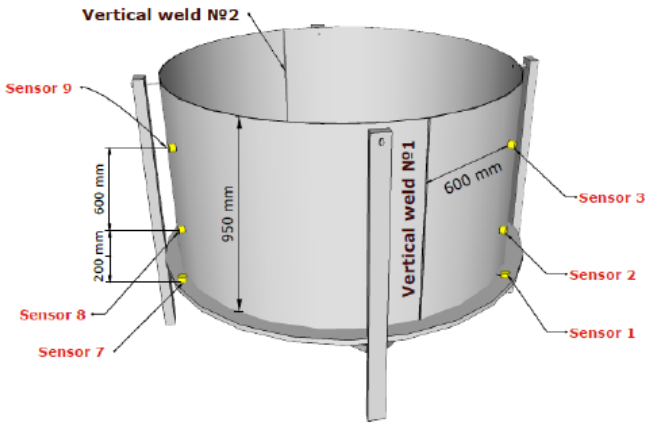


- An acoustic emission (impulsive waveform) is generated at the tank bottom
- The wave propagates (as a spherical wave) in the filling fluid
- The wave reaches the e-siam high-frequency sensors

E-siam® Proof of concept

Laboratory scale prototype.

- Several AE phenomenon characterization:
- Tank charge/discharge
- Galvanic accelerated-corrosion
- Active exciter and screwdriver excitation



e-siam prototype tested on a scaled tank UniBO

- The initial PoC involved the realization of a galvanic process, is a closer approximation of tank corrosion

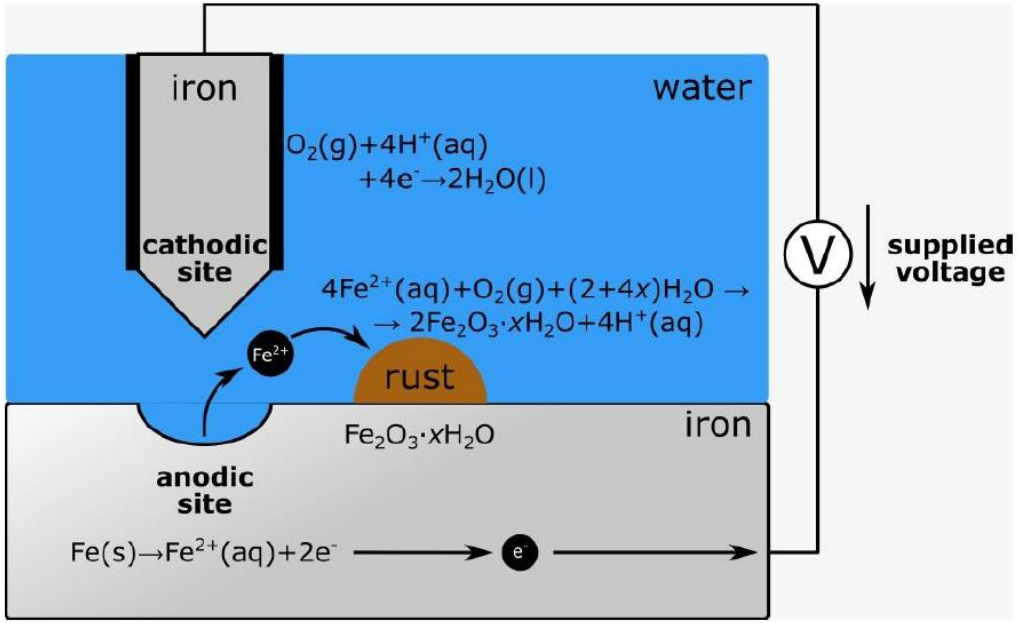
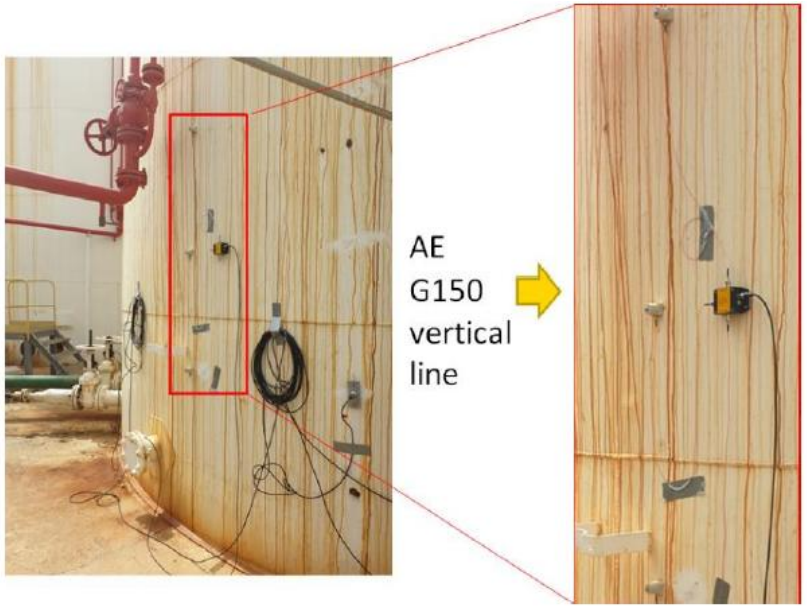


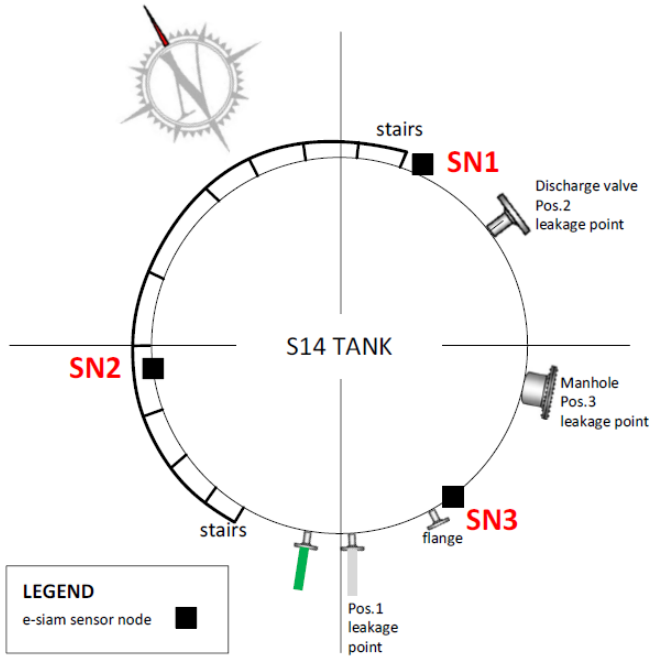
Figure 9: Rust, the Result of Corrosion of Metallic Iron.

e-siam® development

Prototypal system tested (Southern Italy)

- water tank TK-14, D7.39m, H6.1m
- 3 SN with 3 AE sensors each
- noisy industrial scenario
- Leak Detection functionality
- corrosion monitoring (through active sources)





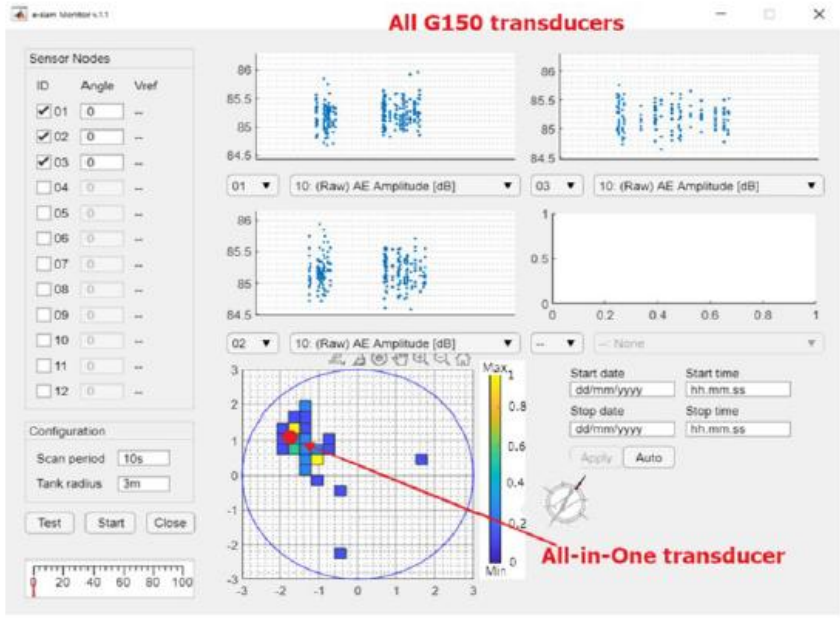


Figure 16: GUI for signal actuation at position “A”.

e-siam project workflow

eni structural integrity acoustic monitoring
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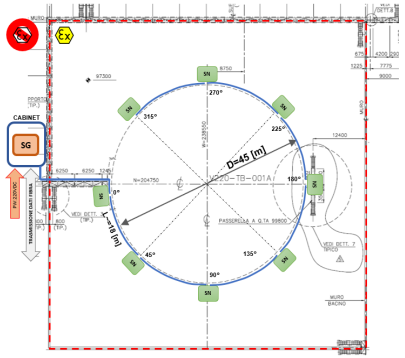
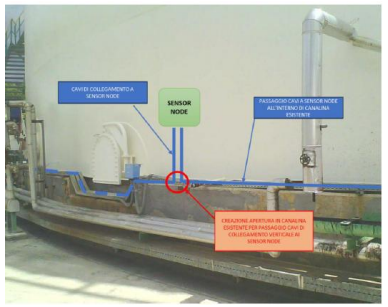
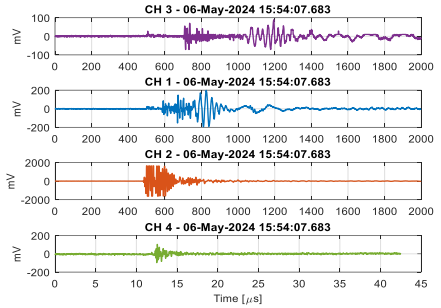
Engineering & procurement



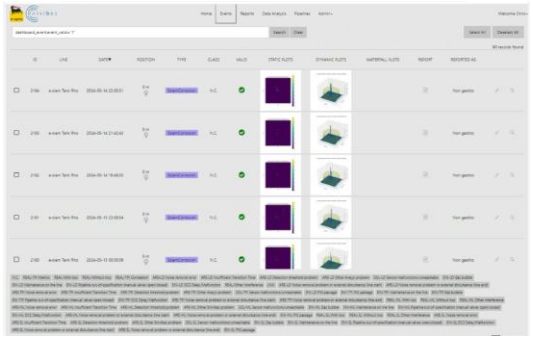
Installation



Calibration

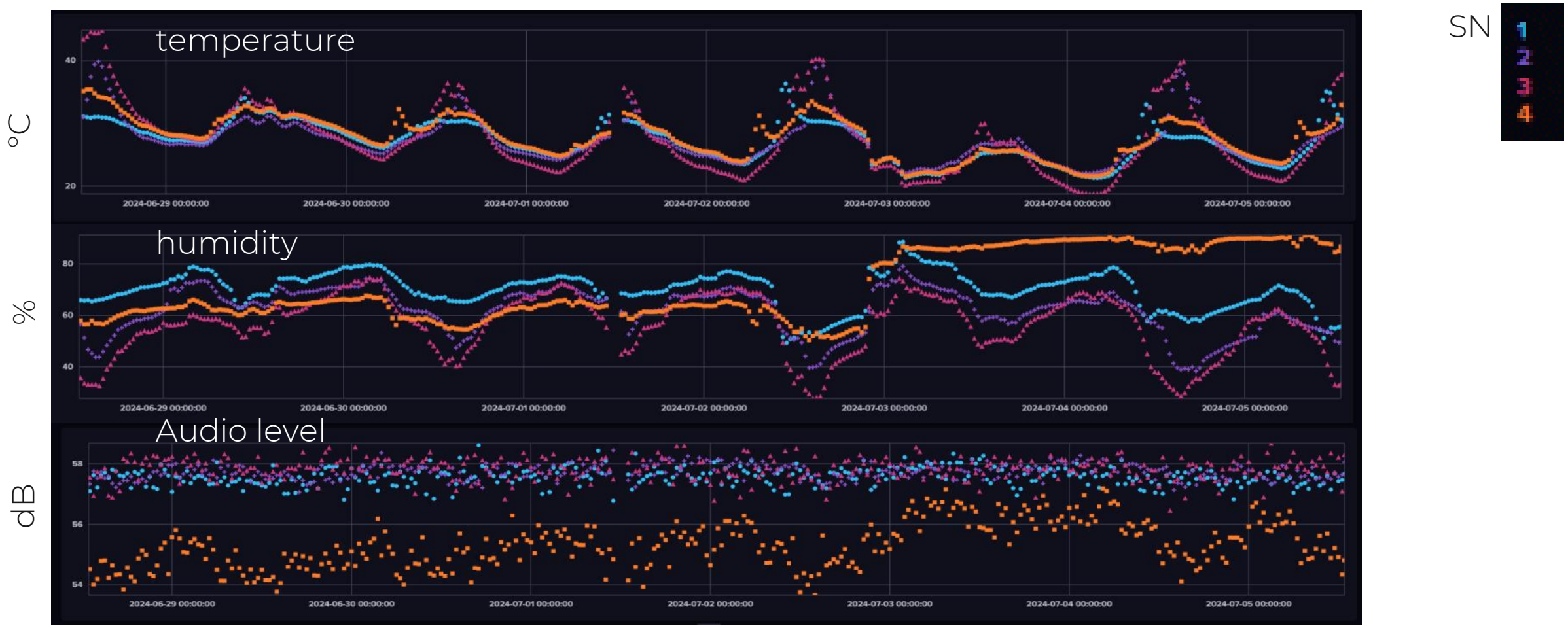


Continuous monitoring



Diagnostics

Monitor of environmental parameters



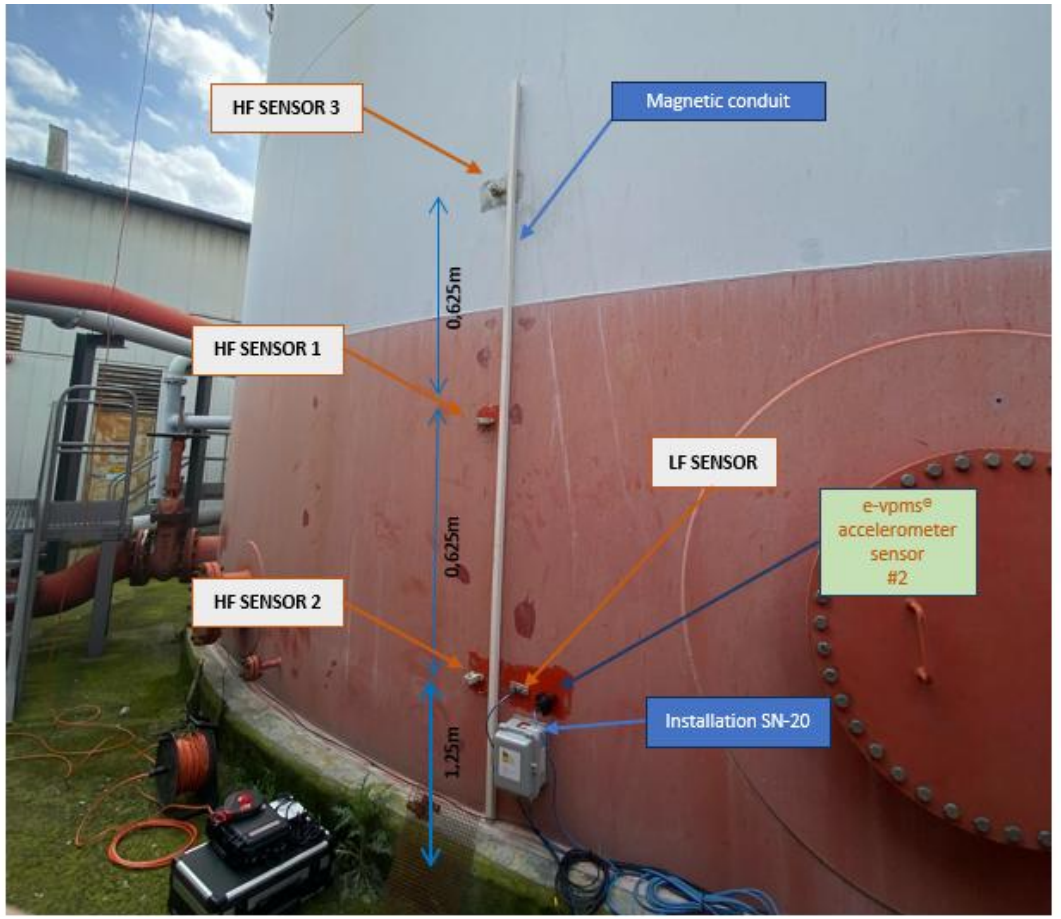
Industrialized e-siam installed

2024: Firefighting water

- Dimensions: D14.4 m, H14.0 m
- No roof
- Fluid: water
- 4 Sensor Nodes

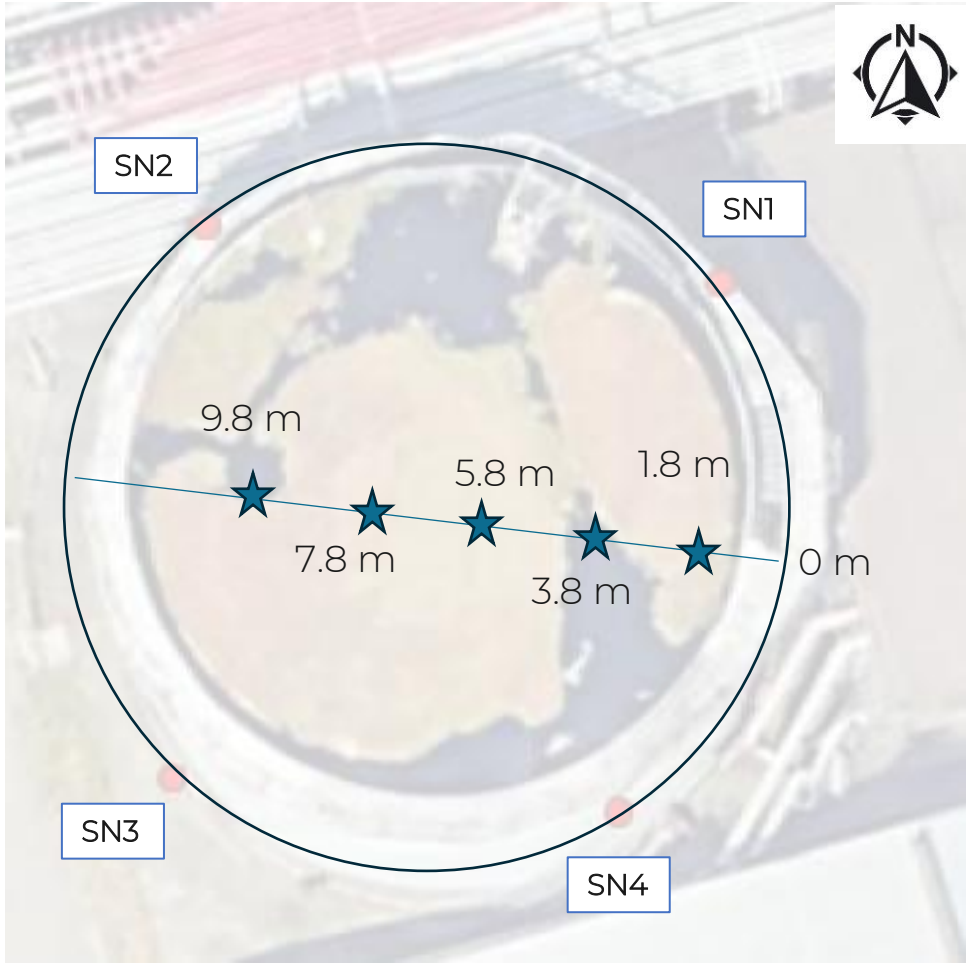
Results:

- Industrialized HW tested
- Measurement chain checked
- Long term monitoring in industrial environment with real and simulated corrosion
- Spill tests for leak detection



Active source

Calibration – Active source at different positions



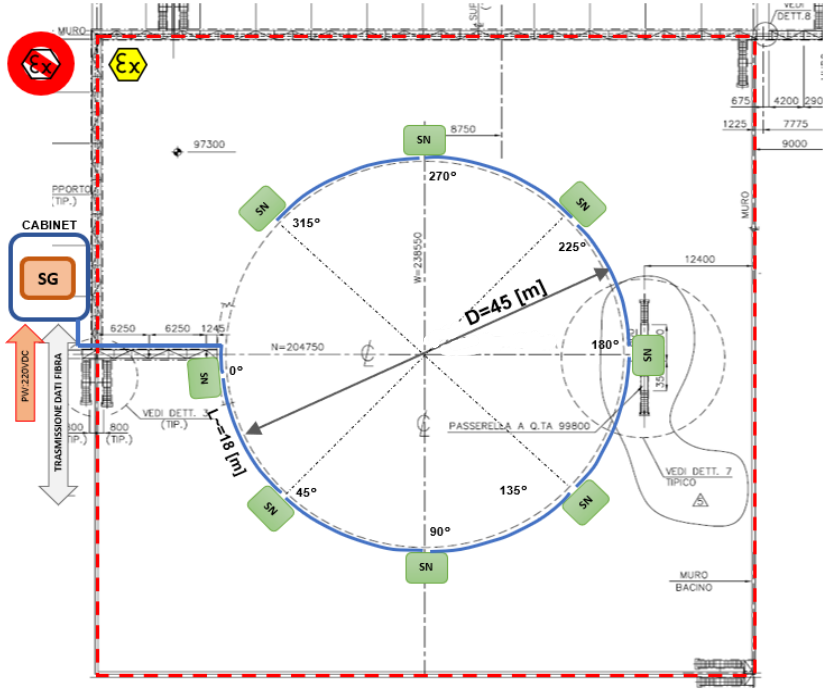
Eni Site D (Eni Subsidiary)

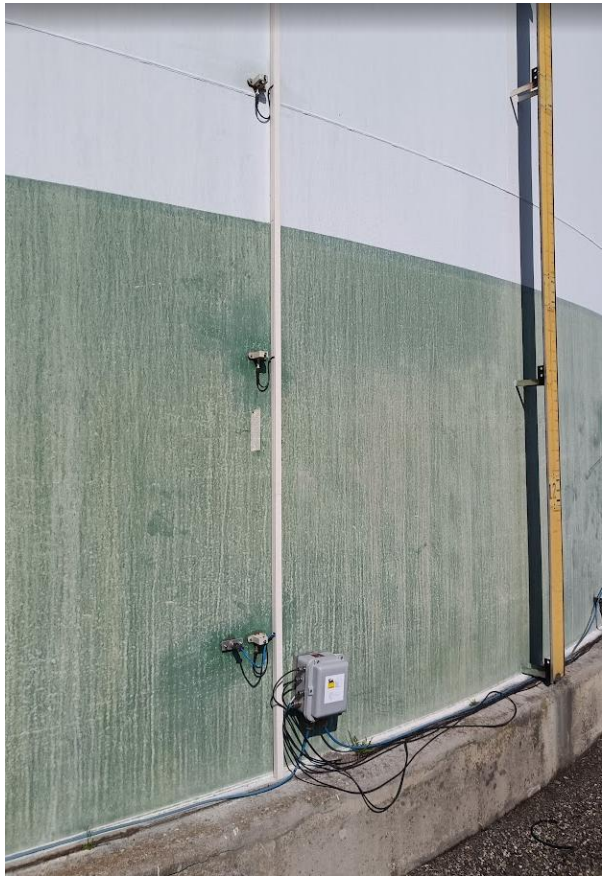
Oil Tank in upstream industrial site

- Dimensions: D45 m, H15.0 m
- Floating roof
- Fluid: **crude oil**
- 8 Sensor Nodes
- Painted on the inside (known initial condition).
- Filling/emptying operating cycle (1–2 weeks).
- ATEX area inside the tank containment basins

Results:

- Industrialized HW tested in **upstream** scenario
- Long term monitoring in industrial environment with real corrosion
- Spill tests for leak detection





Intellectual Property

Trademark e-siam® :

- Registered in Italy, UE, UK, Norway, US.
- Pending: Canada.

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Patent application filed

Conclusion

- Tanks and interconnecting piping are subject to corrosion and need periodic monitoring and maintenance
- Abundant literature claims that corrosion activity is detectable by Acoustic Emission techniques
- Regulatory framework defines Acoustic Emission inspections: method, equipments, results interpretation
- e-siam patented technology aims at providing a monitoring tool which is
  - Integrated in the asset
  - Continuously operating
  - Remotely operated
  - Reliable
- Two versions for two assets
  - E-siam tank
  - E-siam pipe
- Pilot installations in Eni tank farms
  - Crude oil, Diesel, firefighting tanks
  - Interconnecting pipes
- Encouraging results in terms of:
  - Short and long-term corrosion monitoring
  - Leak detection

enivibes

Thank you

Questions?