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Original
Aging facilities prognostic & health management: Data collection, analysis and use / Demichela, M.; Cozzani, V.; Marzani, A.; Baldissone, G.; Messina, M.. - In: CHEMICAL ENGINEERING TRANSACTIONS. - ISSN 2283-9216. - 77:(2019), pp. 925-930. (Loss Prevention 2019 Delft, The Netherlands 16-19 June 2019) [10.3303/CET1977155].

Availability:
This version is available at: 11583/2777989 since: 2020-01-08T14:30:45Z

Publisher:
Italian Association of Chemical Engineering - AIDIC

Published
DOI:10.3303/CET1977155

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CHEMICAL ENGINEERING TRANSACTIONS
VOL. 77, 2019
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Genserik Reniers, Bruno Fabiano

ISBN 978-88-95608-74-7; **ISSN** 2283-9216
DOI: 10.3303/CET1977155

Aging Facilities Prognostic & Health Management: Data Collection, Analysis and Use

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This paper discusses the objectives and early results of the project PROAGE, funded by INAIL under the Saf€ra framework. The aim is to better control of the ageing of equipment, to quantify the impact of operating modes on system reliability, to estimate their residual life and to adapt the maintenance strategy, while respecting safety, regulation and operational performance. Monitored systems in modern process plants can be seen as “intelligent prognostics” system to measure, control, and alert the operating personnel, detecting degradation mechanisms (such as fatigue or corrosion before mechanical integrity is compromised and, in the end, prevent potentially dangerous outcomes. Case studies of industrial interest whose results will disclose the data, the methodologies and the procedures to enhance the capabilities of the organizations of dealing with ageing assets. Data mining techniques applied to the data gained through the automated monitoring and control systems, and the inspections, will allow to extract meaningful indications to support risk- based decision making (Comberti et al., 2018) and the risk management of ageing equipment (Baldissone et al., 2019). Development of professional competencies related to ageing management: specific training for an environment where the volume of data and flexibility of the human machine interface (HMI) systems has increased and is continuously increasing together with the ICT capabilities will be also considered and will be included in a dedicated training case-study, taking advantage of the more recent Serious Game approaches. Within the expected results & outcomes, the Development of a complete theoretical and operational approach to the problem of the ageing equipment, complemented with the methodological and technical tools, resulting in a quantifiable improvement of the safety management in industry is foreseen.

1. Introduction

Figure 1 shows the framework within which the PROAGE project is operating: the purpose of the project is defining and preparing tools to support the risk-based decision making related to ageing equipment. To fulfil project’s scope the research groups involved are working on different case studies, that will be generalised in the final step of the project. The case studies, that are described in the following paragraphs, refer to:

1. Advanced monitoring to control and manage the equipment defects or failures due to ageing, applied to atmospheric vessels;
2. Risk-based decision-making system to support the maintenance planning in case of ageing equipment, considering an analysis of the effects of deferring the planned maintenance, applied to power system turbines;
3. Game based systems to support the training of plant operators towards the management systems, applied to major risk installations safety management systems.

Paper Received: 14 January 2019; Revised: 8 April 2019; Accepted: 19 June 2019

Please cite this article as: Demichela M., Cozzani V., Marzani A., Baldissone G., Messina M., 2019, Aging Facilities prognostic & health management: data collection, analysis and use, Chemical Engineering Transactions, 77, 925-930 DOI:10.3303/CET1977155

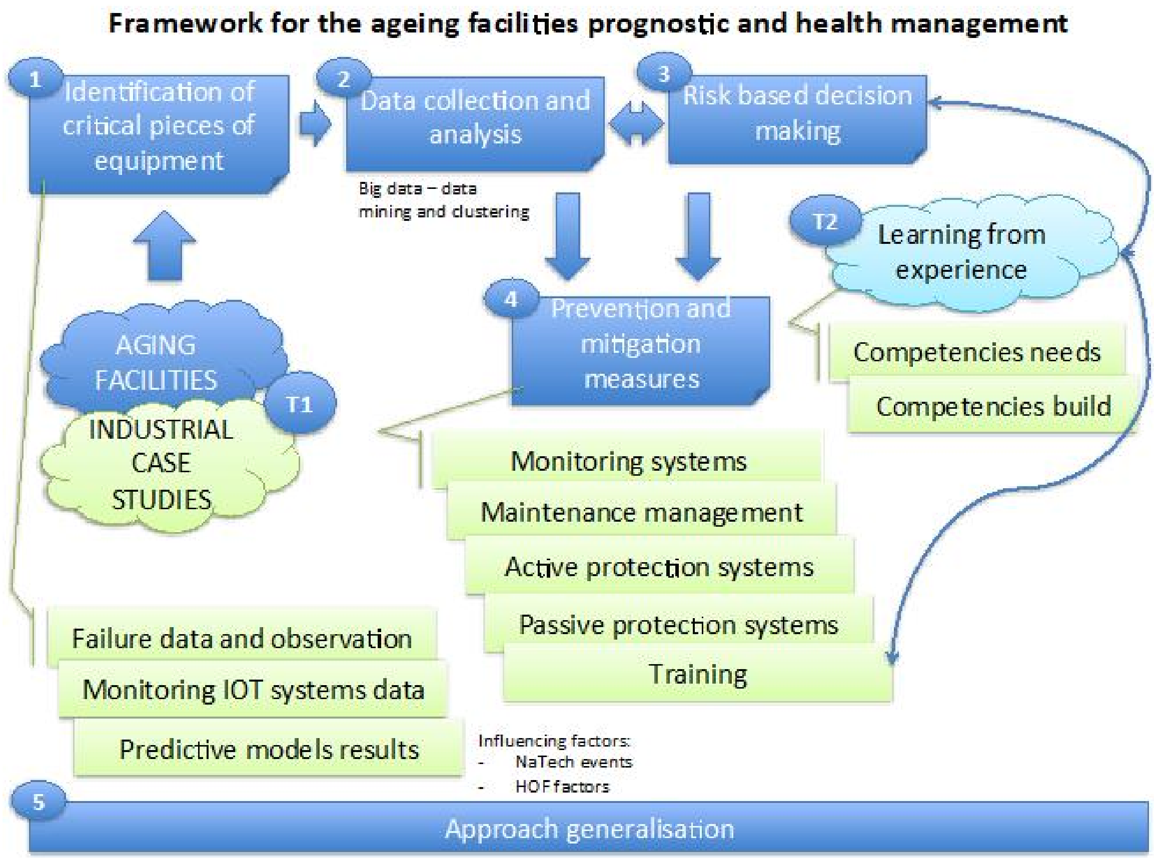


Figure 1 – PROAGE scheme

2. Industrial case study 1 – Ageing atmospheric vessels

In PROAGE (Messina et al., 2018) we propose a strategy to estimate the residual life of atmospheric storage tanks (AST), or pressurized vessels (PV), that relies on the measurement and processing of acoustic emissions (AE). AE are transient mechanical waves that propagate from the wave source location within the structure and are characterized by a frequency content in the range 10-50 kHz. AE can be either generated by cracks or corrosions due to changes of mechanical stresses in the structure (passive AE generation) or by proper devices installed on the structure (active AE generation). AE are generally measured by an array of piezo-transducers bonded to the surface of the structure (see Figure 2). Once acquired, AE signals are further processed to assess the health status of the AST or PV and eventually to estimate their residual life.

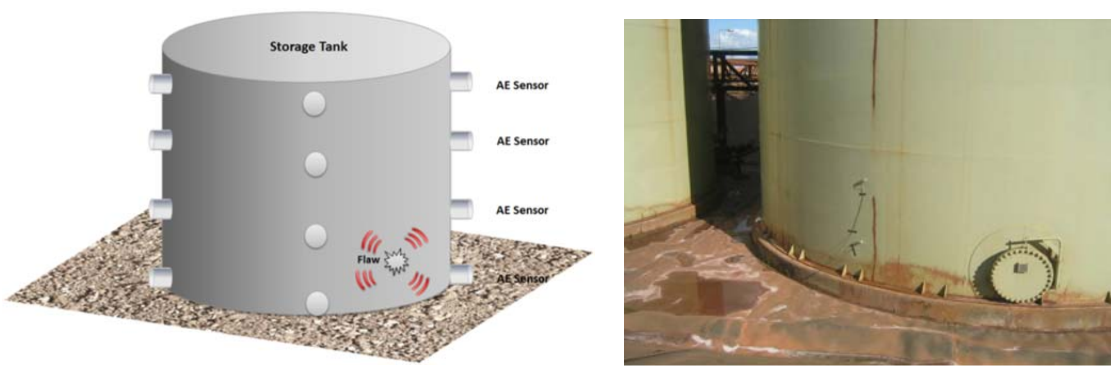


Figure 2 - (left) schematic of a storage tank with a network of transducers bonded on the surface to measure AE. (right) highlight on a real installation of an AE transducer on a tank.

The procedure proposed to estimate the residual life of atmospheric storage tanks (AST) or pressurized vessels (PV) is based on the following three main methodological and technological steps (see Figure 3):

1. AE data acquisition and storage;
2. AE remote signal processing for:
   2a. damage detection;
   2b. damage localization;
   2c. damage growth estimation;
3. Residual life prediction.

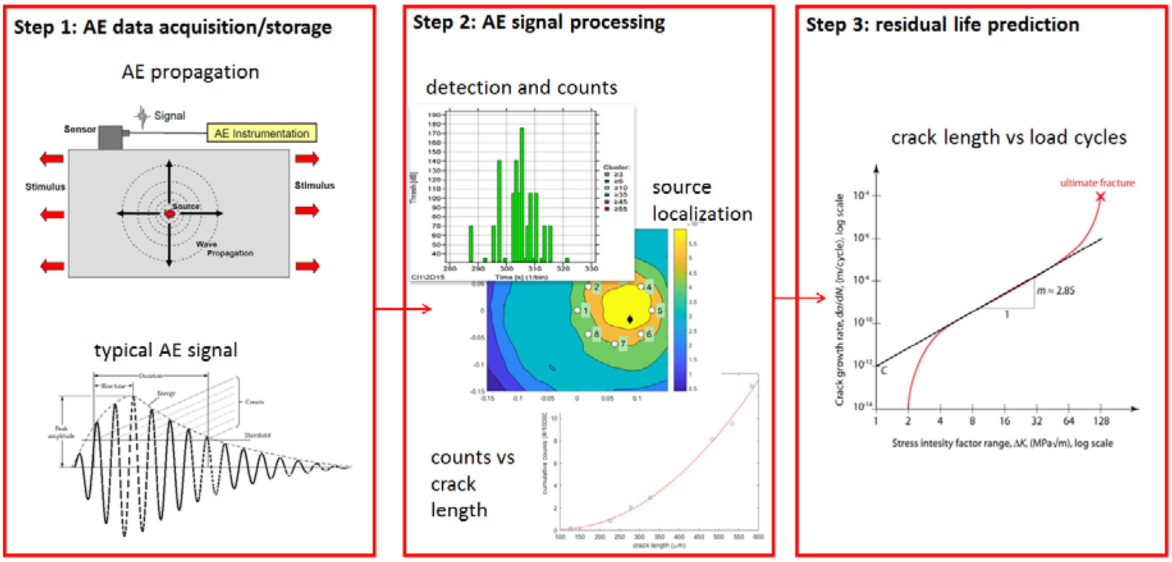


Figure 3 - Schematic of the proposed residual life estimation procedure.

Having a relation between the AE counts and the crack length, and knowing the actual crack length a, the remaining life of the component under cyclic loading can be estimated by exploiting the fundamental laws of linear fracture mechanics. In particular, Paris' Law (also known as the Paris-Erdogan law) relates the variation of the crack semi-length a to the variation of loading cycles N as:

$$\frac{da}{dN} = C\Delta K^m \tag{1}$$

$$\Delta K = K_{max} - K_{min} \tag{2}$$

Where (2) is the delta stress intensity factor (geometry related) experienced during the loading cycle, whereas C, m are two constants related to the material of the structure. Being a power law relationship between the crack growth rate during cyclic loading and the range of the stress intensity factor, the Paris law can be visualized as a linear graph on a log-log plot where the x-axis is denoted by the range of the stress intensity factor and the y-axis is denoted by the crack growth rate da/dN.

For the case of interest, in which the variation of stresses within the structure try to open existing cracks, the stress intensity factor K_I (i.e. the one related to Mode I that consider a spreading apart of the two halves of the crack interface) must be considered:

$$K_I = \sigma Y(a)\sqrt{\pi a} \tag{3}$$

where σ is the applied stress perpendicular to the crack plane, Y is a dimensionless parameter that depends on the fracture mode and structure geometry (can be found in handbooks) and a is the crack length. For a variation of the stress level during cyclic load $\Delta\sigma$, the stress intensity factor changes accordingly to:

$$\Delta K_I = \Delta\sigma Y(a)\sqrt{\pi a} \tag{4}$$

if the crack has not propagated, that is the maximum value of stress is below the one needed to propagate the crack. As such, it is possible to establish a relation between the level of stress σ_{max} needed to propagate the existing crack and a critical value of the stress intensity factor K_{IC}, also known as material fracture toughness (a characteristic of the material), as:

$$K_{IC} = \sigma_{max} Y\left(a_f\right)\sqrt{\pi a_f} \tag{5}$$

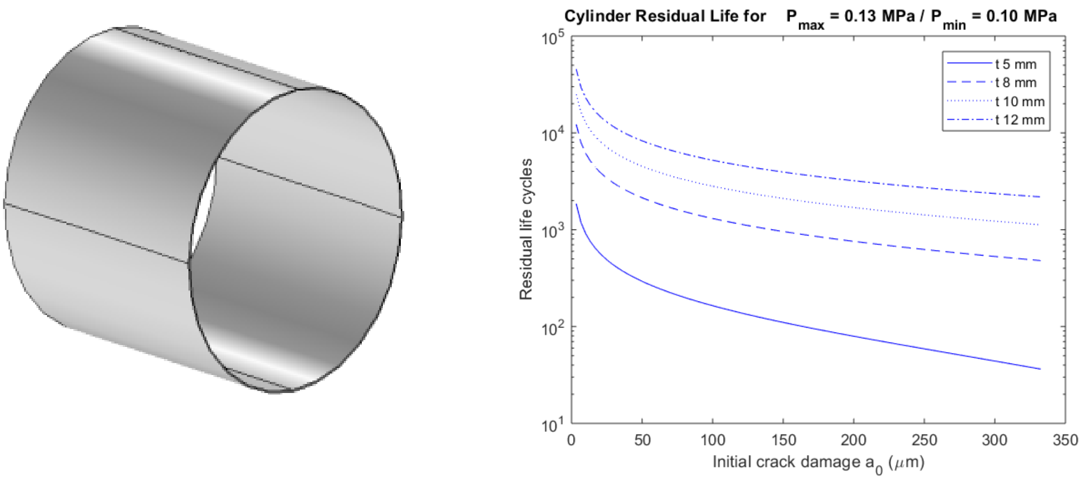
where a_f is the so-called critical crack length. This relation simply states that cracks smaller than a_f will not propagate under σ_{max}, while larger cracks will. It follows that for a crack of initial length a_0, the number of remaining N_f cycles before reaching the critical length a_f can thus be estimated integrating the Paris' Law as:

$$N_f = \frac{1}{C\Delta\sigma^m\pi^{m/2}}\int_{a_0}^{a_f}\frac{da}{a^{m/2}Y(a)^m} \tag{6}$$

As an example, we consider a cylinder (Figure 4), with the following characteristics, as test case:

- Material: Al 7075-T6 K_{IC} = 20 MPa$\sqrt{m}$
- Radius: R = 15 m
- Wall thicknesses: T_{wall} = 5/8/10/12 mm
- P_{max} = 0.13 MPa
- P_{min} = 0.10 MPa

Assuming from an experimental campaign or simulations a cumulative hit counts between 0.1x10^4 and 30x10^4, the remaining cycles can be predicted for the different thicknesses t_{wall} of the cylinder wall according to the previous formulae. Results are plotted on a graph, as in Figure 4.



$a_0 = a_0$(Cumulative Hit counts)

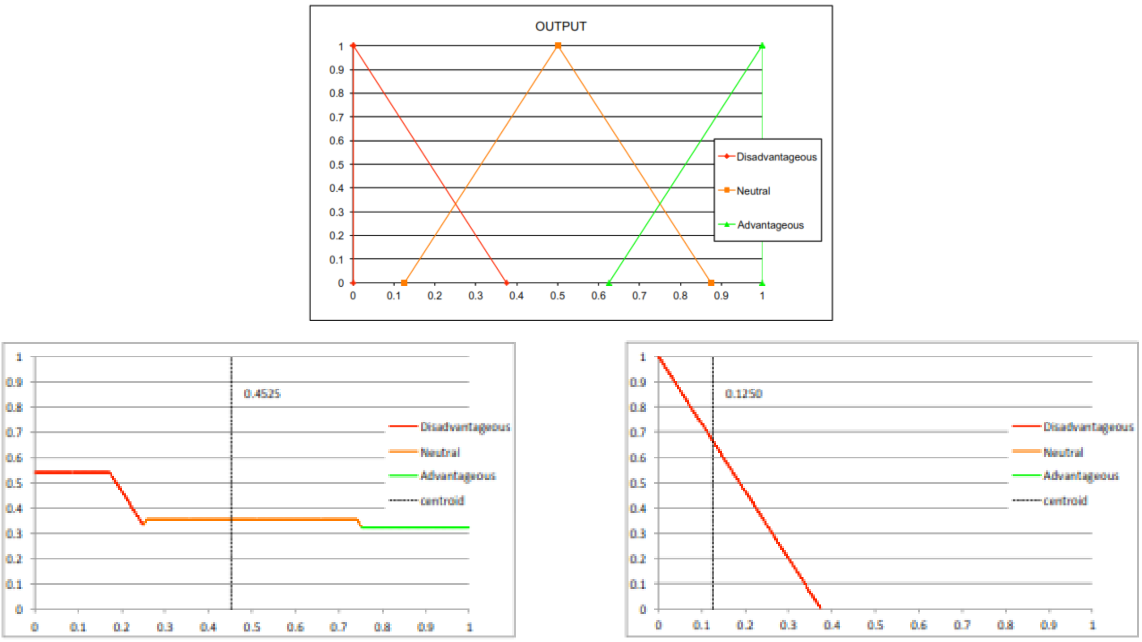
(a) (b)

Figure 4 Cylinder (a) geometry and (b) estimated residual life

3. Industrial case study 2 – Maintenance decision making for ageing energy plants

The decision making in terms of maintenance and inspection in case of ageing equipment is here addressed with reference with the blades' substitution of ageing power turbines.
The adopted approach is a multi-parameter risk-based decision making (Darabnia et al. 2013), whose effectiveness must be compared with the present maintenance philosophy, that will optimize the decision making for ageing equipment. The results of the modelling have been validated through the company experience and data collection.
A fuzzy set based decision support system has been set-up has been proposed to the Loss Prevention Conference in 2019.
The application chosen refers to a process plant Low Pressure Turbine (LP) maintenance: during the LP maintenance the turbine is opened and the blades are tested and replaced where needed. The plant management uses a standard maintenance strategy: the LP turbine is opened, the blades are tested and in case the blades failed they are replaced; to minimize maintenance stop a small number (7) of new blades is stocked. Two other maintenance strategies have been proposed: • Strategy 1: LP module cover lift and replace all the blades with a decrease of the maintenance time since the test of the blades is made after the turbine has been refurbished and restarted; • Strategy 2: LP inner block replacement (rotor and carriers), with a power increase. The management provide the three maintenance strategies data, and the monetary risk is evaluated in Baldissone et al. (2018).
The proposed methods analyses variable as: the cost, the time between the next maintenance, the equipment performance after the maintenance, the maintenance activity duration and the economic risk. The

methodology returns a global judgment on the advantage and the disadvantage of the different strategies. Other variables are going to be included in the model, considering explicitly the operator’s safety and/or the environmental risk
The hypothesized maintenance strategies are compared with the standard one. The results showed that the opportunity to adopt the maintenance strategy 1 is neutral (Figure 5a), instead for the strategy 2 the analysis showed clear disadvantages (Figure 5b) with respect to the standard maintenance strategy.



(a) (b)

Figure 5: Output membership function & graphical representation of the result: (a) strategy 1, (b) strategy 2

Other variables are going to be included in the model, considering explicitly the operator’s safety and/or the environmental risk

4. Case study 3 – Game based training for the management of ageing equipment

A game based training for the management of risks in major risk installation has been initially set in a master thesis at Politecnico di Torino (Sabzevari, 2017). The application was at the time related the whole safety management system for major risk installation. Figure 6 shows a for the strategical and tactical layers of the game, with the information flows patterns. The ongoing work is to develop a more specific case, adapting the game-based training to the INAIL guidelines “Metodo per la valutazione sintetica dell’adeguatezza del programma di gestione dell’invecchiamento negli stabilimenti Seveso” (INAIL, 2018) with the final aim of increasing the sensitivity of plant operators to the ageing problem and the tools and procedures available in the plant to approach them.

5. Conclusion

Within this paper the objectives and early results of the project PROAGE has been discussed. The project, funded by INAIL under the Saf€ra framework has the aim to develop methodologies and tools helping plant managers to to better control the equipment ageing, proceeding through case studies of industrial interest.
The objective of quantifying the impact of operating modes on system reliability and to estimate their residual life relies on the measurement and processing of acoustic emissions (AE) applied to atmospheric tanks case study. The objective of identifying the optimal maintenance strategy, while respecting safety, regulation and operational performance, is pursued through the development of decision-making support methodologies, applied to low pressure turbine maintenance
The objective of increasing the sensitivity of the operators to the ageing problem is pursued through the development of a game-based training system applied to major risk installations.

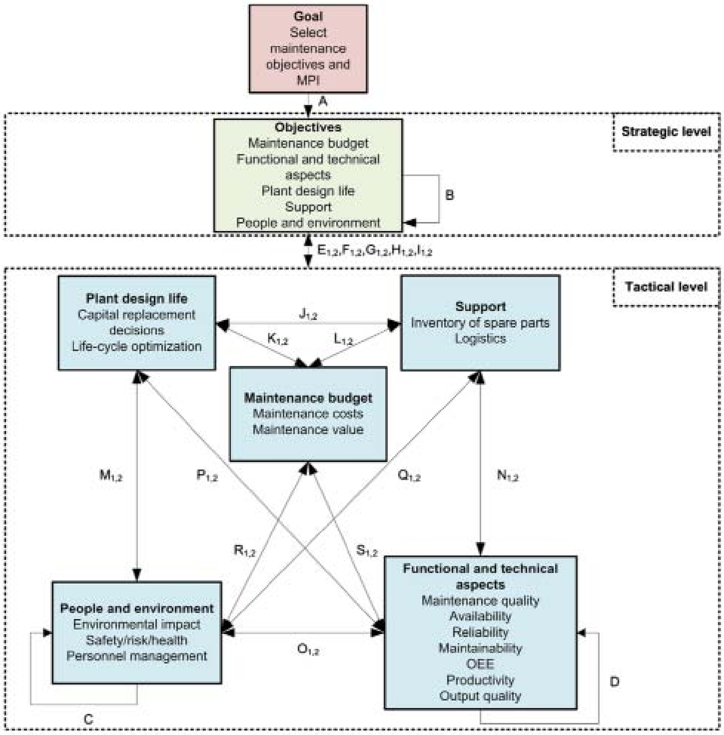


Figure 6: Layers of the game-based training

The generalisation of the developed approaches and tools will be the final step of the project. In the end, this will bring to the development of a theoretical and operational approach to the problem of the ageing equipment, complemented with the methodological and technical tools, resulting in a quantifiable improvement of the safety management in industry.

Acknowledgments

This publication has emanated from research supported by INAIL – project PROAGE 3rd Call SAF€RA

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