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Ageing in Process Industry: Identification of Material Degradation from Past Accidents Analysis

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Abstract: A historical analysis was conducted, analyzing 546 accident events that occurred in the process industry due to ageing of the infrastructure. The analysis is conducted with the help of ARIA (Analysis, Research and Information on Accidents) databases. The keywords “ageing”, “corrosion”, “erosion”, “vibration”, “wear” and “fatigue” were searched. The study revealed that loss of containment occurred most frequently (73%), with corrosion as the primary cause in 47% of cases, followed by vibrations (18%). Utilizing these data points is pivotal in designing preventive strategies and in reducing future accident risks.

Keywords: Material degradation, Equipment ageing, Damage mechanism, Vulnerability, Loss of containment, Accident analysis, Process industry, Safety of process, Fault identification.

1. INTRODUCTION

In the process industry, ageing infrastructure can significantly contribute to losses of containment (LOC) and operational problems. Industrial infrastructures, such as chemical plants, petrochemical plants, power plants, and storage plants require constant attention to ensure their correct functioning and safe operations (Beltramino et al., 2022). Wintle et al. (2006) conducted a historical analysis using three major accident databases to determine the link between ageing and the escalation of the event. The study showed that 60% of the report involved loss of containment were due to technical integrity issues, of which 50% involved ageing. Ageing is not only a question of the age of the equipment, but also related to its condition and how it changes as time progresses. Ageing represents the effect of damage and degradation on the component, generally with an increasing probability of failure over its lifetime, although it is not necessarily related to service time, as defined by Horrocks et al. (2010). It is important to distinguish this type of infrastructure degradation from obsolescence, defined as the change of equipment standards and regulation over time (Milazzo and Bragatto, 2019). Ageing is a significant problem in Europe due to the age of process plants; actually 50% of facilities work beyond the scheduled time (Vairo et al., 2018). Traditional management systems have not been sufficient for monitoring ageing due to a lack of i) adequate regulations, ii) knowledge of deterioration mechanisms, and iii) control methodologies (Hansler et al., 2022). For this reason, the Seveso III Directive (2012/18/EU) includes the inspection of ageing of the infrastructures and their adequacy. The Annex 3 shows the elements to be considered for risk control, including ageing and corrosion, Annex B requires monitoring of the material degradation, finally Annex H proposes a checklist for the inspection in which it is involved. However, the Seveso III Directive does not illustrate evaluation procedures, which is why several studies have proposed qualitative and quantitative methodologies to investigate ageing accurately (Bragatto and Milazzo, 2016; Bragatto et al., 2017; Milazzo and Bragatto, 2019; Vairo et al., 2018; Mocellin and Pilenghi, 2023). In the work conducted by Horrocks et al. (2010), attention was paid to the degradation mechanisms of materials and their manifestation in various types of substances. For the management and evaluation of the ageing of an infrastructure, it is essential to know three elements (Bragatto et al., 2017):

- Information relating to past incidents and maintenance periods, which are important elements of effective infrastructure management.
- Data obtained from non-destructive tests, a crucial element for evaluating the conditions of the materials.
- Knowledge of the fundamental physical and chemical mechanisms underlying equipment deterioration. This element can derive from scientific research, engineering principles, the laws of physics, chemistry, and materials science.

To further understand the mechanisms of deterioration, various studies have conducted historical analyses, examining past incidents in which ageing was a significant factor in the escalation of the event. Bragatto et al. (2022) studied 70 accidents, occurred between 2005 and 2016 in upper-tier Seveso plants, to identify the main causes of degradation, demonstrating that more than 50% of LOCs are due to corrosion of the material. Hansler et al. (2022) classified 83 material degradation accidents that occurred between 2004 and 2016, identifying the age of the installations, the substances involved and the types of material degradation that caused the loss. The cited works are based on a limited number of accidents; for this reason, the present study aims to analyze all accidents caused by the ageing infrastructure and the degradation of materials in the process industry using ARIA (Analysis, Research and Information on Accidents), one of the

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main European databases for the high number of records and the accuracy of the data. Therefore, a historical analysis of the different categories of affected process plants and potential failure scenarios was conducted. Through learning from past mistakes, accidental situations were examined to avoid repeating them in the future. This information represents the initial phase of the analysis, in which the results were examined using a graphical analysis. Through this process, it is possible to identify correlations between the deterioration of the materials used in the process plants and the industrial sector to which they belong, to identify the critical equipment within the plants, as well as to identify the most frequent failure scenarios and the chemical substances most involved. This information is essential to develop targeted risk management strategies and more effective inspection programs, helping to prevent or mitigate process plant failures and to ensure the safety and reliability of industrial operations.

2. MATERIAL AND METHODS

To conduct the analysis, all the reports in which material degradation and ageing play a determining factor in the escalation of the accident event were collected from the open-source accident databases consulted. Each report indicates the date and place of the accident with the explanation of the event; therefore, it was possible to build a repository to summarize all the information. The methodology was integrated with previous research to follow the principle of convergence (Castro Rodríguez et al., 2023; Castro Rodríguez et al., 2024).

2.1 Database consulted

The database consulted is ARIA (Analysis, Research, and Information on Accidents), overseen by the BARPI (Bureau for Analysis of Industrial Risks and Pollutions), which has the concern of collecting, studying and propagating information and experiences in the field of industrial and technological accidents (BARPI, 2022). The database consulted, collected more than 54,000 records at the end of 2022 and, annually, up to 1,500 new events are added, including accidents, incidents and near misses occurring in industrial, domestic and storage installations. The research was conducted with the keywords “ageing”, “corrosion”, “erosion”, “vibration”, “wear”, “embrittlement”, “degradation”, and “fatigue” to remain in line with previous research (Gyenes and Wood, 2016; Bragatto et al., 2022), choosing all the events occurred in the process industry. In this way, a dedicated repository was created, collecting 546 reports.

2.2 Repository structure

The categories classification, outlined by Castro Rodriguez et al. (2024), was structured as follows:

- Macro-sector: corresponds with the type of plant where the event occurs. In accordance with past research, process plants have been classified as: Chemical and Petrochemical, Manufacturing, Pipeline, Power Production, Storage and Warehouse, Transportation and Water Treatment (Ricci et al., 2021).
- Outcome: corresponds to the type of industrial event that occurred. The choice is between Accident, Incident, Loss of Containment and Near Miss. The definitions are reported by Ricci et al. (2021). The near miss event defined by Gnoni et al. (2013) was then implemented.
- Final scenario: corresponds to the effects of the event. They are Toxic gas dispersion (TGD), Environmental contamination (EC), Release with no further consequences (R-NFC), Fire (F), Explosion (E) or Multiple scenarios (MS) (Ricci et al., 2021).
- Direct causes: corresponds to the most frequent deterioration mechanisms defined by Hansler et al. (2022) in the process industry such as:
  - i) Corrosion, a phenomenon that occurs on the surface of the material, which is subject to chemical reactions due to the surrounding environment.
  - ii) Fatigue is the increase in the growth rate of cracks present in the material. This phenomenon is also due to variations in temperature and/or pressure and involves embrittlement.
  - iii) Erosion is a phenomenon due to the removal of part of the material presented on the surface due to external factors (Horrocks et al., 2010).
  - iv) Vibrations refer to the periodic oscillatory motion of an object. They can be harmful to structures with different effects.
  - v) Material degradation was used when the report does not specify the phenomenon occurred, which makes it difficult to classify the event in the previously mentioned categories.
- Equipment involved: corresponds to the categories defined by Horrocks et al. (2010). They are: Primary containment system (PCS), Control & mitigation system, Electrical control & instrumentation (EC&I) system and finally Structures.
- Substances involved: The classification reported by the UNECE (2021) was followed, which divides the substances as Physical Hazard, Health Hazard and Environmental Hazard. Two classes have been added, such as "NA" for non-dangerous substances and "ND" where it was not possible to trace the danger. The study of the substances is fundamental as they can accelerate the degradation process of materials (Baldissone et al., 2020; Baldissone et al., 2022).
- Action taken: corresponds to the measures adopted following the event. This classification considers:
  - i) Inspections: when after the incident the frequency of inspections is improved.
  - ii) Inspections already taken: when the inspection plan has already been scheduled and is followed correctly with high frequency, but the event occurs anyway.
  - iii) Treatments: indicates plants in which it is necessary to implement treatments for materials.

2.3 Data quality

The selected reports are based on the main sectors and scenarios mentioned. The causes of events are always attributable to the deterioration of materials and ageing. BURPI constantly updates the criteria for selecting events to catalog, considering new emerging technologies. Every single event is subjected to a detailed analysis by the DREAL Agency (Environment and Planning), the Risk Prevention Regulatory Offices and professional organizations, before being included in the database (BURPI, 2022). Some reports have gaps or inaccuracies, therefore, to maintain consistency with previous research, the "Unknown" category was introduced to conduct a more precise analysis. As a result, the effectiveness of learning from incidents depends on the data available.

2.4 Data analysis

The data analysis will take place through an in-depth graphic analysis, which represents a study and interpretation methodology based on the examination of graphs, diagrams, and other visual representations of the data. The primary objective of this analysis is to extract relevant information from data presented in the graphical form. This process may include identifying trends, discovering correlations between variables, evaluating behavioral patterns, and effectively communicating findings to other stakeholders.

3. RESULTS AND DISCUSSION

The findings of the historical analysis will be outlined and discussed in the following section. For each accidental event, the repository outlines the date, the location, the industrial macro-sector, the outcome, the final scenario, the cause, the equipment, the actions taken, and the substances involved. 546 reports were collected from 1966 to 2023, with an increasing trend over time. Figure 1 represents the frequency of accidents due to material degradation in the process industry. Over time, the number of accidents increases, but this growth is not constant.

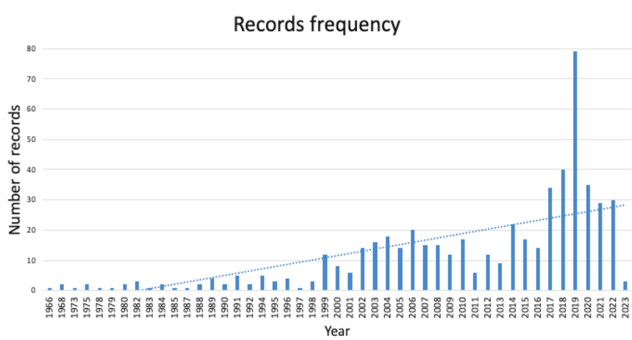

Figure 1: Frequency of 546 events collected over the years involving material degradation.

From Figure 1 it emerges that, until 1998, the number of accidental events caused by ageing infrastructures appears to remain roughly constant, with a number of reports per year varying between 0 and 10. This suggests that events related to ageing could have been less evident during this period. After 1998, a bimodal distribution is noted, with significant peaks in 2006 and 2019. This trend could be explained by several factors, including ageing infrastructure and an increase in efforts in reporting accidental events. The advanced age of infrastructure is a key factor. Many European plants were built after World War II and have been in operation for over 50 years, which can lead to structural and functional problems due to the natural ageing process of infrastructure. It is important to consider that the fourth industrial revolution began in the early 2000s with the introduction of internet to the industry, a factor that may have contributed to an increase in accident reports in online databases. Non-linearity in distribution could also be influenced by regulatory changes, such as the introduction of the Seveso III Directive (2012/18/EU) which highlighted the importance of deterioration of materials. This situation may have led to an improvement in the reporting of incidents related to this phenomenon. Indeed, a second growth has been observed starting from 2012, with an increase until 2019. However, at the end of 2019, with the advent of the Covid-19 pandemic and the consequent interruption of many activities, a relapse occurred. Another possible reason for the decrease could be the introduction, in 2019, of the quantitative assessment of material deterioration (Milazzo and Bragatto, 2019). This system considers the factors that accelerate and delay degradation, allowing rigorous inspections to be carried out depending on the degree of criticality of the equipment involved. The most affected macro-sectors are the chemical and petrochemical plants with an impact percentage of 56%, followed by the manufacturing and bioprocess industries, with 14% and 11% respectively. The results are shown in Figure 2.

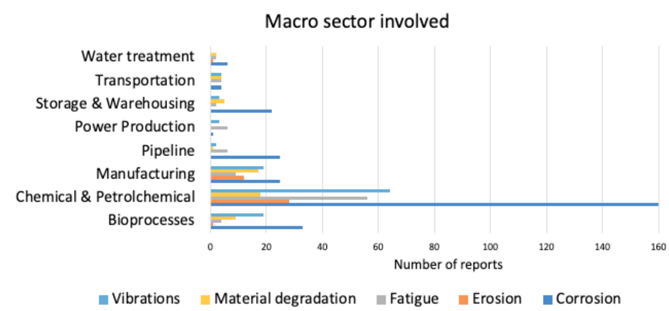

Figure 2: Industrial macro-sectors involved in collected reports: number of events for each cause.

From the data, it emerges that corrosion is the most widespread cause of deterioration in all industrial sectors, except for energy production, where fatigue prevails (60% of events), probably due to the characteristics of the process, in which high temperatures are reached with significant variations that can stress the materials. The deterioration due to material fatigue is mechanical in nature and linked to the operating conditions and their variations. Even in pipelines, fatigue represents a recurring phenomenon, probably in relation to the environmental conditions to which they are exposed. A further aspect worthy of note is that, as the second most common cause, vibrations are found in the chemical, petrochemical, bioprocess, and manufacturing sectors, probably due to the equipment involved. Finally, in the transport sector, it is observed that the different deterioration mechanisms occur with equal frequency, except for erosion, which does not seem to have an impact on this macro-sector. The 84% of the events analyzed involve primary containment structures, with further strengthens the coherence of the results presented, as these structures often contain aggressive chemicals. Primary containment structures are the components most susceptible to problems related to material degradation in the process industry. Figure 3 illustrates the outcomes of the events. The 73% of the analyzed reports present LOC; this is the most frequent result in the presence of ageing infrastructures and degradation of materials. Containment leaks can lead to safety risks, especially if they involve hazardous or environmentally harmful substances.

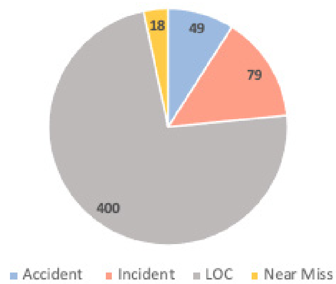

Figure 3: Distribution of outcomes in the 546 records collected.

These incidents could result in pollution, contamination or even harm to people. The finding that containment leaks are so common in the analyzed reports indicates a need for attention and intervention. Table 1 summarizes the final scenarios of the 546 records collected. Figure 4 illustrates the causes of failure and the outcomes of accidents. Interestingly, release with no further consequences is the most common outcome, except in cases of corrosion and material degradation (generic category). This underlines the link between the substances involved and the corrosion process. On the contrary, in the case of fatigue and erosion, release with no further consequences is the clearly predominant outcome, suggesting a more effective management of these phenomena and underlining their mechanical nature. It is also noteworthy that, for vibrations, the harmless release is immediately followed by the dispersion of toxic gases, which may be probably explained considering that, especially in presence of gases, this degradation mechanism easily release substances.

Table 1: Final scenario of the analyzed reports.

Final Scenario	**N. Events**	**%**
R-NFC	129	23.6
EC	120	22.0
TGD	88	16.1
Unknow	61	11.2
F	57	10.4
E	38	7.0
Multiple scenarios	28	5.1
Nothing happened	25	4.6

The data presented in Figure 5 provide important insights into the main causes of accidents. Here are some considerations: corrosion of materials (47%) is a significant cause of accidents, accounting for almost half of all accident events. These data highlight the need to improve current inspection, monitoring and risk management systems relating to corrosion in materials used in industrial infrastructures. Such improvement may require more accurate risk assessments, the implementation of corrosion-resistant materials, and the adoption of adequate preventive measures and maintenance programs. Vibration is responsible for 18% of accidents, indicating a negative impact on the performance of infrastructure or equipment. It is crucial to evaluate and address sources of vibration, carefully analyzing infrastructure and taking measures such as vibration isolation or suspension upgrades to mitigate their effects. Although the number of accidents is not particularly high, it is evident that vibrations

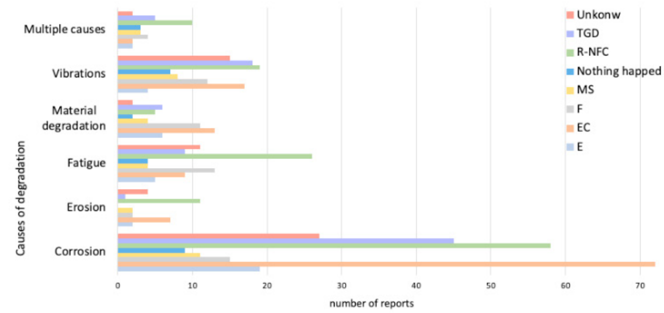

Figure 4: Correlation between the deterioration mechanisms (y-axis) and the frequency of final scenarios (x-axis), expressed by the number of events.

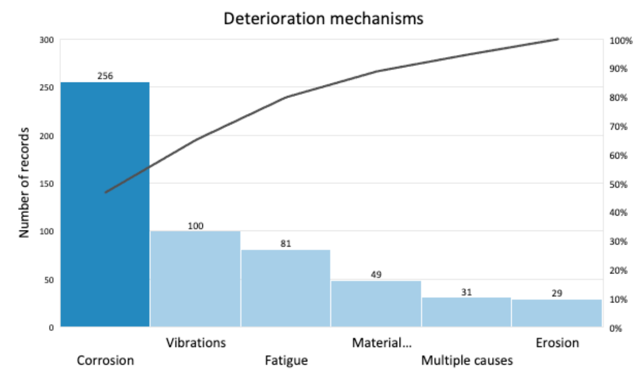

Figure 5: Classification of the deterioration categories considered in the analysis with their incidence.

are not optimally managed, suggesting the need to conduct a more accurate assessment of the risk associated with vibrations to identify the most suitable safety systems. Fatigue, which represents 15% of the causes of accidents, can be linked to the progressive wear of materials and components over time. The risk assessment must consider the intrinsic nature of the materials used and their susceptibility to the operational conditions to which they are exposed. Therefore, continuous monitoring over time is essential to ensure that the preventive measures adopted are always adequate and effective.

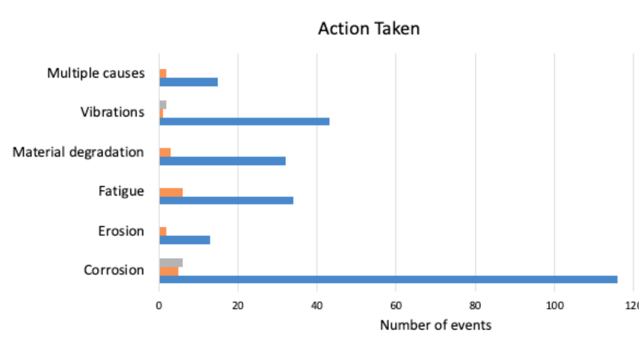

Figure 6: Correlation between the deterioration mechanisms (y-axis) and the frequency of actions taken (x-axis), expressed by the number of events.

Another aspect taken into consideration is the actions taken after the event (Figure 6). It is evident that, for all deterioration mechanisms, the "inspection" category is the most frequent one, highlighting the lack of inspections carried out. However, it is interesting to note that the category "already scheduled inspections" is always present, indicating that even if inspections have been planned, they are not sufficient. This issue arises from the lack of knowledge regarding the optimal frequency of inspections, which should be determined considering all factors that can influence deterioration. The category "treatment" was also introduced to indicate the treatment interventions of the material to increase its resistance to deterioration. It can be noted that this category is mainly present in cases of corrosion and in those involving vibrations, underlining the need to adopt specific treatments for these two mechanisms, which must be planned during the risk analysis.

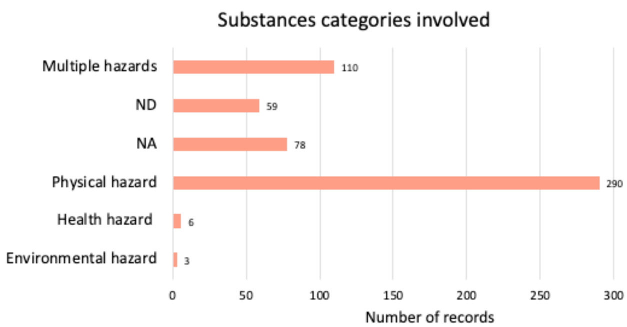

Figure 7: Substances categories involved in the 546 events. On the *x*-axis, instead, it is represented the number of events in which each substance is involved.

To complete the analysis, the substances involved in the events were also examined (Figure 7). In 53% of the reports, substances classified as "physical hazard" were identified, while "multiple hazards" substances (more than one type of hazard) follow with a significant percentage (20%). Among the substances classified as "multiple hazards", 41% were identified as physical hazard and environmental hazard, while 28% were classified as health hazard, environmental hazard, and physical hazard. A relevant aspect is that in all events involving dangerous substances, the risk of physical hazard is always present. This can be attributed to the fact that substances classified as "physical hazard" can often be flammable or corrosive, and therefore can cause deterioration of the materials in which they are contained. The presence of these substances in the reports underlines that physical danger is a common element in situations of deterioration of systems and materials. These findings highlight the importance of appropriately managing hazardous substances and implementing appropriate safety measures to prevent accidents and deterioration. It is interesting to note that 15% of the substances involved in accidents are not dangerous. This underlines that the evaluation of the substances involved alone is not sufficient to evaluate the degradation of the material, but it is necessary to consider different aspects and their mutual interactions. For example, several corrosion incidents involving substances classified as "NA" have been recorded. This implies that other factors, such as particularly aggressive environmental conditions, can contribute to the deterioration of the material, causing corrosion. Likewise, the same can happen for other mechanisms, such as erosion or wear, which can be caused by the action of external factors. Therefore, during risk assessment and management, it is essential to take into account both internal factors, such as process conditions and possible variations, the characteristics of the substances involved and their aggressiveness, together with the materials used for the infrastructure and their interaction with the surrounding environment, and external factors, such as the environmental context. This detailed risk analysis allows to obtain failure frequencies, which can be integrated into the risk analysis to obtain a more complete assessment of critical structures and the most common scenarios.

4. CONCLUSION

A historical analysis was conducted on 546 reports regarding outcomes in the process industry where the ageing of structures plays a role in the triggering of the event. To facilitate this investigation, the ARIA database was used. The data collected cover the period from 1966 to 2023, with an increasing trend in the number of events recorded over time. The data obtained were meticulously organized and categorized based on various criteria, including macro-sector, outcomes, final scenarios, direct causes, equipment involved, and substances present. The study aimed at providing a comprehensive graphical analysis of events related to material deterioration and ageing within the process industry.

This analysis highlights how different factors influence the degradation of materials. These factors can be both internal to the plant, such as the substances involved and process conditions, and external, which can cause deterioration of the materials. It is important to consider both during risk analysis, to implement effective safety management and plan an appropriate inspection program based on the level of risk present. The analysis shows that the critical structures are mainly primary containment systems, especially in the chemical and manufacturing industries. In these cases, the risk is higher, therefore more frequent inspections are necessary. Given the frequency of corrosion as the predominant degradation mechanism, it would be ideal to use treatments and protections for materials, especially in the presence of corrosive substances or aggressive environments. However, it is also important to evaluate machinery vibrations, especially if there are gases involved, to prevent these vibrations from causing structural integrity problems or dispersion of dangerous substances. Prompt action should be taken as the analysis shows that current inspection plans are not adequate to ensure the safety of the infrastructure and surrounding environments. Incorporating these evaluations into safety management and inspection strategy can enhance workplace safety and mitigate the likelihood of accidents. Furthermore, to obtain a more complete global research approach, the consultation of other databases is envisaged to expand the data collection. The study completed an initial data collection phase, including the creation of a dedicated repository, and began a second phase with an overall analysis, which illustrates the incident frequencies present in the repository. The next step of the study, the modeling phase, involves further analysis of the degradation path of the materials through the creation of an event tree. Subsequently, to examine all the correlations and predict the dataset, especially identifying and managing missing data, the Bayesian Networks methodology will be adopted. This will allow to predict the frequencies of each event to quantify the probability of their occurrence. These data can be used in the risk analysis to define both the inspection plan and the related preventive measures. Furthermore, they should be leveraged to drive an ongoing process of improving safety and incident management. This information can be used to develop targeted prevention strategies, helping to reduce the risk of future accidents.

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