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Lessons Learned from Major Accidents Relating to Ageing of Chemical Plants

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Major industrial accidents that occurred in the past and even recently, such as the Flixborough, UK in 1974, the ConocoPhillips, UK in 2001 and the Chevron, US in 2012 show that ageing is still a disturbing phenomenon present in chemical process industries. Further to these cases, it is estimated that 30 % of the major accidents reported in the eMARS accident database run by the Major Accident Hazards Bureau of the European Commission are connected to at least one ageing phenomenon. It is sometimes mistakenly believed that ageing is about how old the establishment or the equipment is. Some countries solely consider corrosion as a sign of ageing. However, ageing of chemical plants has a wider meaning which indicates the degradation of the equipment in use, its overall condition and the change in its condition over time, as it is defined in the study published by the UK Health and Safety Executive. People or written procedures could also be key features of ageing plants. Overall, ageing is related to keywords such as material degradation, fatigue, obsolescence. All these physical states, mechanisms and organisational elements can lead to major accidents. Having engaged in a number of studies relevant to ageing, the Major Accident Hazards Bureau of the European Commission's Joint Research Centre (JRC) performed an analysis of keywords on accident reports in the eMARS database as well as reports on chemical accidents in the French ARIA database. The objective was to determine whether accidents associated with obsolescence and loss of competence due to ageing could be easily identified in the databases. This paper discusses the results of this analysis and makes recommendations on how future accident reports could put more focus on the ageing-related impacts of obsolescence and loss of knowledge and competence.

Introduction

Ageing structures, systems and components of chemical establishments are becoming a major process safety concern worldwide. Everything is connected to a site and its various processes can age, including not only equipment, but also people and procedures. It could be the degradation of the equipment, its overall condition and the change in its condition over time (HSE RR509, 2006). Hence, a good foundation for effective ageing management is when ageing is properly taken into account at each stage of a plant's lifetime, i.e. in design, construction, commissioning, operation and decommissioning (IAEA Tech. Rep. 338).
Ageing studies, such as the International Atomic Energy Agency's safety guide (IAEA No. NS-G-2.12) on Ageing Management for Nuclear Power Plants divides all ageing phenomena into two categories, physical ageing and obsolescence of structures, systems and components. Beyond the nuclear industry, the onshore and offshore industries also recognised the hazards of ageing assets to the chemical processes. For example, the UK Health and Safety Executive (HSE) published various studies and information sheets on the subject, both including onshore and offshore industries (HSE IS9/2004). In its summary guide on managing ageing plant (HSE RR509, 2006) the HSE identified physical assets that are considered relevant to ageing and therefore can contribute to the occurrence of loss of containment events in chemical sites. Within the analysis, four categories of such elements were formed to associate them with the affecting ageing mechanisms. In addition, the HSE conducted an analysis of the accidents reported in the eMARS and RIDDOR databases revealed that ageing had a significant contribution to the loss of containment (HSE RR823, 2010). The French National Institute for Industrial Environment and Risks (INERIS) studied and compared ageing control

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practices and regulations existing in the Netherlands, the United Kingdom, Germany and the USA to reduce the likelihood of major accidents occurring (INERIS, 2009) (INERIS, 2010) (INERIS, 2010).

1. Types of ageing

This section describes the categories of ageing (ESReDA 2006) selected for this study. To maintain plant process safety it is very important to detect ageing effects at each stage of a plant's lifetime. Figure 1 below demonstrates the selected categories of ageing management. To some extent, there is a tendency to focus on equipment ageing because the signs of material degradation are so tangible. Carbon steel corrosion is the most well-known phenomenon although still, failure to address corrosion failure is a major cause of chemical accidents. In addition to fatigue and vibration, there are also some other forms of degradation that receive far less intention and are even ignored, in particular degradation of non-metal materials, such as fiberglass and concrete.

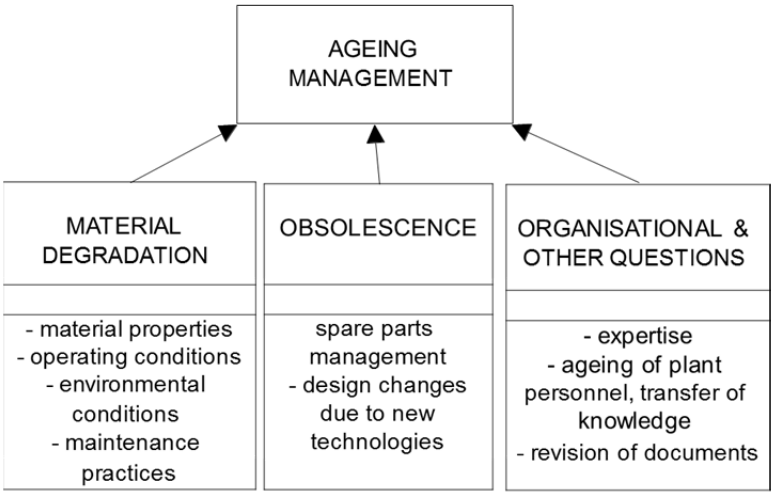

Figure 1: Categories of ageing (Source: ESReDA Report on Ageing of Components and Systems)

Obsolescence is a phenomenon that may adversely affect equipment, processes and procedures. Equipment reaches the end of its life cycle when the equipment is so degraded by the combination of all the deterioration mechanisms, small changes to operating conditions, and build-up of process fluids over the long term that it can no longer be maintained as fit for service. Obsolescence in processes and procedures is rather different, referring to something that is no longer in current use. An obsolete procedure is one that no longer can be considered applicable or appropriate because the situation to which it applied has completely changed. Obsolete technology creates risk that replacement parts may not be found or has inherent safety risks that would no longer be acceptable in accordance with current standards.

The main concern of the ageing organisation is loss of knowledge and expertise. This particular ageing phenomenon is the most challenging to monitor and fix with systematic solutions because it is about trying to compensate for something that is no longer there or not accessible, referring specifically to people and documentation. Indeed, the degradation of performance due to aging of people and procedures can only sometimes be directly observed. On the one hand, procedures and documentation should be associated with each piece of safety critical equipment. Where there are particular imperfections of documentation, especially for older processes and equipment associated with important risk scenarios, the potential impact of lack of information should be assessed and addressed. On the other hand, there are the "unknown unknowns", such as when there is documentation missing about a change made in years past and no one remembers that it took place. To minimize these kinds of risks, audits and investigations should routinely give attention to ageing dynamics and question to identify where the ageing of various equipment, people and/ processes are emerging as a source of serious risk.

2. Study to identify chemical accidents with lessons learned relevant for ageing sites

Recently, the JRC studied more than 400 accidents from eight OECD countries on the same topic (publication forthcoming in 2016). Over the course of this work, the researchers noted that the definition of a cause related

to ageing varied considerably. Most often the cause was equated with equipment corrosion, usually corrosion of carbon steel elements, and more broadly, degradation of equipment, e.g., due to vibration or intensive use.
Nonetheless, in many cases, the actual analysis of these accidents identified other ageing issues, in particular, loss of institutional memory, documentation and expertise. These particular knowledge transfer failures led to important lessons learned for inspection practices, management of change and safety culture.
In addition another underlying cause revealed by the analyses was that the site may have had a habit of working beyond the limitations of the physical system, a phenomenon linked with obsolescence, which in turn has implications regarding site safety culture, Earmarks of such accidents include processes that operate for long periods using degraded equipment or extended periods in which equipment is operated outside original design parameters. The accident at BP Texas City (USA) (2005) is emblematic of a situation in which exceedance of equipment limitations became the norm. (The Baker Report, 2007)).
The work on ageing led the JRC to consider the problem of identifying accidents that have lessons learned with ageing implications, and more importantly, understanding how each of these issues might be addressed by the safety management system. As a result, the JRC performed an additional ageing analysis in which it created a set of key words that could presumably capture all the types of ageing, using the ESReDA report terminology as a main reference with some additions based on experience. These key words were as follows:

Table 1: List of Ageing Keywords Identified by the Study. French versions, when different, are included in brackets

Material Degradation	Obsolescence	Loss of Knowledge/Competence
Corrosion	Obsolescence	(Absence of) Documentation
Erosion	Obsolete	(Loss of) Knowledge
Vibration	Fit (for service) (Apte)	(Loss of) Competence
Degradation	(Forgotten/Old) Design	Wrong (Usage/Equipment/Procedure)
Maintenance	Old, older	Incorrect
Wear (No equivalent)	Age, ageing	(No record of) Change
		(Exceedance of) Parameter

MAHB then searched two chemical accident databases, ARIA and eMARS, using these keywords as well as combinations of these keywords. The ARIA (Analysis, Research and Information on Accidents) database contains 23,376 accidents originating from sites identified as hazardous to human health or the environment in France ("installations classées"). (A substantial portion are translated in English, but also the study tested the French equivalents of words that were different from the English and obtained similar results.) The Major Accident Reporting System (eMARS) was first established by the EU's Seveso Directive 82/501/EEC in 1982 and contains nearly 900 accidents occurring predominantly in the European Union but also accidents reported by OECD countries and China.

3. Findings

Results of the searches on single keywords is provided in Table 2. Combinations of material degradation keywords with other types of keywords were also tried but without exception these combinations did not substantially improve the search results. The results are reported as follows:

Material degradation
It was already known from past ageing studies that the keywords associated with mechanical degradation can be used easily to filter an accident database for ageing accidents. The most populous choice, "maintenance", turned up 871 accidents which is no surprise to any expert in chemical accident analysis. However, only 4 accidents resulted when combining "maintenance" with "age/ageing" or "old/older" in eMARS and 4 resulted in ARIA. Some keywords such as "corrosion" and "degradation" are virtually synonymous with ageing. Furthermore, if one considers premature ageing, "vibration", "erosion" and "wear" also give excellent results. However, as with several keywords, it was understood that not all the accidents could be considered accidents due to ageing, but the text often helped to clarify that ageing was one of the key issues.

Obsolescence
Table 2 shows that a number of accident reports could be identified using all of the selected keywords and they were nearly 100% accurate in identifying accidents with ageing causes. Notably, the French equivalents of "old" and "age", that is, "vieille" and "vieillissement" resulted in 43 hits. However, in both databases, these did not pick up other accidents previously identified from analysis as associated with obsolescence.

Moreover, obsolescence can be a contributor in accidents with maintenance-related factors and only 1 accident in eMARS and 3 in French. (The words are the same in French and English.)

Loss of Knowledge/Competence

For the keywords “design”, “incorrect”, “documentation”, and “parameter” many examples of accidents were found where ageing might have been a factor, but the report did not provide adequate detail to make a determination either way. It seemed plausible that there were accidents involving failures of design, incorrect usage, lack of documentation, and exceedance of design parameters, that may have been linked with ageing but report authors lacked awareness to identify this connection.

Table 2: Results of Keyword Searches

Keywords	ARIA	eMARS	Comments
Maintenance	871	50	A substantial portion are relevant but requires another key word to reduce the number of hits
Corrosion	245	79	All hits were relevant
Design	150	128	Possible in many cases, but rarely clear.
Degradation	112	14	All hits were relevant
Vibration	74	5	Most hits were relevant
Erosion	27	12	All hits were relevant
Parameter	25	5	Possible in many cases, but rarely clear
Knowledge	17	35	Possible in many cases, but rarely clear
Incorrect	15	15	Possible in many cases, but rarely clear
Wear	15	14	Most hits were relevant
Documentation	10	39	A few relevant accidents could be identified
Obsolete	9	2	All hits were relevant
Obsolescence	7	0	All hits were relevant
Wrong	6	55	Possible in many cases, but rarely clear
Competence	4	8	2 (ARIA); Not clear (eMARS)
Age	0	8	All hits but 1 were relevant
Ageing, aging	10	8	All hits were relevant
Old, older	7	7	All hits were relevant

In the section to follow, some case study examples of accidents where obsolescence or loss of knowledge/ competence was a factor but a keyword search did not pick them up. It includes cases that were originally identified by a search on material degradation but a review of the accident description also indicates the presence of obsolescence or loss of knowledge/competence due to ageing.

4. Accident cases

Case 1 – Wrong equipment

A technician detected an odour of mercaptan (foul-smelling gas at < 1 ppb, toxic at high concentrations) in the dialkyl zinc dithiophosphate (ZDDP) unit of a chemical plant producing additives for lubricants. He was sampling a product scheduled for transfer in the adjustment tank when the tank's high temperature alarm went off. Analyses confirmed that the product had thermally decomposed. An inerting tests failed to stop the decomposition. Given the saturation of the unit's scrubber, foul-smelling cloud drifts beyond the site. Tens of thousands of individuals felt discomforted, some complaining of vertigo, headaches and vomiting. Emergency services performed some 20 medical visits in and around Rouen. According to a conservative assessment, this decomposition generated 95 kg of H_2S, discharged via the stack of the scrubber system, and another 545 kg of mercaptans not entirely treated (accounting for a maximum discharge into the atmosphere of 272 kg). Given the geographic spread of the malodorous plume, this accident received heavy media attention both in France and abroad. Operating losses were estimated at several hundred thousand Euros due to plant shutdown for the duration of the incident and a production line still idle 3 months later.

Several causes were identified. A few days previously a technician inadvertently started the adjustment tank stirrer and not the recirculation pump on the unit's control panel. Over two days, a product batch at 94 °C gradually heated until Monday morning, when the thermal decomposition was discovered (T > 110 °C). The filling of a storage tank, combined with limited demand, led the operator to store product in an adjustment tank

whose transfer and recirculation mechanisms were only operable in manual mode following the implementation. The tank had been transferred from another unit 16 year earlier equipped with a stirrer and heat insulator was not suited to the current process; Manual start-up of the pump was exceptional, and the stirrer (assumed consigned 7 years prior yet no longer on consignment following poorly supervised maintenance) was turned on by mistake; The state of the stirrer had not been recorded in the control room log and technicians on watch were not instructed to manually start or visually inspect this stirrer. Temperature in the adjustment tank was only being checked upon recirculation pump start-up before manual sampling. Designed for a massive H2S release (conservative toxic scenario), the scrubber quickly saturated when the mercaptan emissions exceeded the trace amount threshold.
The site responded by: removing the heat insulator from the tank; installing mobile cooling equipment; modernising the unit's operating procedures (e.g. alarm management and block diagrams for the continuous monitoring of temperature and H2S/mercaptan rates at the stack, reliable and redundant temperature measurements); revising the scrubber design for a massive mercaptan release; improving monitoring and intervention procedures for abnormal situations; enhancing technician awareness and training in emergency situations; analysing modifications performed on other equipment; new testing and inspection protocols.

Relevance for Ageing
This summary of operator action implies that the plant procedures were obsolete because they had to be "modernised" and had not been updated. Moreover, the description notes that the relatively old adjustment tank used to contain excess product was not fit for this purpose and its transfer years earlier to the unit had resulted in a disabling of the automatic transfer and recirculation mechanisms. Moreover, its stirrer had not been maintained for several years. This accident was identified with the keyword "design" but design was actually not a factor. A search on words associated with obsolescence and loss of knowledge would not have picked up this accident as an accident associated with ageing.

Case 2 – Degradation of Carbon Steel Pipe Base
At 11:15 pm, a violent and loud bursting occurs within an ammonia (NH3) synthesis unit at a classified nitrogen fertiliser plant. The convex base welded to a heat-insulated, high-pressure water vapour pipe connected to catalytic reforming equipment had burst prior to ignition. The base, a 40-kg block of steel, was projected longitudinally. Inside the shop area, a walkway was ripped off its supports damaging an access ladder. The steel base crossed the ammonia confinement space 25 m further, without causing any damage, then flew over an ammonium nitrate conveyor belt only to land 230 m away in a parking zone for tanker cars full of ammonia awaiting shipment, which on that day happened to be empty. The water vapour, circulated at 520 °C under 120 bar of pressure in the pipeline, tore apart the asbestos cement cladding on the wall located 20 m from the original rupture and escaped into the atmosphere with a load accompanying noise. The two employees present in the unit at the time cut off vapour supply to stop the sound, shut down production operations and cooled the steam reformer with nitrogen. No intervention was required by firefighters who arrived on the scene. No victims were reported and the site's other units were not adversely affected; no operations had to be interrupted. The damaged unit was shut down for several weeks, which in turn caused shutdowns at special fertiliser production units due to the loss of vapour.
A metallurgical assessment of the base indicated that slow creep had initiated on the outer skin, which combined with flow into the material layer was the cause of pipe rupture. The origin of this creep was explained by the metallurgical composition of the base, i.e., ordinary carbon steel containing no alloys and not adapted to temperatures above 425°C. The pipeline was made of a slightly alloyed P22 type steel, which was more resistant to creep and compliant with the original specifications defined 32 years prior for both material elements. Inspections carried out at the time on the convex base did not detect any noncompliance of the steel, given that non-destructive technology had not yet come of age. This creep might have been accelerated as a result of heat treatment performed at 700°C during equipment installation, once the assembly had been welded. Periodic inspections dedicated to pressurised equipment on the damaged pipe were only recorded into the log 25 years after service start-up, at the time of applying for facility recertification. The initial recertification was rendered official without any underlying structural documentation (misplaced), and subsequent inspections never focused on the section of pipe that would burst. .Nine months before the accident, the in-house inspection team had requested adding the mode of "degradation by high-pressure vapour pipe vibrations" to the unit's pipe inspection but this mode had not been included in the inspection programme.

Relevance for Ageing
This accident highlights the challenge of identifying vulnerabilities associated with older parts of process infrastructure. As in the Richmond refinery case of 2012 (U.S. Chemical Safety Board), the failed part was

associated with a pipe of higher specifications that was more resistant to corrosion. Both the inspection programme and hazard identification failed to recognise that the base was of a lower quality composition than the pipe to which it was attached. Unintentionally, a misreading of limited documentation led the site to believe that the mechanical integrity was of a higher grade than it actually was. The accident was identified with keywords “degradation” and “vibration”. The report did not highlight the other ageing aspects.

5. Conclusions

Physical degradation is only one aspect of ageing that influences site risk. Equally, obsolescence and loss of knowledge due to ageing can also augment risk. Sites need to specifically recognise these risks so that they can address them. However, lack of attention to these issues in past accident reports means that finding evidence is challenging. Moreover, measuring the extent to which ageing sites have suffered accidents from these weaknesses is almost impossible. While such causes are often correlated with corrosion and maintenance factors, keywords associated with material degradation identify far more accidents than are relevant. It is not practical for most analysts to sift through 871 maintenance accidents in the ARIA database to find cases of obsolescence and loss of knowledge. Meanwhile, current practice in accident analysis does not sufficiently recognise age-related management of change and design failures (e.g., design exceedances) as ageing issues that should be highlighted along with material degradation. The study findings also suggest that analysis of future accidents should specifically seek to give visibility to causes and lessons learned related to obsolescence and loss of knowledge. Moreover, reports of such accidents should incorporate the keywords in Table 1 related to these topic.

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