PLENARY LECTURE

Corrosion Risk for Process Safety in the Chemical Industry.

Dr. Alec Groysman

Corrosion Risk for Process Safety in the Chemical Industry

Alec Groysman
Chemical Engineering Department, Technion (Israeli Institute of Technology), Haifa, Israel
Honor President of the Israeli Association of Chemical Engineers and Chemists

Riesgo de corrosión para la seguridad de procesos en la industria química

Risc de corrosió per a la seguretat dels processos a la indústria química

RECEIVED: 9 OCTOBER 2023; ACCEPTED: 15 JANUARY 2024; HTTPS://DOI.ORG/10.55815/424213

ABSTRACT

The aim of this work is to analyze how corrosion risk management influences process safety. Both issues occupy an important niche in the chemical industry. *Corrosion risk management* includes identifying, analyzing, assessing, and managing corrosion hazards. *Process safety* is a discipline that focuses on preventing fires, explosions, and accidental releases at chemical process facilities. Corrosion can cause all these detrimental events.

There is much literature about both topics, corrosion risk, and process safety, separately, but there are nearly no research works concerning intersection and influence.

The level of corrosion failure and its consequences, defining corrosion risk, may be different: the leak of crude oil, natural gas, water, liquid and gaseous hazardous chemicals, fire, explosion, damages, deterioration of the environment, injuries, and death of people and animals. Due to the biological and psychological properties of human nature, we are unlikely to exclude human mistakes.

We should pay significant attention to education, dissemination of information, knowledge transfer, collaboration, and communication. Correct corrosion risk management gives rise to the improvement of process safety at stages of design, fabrication, implementation, erection, service, and maintenance of equipment and constructions in the chemical industry.

For this realization, specific corrosion mitigation strategies and technologies are described. They are successfully implemented in the chemical industry. It shows how corrosion management and process safety management can be better integrated into practice.

The future consideration of the prognosis of corrosion risk with process safety is connected with corrosion modeling. Limitations and challenges of such a forecast are discussed too.

Special educational and training programs are developed to help engineers, scientists, professionals, students, and managers learn about corrosion science and engineering.

Keywords: Corrosion risk, process safety, chemical industry

RESUMEN

El objetivo de este trabajo es analizar cómo la gestión del riesgo de corrosión influye en la seguridad de los procesos. Ambas cuestiones ocupan un nicho importante en la industria química. La gestión del riesgo de corrosión incluye identificar, analizar, evaluar y gestionar los peligros de corrosión. La seguridad de procesos es una disciplina que se enfoca en prevenir incendios, explosiones y liberaciones accidentales en instalaciones de procesos químicos. La corrosión puede causar todos estos eventos perjudiciales.

Existe mucha literatura sobre ambos temas, el riesgo de corrosión y la seguridad de los procesos, por separado, pero casi no hay trabajos de investigación sobre la intersección y la influencia.

El nivel de falla por corrosión y sus consecuencias, que definen el riesgo de corrosión, pueden ser diferentes:

***Corresponding author: alecgroysman@gmail.com**

fuga de petróleo crudo, gas natural, agua, productos químicos peligrosos líquidos y gaseosos, incendio, explosión, daños, deterioro del medio ambiente, lesiones y muerte de personas y animales. Debido a las propiedades biológicas y psicológicas de la naturaleza humana, es poco probable que excluyamos los errores humanos.

Deberíamos prestar mucha atención a la educación, la difusión de información, la transferencia de conocimientos, la colaboración y la comunicación. La correcta gestión del riesgo de corrosión da lugar a la mejora de la seguridad de los procesos en las etapas de diseño, fabricación, implementación, montaje, servicio y mantenimiento de equipos y construcciones en la industria química.

Para esta realización, se describen estrategias y tecnologías específicas de mitigación de la corrosión. Se implementan con éxito en la industria química. Muestra cómo la gestión de la corrosión y la gestión de la seguridad de los procesos pueden integrarse mejor en la práctica.

La consideración futura del pronóstico del riesgo de corrosión con la seguridad de los procesos está relacionada con el modelado de la corrosión. También se analizan las limitaciones y desafíos de tal pronóstico.

Se desarrollan programas educativos y de capacitación especiales para ayudar a ingenieros, científicos, profesionales, estudiantes y gerentes a aprender sobre la ciencia y la ingeniería de la corrosión.

Paraules clau: Riesgo de corrosión, seguridad de procesos, industria química.

RESUM

L'objectiu d'aquest treball és analitzar com la gestió del risc de corrosió influeix en la seguretat del procés. Tots dos temes ocupen un nínxol important en la indústria química. La gestió del risc de corrosió inclou identificar, analitzar, avaluar i gestionar els perills de corrosió. La seguretat dels processos és una disciplina que se centra a prevenir incendis, explosions i emissions accidentals a les instal·lacions de processos químics. La corrosió pot provocar tots aquests esdeveniments perjudicials.

Hi ha molta literatura sobre tots dos temes, el risc de corrosió i la seguretat del procés, per separat, però gairebé no hi ha treballs de recerca sobre intersecció i influència.

El nivell de fallada per corrosió i les seves conseqüències, que defineixen el risc de corrosió, poden ser diferents: fuita de cru, gas natural, aigua, productes químics perillosos líquids i gasosos, incendi, explosió, danys, deteriorament del medi ambient, lesions i mort de persones i animals. A causa de les propietats biològiques i psicològiques de la naturalesa humana, és poc probable que excloem els errors humans.

Hem de parar una atenció important a l'educació, la difusió de la informació, la transferència de coneixement, la col·laboració i la comunicació. La gestió correcta del risc de corrosió dóna lloc a la millora de la seguretat del procés en les etapes de disseny, fabricació, implementació, muntatge, servei i manteniment d'equips i construccions a la indústria química.

Per a aquesta realització, es descriuen estratègies i tecnologies específiques de mitigació de la corrosió. S'implementen amb èxit a la indústria química. Mostra com la gestió de la corrosió i la gestió de la seguretat dels processos es poden integrar millor a la pràctica.

La consideració futura del pronòstic del risc de corrosió amb la seguretat del procés està relacionada amb el modelatge de corrosió. També es discuteixen les limitacions i els reptes d'aquesta previsió.

Es desenvolupen programes educatius i de formació especials per ajudar enginyers, científics, professionals, estudiants i directius a aprendre sobre la ciència i l'enginyeria de la corrosió.

Paraules clau: Risc de corrosió, seguretat del procés, indústria química

INTRODUCTION

This work aims to analyze how corrosion risk management influences process safety. Both issues are wide and occupy an important niche in the chemical industry.

Corrosion risk management includes identifying, analyzing, assessing, and managing corrosion hazards. *Process safety* is a discipline that focuses on preventing fires, explosions, and accidental releases at chemical process facilities. Corrosion can cause all these detrimental events. A *hazard* is a substance, object, or situation with the potential for an accident or damage. *Corrosion* is one of the biggest *hazards* because it is related to substances, objects, and situations leading to the interaction between them and the deterioration of both.

Numerous data show that large failures resulting in harmful consequences occur because of corrosion once a week in many chemical enterprises, at oil refineries – every 2-3 days.

There are 740 oil refineries over the world, 67 among them in Europe, 76 in the Mediterranean region, and 9 among them in Spain dispersed in all areas of the country. The Spanish oil refining industry is employing ~200,000 employees. Most of the oil refineries (over 95 percent) were built before 1985, over 40 years old. This is the age when a refinery becomes old with constantly growing corrosion problems. Process safety problems grow accordingly.

Mediterranean oil and gas activity map shows that coastal zones of Spain, Italy, Greece, Israel, Egypt, Tunis, and Libya are full of oil and gas rigs. These constructions represent an increased danger to humans and marine life. Thus, corrosion risk and process safety acquired the main place in the lifetime of all chemical enterprises, including oil and gas, oil refining, and petrochemical industry.

There is much literature about both topics, corrosion risk and process safety, separately but there is nearly no research work concerning intersections and influence. Usually, specialists in process safety do not know much about the subject of corrosion. Accordingly, corrosionists do not specialize in process safety. In this work, I analyze the role of corrosion risk management in the prevention of corrosion accidents related primarily to process safety, namely, asset and technical integrity, personnel, and the environment.

The term '*process safety*' originates in the US; in some other parts of the world '*process safety*' is referred to as '*asset integrity*' or '*technical integrity*'. Personal safety hazards, on the other hand, affect individuals but may have little to do with the processing activity of the plant. Typically, 'personal safety hazards' give rise to incidents such as falls, trips, crushing, electrocutions, and vehicle accidents.

The chemical industry has existed for over 250 years. If corrosion topics began occupying the last 100 years (100 hundred years ago in 1923, in England and Russia, the first text-books in corrosion were published and the first corrosion courses were delivered in Egland by U.R. Evans), process safety began occupying only the last 50 years.

The new chemical plants built in the 1950s - 1960s were larger than earlier ones and operated at higher temperatures and pressures. The result was an increase in serious accidents. This led to the more systematic and technical approach to safety, known as *loss prevention* [1, 2].

By the mid to late 1970s, process safety was a recognized technical specialty, mostly owing to English chemical engineers Trevor Asher Kletz and Frank Lees [1, 2]. The American Institute of Chemical Engineers (AIChE) formed its Safety and Health Division in 1979 [3]. In 1985, AIChE established the Center for the Chemical Process Safety (CCPS), partly in response to the Bhopal tragedy that occurred the previous 1984 year [4]. Certainly, not all accidents in the chemical industry relate to corrosion. I did not find in the literature how many accidents of process safety occurred because of corrosion [5]. Here are some of them.

The Bhopal Gas Leak, India, 1984 is the largest chemical industrial accident ever [6, 7]. Pipelines were made from carbon steel instead of stainless steel as recommended by United Carbide Corporation Manual in contact with methylisocyanate. These pipes corroded. The second cause was the presence of corroded iron ions in methylisocyanate medium which catalyzed the reaction with water. Methylisocyanate reacted with water in the presence of air to form monomethylamine and carbon dioxide. 520,000 persons were exposed to the gases, and up to 8,000 died during the first weeks. 100,000 persons or more have got permanent injuries. The catastrophe has become the symbol of negligence to human beings from transnational corporations. It has thus served as an alarm clock. All the same, industrial disasters still happen, in India as well as in the industrialized part of the world [6, 7].

In August 2018, the Morandi bridge in Genoa, Italy, collapsed resulting in the death of 43 people. The bridge was only 51 years old. The carbon steel cables supporting the bridge failed due to corrosion [8].

The third corrosion accident related to process safety happened at the Chevron Richmond Refinery in California, U.S., in 2012 [9]. It thundered mostly among the process safety community. I heard nothing about this corrosion accident until began dealing with the process safety. A catastrophic pipe rupture at the Crude Unit occurred. The release, ignition, and subsequent burning of the hydrocarbon process fluid resulted in a large plume of vapor, particulates, and black smoke, which traveled across the surrounding area. The atmospheric column separates crude oil feed into different hydrocarbon products through distillation. Light gas oil is a distillation fraction with a boiling point range between 200 and 350°C. In the weeks following the incident, approximately 15,000 people from the surrounding communities sought medical treatment at nearby medical facilities for ailments including breathing problems, chest pain, shortness of breath, sore throat, and headaches.

A damage mechanism was known as sulfidation corrosion that caused carbon steel pipe walls to gradually thin over time. Sulfidation corrosion is not a new phenomenon and was first observed in the late 1800s (100 years before this event!) in a pipe still (crude separation) unit, due to the presence of sulfur compounds in crude oil. Guidelines for Avoiding Sulfidation (Sulfidic) Corrosion Failures in Oil Refineries have existed since 2009 (for instance, API RP 939). When hydro processing was introduced in the 1950s, changes in the corrosion behavior of construction materials were noted. Engineers (good engineers!) knew how to prevent sulfidation. Despite this, carbon steel was not replaced in time! Once again, HUMANS were responsible for this corrosion and further process safety accidents!

I can continue a litany of disasters. I sought to unite three wide phenomena concepts: *corrosion*, *corrosion risk management*, and *process safety*.

Corrosion management is achieved by the use of anti-corrosion measures, corrosion monitoring, regular inspection, corrosion audit, the study of each accident, implementation of meetings, publications of minutes, education, and knowledge transfer, maintenance, and predictability of corrosion rates and failures (see 1.3, Figure 2).

Corrosion risk is achieved by identifying, analyzing, assessing of occurring, and modeling possible corrosion phenomena.

Process safety includes the prevention of unintentional releases of dangerous chemicals and energy during processes that can have a serious effect on the plant and environment. This is achieved by the prevention of equipment malfunction, over-pressures, over-temperatures, leaks, spills, and *corrosion*. All these phenomena are interlinked and interdependent.

Process safety programs focus on the design and maintenance of equipment, effective alarms and control points, procedures, and training. Corrosion risk management is an active instrument in all these aspects of process safety and takes part in achieving its main purposes.

The level of corrosion failure and its consequences, defining corrosion risk, may be different: the leak of crude oil, natural gas, water, liquid and gaseous hazardous chemicals, fire, explosion, damages, deterioration of the environment, injuries, and death of people and animals.

Due to the biological and psychological properties of human nature, we are unlikely to exclude human mistakes. The human factor plays a vital role in both corrosion risk management and process safety, and as a result in the prevention of corrosion failures and improvement of both. We should pay significant attention to education, dissemination of information, knowledge transfer, training, collaboration, communication, use of standards, and documentation. Correct corrosion risk management gives rise to the improvement of process safety at stages of design, fabrication, implementation, erection, service, and maintenance of equipment and constructions in the chemical industry.

1. Corrosion and the link to the process safety

When I began teaching corrosion subject before 2000, I listed five main important reasons to learn corrosion subject in the following order:

a. Economics,
b. *Safety*,
c. Environmental damage,
d. Reliability,
e. Preservation of metal sources.

Beginning from 2000, I put "safety" in the first place instead of economics. Thus, I emphasize that process safety is the main reason in the two last decades (2000 – 2023) why engineers should learn corrosion subject. Unfortunately, this did not occur. *Safety* is valued over production at many chemical enterprises. However, the *corrosion* issue … is not. I am an eyewitness of situations when managers in chemical plants put corrosion subjects and problems not in the first priorities.

According to the definition, *corrosion is a physicochemical interaction between a metal and its environment leading to changes in the properties of both a metal and the environment* [10]. There are about 40,000 alloys (among them 85 pure metals) and an infinite set of environments. The latter may be one-, two-, or three-phase media. Then, the environment may be abiotic (air, water, soil, process media in chemical industry) and biotic (humans – implants and other metallic devices and instruments in human bodies, fauna, and flora).

Corrosion can impact process safety and thus cause great damage to abiotic and biotic environments, namely, destruction of equipment and structures, environmental pollution, the death of animals and plants, injuries, diseases, disability, and deaths of people. The process environments (oil, gas, petroleum products, fuels, solvents, toxic gases, and liquids) play an immense role. We should also emphasize the role of microorganisms in corrosion processes in both abiotic and biotic environments.

There are not so many examples of how corrosion influences process safety in Europe.

The 11th Report of the European Gas Pipeline Incident Data Group (period 1970 – 2019) informed that corrosion was the reason for the failures in 27% of European pipelines [11]. 1,411 pipeline incidents were recorded in 1970-2019 in Europe, namely, 20 incidents in a year, or every 18 days. The total length of the European gas transmission pipeline system increased 5-fold times during 1970 - 2022: from 30,000 to 145,000 km [11]. Aging and corrosion of these pipelines occur at an uncontrolled rate. This situation aggravates the safety situation on the territories of many countries. Thus, refineries, storage facilities, oil pipelines, and terminals are distributed over all Spain territory. Such situation shows increased danger for the country of Spain. Similar corrosion risk of metallic infrastructure constructions is observed in many countries in Europe. Even in such relatively small countries of Austria and Israel, with population ~ 9.1 million, pipelines for transporting oil, gas, fuels, and chemicals lie in highly populated areas. Certainly, corrosion risk for the process safety is high.

Introduction of hydrogen energy and CO_2 utilization with new technologies raises new questions and corrosion problems of correct use of materials, and this also connects to the process safety.

Mediterranean Oil and Gas activity map shows dense disposition of metallic constructions (rigs, etc.) in coastal areas of Spain, Italy, Greece, Israel, Egypt, Tunis, and Libya. Rig explosions, fires, capsizing/sinking, oil spills, and the loss of workers and marine lives have been the most catastrophic forms of offshore oil and gas drilling disasters in recorded history [12]. Investigational reports on some of the world's worst offshore oil rig disasters (including corrosion failures) suggest that most of these accidents could have been avoided.

This situation demonstrates the importance of process safety and corrosion risk management cultures, including the need to establish process safety as a core value, provide strong leadership, and establish and enforce high standards of performance. These two issues should be the priority of legislation in all countries.

1.1 Corrosion relates to the process safety

Let us consider three corrosion events (Figure 1).

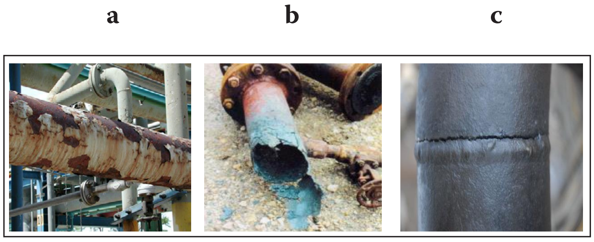


Figure 1. **a** - *Failure of coating on the pipeline with water (90°C) in the atmosphere of the oil refinery, 2 years.* **b** - *Severe corrosion of pipeline transportation of gas containing H_2S to the furnace, 4 years.* **c** - *Hydrogen embrittlement of carbon steel, medium - H_2 at 280°C (with peaks to 380°C) and 46 bar; 16 years.*

We can rank all corrosion incidents' risks according to the service period t before the failure:

- extremely very high risk: $t < 1$ year,
- a very high risk: $1 < t < 3$ years,
- a high risk: $3 < t < 5$ years,
- a medium risk: $6 < t < 10$ years,
- a low risk: $t > 10$ years.

In such a ranking, we did not consider the consequences of the incident.

We should differentiate between the words 'incident' and 'accident'. In safety parlance, it's most common for the word 'accident' to describe an incident that results in serious consequences that the organization wants to avoid [13]. The word 'incident' is then applied to unwanted events that fall short of being an accident. In occupational safety and health (OSH), an incident is always a safety or health event with unwanted consequences. An accident is a type of incident. Accidents have a narrower definition and imply a much more serious outcome. In workplace safety circles, the serious consequences that rise to the level of 'accident' are focused on serious illness or injury, water, air, or soil contamination. An incident would involve other unwanted consequences like minor injury or illness, property damage, or a loss of productivity. Thus, all three corrosion events are incidents and not accidents.

In the first incident (see Figure 1a), the heat released, workers could be hurt by the high temperature of the pipeline's surface or by hot water in the case of severe corrosion and holes' formation. In the second incident (see Figure 1b), an explosion occurred, and operators could be injured, poisoned, and even lose their lives by releasing H_2S and other hot gases. In the third incident (see Figure 1c), a large explosion and fire occurred with the destruction of equipment and structures around the cracked carbon steel pipeline because of hydrogen embrittlement. Fortunately, the staff was absent during these corrosion incidents, and nobody was injured. It would seem that the coating failure after two years had a very high corrosion risk (2 years of service before the failure), and hydrogen embrittlement that occurred after 16 years, had a low risk. However, consequences in the third incident were significantly greater because of property damage (destruction of pipelines and nearby equipment) and loss of productivity as production was shut down. Thus, we reveal that corrosion relates to process safety. But in a different manner.

1.2 Approach to corrosion as a hazard/threat

A hazard is a substance, object, circumstance, or situation with a potential for an accident or to cause damage to health, life, property, or any other interest of value [14]. A hazard is a potential source of harm. The probability of that harm being realized in a specific 'incident', combined with the magnitude of potential harm, makes up its risk. Hazards can be classified as natural, anthropogenic, and technological.

Corrosion is one of the biggest hazards or threats because it relates to substances, objects, circumstances, and situations leading to the interaction between them and deterioration of both. Corrosion is a natural physicochemical process that can be exaggerated by anthropogenic factors including also technological ones.

Corrosion hazards/threats may lead to a hazardous event (corrosion), and the hazardous incident may in turn lead to many different consequences. Risk relates to a technical system in which events can occur in the future and that have unwanted consequences to assets that we want to protect [15]. The system may be any type of engineered system, from small equipment up to complex process plants.

Now, we should define what risk is. *Risk* is the possibility of something bad happening [16].

Risk is the effect of uncertainty on objectives [17]. An effect is a deviation from the expected negative in the corrosion case. Objectives can have different aspects (financial, health and safety, and environmental goals) and can be applied at different levels (strategic, project, product, and process). Risk is characterized by potential (probable) events (corrosion) and consequences. The formula is [18]:

$$Risk = Probability \times Consequence \quad (1)$$

Where:

Probability - likelihood of failure for individual equipment by examining the potential damage mechanisms – expert judgement, rate models, statistical and physical models.

Consequence – magnitude (result) of failure - how much it would cost if a particular equipment broke down.

Consequences of failure are divided into four categories [19].

- Safety – instant consequences on humans within or outside the plant's area.
- Health consequences – long-term effects on humans within or outside the plant's area.
- Environmental consequences.
- Business consequences of failure.

Uncertainty is the state of deficiency of information related to, understanding or knowledge of, an event, its consequence, or likelihood.

These two factors (probability and consequence) are categorized in three groups:

- health and safety impacts,
- environmental impacts,
- business impacts.

Risk analysis is a systematic use of available information to identify hazards and to estimate the risk to individuals, property, and the environment [15]. A risk analysis deals with potential incidents and is carried out in three main steps:

- *Hazard identification.* In this step, corrosion hazards/threats related to the system are identified together with the potential corrosion events.
- *Frequency analysis.* This step involves the causes and frequency of each corrosion event based on experience data and/or expert judgments.
- *Consequence analysis.*

Corrosion Risk Management is identifying, analyzing, evaluating, and eliminating (treatment) corrosion hazards. Mitigating activities and corrosion risk reduction is based on the risk assessment: safety, health, environment, and business [19]. Mitigating activities may be maintenance/inspection, redesign, and operational constraints. This is a general scheme of anti-corrosion policy at any enterprise in the chemical industry and depends on the actual case and real conditions.

Risk Analysis came from the nuclear and chemical industries, was standardized, and found wide application in Corrosion Management in oil refining and other industries.

American Petroleum Institute (API) developed two main standards: API RP 580 (2016) Risk Based Inspection (RBI) [20] and API RP 581 (since 2000) Risk Based Inspection Technology [21]. The first one includes definitions and concepts and focuses on loss of containment of pressurized equipment due to material deterioration. These risks are managed through inspection. The second standard involves implementing methodology on 652 pages. It provides quantitative procedures to establish an inspection program using risk-based methods (Risk = Probability *x* Consequence) for pressure vessels, piping, tankages, pressure relief devices, and heat exchanger tube bundles. There are other standards on the RBI [19, 22-24].

There are four levels of risk-based assessment: lower risk, medium risk, medium-high risk, and high risk. They can be evaluated as qualitative, semi-quantitative, and quantitative [25].

Qualitative estimation is used to determine the risk associated with whole or large portions of process units. It takes into consideration descriptive data based on the judgment and experience of inspectors. The semi-quantitative and quantitative evaluations are applied to determine risk associated with individual pieces of equipment. Inspectors base their assessment on statistics and probability. The overall goal is to mitigate the number of failures by optimizing maintenance activities for high-risk equipment and saving resources on low-risk assets.

It was marked that the standardized methodology [20, 21] of quantifying corrosion risk is based on several flawed assumptions, and the main of them is that "risk is an elusive thing, in particular in probability part" [26, 27]. Such criticism may help in improving RBI methodology and wider implementation into practice at the enterprises of the chemical industry. Certainly, an application of RBI helps in diminishing and avoiding corrosion failures and improving process safety.

1.3 Corrosion management and process safety management

Corrosion management is planning actions of selection, design, corrosion mitigation, prevention, monitoring, inspection, and prediction of corrosion phenomena and their rates. Corrosion management includes 15 activities (Figure 2).

One can find a detailed description and explanation of each of these activities in [18]. Correct corrosion risk management gives rise to the improvement of process safety at stages of design, fabrication, implementation, erection, service, and maintenance of equipment and constructions in the chemical industry. For this realization, specific corrosion mitigation strategies and technologies (*anti-corrosion measures*) should be applied [18, 28]:

a. *The use of coatings* (organic, inorganic, and metallic).
b. *The use of electrochemical methods*: cathodic and anodic protection.
c. *Change the environment*: the use of corrosion inhibitors; removal of the aggressive components, such as oxygen (deaeration), hydrogen sulfide, chlorides, and ammonia; neutralization (injection of alkalis into acidic solutions, or acids into alkali solutions); drying the atmosphere (removal of water vapors); use of biocides.
d. *Correct selection of materials*: corrosion-resistant metals and alloys, polymeric materials, ceramics, glasses, and composites.
e. *Correct design*. Metallic equipment must be designed in such a manner that they would be convenient for drainage, cleaning, surface preparation, and painting; not to use different alloys in a general electrolyte solution, in order to prevent galvanic corrosion, not to use sharp elbows; etc.

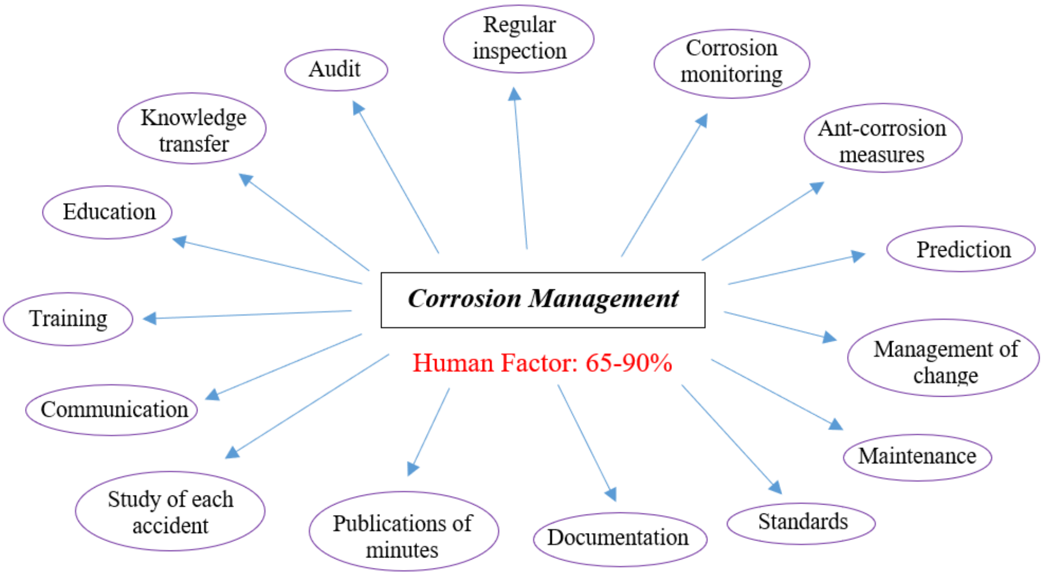


Figure 2. *Corrosion Management scheme (15 activities)*

f. *Technological measures*: changes in process conditions. For instance, keeping the temperature 20 to 30°C above the dewpoint to prevent condensation of corrosive species (H_2O and dissolved HCl, H_2S, H_2SO_4); decrease flow velocity of liquid in the case of erosion, or increase its flow in the case of stagnation, to prevent formation of deposits (fouling and, as a result, a possible under deposit corrosion).

All these mitigation strategies and technologies have been successfully implemented in the chemical industry. Only by using them, we can diminish corrosion incidents significantly.

Corrosion problems appear because of insufficient corrosion management, namely:

a. Standards, codes, specifications, rules, guidelines, and knowledge are not effectively used.
b. Specialists are often not familiar with existing literature, experience, and achievements of others.
c. Control and monitoring measures, inspections and audits are not always carried out on a regular basis and on time.
d. About 30% of corrosion incidents are not registered. The Human Factor (65-90%) plays a vital role!

The reasons for humans' mistakes are:

- Lack of knowledge, education, and training.
- Incorrect design and insufficient review.
- Wrong operation.
- Insufficient control and supervision.
- Lack of incentives to reduce corrosion risk.
- Element of change and lack of communication and collaboration.
- Inattention to warnings/technical information.

Process safety management (PSM) is a way to prevent disasters involving hazardous chemicals in industrial processes [29]. PSM was developed by OSHA (The Occupational Safety and Health Administration) in 1992 after a series of fatal accidents in the 1980s, such as the Bhopal gas leak [6, 7] and the Piper Alpha fire [30]. Put attention, PSM was developed at the same time (1992) when RBI was introduced in 1993 by API.

PSM applies to any process that uses or stores highly hazardous chemicals above a certain threshold, such as flammable, toxic, reactive, or explosive substances. PSM aims to reduce the risk of fires, explosions, toxic releases, and other incidents that could harm workers, the public, or the environment. It defines and regulates a PSM program for plants, using, storing, manufacturing, handling, or carrying out on-site movement of hazardous materials above defined amount thresholds. The PSM program requires 14 elements (like 15 activities in *corrosion management* – see Figure 2):

- Employee participation
- Process safety information
- Process hazard analysis
- Operating procedures
- Training
- Contractors
- Pre-startup safety review
- Mechanical integrity
- Hot work permit
- Management of change
- Incident investigation
- Emergency planning and response
- Compliance audits
- Trade secrets

All the elements are interlinked and interdependent. Comparing with Figure 2, one can reveal that many similar elements (14!) are present as activities (15!) in corrosion management. Therefore, we can include *corrosion management analysis* in PSM programs. According to my personal experience in the oil refining and petrochemical industry, a corrosion engineer and process safety engineer should analyze and sign any project which should include both *corrosion risk management* and *PSM programs*. Unfortunately, there is a gap in their interaction and cooperation. I can tell you how corrosion management and process safety management can be better integrated into practice. In order to solve corrosion problems at one oil refinery, two committees were organized: corrosion and cathodic protection. These commissions were dynamic, that is professionals of different specialties were invited each time for discussion and solving some corrosion problem. What was constant, the participation of corrosion and process safety professionals. Any program for a new year including education and training was compiled together. Thus, corrosion and process safety specialists penetrated each other.

Now, we turn to the main point – *EDUCATION* - that unites *process safety management* and *corrosion management*.

1.4 Education is critical

Determination of *Corrosion Risk* involves the study and analysis of corrosion cases and situations and prediction, planning for corrosion control actions, and creating a monitoring system. It is impossible to carry out all these stages without *education*. Thus, the human factor plays an important role in both the control, monitoring, and prevention of corrosion phenomena and in industrial process safety. Usually, we reveal three causes of accidents:

"I didn't know, I didn't think, or I didn't see!"

The priority occupies a culture of education including teaching.

Who learns corrosion subject?

Materials engineer, chemist, electrochemist, mechanical engineer, metallurgist, energy engineer, electrical engineer, chemical, petroleum, biotechnology, and environmental engineer, and microbiologist. Some universities and colleges have discipline "corrosion engineer". Only an engineer possessing the abovementioned basics and background can become a corrosion engineer after about 5 years of practice. Corrosion is an interdisciplinary subject and multidisciplinary study. Unfortunately, process safety engineers do not study the subject of corrosion. It is impossible to carry out risk analysis without knowing corrosion basics and corrosion failure modes. Thus, education is critical.

1.4.1 Education and knowledge transfer

About 75% of all corrosion failures happen because of insufficient education, knowledge, information, communication, interaction, and management. I will describe mostly education and knowledge. Certainly, not every scientist and engineer can teach. First, we should give pedagogical skills to scientists and engineers to be teachers and educators. Then, to improve corrosion education among all categories of the workforce including management.

Special educational and training programs were developed in the oil refining industry in Israel in 1990s-2010s and in Kazakhstan in 2019-2023 to help engineers, scientists, professionals, students, specialists of different levels, and managers to learn about corrosion science and engineering concentrating on their special demands and needs concerning real technological units, structures, equipment, apparatus.

My strategy is the creation of blocks of text-books and curricula for categories of workforce at different industries (like the building of the "Lego"):

- Educators and teachers – how to teach, educate, and train in a logical, methodologically consistent, exciting, passionate, and interesting manner.
- Students at schools, colleges, universities.
- Young engineers and scientists.
- Experienced engineers and scientists.
- Managers of different levels.

Thus, corrosion basics should be obligatory for all engineering disciplines where metals occupy a significant role, at least in the chemical industry.

We should also differentiate between pedagogy and andragogy. Today, *pedagogy* refers to the theories and methods used in teaching. However, in the past, pedagogy referred specifically to the methods used to educate children. *Andragogy* was coined to focus on the practices used to teach adults [31].

We should follow the words by Maimonides (Rambam) (1138 or 1135-1204), a Jewish philosopher, lived in Spain: "*Give a man a fish and you feed him for a day; teach a man to fish and you feed him for a lifetime*" [32].

Knowledge management (KM) is the collection of methods relating to creating, sharing, using, and managing the knowledge and information of an organization [33]. KM is any developed system that assists personnel in an organization to create, distribute, access, and update knowledge and information related to the business and their responsibilities. Here are some types of KM: written documents, training programs, and courses. KM includes working committees and discussion forums, apprenticeships, libraries, professional training, and mentoring programs [34]. Knowledge transfer is an important component of KM and is the sharing or disseminating of knowledge and the providing of inputs to problem-solving. Like KM, knowledge transfer seeks to organize, create, capture, and distribute knowledge and ensure its availability for future users (generations).

The psychology of relationships among different categories of personnel at the enterprise plays a significant role. We can divide knowledge into *explicit* and *tacit* (*implicit*).

Explicit knowledge (expressive knowledge) is knowledge that one can find in encyclopedias, books, and magazines, namely, can be readily accessed [35]. *Tacit knowledge* (personal or implicit knowledge) is knowledge that is difficult to extract from the heads of professionals based on their experience [36]. The Hungarian-Jewish scientist Michael Polanyi (one of the authors of the transition state theory in chemistry developed in 1935) was the first who introduced the term *tacit knowledge*: "*we can know more than we can tell*" [37, 38]. Not all professionals are ready to share their tacit knowledge. How to encourage them? Most companies do not encourage retired specialists to share their tacit knowledge at all.

Let me share my own experience in education and knowledge transfer as a part of KM and corrosion management in an oil refining company in Israel where I worked for 22 years. First, we created working committees with the titles "corrosion problems" and "cathodic protection" (see 1.3). The corrosion engineer led the activity of these two committees. Representatives of various departments took part in their activity. Corrosion problems arose every 2-3 days, but committees gathered only in the case of an unclear (problematic) event. Usually, once a month. The result was a report to all personnel.

A three-hour video "*Introduction to corrosion problems at oil refinery*" was prepared. Each new worker could watch it on his computer. Special different twelve-hour courses were prepared and delivered for five categories of the workforce (see section 1.3) once a year. At the end of each year, a corrosion engineer prepared a report summarizing all corrosion cases with analysis, recommendations, and calculations of economic losses from corrosion. The next step is to connect to the process safety.

2. How to predict and prevent (decrease) corrosion events?

I compare the behavior of the metal-environment system with the life of people. Can we predict the illnesses and deaths of people? Only in some simple cases. In general, we cannot predict illness, aging, and death. The 2nd law of thermodynamics governs our life and behavior of all objects in the Universe. This means that we cannot prevent movement from order to chaos. However, we can control and try slowing down this movement. In this direction, we see the following steps:

a. To develop and apply *corrosion management* culture (see Figure 2).
b. To improve 15 activities composing *corrosion management*:

- Safety always starts with correct engineering anti-corrosion design.

- Forcing managers to establish penalties and incentives in corrosion and anti-corrosion activity.
- Legislation in the field of corrosion management on the governmental and federal levels. National institutes of standards and ministries should be attracted to this job.
- Searching how chaotic corrosion processes result in failure.
- Creation of models like weather models. Using Big Data (data mining - histories).
- Change awareness and relationships of society and governmental organization to corrosion problems like to the protection of the environment which occurred during the last 30 years (1990-2023). Corrosion specialists and journalists should stop using *fighting, combat, battle with corrosion, hated, abhorrent and nasty phenomenon.* We may use only the word *control* regarding corrosion.

2.1 Corrosion models for the process safety

The *weather* is constantly changing the state of the atmosphere. *Humans* are constantly changing the state of people` organisms in the environment. *Corrosion* is constantly changing the state of a metal-environment system. There are some models for the forecast of weather. Until physicists and mathematicians entered meteorology, the weather forecast was not reliable. The more initial data is included in the model and the more data is changed with the time that we know, we obtain the more reliable model of weather. Big data (historical) and data mining are an integral part of these models. Even nowadays, with the success of such chaotic weather models, we can obtain reliable prognoses only for 3-5 days ahead. With increasing time of forecast, reliability, and accuracy of weather prognosis decrease.

What happens in the field of corrosion modeling?

Since the 1980s various corrosion models have been developing, for instance, for the prediction of corrosion behavior of inner surfaces of pipelines in oil and gas industry [39-42], and for the prediction of high temperature corrosion in the oil refining industry [43]. I worked for the oil refining industry for 22 years and did not reveal that any corrosion model for the prediction of corrosion worked.

In any case, we should endeavor to create corrosion models which should be helpful and critical in the PSM. The future consideration of the prognosis of corrosion risk in process safety relates to corrosion modeling. Literature is full of developing corrosion models, especially during the last three years (2021 – 2023) [40, 44-47]. This singularity (explosion of research works and information) occurred owing to the use of Artificial Intelligence (AI) methods [48-53]. A comprehensive review and analysis of AI application in corrosion is outside of the scope of this paper. Separate paper should be prepared. I will give only a short description of AI use in the creation of corrosion models and then the limitations and challenges of the forecast of corrosion behavior of metallic constructions.

2.1.1 Artificial Intelligence (AI) in corrosion modelling

Artificial intelligence (AI) is the intelligence of machines or software, as opposed to the intelligence of humans or animals. It was a field of study in computer science which developed and studied intelligent machines [54]. Such machines may be called AIs. AI technology is widely used both in industry and in science. Nowadays AI is mostly engineering than science.

An English mathematician Alan Mathison Turing (1912-1954) was the first who carried out substantial research in the field that he called Machine Intelligence.

Artificial intelligence was founded as an academic discipline in 1956. The field went through multiple cycles of optimism followed by disappointment and loss of funding. Funding and interest vastly increased after 2012 when deep learning surpassed all previous AI techniques, and after 2017 with the transformer architecture. This led to the AI spring in the 2020s, with companies, universities, and laboratories overwhelmingly based in the US pioneering significant advances in artificial intelligence.

According to the Britannica [55], "artificial intelligence (AI) is the ability of a digital computer or computer-controlled robot to perform tasks commonly associated

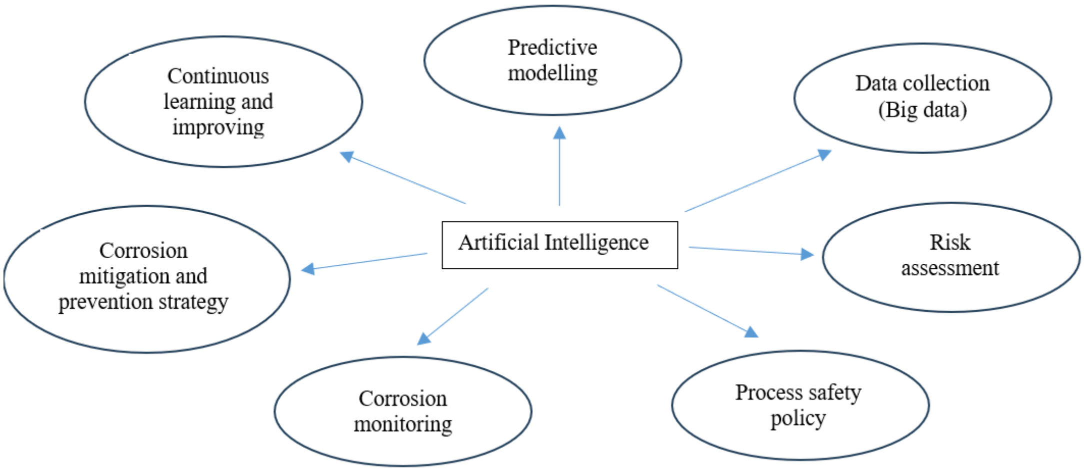


Figure 3. *Artificial Intelligence for Corrosion Control, Monitoring, and Behavior Prediction of Metallic Equipment*

with intelligent beings". The term is frequently applied to the project of developing systems endowed with the intellectual processes characteristic of humans, such as the ability to reason, discover meaning, problem-solving, generalize, perception, and learn from experience.

Among the different AI techniques, machine learning (ML), pattern recognition (PR), and deep learning (DL) have recently acquired considerable attention in corrosion engineering [44-52].

AI techniques allow the detection of degradation, improve modelling of materials durability and assist decision-making by analysis of large sets of degradation data, and finally forecasting of service life. These models take into account various parameters, including environmental conditions, equipment characteristics, and historical corrosion data (big data and data mining). Through continuous learning and refinement, the predictive models become more accurate in estimating corrosion rates, predicting potential corrosion hotspots (corrosion risk area), and projecting the remaining useful life of equipment and structures [50]. Finally, AI improves the process safety (Figure 3).

2.1.2 The assessment and creation of corrosion models

The assessment and creation of corrosion models consist of two steps:

a. Identification of the corrosion hazards by defining the corrosion type, mechanism and expected corrosion rate without mitigation measures.
b. Defining corrosion mitigation strategy and predicting corrosion rate of protected equipment.

The difficulty of creating corrosion models is based on the complexity of corrosion phenomena. We should introduce the properties of both a metal and the environment. These properties are changing with time. The use of Artificial Intelligence will help in the creation of dynamic corrosion models. Corrosion phenomena (corrosion damage) can be complicated and can be classified into two types (Figure 4): uniform (general) corrosion and localized corrosion, and the quantitative description of these two cases is quite different. General corrosion may occur in acidic or alkali solutions. Localized corrosion may be of 15 types with the appearance of pits or cracks [28]. Pits may be the result of galvanic, crevice, erosion, cavitation, or MIC; result of impact CO_2, H_2S, Cl^-, O_2, or under deposits. Cracks may be the result of intergranular corrosion, hydrogen attack, dealloying, fretting corrosion, or SCC. Then, some metals and alloys have passive metastable protective films. Specific corrosion phenomena occur in the chemical industry: corrosion under thermal insulation, dew point corrosion, and corrosion under fouling (undesirable deposits).

Then, environments and conditions in the chemical industry (including oil and gas, oil refining and petrochemical) are very diverse (Figure 5).

For instance, corrosion rate of inner surface of metallic pipelines is influenced by

- inner factors (type of alloy, geometry of pipeline),
- outer factors (oil and water chemistry, CO_2 and H_2S concentrations, pH, the presence of acetic acid, ionic strength, temperature, pressure, flow rate, a quantity of phases, effect of inhibition by crude oil, effect of glycol/methanol),
- conditions at the border metal-environment (formation of protective films, such as ferrous carbonates and sulfides, corrosion inhibitors, electrochemistry of this border).

Such diversity of corrosion processes and appearances complicates corrosion assessment, corrosion mitigation strategy and creation of prediction models (corrosion rate) of protected equipment.

In the general case, prediction of corrosion damage can be done only in probabilistic terms. The best form of predicting localized corrosion damage would be prediction of the probability of failure, P_f [56]:

$$P_f = P_f (a_{cr}; t ; X_i ; Y_i ; S) \quad (2)$$

that is, the probability that at least one corrosion event of any form (pit, crack) reaches some critical depth, a_{cr}*, at a given observation time, t, for any given set of environmental conditions. a - depth of a corrosion event.*

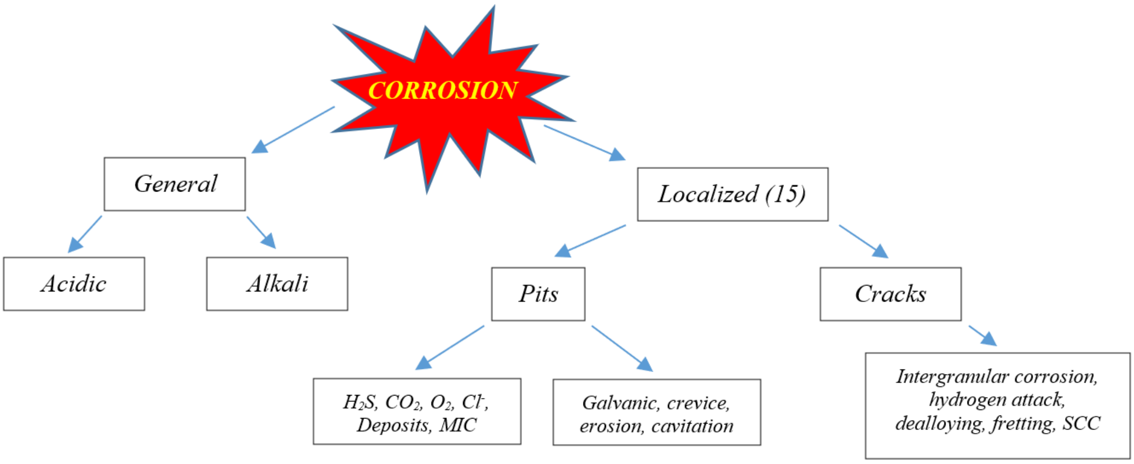
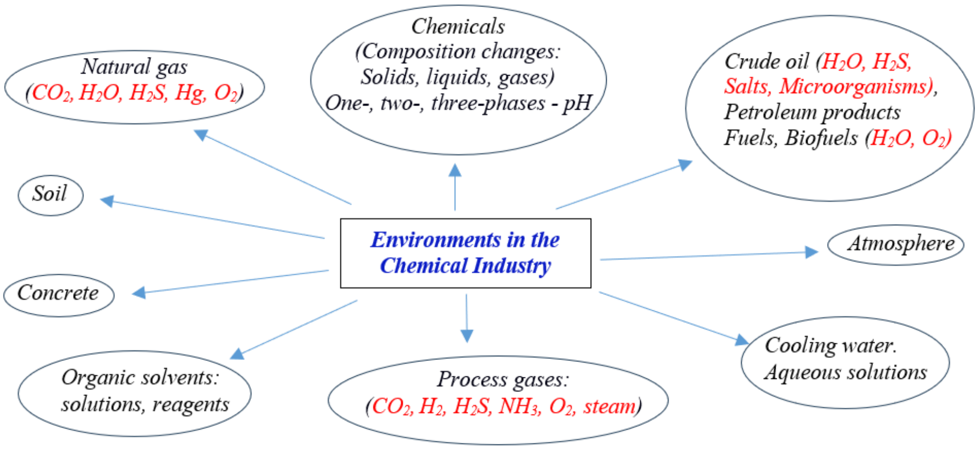


Figure 4. *Corrosion types and their appearances. MIC - microbiologically influenced corrosion. SCC – stress corrosion cracking.*



Conditions: Temperature from -200ºC up to 1,400ºC. Pressure from vacuum up to 1,000 bars.

Figure 5. *Environments and conditions in the chemical industry (including oil and gas, oil refining and petrochemical), Red – corrosive species.*

X_i and Y_i - internal and external independent variables, respectively, that determine the damage propagation rate. Examples of internal variables are grain size and orientation, texture, electrochemical thermodynamic and kinetic parameters, and other microstructural properties. The external variables include loading and environmental conditions (concentrations of corrosive and anti-corrosive species, temperature, flow rate). S – surface area.

Chemical thermodynamics and kinetics are two main subjects that can help in solving corrosion tasks: thermodynamics - to assess the possible direction of corrosion process, and kinetics - to define its velocity. If chemical thermodynamics possesses theoretical means to define the possible direction of corrosion, chemical kinetics has no such apparatus. Only for simple chemical reactions, there are satisfactory models. Corrosion is a complicated physicochemical process including several steps/reactions. Up to now, only kinetic experiments with metal in real environment can give us answers about the forecast about metal behavior.

Despite this statement, numerous corrosion models were created. Detailed consideration and their analysis are beyond the scope of the present paper. I will give only several examples.

Some companies (i.e., Shell Global Solution, USA) developed an information system used to manage corrosion of metals and alloys by high temperature gases found in many different oil refining, petrochemical, power generation, and chemical processes [43]. The database currently represents about 7.9 million hours of exposure time for about 5,500 tests with 89 commercial alloys for a temperature range of 200 – 1,200 °C.

The corrosion mechanisms emphasized are oxidation, sulfidation, sulfidation/oxidation, and carburization. These models have the potential to be used in corrosion research, alloy development, failure analysis, lifetime prediction, and process operations evaluations.

In recent 3-5 years, with the rapid development of AI, machine learning algorithms such as artificial neural network (ANN), support vector regression (SVR) and random forest (RF) have been widely used in various types of corrosion prediction [51].

In order to predict the behavior of AISI 304 stainless steel design of experiment and artificial neural network methods were applied [57]. Experimental research included observation of corrosion and pitting potential on AISI 304 stainless steel at different temperature, pH value and chloride ions concentration. Both models were developed with the aim to predict behavior of corrosion and pitting potential on AISI 304 in different environmental conditions.

A proprietary predictive model has been developed encapsulating data Honeywell`s crude corrosivity Joint Industry Program conducted in 2006-2011 [58]. This prediction model facilitates quantification of corrosion rates as a function of concentration of organic (including naphthenic) acids and active sulfur species, temperature, and wall shear stress, for eight alloys.

There are two main approaches for predicting corrosion damage – empiricism and determinism [56]. 'Determinism' is used in the physics sense to describe a model whose predictions are constrained to the 'physically viable' realm by the natural laws. The term 'determinism' is often used in engineering disciplines to indicate a model that provides a definite output in response to a definite input. 'Empiricism' is the philosophy that everything we can ever know must have been experienced. On the other hand, 'determinism' is the philosophy that we may predict the future from the past via the natural laws. Within the broad class of 'deterministic' models, there can exist 'definite' models that yield a single output for a given set of input values; and probabilistic models, in which the inputs are distributed resulting in a distributed output from which the probability of an event occurring can be estimated. Up to 2000s, the prediction of corrosion damage has been largely based on the application of empirical models and only beginning in 2000s, have deterministic models been developed [56].

Complex systems in the chemical industry are unique, even when they are of the same design, because they endure different operating conditions and histories. All 9 oil refineries in Spain produce similar fuels, but units and equipment work under different burden, capacity, history. Certainly, such conditions complicate the creation of united corrosion model general for all refineries.

Therefore, deterministic models pose many challenges [56]. The most important of these are:

a) Corrosion is an extremely complex phenomenon that depends on a multitude of factors, including the chemistry of the environment, metallurgy, and thermomechanical history of the corroding metal, hydrodynamics of multiphase flow, geometry, stress, temperature, pressure;
b) The lack of information on kinetic parameters of the corroding system. This is a chaotic one, and relevant mathematics should be applied.

Some companies provide domain expertise with an extensive chemistry property database, differentiated thermodynamic and kinetic models and proven software platforms [59, 60]. I personally had conversations with two companies with the aim of confirming where their models were examined. Unfortunately, they did not provide verified data. Therefore, we should be careful using corrosion models.

COLLABORATION IS CRITICAL

Homo sapiens is the only species on the Earth capable of cooperating flexibly in large numbers [61]. Corrosion management should work together with process safety management. Collaboration is critical. Safety and Corrosion should be of concern to everyone: employer, employee, and contractor. This collaboration should be based on competence, control, and communication. Our goal is to be *safe* and *healthy* in the chemical industry, and intention to ZERO emission and environment impact. These goals are unlikely to be achieved without collaboration with corrosion professionals. *Corrosion management* and *process safety management* play a primary role.

FUTURE DEVELOPMENT OR INSTEAD THE END

We solve old corrosion problems with known materials and media. New materials and new hostile media appear as a result of the development of new chemical technologies. Thus, new corrosion problems appear:

- New oil and gas deposits.
- Carbon capture, utilization, and storage.
- Alternative and synthetic fuels.
- Synthesis of new chemicals, drugs, materials.
- New materials for service in new energy systems.
- Hydrogen energy.
- Biomaterials.
- Metal artifacts and the works of art.
- Aging infrastructure.
- Prognosis: creation of corrosion models using AI.

Probably, the French president Georges Pompidou (1911-1974) once said: "*We do not solve problems. We live with problems.*" I may also say that we solve old problems and new ones arise. Thus, we live all time with technological problems …

EPILOGUE

When I nearly finished this paper, I learned about absolutely terrible case when corrosion of pipeline transporting boiling water led to the rupture of pipeline and death of four employees in supermarket in the Moscow shopping center "Seasons" (Vremena Goda) on 22th July 2023 [62]. These four people were boiled in boiling water. Ten victims with severe burns were taken to the hospital. The cause of this criminal case was uncontrolled corrosion of pipeline transporting boiling water. Who was responsible for such cases? HUMANS! They did not connect corrosion risk of pipeline to safety!

Preparing this paper, I wrote a letter to Ronald Willey - one of the prominent leaders in the field of the process safety and the editor of the journal Process Safety Progress. He answered me with interesting data. He did a word search on the "corrosion" in the Process Safety Progress journal for the last 10 years. The word "corrosion" appeared 399 times in Process Safety Progress journal. He sent me the top 20 "corrosion" articles published in this journal. I analyzed these papers and found that there was no systematic and logical methodology in representation of corrosion issues in the Process Safety Progress journal. This situation confirmed that the topic of my paper is important for both engineering subjects, corrosion and process safety [62].

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