الجمهورية الجزائرية الديمقراطية الشعبية
People's Democratic Republic of Algeria
وزارة التعليم العالي والبحث العلمي
Ministry of Higher Education and Scientific Research

20 August 1955 – Skikda University
Faculty of Technology
Process Engineering Department

جامعة 20 أوت 1955 سكيكدة
كلية التكنولوجيا
قسم هندسة الطرائق

Ref: D012125022D

Thesis

Submitted in partial fulfilment of the requirements for the degree of: LMD Doctorate

Risk management and control related to fixed pressurized equipment failure

Presented and defended on:

24/05/2025

Field of study: Industrial health and safety

Specialization: Industrial health and safety

by:

Khawla DIB

In front of the jury:

President:	Pr. Lilia ZIGHED	U-20 Août 1955. Skikda
Thesis supervisor:	Pr. Youcef ZENNIR	U- 20 Août 1955. Skikda
Co-supervisor:	Dr. Hichem BOUNEZOUR	U- 20 Août 1955. Skikda
Examiner:	Pr. Fares INNAL	U-20 Août 1955. Skikda
Examiner:	Pr. Hamid BENTARZI	U- Boumerdess
Examiner:	Dr. Yamina boudinar	20 Août 1955. Skikda

Year: 2024/2025

ملخص

المعدات الثابتة ذات الضغط، مثل الفاصل والمفاعلات والسخانات وخزانات التخزين، هي جزء أساسي من التشغيل الآمن لمنشآت النفط والغاز. حسب ظروف التشغيل، يمكن أن تحدث عدة آليات للتلف تؤدي إلى الفشل. إن إدارة المخاطر المرتبطة بهذه الأصول أمر بالغ الأهمية لمنع الحوادث والتسريبات والفشل الذي قد يؤدي إلى أحداث كارثية. يضمن نهج إدارة المخاطر القوي الحفاظ على سلامة هذه المعدات طوال دورة حياتها. أنابيب سخانات المصلح التحفيزي، التي تعمل تحت درجات حرارة وضغط وبيئات تآكلية قاسية، معرضة لعدة آليات تلف قد تؤدي إلى الفشل. لتقييم هذه المخاطر، يتم استخدام مزيج من تقنيات الفحص لتحديد آليات التدهور الرئيسية. بناءً على هذه النتائج، سيتم إجراء دراسة فحص قائم على المخاطر (RBI) لتطوير استراتيجية فحص مستهدفة تهدف إلى التخفيف من المخاطر المحددة. بالإضافة إلى ذلك، يتم اقتراح عدة توصيات لمنع حدوث أضرار مشابهة في المستقبل، مما يعزز السلامة وموثوقية المعدات.

الكلمات المفتاحية: أنابيب السخانات، فولاذ سبائكي فيريتيك، سلامة العمليات، صيانة وقائية، تفتيش قائم على المخاطر

Abstract

Fixed pressurized equipment, such as separators, reactors, heaters and storage tanks, are integral to the safe operation of oil and gas facilities. Depending on the operating conditions, several damage mechanisms can occur and lead to failure. Managing the risks associated with these assets is critical to preventing accidents, leaks, and failures that could lead to catastrophic events. A robust risk management approach ensures that the integrity of this equipment is maintained throughout its lifecycle. catalytic reformer heater tubes, operating under extreme temperatures, pressure, and corrosive environments, are prone to various damage mechanisms that can lead to failure. To assess these risks, a combination of inspection techniques is used to identify the key degradation mechanisms. Based on these findings, a Risk-Based Inspection (RBI) study will be conducted to develop a targeted inspection strategy aimed at mitigating identified risks. Additionally, several recommendations are proposed to prevent similar damage in the future, enhancing both safety and equipment reliability.

Key words: Heater tubes, ferritic alloy steel, process safety, preventive maintenance, risk-based inspection

Résumé

Les équipements statiques sous pression, tels que les séparateurs, les réacteurs, les fours et les réservoirs de stockage, sont essentiels à la sécurité des opérations dans les installations pétrolières et gazières. En fonction des conditions d’exploitation, plusieurs mécanismes de dégradation peuvent survenir et entraîner des défaillances. La gestion des risques associés à ces actifs est cruciale pour prévenir les accidents, les fuites et les défaillances qui pourraient entraîner des événements catastrophiques. Une approche solide de gestion des risques garantit que l’intégrité de cet équipement est maintenue tout au long de son cycle de vie. Les tubes de fours catalytiques, qui opèrent sous des températures extrêmes, des pressions élevées et des environnements corrosifs, sont sujets à divers mécanismes de dégradation pouvant conduire à des défaillances. Pour évaluer ces risques, une combinaison de techniques d’inspection est utilisée afin d’identifier les principaux mécanismes de dégradation. Sur la base de ces constatations, une étude d’inspection basée sur les risques (RBI) sera réalisée pour développer une stratégie d’inspection ciblée visant à atténuer les risques identifiés. De plus, plusieurs recommandations sont proposées pour prévenir des dommages similaires à l’avenir, améliorant ainsi la sécurité et la fiabilité des équipements.

Mots-clés : tubes des fours, maintenance préventive, sécurité des procédés, Inspection basée sur les risques.

Acknowledgments

First and foremost, I express my deepest gratitude to Allah, the Almighty, for granting me the will, health, and patience throughout my years of study.

I would like to extend my heartfelt thanks to Professor Youcef ZENNIR, my thesis supervisor, Professor at the University of Skikda, and head of the Institute of Applied Technological Sciences. This thesis is the result of more than four years of collaboration with him. It is under his guidance that I truly learned the significance of rigor and precision.

I am also deeply grateful to Professor Hichem BOUNEZOUR, my co-supervisor and Doctor at the University of Skikda, for his continuous support throughout this research. I am thankful for the brilliant insights he shared with me, as well as his kindness, constant availability, and the numerous words of encouragement he offered me.

My sincere thanks also go to Professor Lilia ZIGHED, Professor at the University of Skikda, for graciously agreeing to chair the defense jury.

I would like to express my gratitude to Professor Fares INNAL, Professor at the University of Skikda, as well as to Professor Hamid BENTARZI, Professor at the University of Boumerdes, and Doctor Yamina BOUDINAR, Professor at the University of Skikda, for kindly agreeing to serve as examiners.

Lastly, I am deeply appreciative of all the persons who helped me to accomplish this work.

To my parents

To my husband

To my sisters

To my brother

To all my loved ones

Table of contents

Abbreviations, acronyms

ALARP	As Low As Reasonably Practicable
ANSI	American National Standards Institute
API	American Petroleum Institute
ARH	Autorité de Régulation des Hydrocarbures (Hydrocarbon Regulatory Authority)
ASME	Analyse des Modes de Défaillances, de leurs Effets et de leurs Criticité
ASSE	American Society of Safety Engineers
ASTM	American Society for Testing and Materials
BPVC	Boiler and Pressure Vessel Code
CA	Corrosion Allowance
CFR	Code of Federal Regulations
CR	Corrosion Rate
CUI	Corrosion Under Insulation
DCR	Design Corrosion Rate
DCS	Distributed Control System
DMT	Design Metal Temperature
DPT	Dye Penetrant Testing
ECR	Estimated Corrosion Rate
ESD	Energy Dispersive X-ray Spectroscopy
FCA	Future Corrosion Allowance
FFS	Fitness-For-Service
HSE	Health, Safety and Environment
HSE MS	Health, Safety, and Environment Management System
HT	Hardness Testing
HTHA	High-Temperature Hydrogen Attack
IEC	International Electrotechnical Commission
IF	Infrared Thermography
IRIS	Internal Rotary Inspection System
ISA	Instrument Society of America
ISO	International Organization for Standardization

LT	Long Term
MCR	Measured Corrosion Rate
MI	Mechanical integrity
MT	Magnetic Testing
NDT	Non-Destructive Testing
OSHA	Occupational Safety and Health Administration
OD	Outside Diameter
OHSAS	Occupational Health and Safety Assessment Series
VPP	Voluntary Protection Programs
P&ID	Piping & Instrumentation Diagram
PE	Pressurized Equipment
PEMS	Pressurized Equipment Management System
PFD	Process Flow Diagram
POF	Probability of Failure
PSM	Process Safety Management
PS-MS	Process Safety management system
PT	Penetrant Testing
RBI	Risk Based Inspection
RP	Recommended Practices
RRT	Pulse Eddy Current Testing
SCH	Schedule
SCR	Selected Corrosion Rate
ST	Short Term
TEMA	Tubular Exchanger Manufacturers Association
UT	Ultrasonic Testing
UTG	Ultrasonic Thickness Gauging
UTS	Ultimate Tensile Strength
VI	Visual Inspection

List of figures

List of tables

General Introduction

1. Problem statement

The integrity of static pressurized equipment is essential for ensuring the safety and reliability of industrial operations. These types of equipment, including furnace tubes, operate in extreme conditions characterized by high temperatures, high pressures, and exposure to corrosive atmospheres. Such environments subject the equipment to complex stresses that can lead to material degradation overtime [1]. Depending on the operating conditions, various damage mechanisms may emerge, compromising the integrity of the equipment and increasing the risk of failure. Fatigue caused by repeated mechanical or thermal loading cycles can result in the formation of cracks, eventually leading to structural failure. Corrosion, driven by chemical reactions between the equipment surface and the surrounding atmosphere, is further exacerbated by high temperatures, weakening the material. In addition, thermal degradation processes, such as oxidation, creep, carburization, and softening, are prevalent under prolonged exposure to elevated temperatures, significantly reducing the material's strength and reliability [2,3].

For heater tubes, these challenges are particularly severe due to their continuous exposure to high radiant heat, combustion byproducts, and fluctuating operational conditions. Failures in heater tubes are critical as they often lead to loss of containment, which poses significant safety, operational, and financial risks. Loss of containment can result in the release of flammable or toxic substances, endangering personnel and the environment. Operational disruptions caused by unplanned shutdowns can lead to significant production losses, while the associated repair costs and potential penalties can have a substantial economic impact. The integrity of heater tubes is therefore a critical factor in ensuring both operational safety and performance.

Understanding the root causes of heater tube failures is imperative to address these challenges effectively. High operating temperatures beyond design limits can lead to overheating, weakening the tube material and accelerating damage. Internal fouling caused by deposits on internal surfaces reduces heat transfer efficiency, causing localized overheating and increasing the risk of failure. On the external surfaces, oxidation and scaling caused by high oxygen levels and temperatures further accelerate degradation, forming insulating layers that reduce efficiency and compromise structural integrity. These factors combined create a complex environment where the risk of failure grows if not managed proactively.

This thesis seeks to address these challenges by exploring the main causes of failures and loss of containment in furnace tubes while investigating effective mitigation strategies. The research focuses on identifying the key damage mechanisms, including thinning, thermal fatigue, creep, and other degradation processes that affect the performance of heater tubes. Furthermore, it emphasizes the application of a risk-based inspection (RBI) approach, which prioritizes inspection and maintenance activities based on the likelihood and potential consequences of failures. By integrating a detailed analysis of damage mechanisms with an RBI framework, this study aims to enhance operational safety by reducing the likelihood of catastrophic failures, improve equipment reliability through proactive maintenance, and minimize economic losses by optimizing inspection intervals and reducing unplanned shutdowns.

The research explores the following question: What are the main causes of failures and loss of containment in furnace tubes, and how can the identification of damage mechanisms, combined with a risk-based inspection (RBI) approach, contribute to improving operational safety and reducing the costs associated with unplanned shutdowns?

Studies, such as those by Viswanathan et al. (1995), emphasize the importance of understanding high-temperature failure modes like creep and thermal fatigue in optimizing the design and operation of heater tubes. The use of API 571 has proven effective in categorizing these mechanisms systematically [4].

Research by Khan et al. (2004) demonstrates how RBI methodologies, aligned with API 580/581, enable industries to prioritize inspection efforts based on the likelihood and consequence of failures. This approach enhances resource allocation and reduces the probability of unexpected failures [5].

Multiple case studies, such as those documented by Hertzberg et al. (2014), show the value of employing non-destructive evaluation (NDE) techniques, such as ultrasonic testing and replica metallography, to detect early-stage damage in heater tubes. These techniques, combined with regular monitoring, are essential for extending the lifespan of equipment [6].

To address the previous question, in our thesis, we explore the integrity and risk management of fixed pressurized equipment in the oil and gas industry, emphasizing safety and reliability. We begin by highlighting the critical role of maintenance and inspection in mitigating risks such as corrosion and thermal fatigue. Through the lens of Process Safety Management (PSM), we discuss essential safety frameworks, focusing on hazard evaluation and operational risk mitigation. We then analyze damage mechanisms in catalytic reforming furnace tubes, particularly the impact of oxidation and scaling on their longevity. Finally, we demonstrate the practical application of Risk-Based Inspection (RBI) methods, aligning with API RP 580 standards, to identify high-risk areas and enhance inspection strategies. This work integrates theoretical insights and practical applications, contributing to proactive risk management and operational efficiency.

2. Objective

Based on the above, the objectives of this thesis are summarized below.

- The first objective is to enhance the understanding of the industrial process safety management approach, particularly regarding static pressure equipment, with an emphasis on mechanical integrity.
- The second objective is to identify the damage mechanisms that affect catalytic reforming furnaces, drawing on API 571 and 573 standards, and to carry out a detailed damage analysis on a catalytic reformer heater tube.

- The third objective of this doctoral thesis is to conduct a risk-based inspection study, with the goal of developing an effective inspection plan centered on component criticality or risk. This approach aims to enhance inspection efficiency by precisely defining how, where, when, and what to inspect.
- The fourth and the final objective is to provide practical recommendations to strengthen tube integrity, improve industrial operational safety, and reduce costs associated with failures and unplanned downtime.

3. Thesis organization

To meet the stated objectives, this manuscript has been divided into four chapters.

The first chapter introduces the foundational concepts that underpin this thesis. It begins with an overview of fixed pressurized equipment in the oil and gas industry, focusing on their maintenance, inspection practices, and the critical role they play in operational integrity. Additionally, we identify the common risks and potential failures associated with such static equipment, setting the stage for the subsequent analysis.

The second chapter provides an in-depth exploration of Process Safety Management and its significance in industrial safety. We start by examining management systems in general, creating a foundation for understanding how PSM functions within the broader safety framework. The discussion then shifts to the core elements of an effective PSM system, emphasizing its role in minimizing operational risks. A detailed risk management process follows, where we analyze the methodologies used for risk assessment, focusing on identifying, evaluating, and mitigating hazards in industrial operations.

In the third chapter, we explore the concept of mechanical integrity, specifically focusing on damage mechanisms affecting catalytic reforming furnace tubes. A detailed damage analysis was performed on Ferritic Alloy Steel Heater Tubes in a catalytic reforming unit, utilizing various inspection techniques such as visual inspection, microstructure examination, metallography, and mechanical properties testing. The results reveal extensive oxidation and scaling on the external tube surfaces, primarily due to operational conditions that exceeded recommended limits. The findings highlight critical factors impacting the longevity and integrity of furnace components.

The fourth chapter outlines the principles of the risk-based inspection (RBI) approach, with emphasis on key parameters such as the probability and consequences of failure in oil and gas processes, following the API RP 580 standard. A practical case study is presented, focusing on the application of the RBI methodology in identifying high-risk areas within the furnace. The analysis delves into specific scenarios where the heater is exposed to heightened risk of failure, discussing the potential consequences for operational safety and plant productivity. This chapter demonstrates the value of a risk-based approach in preventing incidents, improving inspection strategies, and supporting informed decision-making. The case study results are critically analyzed to showcase the effectiveness of RBI in proactive risk management

Chapter 1

State of the art on Fixed Pressure Equipment and the Associated

1.1. Introduction

Fixed pressure equipment are critical components used throughout all stages of oil and gas operations, from initial separation to processing, conditioning, treating, and storage. Ensuring their safety is paramount to maintaining the integrity of the entire process [7, 8].

This chapter is first dedicated to the main basic concepts presented in this thesis. Then, the fundamentals of fixed pressurized equipment are described in sufficient detail, particularly regarding their maintenance and inspection. Finally, common risks and failures associated with fixed pressurized equipment are discussed at the end.

1.2. Basic Concepts

In order to simplify the reading of this document, we will first begin with a clarification of the main terms used.

1.2.1. Concept of a System

The term "system" can be understood in various ways. For the purpose of this discussion, we will adopt the following definitions:

The ISO and IEC 15288 standard defines a system as "a combination of interacting elements organized to achieve one or more stated purposes" [1, 9].

According to the American National Standards Institute, a system refers to a collection of components arranged to perform a specific function or a set of functions [2, 10].

API 580 describes a system as a group of equipment assembled to perform a specific function within a process unit. Examples include service water systems, distillation systems, and separation systems [11].

Rob Dekkers defines a system as a collection of elements within the total reality, distinguished based on the investigator's objectives. These elements must have at least one relationship with another element in the system and may also interact with elements outside the system [12].

1.2.2. Concept of Equipment

Equipment, as described by various standards and organizations, encompasses a wide array of physical assets used in processes and systems.

- According to ISO 14224 : 2016, equipment includes hardware items such as machinery, devices, tools, instruments, and apparatus that are integral to a process [13].
- API 580 defines equipment as individual items within a system [11].

The ASME Boiler and Pressure Vessel Code defines equipment as any machinery, apparatus, or device involved in boiler or pressure vessel operation, including associated accessories [14].

OSHA, under 29 CFR 1910, describes equipment as machinery, tools, or other devices used in the workplace, emphasizing the need for maintenance and safety measures to ensure proper operation and protect worker safety [15].

1.2.3. Concept of Risk

Risk is commonly defined as the combination of probability and consequences, where consequences relate to health, safety, or other objectives, such as loss of life or injuries. This aligns with the ISO definition.

According to ISO 31000, risk is defined as a combination of an event's consequences and its likelihood, with key terms explained as follows:

- Event: An occurrence or alteration in circumstances.
- Consequence: The result of an event impacting objectives.
- Likelihood: The probability or chance of an event occurring assessed using qualitative or quantitative methods and expressed in general terms or mathematically.

Risk is often described mathematically as the product of probability and consequences (expected value). This concept is reflected in standards such as OHSAS 18001, which defines risk as the combination of the likelihood of a hazardous event or exposure and the severity of resulting injury or illness [16, 17].

Mathematically, risk is often represented by the following equation:

$$\boldsymbol{R} = \boldsymbol{P} \times \boldsymbol{G} \qquad (1.1)$$

Where P denotes the probability of a hazardous event occurring, while G represents the severity of its consequences.

1.2.4. Concepts of Failure

Failure is defined across various standards, with slight variations based on context:

- ISO 26262-1 Failure is defined as the cessation of an element's or item's intended function, due to the occurrence of a fault, which is an abnormal condition that can lead to failure. [18].
- IEC 61508-4 describes failure as the inability of a functional unit to perform its required function or as operating in a way other than intended [19].
- API 570 defines failure as the loss of a system, structure, equipment, or component's ability to contain fluid, often referred to as "loss of containment." Failures may be:
    - Unannounced: Occurring without immediate detection (e.g., slow leaks under insulation or buried piping).
    - Announced: Detected immediately through noticeable signs (e.g., ruptures or sudden pressure drops) [20].

1.2.5. Concepts of Safety

Safety is defined differently across various standards, but all emphasize the goal of minimizing risk:

- ISO, IEC Guide 51 defines safety as "the absence of intolerable risk" [21].
- The American Department of Defense expands this to include "the absence of conditions that can cause death, injury, occupational illness, damage or loss of equipment or property, or harm to the environment" [22].
- IEC 61508 describes safety as freedom from unacceptable risk [19].
- Fares Innal defines it as "the ability of a system to operate or fail without causing a dreaded event against itself and its environment, particularly humans." This ability is assessed based on applicable risk criteria, with peak safety achieved when only negligible or acceptable risks are present [23].

1.3. Fundamentals of Fixed Pressurized Equipment

1.3.1. Definition and Purpose

Fixed equipment, also known as static equipment, refers to non-mobile equipment used in the oil and gas and process industries such as pressure vessels. Conversely, fixed equipment excludes machinery such as pumps, compressors, turbines, electrical systems, and instrumentation, even though these devices typically remain stationary during operation.

1.4. Types of fixed pressure equipment and working principles

1.4.2. Heat Exchanger

A heat exchanger, as defined by international standards like ASME Section VIII (for pressure vessels) and TEMA Standards, An apparatus intended to enable the efficient conduction of heat between two or more fluids is called a heat exchanger. These fluids can be liquids, gases, or a mix of both, and the heat transfer occurs through mechanisms such as conduction and convection. [14, 24].

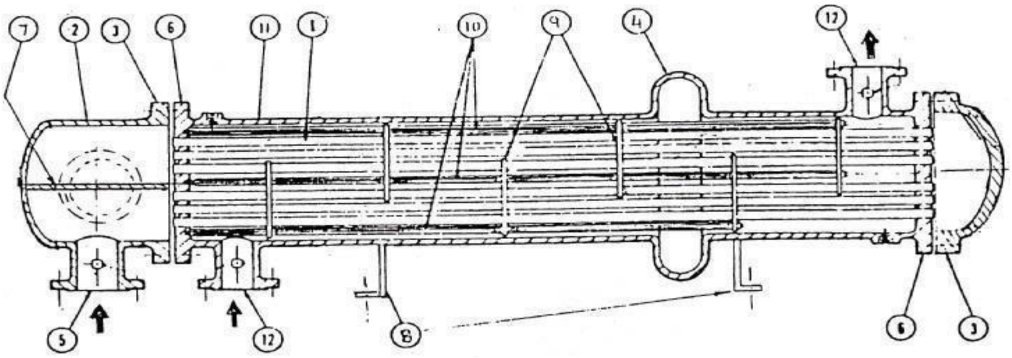
1.4.2.1. Function of Heat Exchangers

According to API 660 Heat exchangers serve several functions:

- Cooling function: Cools the process fluids without phase change, includes coolers, air coolers, and final coolers.
- Condensation function: Condenses process vapor stream. Hence involves a phase change, includes condensers and air condensers.
- Heating function: Employs steam or a heated process stream to heat or vaporize the feed to processing unit, Includes heaters, preheaters, economizers, and superheaters.
- Vaporization function: includes vaporizers, reboilers, and steam generators [25].

1.4.2.2. Types of Heat Exchangers

The choice of a heat exchanger for a given application relies on various factors, such as fluids physical properties and aggressiveness, as well as the operating temperatures and pressures. Space constraints and maintenance requirements must also be considered, along with economic factors. Clearly, having a well-suited, properly sized, well-constructed, and effectively used heat exchanger enhances efficiency and reduces energy consumption in processes. A heat exchanger is fundamentally a device that transfers heat from a hot fluid to a cold fluid. They are widely used in process plants and are often given specific names based on their particular function. [8, 26]. The heat exchangers components are illustrated in figure 1.1.



1 Tubes

2 Stationary Head

3 Stationary Head Flange

4 Expansion Joint

5 Stationary Head Nozzle

6 Tube Sheet

7 Pass Partition

8 Support Saddle

9 Transverse Baffles

10 Tie Rods

11 Shell

12 Shell Nozzle

Figure 1.1: Heat exchangers components [24].

The three primary types of shell-and-tube heat exchangers are the fixed tube sheet design, U-tube design, and floating-head design. In these configurations, the front-end head is fixed, while the rear-end head may either be fixed or floating, as illustrated in Figure 1.2.

The selection of this configuration depends on the thermal stresses in the shell, tubes, or tube sheet, which arise from temperature variations due to heat transfer [26].

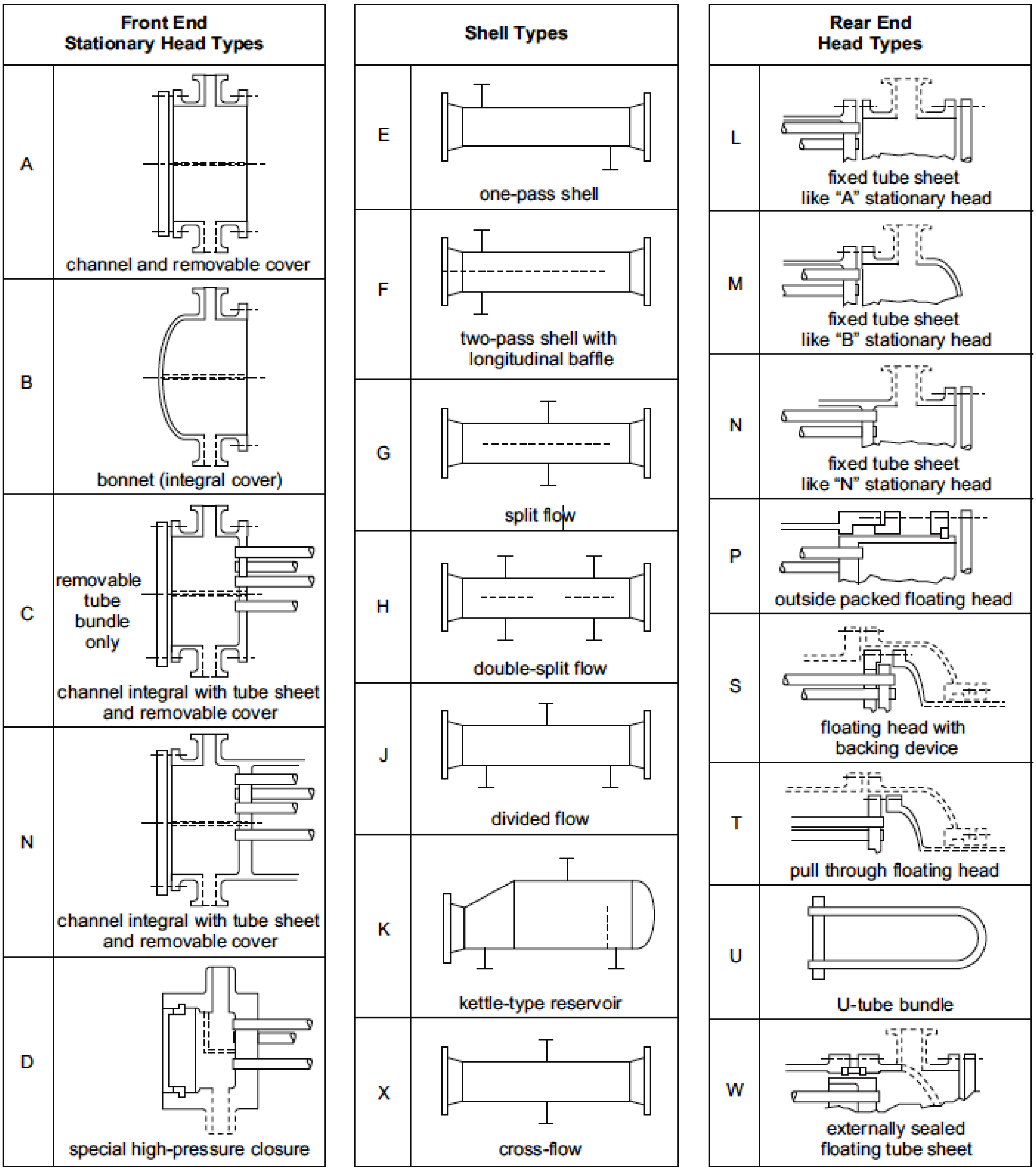


Figure 1.2: Standard shell types and front- and rear-end head types [24, 26].

1.4.3. Storage Tank

Storage tanks play a critical role in refinery, chemical, and petrochemical operations by holding various fluids. The type, size, and construction materials of the tank are influenced by factors such as the fluid's quantity, volatility, chemical properties, corrosiveness, as well as the required storage pressure and temperature.

1.4.3.1. Non-pressurized Storage (at atmospheric pressure)

An atmospheric storage tank refers to any tank designed to be used with a few psi above or below the atmospheric pressure. It is commonly used to store liquids that remain stable at ambient temperature (the absolute vapor pressure at ambient is less than 1.013 bar). In industry, two common types of tanks are fixed-roof and floating-roof tanks [27].

- Fixed Roof Tank:

These are generally tanks with vertical cylindrical walls, with either a flat or domed bottom. They can have a conical or domed roof. The figure 3 represents a corn roof tank and its components.

Fixed cone roof tanks are the most widely used type of atmospheric tanks, Fixed cone roof tanks are typically designed with diameters of up to 300 feet (91.5 meters) and heights of 64 feet (19.5 meters), though larger tanks can be constructed. These roofs are generally supported by internal rafters, girders, and columns. However, smaller tanks with diameters of 60 feet (18.3 meters) or less may be self-supporting.

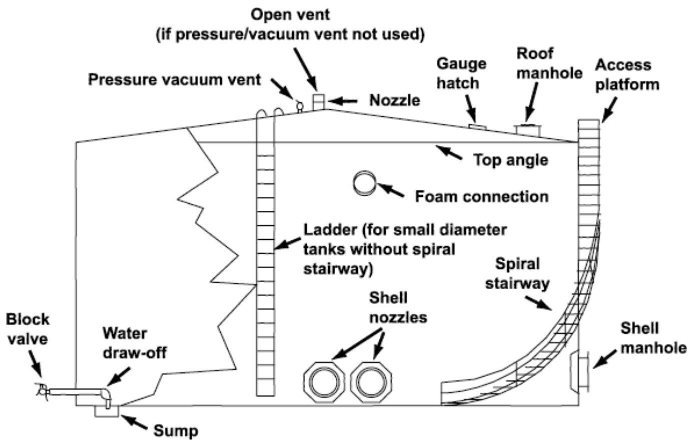


Figure 1.3: Cone Roof Tank [28].

- Floating roof:

Floating Roof Tanks are commonly used atmospheric storage tanks designed to reduce hydrocarbon vapor losses during filling and emptying by floating on the stored liquid. These tanks minimize vapor space or maintain a small, consistent one. The shell and bottom resemble those of cone roof tanks, with the annular-pontoon type being the most common. For larger tanks, a double-deck design is used for added stability [27, 28]. Figures 1.4 and 1.5 illustrate these tanks.

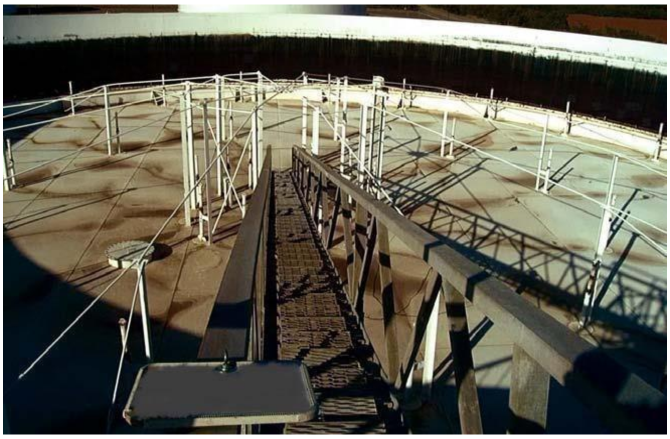


Figure 1.4 Pan-type floating-roof tank [27].

- Internal Floating Roof (With Fixed Roof):

Fixed Roof tanks with Internal Floating Roofs typically feature a cone roof storage tank that houses a floating roof inside, which may be of the pan-type, panel-type, or pontoon-type. This roof, referred to as the internal floating roof, can be made from materials like aluminum or plastic, in addition to steel. Figure 5 provides this type of roof.

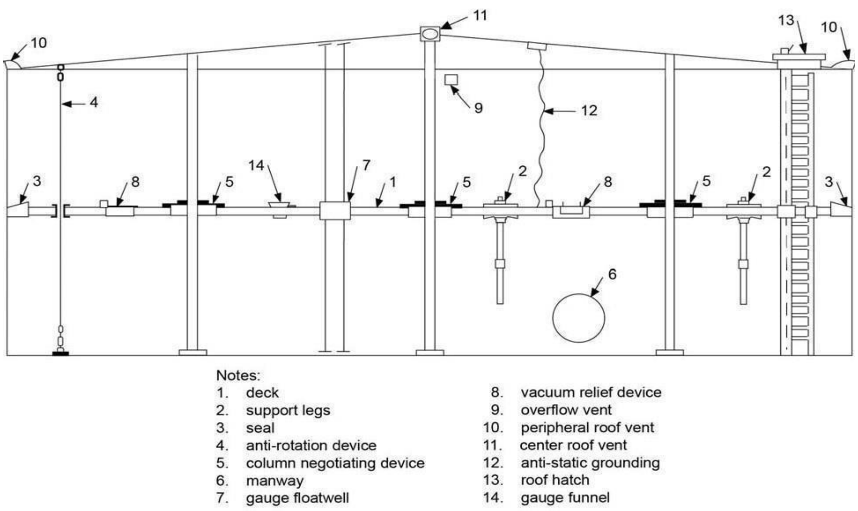


Figure 1.5: typical internal floating roof components [27].

The internal floating-roof tank offers the advantages of a floating roof in terms of reducing evaporation while the fixed roof provides protection from weather conditions. The tank is shaped like an inverted bowl and does not require a drainage or snow removal system [28].

1.4.3.2. Pressurized Storage Tanks

Pressurized storage is designed to store volatile liquids with a boiling point equal to or lower than ambient temperature and an absolute vapor pressure at ambient equal to or greater than 1.013 bars. This applies to horizontal cylindrical tanks, spheres, underground storage, storage under embankments. Figure 1.6 shows a spherical pressurized storage tank [19].

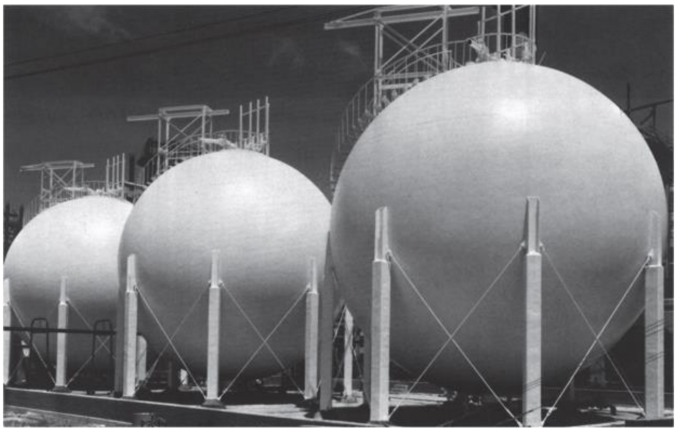


Figure 1.6: Spherical pressurized storage tank [26].

1.4.3.3. Refrigerated Storage

Refrigerated storage is intended for liquefied gases maintained at temperatures close to or below 0°C, allowing for lower storage pressures. This method typically utilizes insulated aboveground spheres shown in figure 1.7. Additionally, double-wall insulated tanks feature an inner tank for the refrigerated liquid and an outer tank providing insulation, with different design and testing requirements for each layer to ensure safety and functionality, it is represented in figure 1.8 [29, 30].

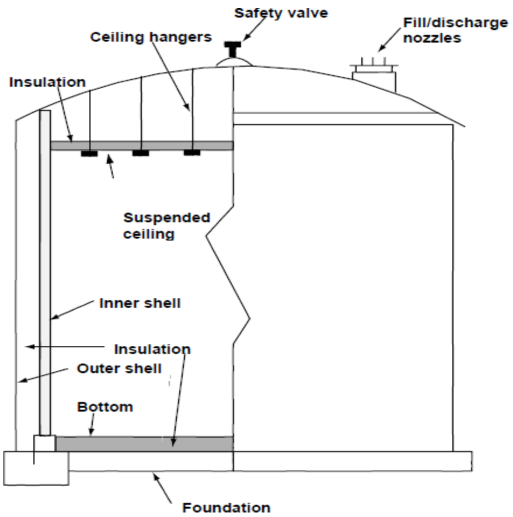


Figure 1.7: Double-Walls, Low-Temperature Storage Tank [28].

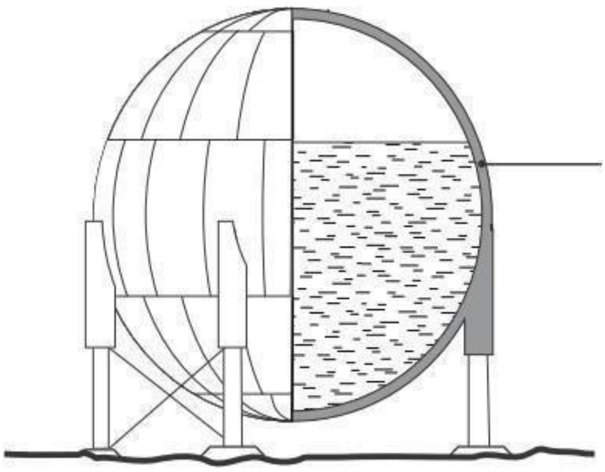


Figure 1.8: Refrigerated insulated sphere [31].

1.4.4. Separators

A separator is a pressure vessel designed to induce a slowdown in the flow rate of effluent, facilitating the separation of fluids based on density differences. Typically presented as a cylindrical tank with nozzles equipped with valves and measuring instruments for operational control, separators allow heavier liquids to accumulate at the bottom while lighter gases escape from the top.

1.4.4.1. Types of Separators

The two primary types of separators are vertical and horizontal. The vertical separator features a cylindrical body with domed caps at both ends, where effluent enters laterally and is given a circular motion by a deflector, promoting primary separation. The resulting liquid flows down the walls into a settling chamber, while free gas rises and exits through the upper outlet. In contrast, the horizontal separator operates similarly but is oriented horizontally, which eases loading, transport, and installation. In this design, effluent enters through one end, disperses in the primary chamber, and allows gases to escape upwards while liquids settle in the chamber. Remaining mist is removed through a tranquilization section and a mist extractor [32, 26]. The figure 1.9 represents a horizontal separator.

Figure 1.9: horizontal separator [26].

In our thesis, we will thoroughly examine the problems and failures associated with static pressure equipment, with a particular focus on fired heaters.

1.4.5. Fired Heaters

Heaters are industrial device that transfer heat from burning fuels, such as natural gas, oil, or other hydrocarbons, to process fluids. Widely used in refining, petrochemical production, and chemical processing, fired heaters transfer heat directly from combustion gases to fluids circulating through tubular coils. To maximize heat recovery, these gases move rapidly through a tube bundle, where most of the heat exchange takes place by convection, in what is known as the convection section [2].

Tubular fired heaters are available in various designs, such as box, cylindrical, and cabin types. In these heaters, radiant tubes in the radiant section absorb heat mainly through radiation from the burner flame and flue gases. Shield tubes at the entrance to the convection section absorb both radiant and convective heat, protecting the other tubes from excessive heat. The convection section transfers heat primarily through convection, with finned or studded convection tubes increasing the surface area for heat transfer. In some cases, the lowest rows of convection tubes absorb more heat than the radiant tubes. [2, 33].

1.4.5.1. Fired Heaters Types

The selection of a furnace type is primarily influenced by factors such as the characteristics of the heated product, operating conditions (including flow rate, temperature, and pressure), the presence or absence of a catalyst in the tubes, the type of fuel used, space requirements, ease of construction or transport, and the cost for a given application.

As outlined in API 560, fired heaters are classified into three primary configurations vertical cylindrical heaters, cabin heaters, box heaters.

Figures 1.10 and 1.11 respectively illustrate typical heater types and common burner arrangements.

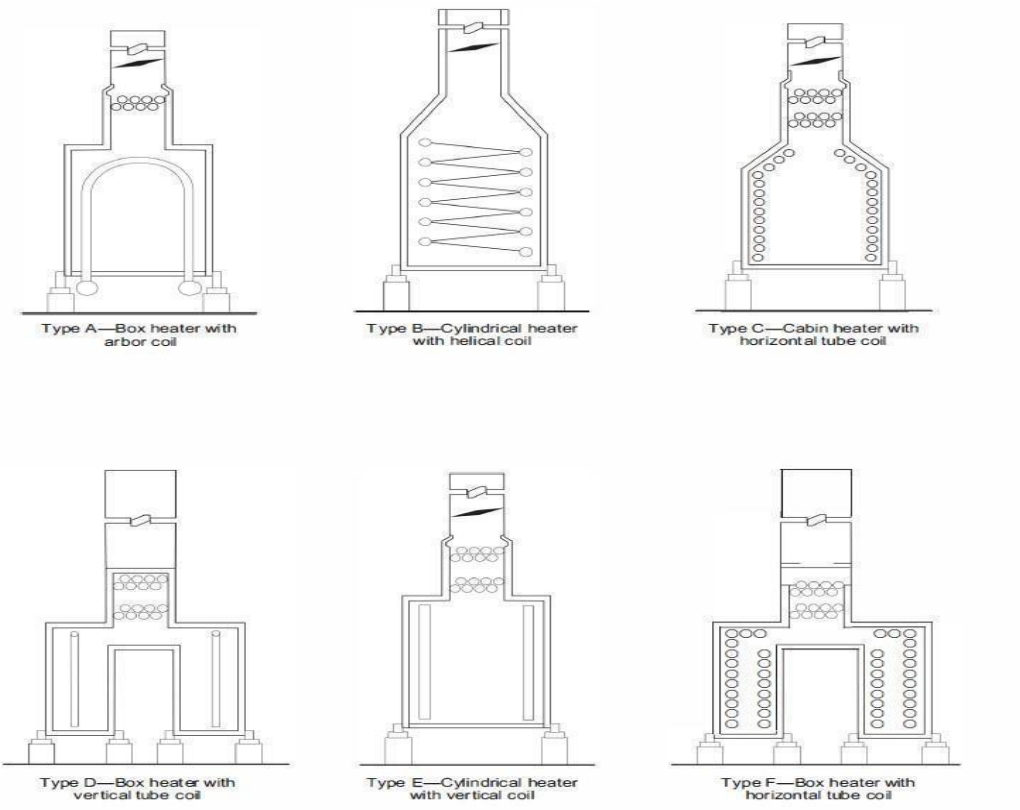


Figure 1.10: Typical Heater Types [33].

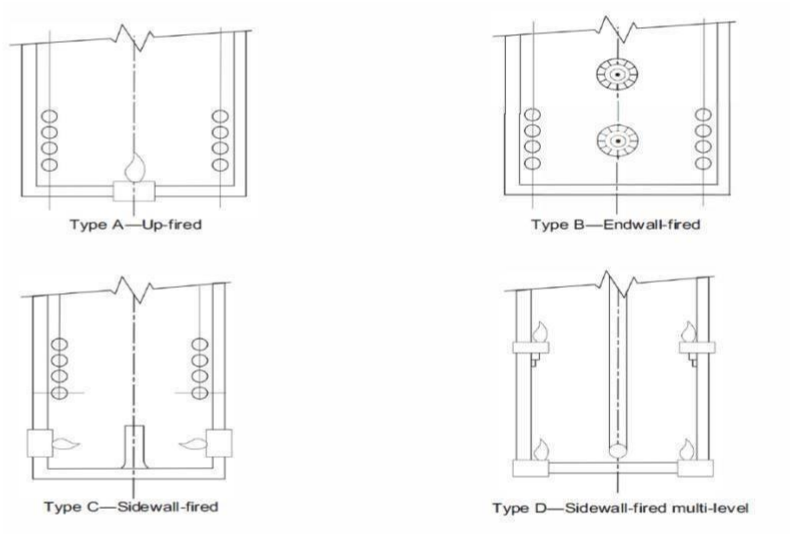
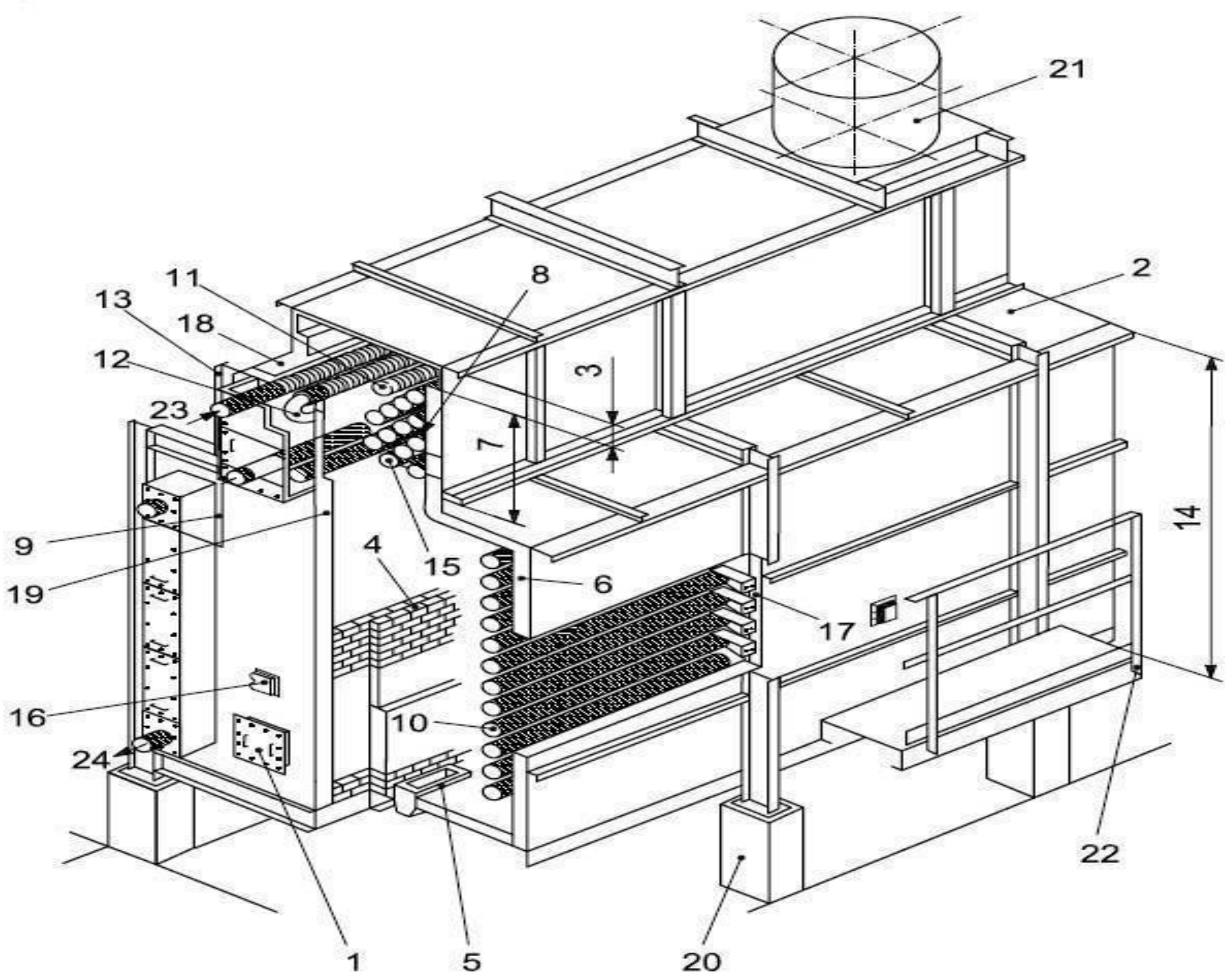


Figure 1.11: Elevation View of Typical Burner Arrangements [33].

1.4.5.1.1. Box-type Heaters

A box-type heater has a box-like structure with various tube coil configurations, such as horizontal, vertical, or arbor setups. Figure 1.12 illustrates a typical box-type heater with a horizontal coil and highlights its main components. The heater's design allows for zones with varying heat densities, and the tube arrangement depends on the heater's intended use , required heating surface, and flow rate. Box-type heaters typically feature updraft or downdraft designs, with gas or oil-fired burners positioned at the end, side wall, or floor, or sometimes in the roof. Additionally, auxiliary tubes are often included to preheat combustion air or generate/superheat steam.



Key

1	access door	7	convection section	13	header box	19	end-tube sheet
2	arch	8	corbel	14	radiant section	20	pier
3	breeching	9	crossover	15	shield section	21	stack/duct
4	bridgewall	10	tubes	16	observation door	22	platform
5	burner	11	extended surface	17	tube support	23	process in
6	casing	12	return bend	18	refractory lining	24	process out

Figure 1.12: Heater Components [33].

- Arbor Coils heaters

These heaters are commonly used in catalytic reforming units for preheating and reheating, as well as for heating process air or gases. These heaters feature a radiant section made up of inlet and outlet headers connected by inverted or upright L or U tubes arranged in parallel. The convection section consists of conventional horizontal tube coils. [2, 33].

- Vertical Coils Heaters

A vertical coil heater can be installed in either a cylindrical or rectangular (box-type) heater. Typically, these heaters are bottom-fired, with the stack positioned directly on top of the unit. In some specialized applications, such as steam-methane reformers, down-fired vertical heaters may also be used [2, 33].

1.4.5.1.2 Cylindrical Heater

This type of heaters has a cylindrical design; they are generally smaller in volume compared to cabin heaters, widely used for heating fluids, gases, or processes in various applications [2, 33].

- Helical Coils heaters

They are cylindrical in shape, with the radiant section designed as a spiral coil that ascends along the heater's wall. If a convection section is included, it may feature a flat spiral arrangement or a series of horizontal tubes [2, 33].

- Cylindrical heaters with Vertical Coils (same as 3.3.1.2).

1.4.5.2. Tube Material Selection

The choice of materials for heater tubes is based on the required design temperature and pressure requirements, as well as the anticipated damage mechanisms associated with the process. Table 1.1 provides a list of common tube materials along with their corresponding ASTM tube or pipe specifications. The design metal temperature (DMT), which defines the upper threshold of rupture strength reliability, can be referenced in API 530. Tube wall calculations must be conducted in accordance with API 530 to evaluate the tube's durability at these temperatures. However, other considerations, such as hydrogen partial pressure and oxidation resistance, could impose more stringent lower temperature limits. For further details, consult API 941.

Table 1.1: Common Heater Tube Metallurgies [2].

Material Seamless Tube	Specification	Seamless Pipe
Carbon Steel	A179/A192	A53/A106
1 1/4 Cr-1/2 Mo	A213 T11	A335 P11
2 1/4 Cr-1 Mo	A213 T22	A335 P22
3 Cr-1 Mo	A213 T21	A213 P21
5 Cr-1/2 Mo	A213 T5	A335 P5
5 Cr-1/2 Mo-Si	A213 T5b	A335 P5b
9 Cr-1 Mo	A213 T9	A335 P9
9 Cr-1 Mo-V	A213 T91	A335 P91
Type 304H	A213 TP304H	A312 TP304H
Type 316	A213 TP316	A312 TP316
Type 321	A213 TP321	A312 TP321
Type 347	A213 TP347	A312 TP347
Alloy 800H/800HT B407	B407 Gr 800H/800HT	Gr 800H/800HT
HK	A608 Gr HK40 (see Note)	—
HP	—	A297 HP

1.5. Maintenance and Inspection of Static Pressure Equipment

Separators are part of ESP (gas pressure devices), and as such, their inspection is subject to national and international regulations.

- The triennial inspection: All ESPs must undergo an inspection (following a shutdown and isolation) every three years. This includes internal cleaning, external inspection, wall thickness measurement, removal and cleaning of demisters, and verification of control and safety devices.

- The decennial inspection: This occurs after every two triennial inspections. It involves the same steps as the previous inspection, with the addition of a hydrostatic pressure test. More details on the maintenance of static pressure equipment will be discussed in Chapter 4 [34, 35].

1 .6. Common Risk and failure associated with fixed pressurized equipment

Ageing describes the process by which equipment deteriorates and its performance changes over time, reflecting its condition rather than its actual age [36]. It manifests as material deterioration and damage, which increases the probability of failure throughout the equipment's service life. Ageing heightens the risk of containment loss and other failures, making it a significant factor in incidents and accidents. Fixed equipment failures can arise from several factors, including corrosion, fatigue, overloading, and improper design or fabrication [37, 38].

1.6.1. Common Problems and Failures in Heater Tubes

Fired heaters and furnaces experience unique degradation due to heat, pressure, and process fluids properties. Alloys used to combat corrosion may have sensitivities that require specialized inspection and control methods. Inspectors should review the equipment's history, corrosion control measures, integrity operating windows (IOWs), past issues, and repairs. Monitoring critical variables and trends, along with using visual and infrared techniques, helps identify issues like excessive heat flux, sagging, localized corrosion, and coking. This data is crucial for developing risk-based plans to maintain the structural integrity and safe operation of fired heaters. The principal risks associated with fired heater tubes include the potential for tube rupture and the release of high-temperature fluids or gases. Tube ruptures can occur due to mechanisms such as thermal oxidation, high-temperature creep, carburization, or excessive thermal cycling. When a heater tube fails, the release of flammable or hot fluids can trigger fires, while the sudden rupture may result in pressure imbalances that cause mechanical damage to surrounding equipment. In some cases, tube fragments can be ejected, potentially initiating a domino effect that leads to additional failures in nearby systems. The release of hazardous fluids and the ignition of fires pose significant threats to both the facility and personnel, making regular inspection, monitoring, and maintenance of fired heater tubes critical to minimizing these risks [2, 3].

In Bonaccorsi's study, the analysis of Fe-Cr-Ni alloy tubes in reforming furnaces revealed a subtle but significant weakening in the form of creep deformation. The study used laser optic measurements and metallographic techniques to pinpoint when tube diameter growth reached a critical threshold of 1.5%. This conservative limit served as a marker for when tube replacement should be considered, protecting the integrity of the furnace [39].

Archisman's work highlighted the silent erosion of reformer tubes through the formation of microscopic voids, called creep cavitations. These cavitations, born of high temperatures and stress, undermine the tubes' structural resilience over time. His study showed that certain alloying elements, through carbide precipitation, could be deployed as a countermeasure, boosting the tube's strength and flexibility under extreme conditions [40].

Shalaby's study uncovered a more insidious type of damage in a 321 stainless steel heater tube, processing heavy crude oil. Over time, a harmful accumulation of salts and coke caused the sensitization of the tube's surface, this, consequently, initiated sulfidation at grain boundaries. The cracking began along these weak points, but soon it crept transversely, as chloride stress corrosion, fueled by sulfur compounds, gnawed deeper into the metal. The remedy proposed was a dual approach better desalter efficiency and routine decoking to strip away the harmful deposits before they could cause catastrophic failure [41].

Chapter 3 will provide a comprehensive analysis of the issues faced in fired heaters, such as mechanical damage, material degradation, and operational failures. We will explore the underlying mechanisms behind these failures, including corrosion, thermal fatigue, and oxidation, while also discussing their impact on the overall safety and efficiency of the equipment.

1.7. Conclusion

Fixed Pressurized equipment plays a key role in the oil and gas industry, controlling the risks tied to this equipment is essential to keep facilities safe and prevent major accidents occurrence. To achieve this, a robust risk management approach must be adopted. This includes integrating process safety management (PSM) principles to systematically manage potential risks. By doing so, the industry can prevent catastrophic events, protect personnel, and minimize environmental impacts. The next chapter will delve into the application of risk management strategies and process safety systems to enhance equipment reliability and operational safety.

Chapter 2

Process safety management approach

2.1. Introduction

Process Safety Incidents can occur due to technological failures, human errors, deficiencies in management systems, and external events or natural disasters. To prevent these events, companies initially focused their incident prevention efforts for many years on enhancing technology and addressing human factors. Prior to the mid-1980s, after a series of major process-related accidents around the world, stakeholders began to recognize that management systems were an indirect cause of these accidents [42]. To address this issue, several initiatives were undertaken to accelerate the adoption of PSM approach, including the publication of regulations by governments, the establishment of standards by industries, and the development of policies by companies. Several management systems models have been developed worldwide, including:

The Seveso III Directive (2012/18/EU) was implemented as a regulation governing process safety to limit risks associated with the storage and handling of dangerous chemicals.

In the United Kingdom, the 2015 Control of Major Accident Hazards (COMAH) regulations govern process safety.

In the USA, the OSHA 29 CFR 1910.119 regulation of 1992 governs the safety of hazardous chemical processes [15].

In the Middle East, several countries have adopted management systems that integrate process safety.

Similarly, Algeria has developed several regulatory texts governing major risks, such as Executive Decree No. 21-319 relating to the specific operating permit regime for facilities and structures in hydrocarbon activities [43].

In this chapter, we will explore the management systems concept, followed by the definition of process safety management (PSM), its history, and its various elements or pillars. The aim is to prevent unexpected failures and ensure that the equipment and assets of the facility are designed, installed, properly maintained for their intended purpose throughout their operational lifespan. This approach enhances efficiency, increases availability, and reduces operational costs and risks.

2.2. Management Systems Concept

Management System is management of an important activity requires the implementation of policies, procedures, work instructions and documentation. It is imperative to ensure roles and responsibilities are assigned, authority is given, supervision is provided, resources are made available, and people are held accountable for activities.

A safety management system (SMS) is intended to manage and control safety with a particular emphasis on safety within an organization. It combines three perspectives: safety, management, and system, each contributing to its evolution. Safety concerns accidents, losses, or injuries, often described through models and metaphors Management encompasses the functions of planning, organizing, leading, and controlling, while a system follows the input-process- output principle [44-48].

An SMS is defined as the set of management procedures, elements, and activities aimed at improving an organization's safety performance. Modern SMSs are seen as a collection of necessary activities to fulfil responsibilities under self-regulation [49]. Safety management systematically controls employee behavior, equipment functionality, and the workplace environment. [50]. An SMS organizes all safety management activities systematically, making it an effective approach adopted by various industries.

2.2.1. Occupational Health and Safety Management System

Workplace health and safety management should be handled systematically in any organization of substantial size. This systematic approach is known as an Occupational Health and Safety Management System. Two internationally recognized OHSMS frameworks are widely used: ILO-OSH 2001 and ISO 45001. The first is the International Labour Organization's system, outlined in its "Guidelines on occupational safety and health management systems.ISO 45001, published by ISO, is another global standard. While organizations can develop their own OHSMS, adopting a recognized standard offers numerous advantages.

Both are founded on the PDCA management cycle:

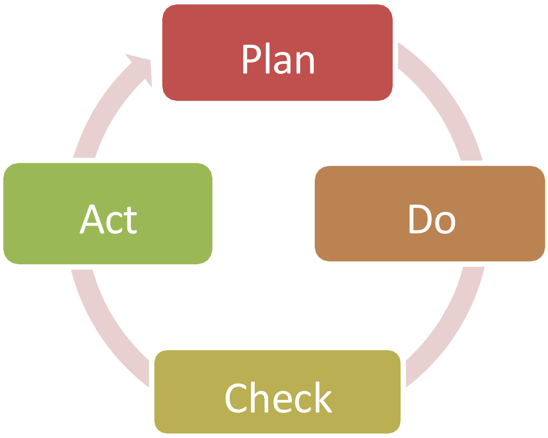


Figure 2.1: The PDCA cycle [51, 52].

- Plan: Define your goals and objectives, and then develop a strategy to achieve them.
- Do: Execute your plan and put it into action.
- Check: Assess your progress toward the goals and objectives you set.
- Act: Regularly evaluate your progress and adjust your actions if you are not meeting your targets [52, 53].

2.2.1.1. The ILO Occupational Safety and Health Management System

The ILO standards for safety management systems emphasize a structured approach to health and safety, ensuring clear roles, responsibilities, and ongoing risk management throughout the organization. The ILO-OSH 2001 OHSMS can be outlined as: Policy, Organizing, Planning and Implementation, Evaluation, Action for Improvement, and Audit. This framework is depicted in Figure 2.2.

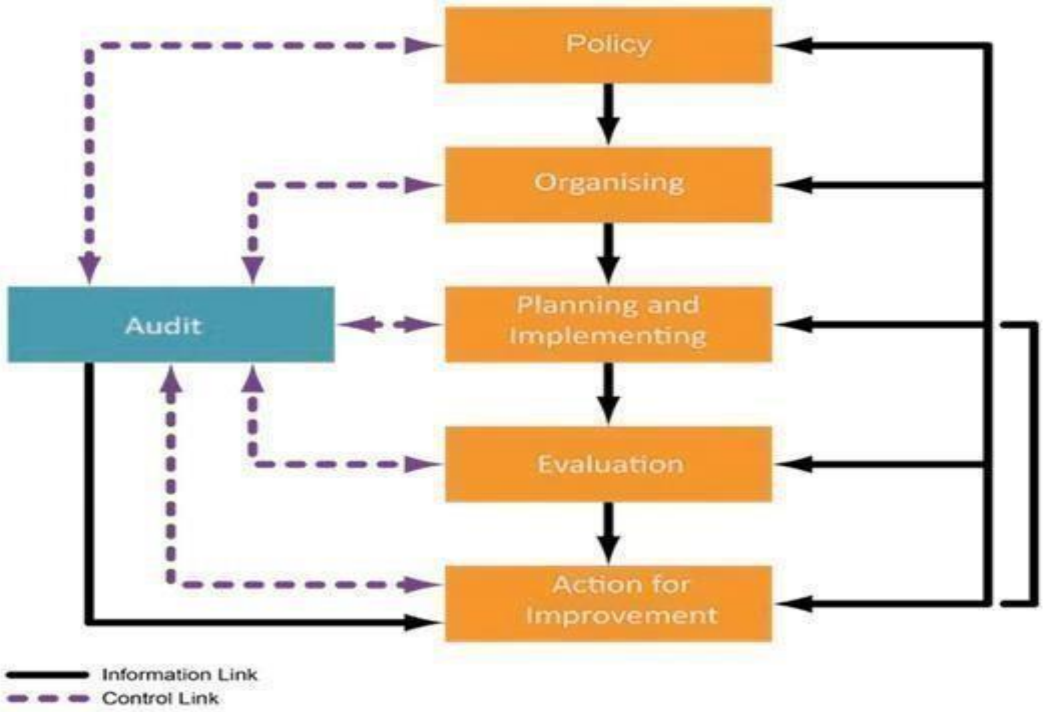


Figure 2.2: ILO Occupational Safety System and Health Management System [52].

- Policy (Plan) – Management must make a clear commitment to health and safety at all levels, particularly at the top.
- Organizing (Plan) – Roles and responsibilities for health and safety should be defined across the organization, from senior management to workers, including appointing specialists.
- Planning and Implementing (Do) – Effective management of health and safety must be arranged, focusing on risk assessments and the implementation of safe work systems.
- Evaluation (Check) – Systems for monitoring and reviewing the effectiveness of health and safety measures should be established, either reactively (e.g., accident statistics) or proactively (e.g., inspection reports).
- Audit (Check) – A systematic and independent audit should be conducted to ensure the SMS is functioning properly.
- Action for Improvement (Act) – Any issues identified should be addressed promptly by adjusting the policy, organization, and implementation strategies.
- Continual Improvement – The SMS should evolve and improve over time to better serve the organization's needs [52].

2.2.1.2. The Occupational Health and Safety Management System Standard ISO 45001

The ISO 45001 offers a standard for an OHSMS that allows organizations to undergo external audits. Gaining certification shows that the organization has a robust SMS that can withstand thorough evaluation, providing assurance to stakeholders like clients. Built on the PDCA management cycle, ISO 45001 is compatible with other ISO management standards, such as ISO 9001 (quality management) and ISO 14001 (environmental management). Figure 2.3 illustrates the alignment between the PDCA cycle and the ISO 45001 framework.

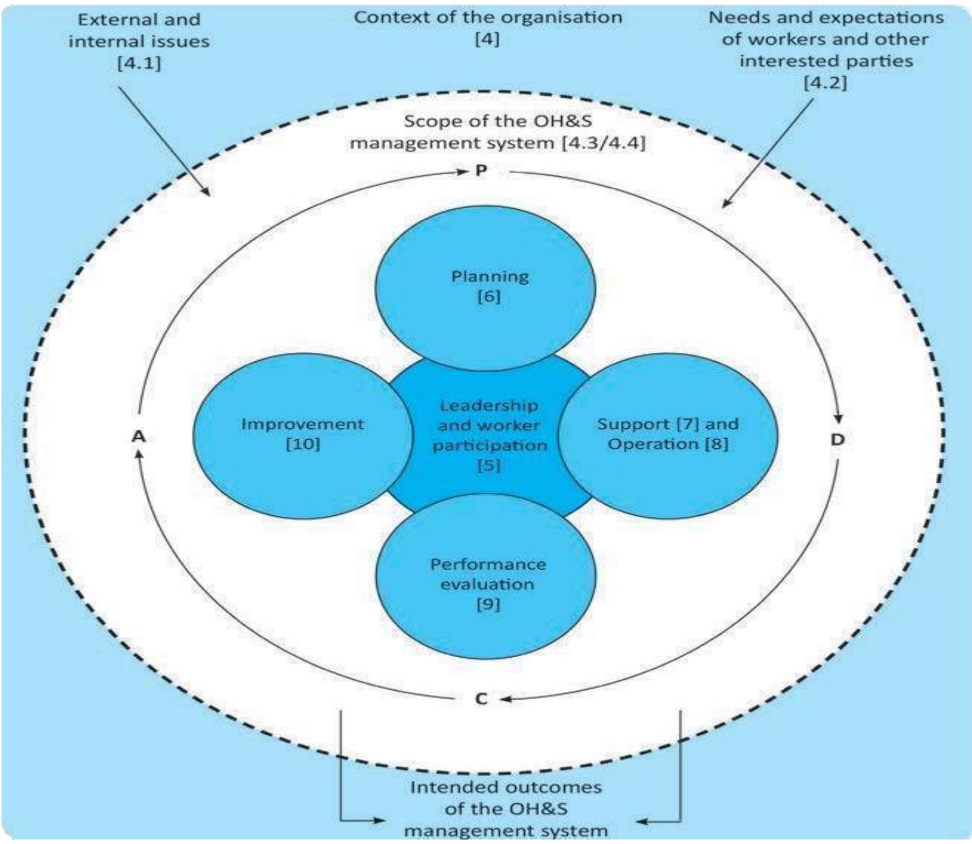


Figure 2.3: Relationship between PDCA and the ISO 45001 framework [51].

- Context of the organization: The OHSMS must be tailored to fit the organization and its operational environment, setting the stage for the system's boundaries and operation.
- Leadership and worker participation: Top management must lead the OHSMS, with active involvement from all employees, emphasizing leadership as central to the system's success within the PDCA cycle.
- Planning (Plan): Ongoing planning ensures hazards, risks, and improvement opportunities are identified, including emergency planning and risk assessments.

- Support (Do): Resources and support must be provided to establish, implement, and improve the OHSMS.
- Operation (Do): The system must effectively manage hazards and risks in daily operations.
- Performance evaluation (Check): Internal monitoring and reviews are required to ensure continuous improvement in OHS performance.
- Improvement (Act): Learning from incidents and non-conformities ensures the system evolves, driving ongoing improvements and closing the loop of the PDCA cycle [51].

2.2.2. Process Safety Management System

The causes of most accidents in the process industry are often linked to process safety concerns, including a weak safety culture, poor communication, asset integrity challenges, inadequate management leadership, and human factors. These accidents, which can have devastating impacts on human life, the environment, and business continuity, could have been avoided with the proper implementation of a strong Process PSMS. It addresses these challenges by establishing stringent safety protocols, improving communication, ensuring asset integrity through regular maintenance and inspections, promoting strong leadership commitment to safety, and providing continuous employee training. By adopting a comprehensive PSM system, organizations can greatly mitigate the risk of accidents and promote safety culture and operational excellence within the process industry. The Occupational Safety and Health Administration (OSHA) describes a Process Safety Management (PSM) system as an extensive management program aimed at identifying, understanding, and controlling process hazards, incidents, and catastrophic releases of hazardous chemicals [15].

PSM was initially introduced in 1971 by specialists from the European Federation of Chemical Engineering, eventually leading to the development of systems and frameworks in the 1980s [53]. Over the years, various PSM systems have been created, each with its own advantages and limitations [54].

2.2.2.1. Process Safety Management System Pillars as Per CCPS

The PSMS, originally proposed by the CCPS, is built around 12 fundamental elements that form the backbone of a robust safety framework. These elements, depicted in Figure 2.4, are thoroughly explained in this section.

Both regulators and process industry managers are acknowledging that certain essential process safety elements must be incorporated into any process safety management system (PS-MS) and should address the core functional pillars of process safety, as depicted in Figures 2.5, 2.6, 2.7, and 2.8.

The figure 4 is a combination of four foundational blocks of process safety management, along with the associated programs, tools, and practices, create the framework necessary for a robust and comprehensive process safety management system.

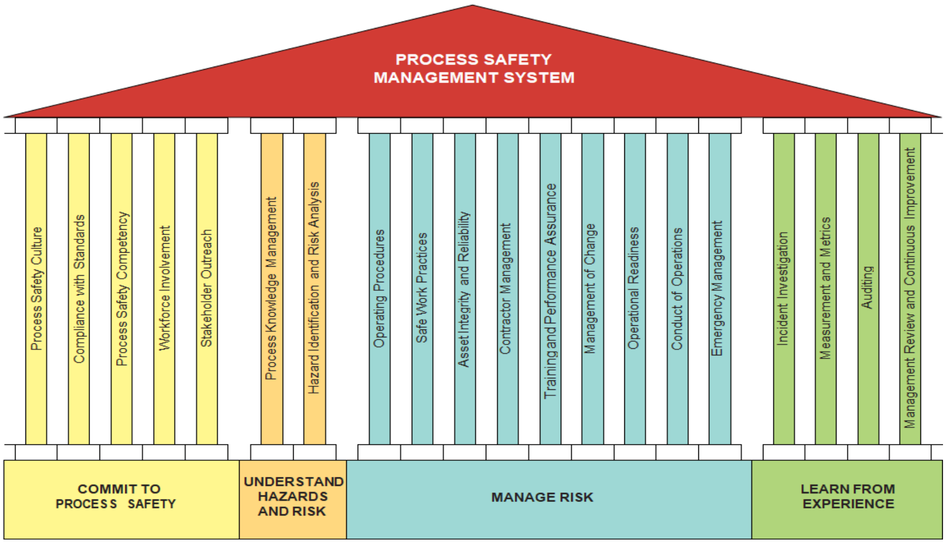


Figure 2.4: CCPS's Risk Based Process Safety Management System [55].

2.2.2.1.1. Commit to Process Safety Foundation Block

The Commit to Process Safety foundation block supports five pillars shown in figure 14.

1. Process Safety Culture: This pillar represents the collective values and behaviors that shape how process safety is managed. It can range from a negative culture of uncontrolled risk-taking to a positive one where risks are actively identified and managed. A strong safety culture is supported from the top down and requires continuous reinforcement through vulnerability awareness, empowerment of individuals, expertise, open communication, trust, and timely responses to safety concerns

2. Compliance with Standards: Organizations must identify, understand, and implement relevant safety standards, including voluntary and mandatory regulations. This involves

developing a consistent understanding of standards, creating implementation strategies, ensuring the right competencies, and conducting audits to maintain compliance and drive continuous improvement.

3. Process Safety Competency: This involves three key actions: improving knowledge and skills, ensuring access to necessary information, and consistently applying learned principles. Competency is achieved when all employees understand their responsibilities and are empowered to fulfill them through effective training and documentation processes.

4. Workforce Involvement: PSM must engage employees at all levels, from front-line workers to top management. Educating and empowering the workforce ensures effective protection against catastrophic events. Involving employees, including contractors, in the development of action plans for PSM promotes a proactive approach and leverages their insights for addressing safety issues.

5. Stakeholder Outreach: involves three main activities: Identifying Affected Parties (Actively seek individuals and organizations impacted by company operations for discussions on process safety), Building Relationships, establish and Sharing Information [53,58].

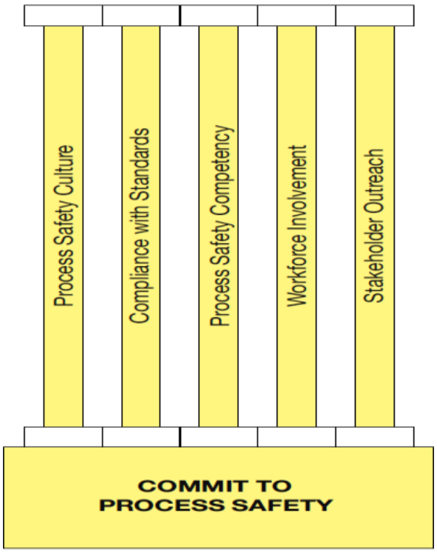


Figure 2.5: The commit to process safety foundation block [56].

2.2.2.1.2. Understand Hazards and Risk Foundation Block

The Understand Hazards and Risk foundation block supports two key pillars:

1. Process Knowledge Management: This pillar focuses on gathering and managing essential information, including:
   - Chemical Hazard Information: Identifying and understanding the hazards associated with each chemical, typically provided in Material Safety Data Sheets (MSDS), which must be kept current and accurate.
   - Process Technology Information: Characterizing the technology behind each process, which should be documented in design records and updated through a Management of Change (MOC) program.
   - Process Equipment Information: Documenting specifications, safe operating limits, and approved uses for all equipment, ensuring that updates occur when modifications or replacements are made.
2. Hazard Identification and Risk Analysis: Known as Process Hazards Analysis (PHA), this pillar employs various methodologies to identify and analyse hazards, including What-if Analysis, HAZOP Analysis, FMEA, FTA, Cause-Consequence Analysis, Event Tree Analysis

These techniques help translate identified hazards into risks, supporting the development of a robust risk management program [53, 58].

Figure 2.6: Understand Hazards and Risk foundation block [56].

2.2.2.1.3. The Manage Risk Foundation Block

The Manage Risk foundation block comprises nine essential pillars that help facilities identify and manage risks effectively:

1. Operating Procedures: Written instructions outlining steps for tasks, detailing processes, hazards, tools, protective equipment, and controls. Procedures should be collaboratively developed and monitored for changes through a Management of Change (MOC) process.

2. Safe Work Practices: Documents and routines for specific tasks, like hot work or confined-space entry, that aren't fully detailed in operating procedures. These practices require permits due to potential new hazards.

3. Asset Integrity and Reliability: Procedures that guarantee equipment is correctly designed, installed, and maintained to perform reliably until removed. An asset integrity policy should be in place for each facility.

4. Contractor Management: Education and oversight of contractors to ensure they understand facility hazards and do not introduce new risks. Contractors must adhere to the same safety standards as employees, and regular safety reviews should occur.
5. Training and Performance Assurance: Training programs that equip employees and contractors with the necessary knowledge and skills for safe job performance. Mastery of training content is essential, with front-line workers often serving as effective trainers.
6. Management of Change : A crucial process for identifying, analyzing, and managing changes that may impact safety. MOC includes evaluating change impacts, approving or rejecting changes, and ensuring proper documentation and follow-up.
7. Operational Readiness: Comprehensive inspections and testing before restarting processes that have been shut down, verifying equipment condition, personnel training, maintenance preparedness, and compliance with regulations.
8. Conduct of Operations: Systematic execution of operational tasks by trained personnel, in compliance with approved procedures. This includes defining a clear hierarchy and assigning specific responsibilities.
9. Emergency Management: Developing and reviewing emergency response plans based on potential risks, conducting training and drills for stakeholders, and ensuring readiness to respond effectively to emergencies [53, 58].

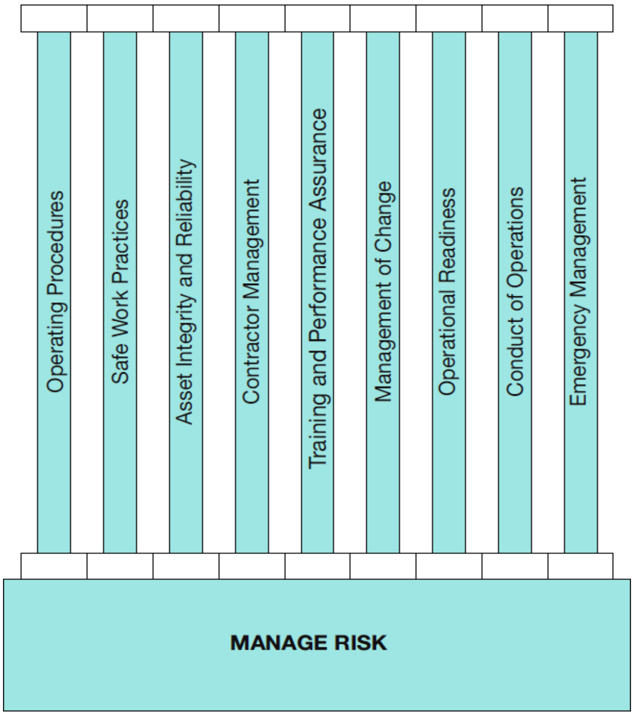


Figure 2.7: Manage Risk foundation block [56].

2.2.2.1.4. Learn From Experience Foundation Block

The Learn from Experience foundation emphasizes the importance of capturing and applying lessons learned from both personal experiences and observations of others. It advocates for an infrastructure to document and share these learnings, facilitated by networks and resources like the CCPS Process Safety Incident Database (PSID).

The Learn from Experience foundation supports four pillars shown in figure 2.8:

1. Incident investigation: this pillar involves analyzing safety incidents to uncover both primary and contributing causes. A formal process includes documenting and tracking incidents, as well as implementing corrective actions. Investigations aim to determine what happened, how it occurred, and why it transpired, often utilizing fault tree analysis to visualize the sequence of events leading up to the incident.
2. Measurement and Metrics: this pillar focuses on tracking performance through real- time, lagging, and leading metrics. Lagging metrics assess past incidents, while leading metrics predict future performance based on key processes. Companies should define parameters for measurement, tracking, and reporting.
3. Auditing: This pillar involves systematic reviews aimed at identifying weaknesses in Process Safety Management (PSM) systems. Audits verify compliance with established

standards and encompass an examination of both management systems and manufacturing processes. The primary goal is to pinpoint deficiencies and implement corrective measures to enhance overall safety.

4. Management Review and Continuous Improvement: The final pillar emphasizes the importance of routinely evaluating and enhancing existing Process Safety Management (PSM) systems to ensure their effectiveness. Weaknesses in management systems often become evident in processing areas, necessitating the implementation of corrective measures, as multiple deficiencies may stem from a single failure. Once identified, action plans should be developed and tracked to completion, guided by OSHA's PSM audit guidelines. Regular management reviews are essential to keep PSM systems current and aligned with evolving needs and expectations, underscoring the necessity for continuous improvement as previously effective systems may become outdated [53,58].

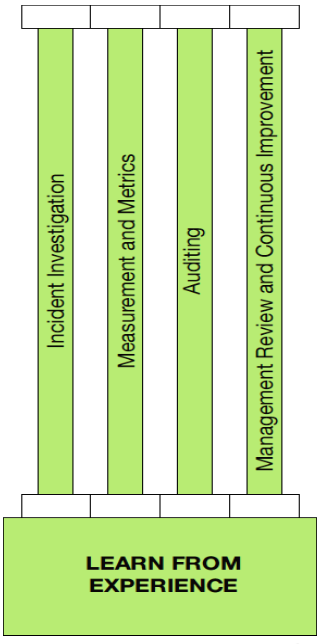


Figure 2.8: Learn from Experience foundation block [56].

2.2.2.2. Key Element of PSM System as Per OSHA and Its Requirements

Process Safety Management systems are the ensemble of standards and guidelines that set out fundamental elements of process safety management in industries that involve hazardous materials. The most prominent standards and frameworks stress different critical aspects of PSM.

1. Employee Involvement: Employers are required to develop a written plan to guarantee employee involvement in process hazard analyses (PHAs) and other PSM elements. Employees and their representatives must be provided access to pertinent information and actively engaged in the process.

2. Process Safety Information (PSI): Before conducting a PHA, employers must compile detailed safety information on chemicals, process technology, and equipment. This ensures a thorough understanding of the risks linked to highly hazardous chemicals.

3. Process Hazard Analysis (PHA): Employers must conduct a systematic PHA for all processes involving hazardous chemicals, using methods like What-if analysis, HAZOP, or FMEA. PHAs evaluate potential hazards and recommend controls.

4. Operating Procedures: Clear, documented operating procedures must be established, in line with process safety information. These procedures must be accessible, regularly reviewed, and form the basis for employee training.

5. Training: Employees involved in processes must receive initial and refresher training on process operations, hazards, and safety practices. Training records must be maintained to ensure compliance.

6. Contractor Management: Employers must assess contractors' safety performance, inform them of hazards, and ensure their work follows safety rules. Contractors are responsible for training their employees and adhering to safety practices.

7. Pre-Start-Up Safety Review: Before introducing hazardous chemicals or making major changes, employers are required to ensure that safety, operating, and emergency procedures are established, and that equipment complies with design specifications

8. Mechanical Integrity: Employers must maintain the mechanical integrity of critical equipment through inspections, tests, and maintenance, adhering to recognized engineering practices. Records of inspections and corrections must be kept.

9. Hot Work Permit: A permit is required for any hot work near a process. It must verify that fire protection measures are in place, and the permit must be filed until the work is completed.

10. Management of Change (MOC): Employers must evaluate changes to chemicals, technology, or equipment to assess their impact on safety. Changes must be documented, and employees must be trained before resuming work.

11. Incident Investigation: Incidents involving the discharge of hazardous chemicals must be investigated within 48 hours. Reports should include a description, causes, and corrective actions, with records kept for 5 years.

12. Emergency Planning and Response: Employers must have an emergency action plan, including procedures for handling small releases of hazardous chemicals, and ensure employees are trained on how to respond.

13. Compliance Audits: Employers must conduct compliance audits at least every three years to evaluate PSM practices. A report of the findings must be kept, addressing any deficiencies identified.

Trade Secrets: Employers must provide all necessary information for PSM compliance, even if it is a trade secret, while protecting confidentiality through appropriate agreements [59].

Figure 2.9: PSM keys elements as per OSHA [59].

Figures 2.9, 2.10, 2.11 and 2.12 outline the key elements of various PSMS proposed by different industry leaders.

Figure 2.9 illustrates the PSM system developed by OSHA, while Figure 2.10 and 2.12 outline the approach recommended by IChemE (Institution of Chemical Engineers), and Figure 2.11 presents the framework from the Energy Institute.

Figure 2.10: Six functional pillars of process safety [60].

Figure 2.11: Four functional pillars proposed by the Energy Institute [61].

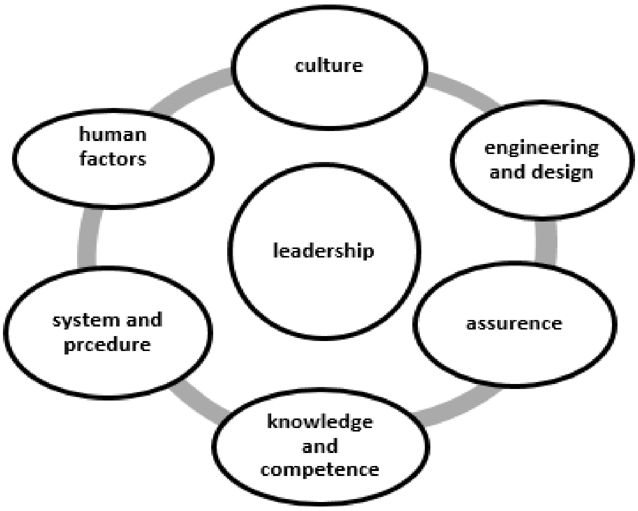


Figure 2.12: Seven functional pillars proposed by the IChemE Safety Centre [62].

Each of these frameworks offers a different perspective on managing process safety, but they all share the same fundamental pillars that aim to achieve the common objective of identifying, understanding, and controlling process hazards to reduce risks and prevent incidents.

2.2.2.3. Process Safety Management (PSM) Framework of SONATRACH

This framework serves as a guide for SONATRACH's Process Safety Management PSMS, primarily inspired by the RBPS system proposed by CCPS. This guide is a tool that enables SONATRACH sites to:

- Evolve their approach to accident prevention related to processes, from a strategy solely based on compliance to one based on both risk and compliance;
- Continuously improve the effectiveness of the management system;
- Integrate process safety performance analysis into the operational management processes of a site [42].

The risk-based system adopted in this framework is built on four main pillars:

2.2.2.3.1. Commit To Process Safety

A deep commitment and strong leadership are essential for achieving process safety excellence. When employees perceive that safety is a fundamental value fully supported by management, they are more inclined to make the right decisions, act appropriately, and follow proper procedures, even when unsupervised. This mindset should be consistently fostered throughout the organization.

"Ensuring the safety of its assets and ensuring that all risk control measures are constantly operational and effective; It is also committed to improving its asset integrity programs to prevent accidental events" [63].

This highlights SONATRACH's dedication to not only upholding process safety but also continuously enhancing its safety and integrity management practices to mitigate risks and prevent accidents.

2.2.2.3.2. Understand Hazards and Risks

This pillar serves as a strong foundation, ensuring the most effective allocation of resources for managing process-related risks by leveraging information on identified hazards and assessed risks. By focusing on understanding and addressing specific risks, this approach enables the organization to prioritize efforts and allocate to the areas that will have the most significant effect on enhancing safety and preventing incidents.

2.2.2.3.3. Manage and Control Risks

The approach centers on three key areas:

- Safely operating and maintaining processes that pose risks.
- Effectively managing changes to these processes to keep risks within acceptable limits.
- Preparing for and managing incidents to ensure a swift and effective response.

2.2.2.3.4. Learn From Experience

Sites must be prepared to transform their mistakes and those of others into opportunities. The most cost-effective ways to learn from experience include:

- Applying best practices to make the most of available resources,
- Addressing gaps revealed by internal incidents, and
- Implementing lessons learned from other companies.

By adopting these strategies, SONATRACH can foster a culture of continuous improvement, ensuring that knowledge gained from experiences is effectively integrated into its operations to enhance safety and efficiency.

These pillars emphasize the importance of actively controlling risks and continuously improving through lessons learned from past incidents or near misses. By focusing on these four pillars, SONATRACH's risk-based process safety system aims to create a proactive safety culture, reducing the likelihood of major accidents and enhancing overall operational safety [54].

2.3 Risk Management

Risk management serves as a vital cornerstone in the Process Safety Management (PSM) system. ISO31000 define risk management as coordinated activities to guide and control an organization in relation to potential risks [64].

Risk management aims to protect people, the environment, and assets by balancing health, environment, safety (HES), and costs. It involves preventing hazards and reducing their impact. The approach has shifted from strict rules to a goal-oriented system focused on desired outcomes rather than methods.

2.3.1. Risk Management Process

The risk management process involves the structured implementation of policies, procedures, and practices in activities like communication and consultation, setting the context, and evaluating, mitigating, monitoring, reviewing, documenting, and reporting risks.

This process is provided in a more complete and detailed manner in the ISO 31000 standard [64], as shown in Figure 2.13 the different steps of this process are briefly explained with reference to this same standard.

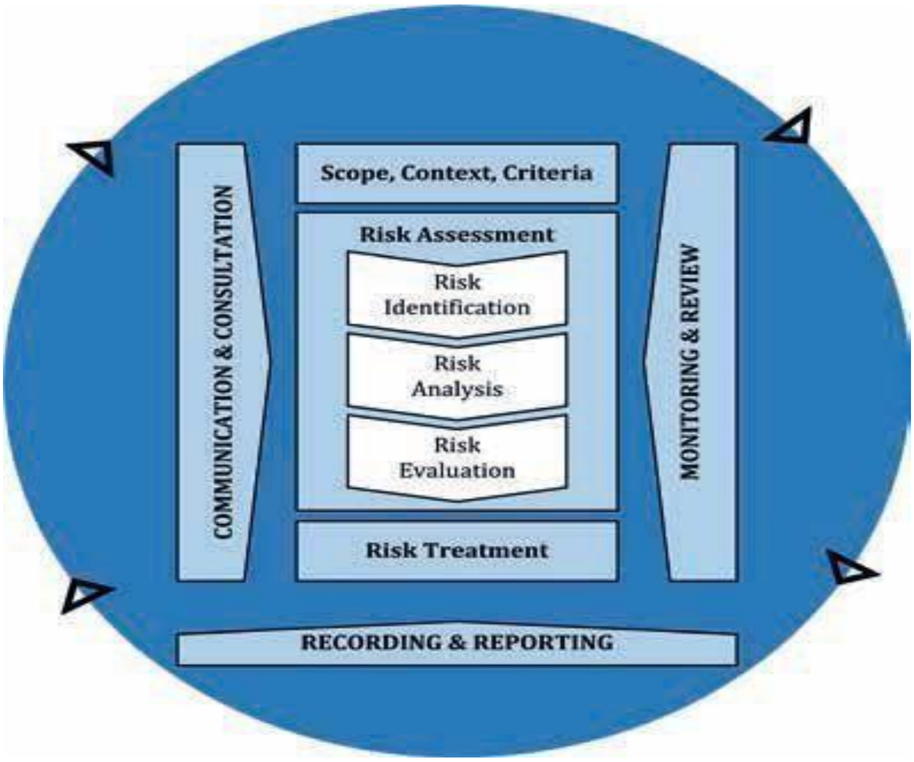


Figure 2.13: Risk management process [64].

2.3.1.1. Definition Of Scope, Context And Criteria

Defining the context establishes the framework for managing risks by outlining the scope of the process, considering both internal and external environments, and identifying specific risk management goals. It also involves understanding their interaction, setting decision criteria, and implementing structures to ensure effective risk assessment [65, 66].

2.3.1.2. Risk Assessment

Risk assessments can be conducted for various reasons and serve multiple purposes. According to the ANSI/ASSE Z690.3-2011 standard (the national adoption of IEC/ISO), 31010:2019), the aim of risk assessment is to provide evidence- based information and analysis to make informed decisions on how to treat particular risks and how to select between options. Using a structured risk assessment process enables an organization to comprehend risk levels, compare them, and prioritize addressing the highest risks first [67].

2.3.1.2.1. Risk Identification

Hazards are the source of risks, and to assess risks, hazards must first be identified. Risk identification involves detecting, recognizing, and documenting potential risks, including their causes, sources, events, and the potential impact on objectives. After identifying risks, existing controls should also be noted [68]. A systematic approach is typically more thorough and reliable in identifying hazards, with several common methods used by safety professionals:

- Brainstorming.
- Checklists.
- Regulations like OSHA, EPA, DOT, etc.
- Consensus industry standards like ANSI, ASTM, NFPA, etc.
- Experts.
- Job hazard analyses/job safety analyses.
- Accident/incident investigations.
- OSHA injury and illness records.
- Insurance claims.
- Formal hazard/risk identification techniques [69].

Each of these hazard identification techniques listed previously and those listed in ISO 31010/ANSI Z690.3 have their own strengths, weaknesses, and limitations.

2.3.1.2.2 RISK ANALYSIS

According to ISO 31010/ANSI Z690.3, risk analysis involves developing an understanding of the risk, which includes tasks such as determining the severity of consequences, estimating the likelihood of occurrence, assessing the effectiveness of existing controls, and estimating the risk level. Risk analysis can be qualitative, semi-quantitative, or quantitative, depending on the context and available data. Qualitative analysis, the most common, uses descriptors like "high," "serious," "medium," and "low" for severity, likelihood, and risk levels. Semi-quantitative methods assign numerical ratings to consequences and likelihood to determine risk levels based on qualitative criteria. Quantitative analysis, less common, uses estimated values for consequences and likelihood to produce numerical risk values. However, full quantitative analysis may not always be feasible or necessary due to limited data, and in such cases, a semi-quantitative or qualitative ranking by qualified assessors is often preferred for the assessment [67].

2.3.1.2.3. Risk Evaluation

Risk evaluation helps guide decision-making by comparing the findings of risk analysis with established criteria to determine if further action is necessary. It combines estimated consequences (severity) and likelihood, drawing on information from hazard identification and analysis to rank risks. A risk assessment matrix is a valuable tool in this process, using a severity and likelihood table to assess the acceptability of risks. The matrix is adaptable to different situations, such as evaluating injury severity for physical hazards, and is particularly effective in qualitative (Q) and semi-quantitative (SQ) methods. As the complexity of risk assessment increases from Q to fully quantified risk assessments (QRA), the matrix continues to provide structured risk ranking [70].

A widely used international concept in risk management decision making is known as "As Low As Reasonably Practicable". After assessing the risk associated with an operation or item, it is essential to evaluate the effectiveness of the controls implemented [71].

"Acceptable Risk" refers to the level of risk where the probability of a hazard-related incident or exposure, along with the potential severity of the resulting harm or damage, is minimized to a point that is both feasible and tolerable within the given context [72].

The "as low as reasonably practicable" (ALARP) standard is applied to determine when the cost of additional risk reduction becomes disproportionate to the safety benefits achieved. Figure 2.14 demonstrates the ALARP principle

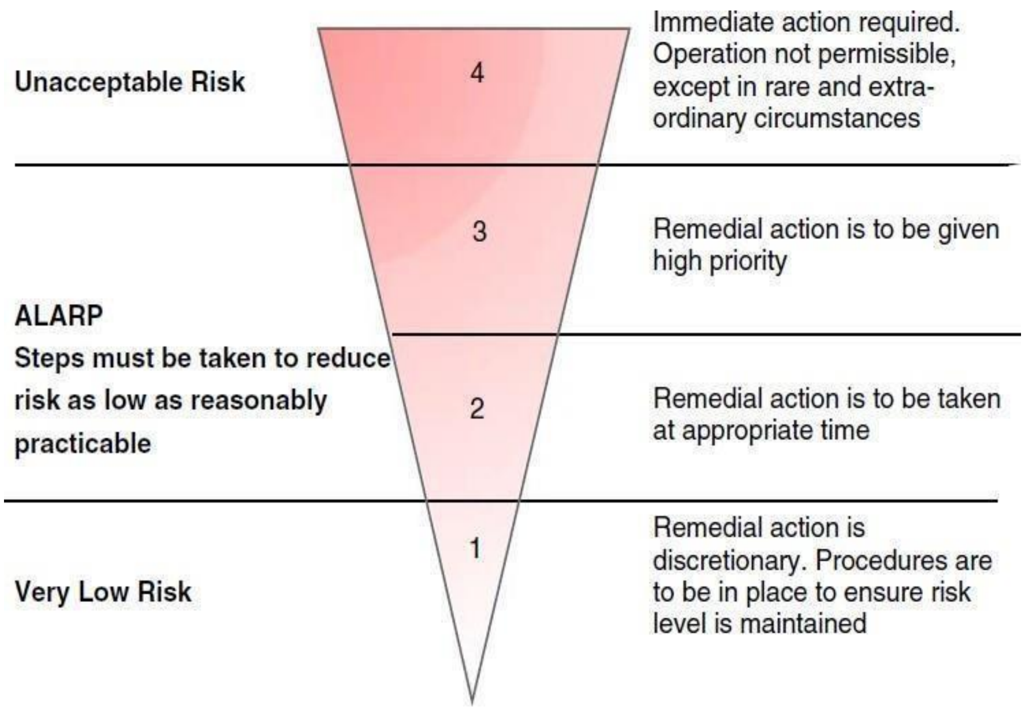


Figure: 2.14: The ALARP Model [73, 10]

2.3.1.3. Risk Treatment

Risk treatment is a process intended to modify a risk (risk reduction). It generates or modifies the means of risk control. Treatment options may include risk refusal, elimination of the risk source, modification of likelihood (preventive measure), modification of consequences (protective measure), etc. It is important to note that a means of risk control refers to a safety barrier as defined in the first part of the IEC 50126 standard (IEC EN 50126- 1, 2019): "physical or non-physical means that reduce the frequency of a hazard and/or a potential accident resulting from the hazard and/or mitigate the severity of potential accidents resulting from the hazard" [74, 75].

2.3.1.3.1. Hierarchy Of Control

The Hierarchy of Control outlines a prioritized ranking of risk control methods, starting with the highest level of protection and reliability and progressing to the lowest. It emphasizes that often a combination of controls is necessary to effectively manage risks. It's important to also assess the feasibility of these controls in each situation to ensure their practicality and effectiveness in protecting workers [76].

Based on ISO 45001 and ILO-OS 2001 the hierarchy organizes control measures in order of their effectiveness, from most to least preferred, as follows: elimination, substitution, engineering controls, administrative controls PPE [51,52]. It is illustrated in figure 2.15

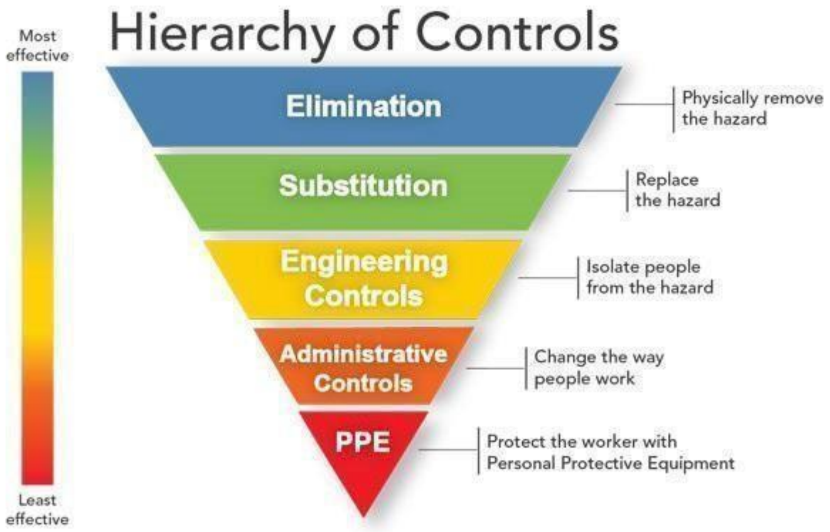


Figure 2.15: NIOSH model of Hierarchy of control [77].

In this hierarchy of controls (HOC), the safety risk management strategies are ranked by effectiveness:

- Elimination: The most effective method, Eliminating risks by removing hazardous tasks or processes from the work system . This removes human interaction with dangerous materials or equipment, reducing the chance of human error.

- Substitution: This involves replacing hazardous methods, materials, or equipment with safer alternatives, like switching dangerous chemicals for less-hazardous ones or automating tasks. While effective, it doesn't eliminate risks as fully as elimination.
- Engineering Controls: These use safety devices and built-in systems like guards, alarms, or safety nets to physically separate workers from hazards and reduce the risk of error. It controls risks by modifying the design of equipment and processes.
- Administrative Controls: This approach focuses on influencing human behaviour through training, work methods, supervision, signage, and safety procedures. While it plays a crucial role, it's less effective than elimination or substitution, as it relies on consistent human adherence.
- Personal Protective Equipment: The least effective, PPE mitigates risks but doesn't remove them. It requires proper identification, training, and maintenance to be effective and is used when higher-level controls can't fully address the hazards [78].

2.3.1.4 Monitoring and Review

Monitoring and review aim to ensure and enhance the quality and effectiveness of process design, implementation, and outcomes. Ongoing monitoring and periodic reviews of the risk management process and its results should be planned elements of the overall risk management strategy, with clearly defined responsibilities. These activities should occur at every stage of the process, involving tasks such as planning, collecting and analyzing data, recording results, and offering feedback [64, 68].

2.3.1.5 Recording and Reporting

The risk management process and its outcomes should be recorded and communicated through suitable reporting mechanisms [64, 68].

2.3.1.6. Communication And Consultation

Effective communication throughout the risk assessment process is essential to prevent serious consequences. It is required by standards such as ISO 31010/ANSI Z690.3, ANSI Z590.3, and OHSAS 18001. Despite this, poor communication remains a leading cause of negative outcomes, including fatal incidents.

The IEC 31010 standard offers a wide range of techniques illustrated in Figure 2.16.

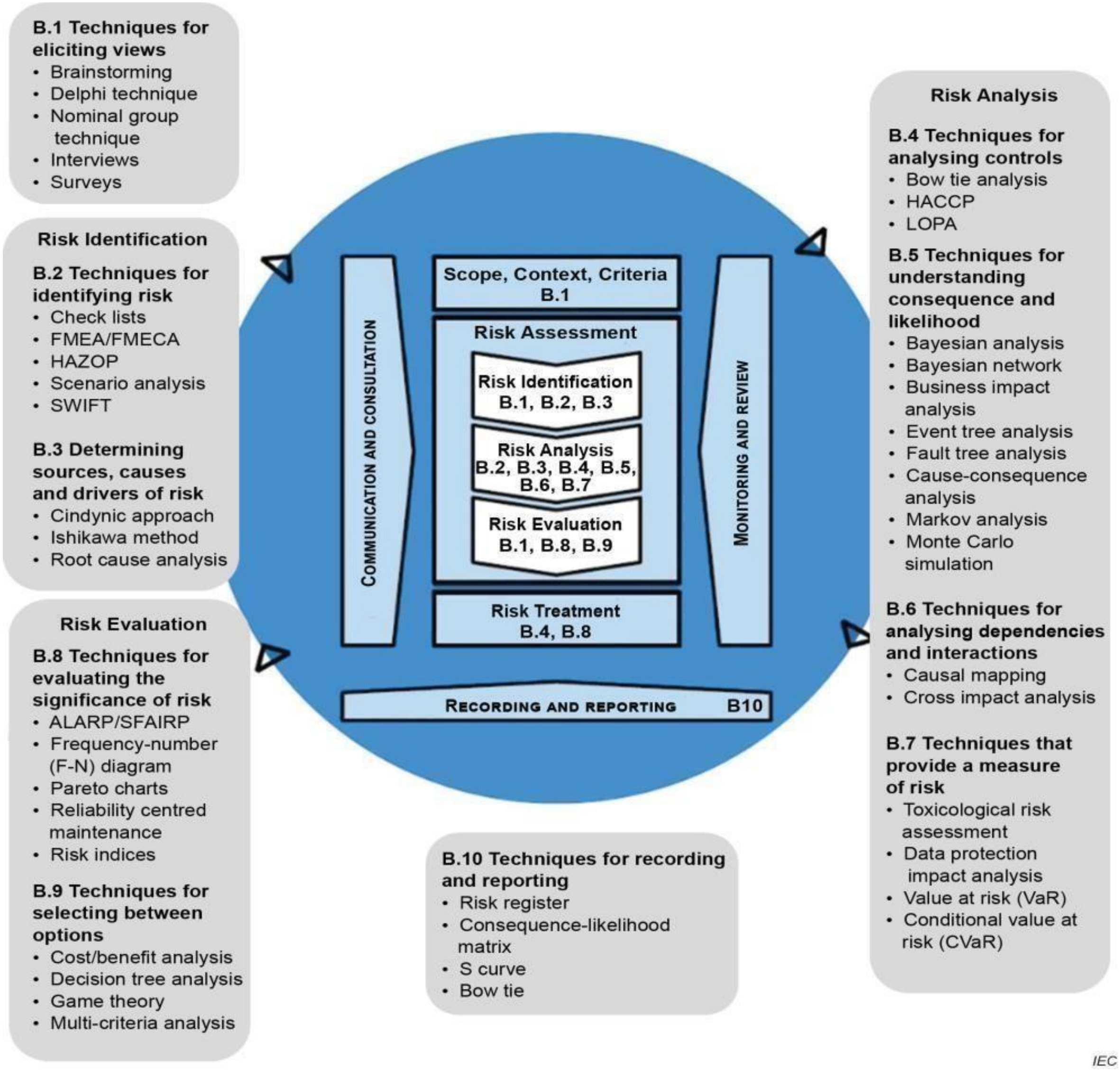


Figure 2.16: Application of techniques in the ISO 31000 risk management process [64].

2.4. Conclusion

In this chapter, we explored the essential role of PSM in minimizing the risk of catastrophic incidents in the process industry. A robust PSM system not only protects lives but also ensures operational reliability and safety. Within PSM, the third pillar, known as the Asset Integrity and Reliability element, includes Mechanical Integrity (MI) as a critical component. This element is central to maintaining the safety of essential equipment through systematic inspection testing, maintenance, and repairs, which collectively help to prevent equipment failures that could lead to hazardous incidents. The next chapter will delve into Mechanical Integrity, presenting a case study that analyses damage parameters in reformer heater tubes and offers insights to further reduce the risk of major accidents.

Chapter 3

Mechanical integrity and Inspection of catalytic reformer heaters

3.1. Introduction

Reformer heaters are extensively utilized in the petroleum industries to produce reformate, which is essential for blending processes. Among their components, radiant tubes are the most critical, as they endure prolonged operation under high temperatures and pressure [39]. Tubes in catalytic reformer heaters can deteriorate. Various damage mechanisms may arise due to factors such as unusual operation, low flow, elevated temperatures, or flame impingement. These issues can compromise the structural integrity of the tubes, potentially resulting in damage and, in cases of loss of containment, a risk of fire [2,3,40,79,1].

Leaks or failures in a piping system can have diverse effects, ranging from a minor issue for low-consequence fluids to a significant safety hazard for high-consequence fluids, influenced by factors such as temperature, pressure, contents, and piping location (API 570, 2016). Recognizing potential damage mechanisms and failure modes in tube heaters is key to ensuring the reliability and precision of risk analysis [11]. A clear understanding of these mechanisms is essential for evaluating the likelihood of failure, determining optimal inspection intervals, selecting inspection locations and methods, and enabling well-informed decision-making [80, 1].

A primary goal of maintenance strategy is to reduce hazards to both human safety and the environment, which can result from unexpected equipment failures. Preventive maintenance is one approach used to avoid such failures and is widely implemented in process industries to minimize issues with fixed equipment like piping, which is vulnerable to damage in petrochemical plants. Metallurgical properties, including strength, ductility, toughness, and corrosion resistance, can degrade over time due to microstructural changes induced by thermal aging at high temperatures [81].

Mechanical integrity plays a crucial role in PSM, ensuring the safe operation of equipment throughout its lifecycle. In this chapter, we will discuss the importance of mechanical integrity for static equipment, particularly focusing on industrial fired heaters, with a special emphasis on the specific damage mechanisms that can arise in catalytic reforming furnaces.

The chapter is devoted to the study conducted on the catalytic reforming furnace, commencing with a description of the reforming unit. It begins with a description of the reforming unit, followed by a detailed description of the system studied. We then explain the methodology adopted to carry out this analysis. The approach used combines various inspection techniques, such as visual inspection, microstructural observation, metallographic analysis, and testing of mechanical properties. The findings identified significant oxidation and scaling on the tubes' outer surface, recommendations provided to prevent similar damage.

3.2. Mechanical Integrity of Fixed Equipment

The Mechanical Integrity system is a crucial component of an organization's HSE MS, designed to prevent or mitigate major incidents involving hazardous substances. It focuses on maintaining equipment reliability through risk-based inspections, maintenance, and operational strategies that account for facility deterioration. The MI system safeguards the integrity of equipment and ensures that processes operate safely, with a focus on containing hazardous substances. It also strengthens the lines of defense against potential failures. A well-implemented MI system not only protects people and assets but also aligns closely with HSE activities, with the MI Custodian responsible for ensuring appropriate links to change control measures throughout the equipment lifecycle [82]. Figure 3.1 below illustrates the relationship between MI activities with various stages of equipment lifecycle.

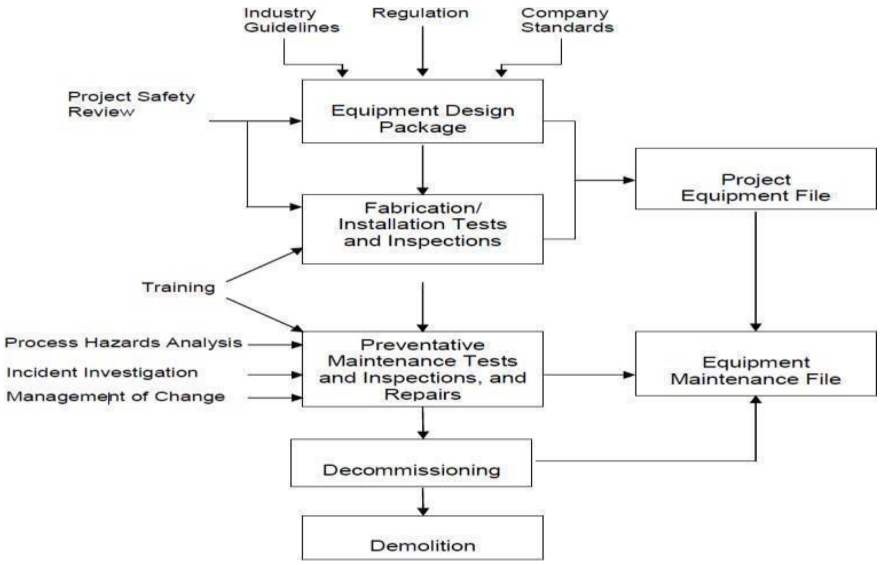


Figure 3.1: Process Equipment Integrity Chart [56].

This Mechanical Integrity Program applies to processes which handle hazardous chemicals as defined by OSHA 29 CFR 19.10119 and applies to:

- Pressure Vessels covered by API 510.
- Piping Components covered by API 570.
- Storage Tanks covered by API 653.
- Pressure relieving devices covered by API 576.

- Heaters and boiler covered by API 573

3.3. Heater Mechanical Integrity and Inspection

3.3.1. Inspection of Fired Heaters

Heaters in refineries and petrochemical plants face distinct degradation mechanisms arise from the combined effects of heat, internal pressure, and chemical properties of fluids. While specialized alloys are used to combat corrosion, they often introduce other sensitivities that require tailored inspection techniques. Inspectors must thoroughly review furnace histories, including corrosion control methods, operating conditions, and repair records, to prepare for inspections. Monitoring operating parameters, using thermographic cameras, and conducting visual inspections are essential to detect heat flux issues, deformation, corrosion, and other damage. This data supports risk-based inspection plans to maintain furnace integrity. API 573 provides guidelines to enhance furnace reliability and safety by outlining effective inspection practices that assess equipment performance over time [2].

Maintenance outages offer the chance to access tubes and other internal components, allowing for the assessment of their current condition and the collection of data to help predict the reliability of the equipment

Inspections that can be conducted during outages include, but are not limited to:

- Visual inspections
- Measuring wall thickness
- Checking for tube sagging or bowing
- Gauging pit depth
- Using intelligent pigging
- Conducting radiographic tests
- Performing hardness testing
- Utilizing borescopes and video probes
- Conducting in situ metallography and replication
- Performing dye penetrant testing
- Conducting magnetic particle testing
- tube removal sections for creep testing
- tube removal e sections for metallographic examination

- tube removal for detailed visual examination,
- testing of tube skin thermocouples.
- refractory examination, and tube support examination [2].

3.3.1.1. Visual Inspection

Visual inspections are one of the most basic but crucial methods for assessing furnace tubes. On-stream visual inspections focus on flame patterns, which can indicate potential issues such as flame impingement, coking on the burner tip, or tube leaks. An erratic flame may suggest damage to swirl vanes or improper air/fuel mixtures, leading to hot spots and localized overheating. During planned downtime, tubes are examined closely for physical signs like bulging, sagging, scaling, corrosion, and tube misalignment. Bowing and tube supports are also checked, as misaligned supports can hinder thermal growth and cause stress. Refractory materials and external casing are inspected for damage, and any discoloration or cracking is monitored to prevent further deterioration. Visual aids like boroscopes or video cameras can be used to inspect internal surfaces of the tubes, and records such as videotapes are kept for future reference [83].

3.3.1.2. Wall Thickness Measurement

Measuring the wall thickness of tubes and fittings is a critical aspect of inspection. It allows for the identification and monitoring of thinning damage.

This can be done using nondestructive methods, such as ultrasonic, laser, electromagnetic instruments, radiography, or by measuring internal and external diameters. While destructive methods, like removing tube sections from inaccessible areas, have traditionally been used, advancements in internal ultrasonic-based intelligent pigs have reduced the need for such invasive inspections [2].

3.3.1.3. Tube Growth Measurements

Over time, furnace tubes may experience bulging or creep growth because of extended exposure to high temperatures and stress. Monitoring this growth is essential to detect early signs of damage. Pre-set gauges can be employed to swiftly measure the entire length of a tube. for diameter changes, and more precise measurements are taken with micrometers at pre-selected locations. New laser measuring techniques now offer more accurate assessments of creep growth, allowing operators to monitor thermal expansion and material deformation more effectively. This helps identify tubes that are nearing the end of their safe operational life [83].

3.3.1.4. Carburization Assessment

Carburization is a damage mechanism that occurs when carbon diffuses into the steel, causing it to become brittle. This process happens at high temperatures and is especially problematic in areas exposed to carbonaceous environments. For more precise analysis, eddy current instruments and magneto-scopes are used to measure the extent of carburization, helping build a history of carburization levels in furnace tubes. Follow-up inspections with dye penetrant or radiography are performed to check for cracks and determine the condition of the internal surface [83].

3.3.1.5. Radiography

Radiographic inspection is used to examine welds, return bends, and tube walls for signs of internal damage such as thinning, deposits, pitting, and cracking. It is particularly useful for detecting damage on the fire-exposed side of the tubes. In circular heaters, panoramic exposures can capture the condition of multiple tubes at a specific elevation in one image [83].

3.3.1.6. Hardness Testing

Hardness tests are performed to assess material degradation. Increased hardness is often correlated with carburization or thermal damage. Both mechanical and electronic hardness testers are used, but care must be taken when testing thin materials, as erroneous readings may occur. Hardness measurements are especially important when assessing the condition of welds, base metal, and heat-affected zones, providing a clear indication of material wear and tear over time [83, 84].

3.3.1 .7. Metallurgical Analysis

When furnace tubes approach their design life, or when inspections reveal potential damage, samples may be removed for detailed metallurgical analysis. Techniques such as tensile testing, optical and scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), and X-ray diffraction (XRD) are used to assess the mechanical integrity of the material. Metallurgical analysis focuses on identifying high-temperature creep damage, oxidation, carburization, embrittlement, and other forms of material degradation. This analysis is crucial for making informed decisions about repairs or tube replacements [83,85, 86].

3.3.2. Inspection Interval

According to API 573 the reliability of furnaces typically relies on regular internal inspections as well as ongoing routine checks and assessments. Generally, furnaces are integral to a processing unit, so internal inspection can only be undertaken during unit shutdowns. However, the interval between internal inspections should consider the history and expected degradation rates of components, monitoring and inspection results, and the effectiveness of prior maintenance activities.

These routine inspections essentially include:

- VI of the fire boxes and the burner flame patterns by operating personnel on a regular basis.
- Installation and monitoring of tube skin thermocouples.
- Periodic infrared inspection of the tubes to detect "hot spots," heating ducts, and furnace shells to determine if refractory or insulation degradation has occurred.

According to the Executive decree No. 21-261 related to regulating pressure equipment and electrical equipment intended to be integrated into installations within the hydrocarbons sector. The owner or user can benefit from adjustments at the intervals defined in Articles 38 and 43, when Owner or User has a specific inspection plan based on an integrity management system of pressurized equipment and safety devices, made in accordance with the standards and standards derived from international best practices applicable in the oil and gas industry.

- Article 38: The maximum periodicity for regulatory inspections of pressurized equipment and associated safety equipment is thirty-six (36) months for vessels and furnaces and twenty-four (24) months for steam generators.

The maximum periods are counted, as applicable, from the date of commissioning, the previous regulatory inspection, or requalification. These periods may be reduced to align with the manufacturer's recommendations.

- Article 43: With the exception of piping, safety equipment, and pressure accessories, the periodic requalification of pressure equipment (PE) must be renewed at intervals not exceeding ten (10) years for fixed pressurized equipment and five (5) years for mobile pressurized equipment.

After a PE has been successfully tested, a report is issued by the ARH or its duly authorized representative. The periodic requalification of a fixed PE must be renewed when the equipment is moved to another operating site [34].

3.4. Damage Mechanisms Affecting Catalytic Reformer Heater Tubes

Tubes can undergo deterioration, with typical mechanisms outlined in the following subsections and detailed in API 571. Table 3.1 gives a summary of common damage mechanisms that can affect catalytic reformer heater.

Table 3.1: Tube Damage Mechanisms Common to catalytic reformer heater [3].

Unit	Typical Tube Materials	Damage Mechanism	Comments
Catalytic Reformer	$1^1/4$Cr-$^1/2$Mo $2^1/4$Cr-1Mo 5Cr-$^1/2$Mo 9Cr-1Mo	Creep External oxidation	Caused by abnormal operation, low flow, or flame impingement.
		High-temperature hydrogen Attack	Caused by operation of tube materials above API 941 Nelson curves.
		Carburization/metal dusting	Caused by high carbon activity and high-temperature operation and occurs under specific conditions.
		Spheroidization	Probablein$1^1/4$Cr-$^1/2$Moafterlong-term service.

3.4.1. Internal Corrosion

Internal corrosion in tubes is influenced by the chemical composition of the process fluid, tube material, fluid velocity, and temperatures. Key corrosive agents like sulfur compounds and organic acids, such as naphthenic acid, affect the rate and type of corrosion. Sulfur compounds cause sulfidic corrosion, leading to tube wall thinning, while organic acids cause localized corrosion in turbulent areas. The highest corrosion rates are observed at elevated temperatures, particularly on the fire-side front face of the radiant tube. This damage is shown in figure 3.2 [3].

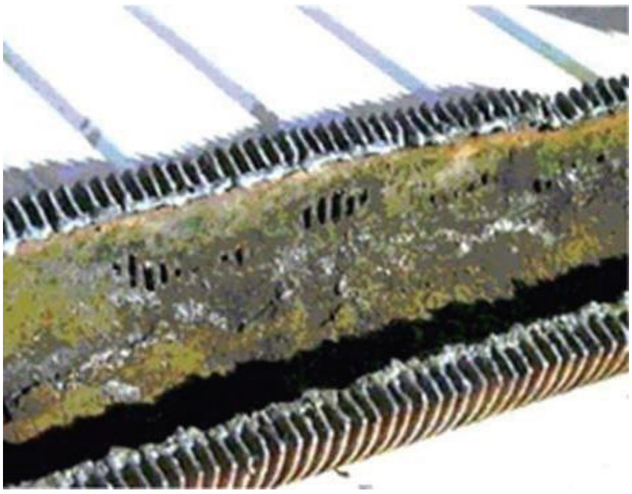


Figure 3.2: Convective Tube Failure from Internal, High-temperature Sulfidic Corrosion [3].

Tube failures caused by corrosion typically result from local stress rupture, where the wall thickness decreases to a critical point and becomes overstressed at the operational temperature of the metal. These failures can manifest as small leaks through pits or as "fish- mouth" ruptures when there is general thinning or longitudinal grooving occurs [2,3].

3.4.2. External Corrosion

External tube corrosion is influenced by the atmosphere and operating temperatures, typically resulting in oxidation. Excessive oxidation and scaling occur when tubes are operated beyond recommended temperature limits, which may result from furnace overheating or internal fouling that raises tube wall temperatures. Combustion deposits can resemble oxide scales but are distinguishable by magnet testing [2, 3]. Figure 3.3 demonstrates a tube exhibiting external corrosion.

Figure 3.3: General metal loss and pitting of tubes exposed to moisture [3].

3.4.3. Oxidation Issues In Radiant Tubes Of Catalytic Reforming Furnaces

Radiant tubes in flame-fired applications of petroleum refineries are typically made of alloy steel, ASTM A335 P22, P5, or P9, which have respective chromium contents of 2.25%, 5%, and 9%. Radiant tubes oxidize at operating temperatures, and scale continuously grows on the surface, often reaching up to 2 mm in thickness in high-temperature/high-heat-flux units.

Oxidation layers are highly insulating and pose a significant barrier to heat transfer by conduction to process fluids. During operation of the flame-fired furnace, it becomes necessary to increase heating power to maintain sufficient heat flux through the process line inside the tubes and thereby overcome the insulating effects of the oxide layers.

The open porosities and the morphology of cracks in the zirconia deposit, along with its high ionic conductivity of oxygen, contribute to the oxidation of the underlying metallic substrate. Depending on the chemical composition of the substrate and diffusion kinetics, the oxide layers formed primarily contain alumina and chromium oxides. Compression stresses develop within these layers during oxide growth. Upon cooling, these growth stresses combine with stresses generated by differences in thermal expansion coefficients. The accumulation of these two types of stresses can lead to flaking of the oxide layer.

Moreover, it has been shown that beyond a certain thickness, which varies depending on the type of substrate and/or ceramic, the oxide layer becomes more brittle and prone to damage. Figure 3.4 represents the oxidation carbon steel furnace's Outer Diameter.

Figure 3.4: Oxidation of the OD of a carbon steel furnace transfer line [3].

In cases where oxidizing and reducing conditions fluctuate, metal dusting may take place. RT is used to assess the remaining thickness of a component when oxidation impacts its external surface. If oxidation is present, the oxide layer can be removed using a flapper wheel, allowing UT to precisely measure the remaining wall thickness. For internal surface oxidation, UT can also be used to gauge the remaining thickness. In situations where oxidation is evident, a combination of RT, UT, and magnetic techniques may be applied to enhance measurement accuracy [2,3]. [2,3].

3.4.4. Creep And Stress Rupture

At elevated temperatures, metal components can gradually deform under load even when the applied stress is below the yield point. This time-dependent deformation is known as creep. The early stages of creep damage can only be detected through scanning electron microscope metallography. Creep voids usually appear at the grain boundaries and, in later stages, develop into fissures and cracks. The threshold temperatures for creep are 370°C for carbon steel, and between 400°C and 425°C for C-Mo and Cr-Mo steels. Figure 3.5 represents creep rupture of an hk40 heater tube.

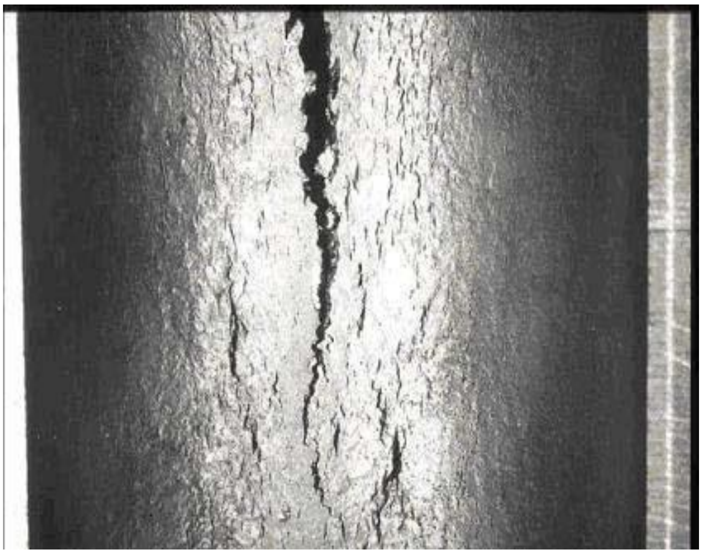


Figure 3.5: Creep rupture of an HK40 heater tube [3].

Distinct methods are used to detect creep damage. Visual testing identifies external abnormalities but does not reveal internal damage. Ultrasonic testing measures wall thickness to pinpoint areas for further inspection, while dimensional inspections detect diametric growth due to creep. However, these methods have limitations in detecting internal creep damage, often requiring additional non-destructive evaluation (NDE) for a more thorough assessment [2, 3].

3.4.5. High-Temperature Hydrogen Attack

HTHA takes place when steel is exposed to hydrogen gas at elevated temperatures and pressures, leading to a reaction between hydrogen and carbon or carbides in the steel. This reaction produces methane (CH4). This reaction can cause surface decarburization, which, while not typically life-limiting for equipment, may indicate more severe internal HTHA. If the diffusion of carbon to the surface is limited, internal decarburization occurs, forming CH4 within the steel. The CH4 pressure builds up, enabling to the generation of bubbles, micro fissures, and eventually cracks, which can significantly weaken the steel and cause equipment failure. Additionally, blistering may occur due to the accumulation of molecular hydrogen or CH4 in laminations or other conducive sites in the steel. For more detailed information, refer to API RP 941 [3].

Creep damage detection is carried out using various NDE methods. Visual Testing provides an initial assessment, and Focused Microwave Radiometry (FMR) can assist, though it's not a primary method. Advanced techniques like Automated Ultrasonic Backscatter Testing (AUBT), Angle Beam Spectral Analysis (ABSA), Time-of-Flight Diffraction (TOFD), and Phased Array Ultrasonic Testing (PAUT) are effective in identifying creep damage. Traditional methods, such as Magnetic Particle Testing (MT) and Liquid Penetrant Testing (PT), are less effective unless significant cracking occurs [2, 3].

3.4.6. Carburization

Different species can interact with the carbon present in steel, affecting its carbon content. Since the strength of steel is often directly related to its carbon concentration, any alteration in the carbon level will affect the steel's mechanical properties. Carburization is an increase of the carbon content to the steel. This results in a higher strength and hardness but also in embrittlement. For chromium-containing alloy this can also result in decreases of the corrosion resistance.

Figure 3.6 illustrates the carburization of an ethylene furnace after three years of operation at 1900°F.

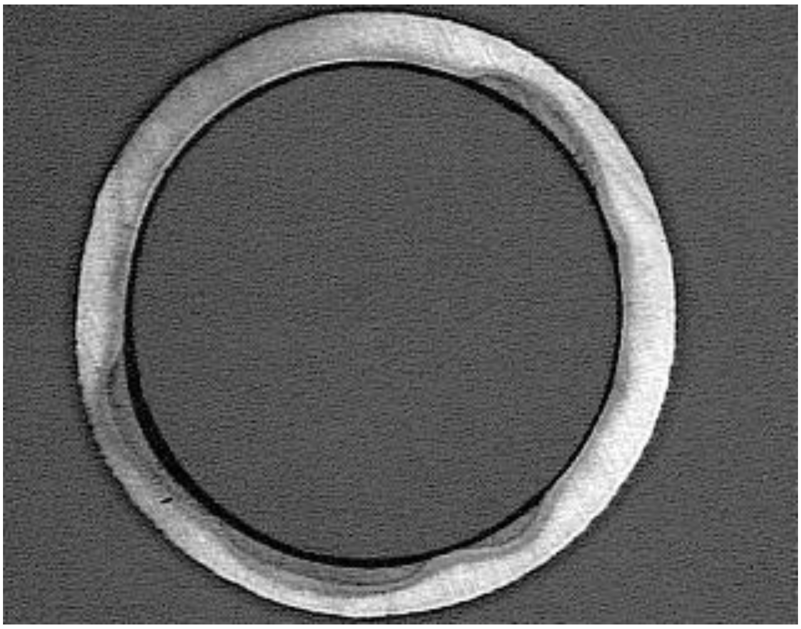


Figure 3.6: Carburization (dark areas) of an HP-modified tube from an ethylene furnace [3].

Carburization and metal dusting detection during inspections is challenging. Visual testing (VT) is often ineffective, as carburization occurs at shallow depths and may not be visible early on. Once the environment changes to oxidizing, carbon is burned off, leaving shallow pits. Metal dusting, typically detected after significant damage, requires destructive testing for confirmation. When internal surfaces are accessible, VT can reveal metal loss, pits, and perforations, while radiographic testing (RT) helps identify pitting, cracking, and wall thinning associated with metal dusting [2, 3].

3.4.7. Metal Dusting

Metal dusting occurs when materials are exposed to alternating oxidizing and reducing environments, leading to carburization at shallow depths. In reducing conditions, carbon is deposited on the metal, and in oxidizing conditions, it is burned off, leaving pits and oxide powder. This degradation is common in environments with carbon and hydrogen but little oxygen, leading to the formation of iron carbides. These carbides can break down into iron and graphite, accelerating damage and weakening the material. Metal dusting can cause significant failure, as seen in the carburized carbon steel separator plate from a natural gas preheater. Effective inspection and prevention are critical to mitigate this issue. as shown in Figure 3.7. This pattern highlights the critical need for effective monitoring to avoid further deterioration.

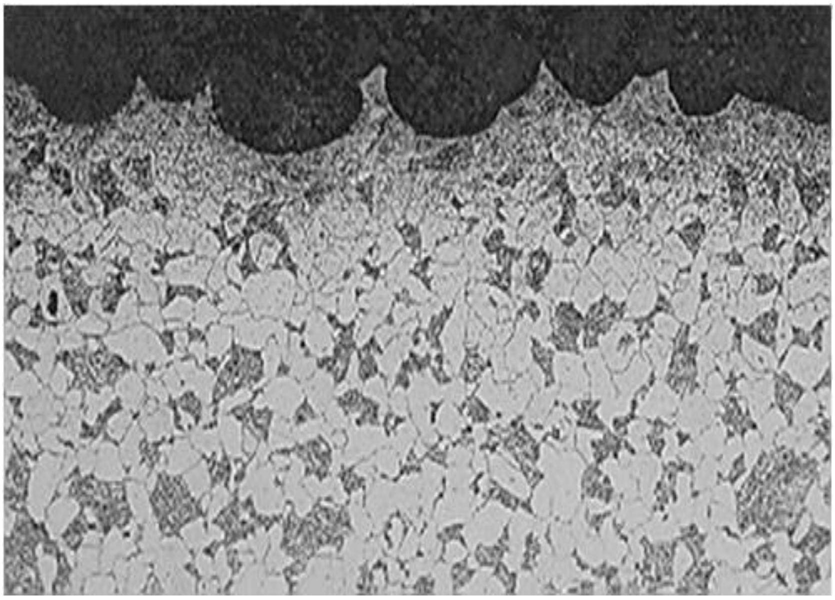


Figure 3.7: Carbon steel separator plate in a natural gas preheater showing classical pattern of carburization and pitting [3].

Metal dusting is often detected once a failure takes place and metal loss across the wall. While destructive testing, such as chemical or physical sampling, is the most accurate way to confirm metal dusting, other methods can help identify damage. If internal surfaces are accessible, visual testing (VT) can reveal severe metal wastage, including pitting, uniform thinning, and perforations. Additionally, radiographic testing (RT) can be used to detect pitting, cracking, and thinning of the metal wall [3].

3.4.8. Spheroidization (Softening)

Spheroidization is a microstructural change that occurs in steels exposed to temperatures between 850 °F and 1400 °F (440 °C to 760 °C). During this process, carbide phases in carbon and C-½Mo steels become unstable, transforming from plate-like structures to spherical forms. In Cr-Mo steels, finely dispersed carbides can agglomerate into larger particles. This change can lead to a reduction in strength and creep resistance. Spheroidization affects various grades of carbon and low-alloy steels, such as 1 C-½Mo, 2¼Cr-1Mo steels. A high-magnification photomicrograph shown in Figure 3.8 illustrates this microstructural alteration.

Spheroidization is typically detected through Field Metallurgical Replication (FMR) or by removing samples for metallographic evaluation. Since spheroidization can reduce tensile strength and consequently, hardness field hardness testing may provide an initial indication of its presence. However, this should be confirmed with sampling and/or FMR for accurate assessment [3].

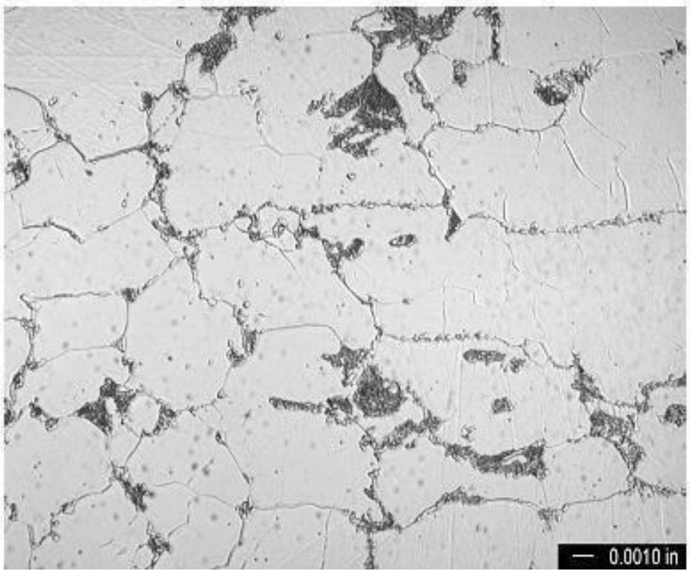


Figure 3.8: High-magnification photomicrograph of metallographic sample showing spheroidized carbides [3].

3.4.9 Short-term Overheating / Stress rupture

Localized overheating can cause permanent deformation at low stress levels, which often results in bulging and ultimately leads to failure through stress rupture. Figure 3.9 depicts the failure of a 21-year-old hydrocracker radiant tube due to short-term overheating.

Figure 3. 9: Short-term overheating failure of a vertical, 4.5-in. OD hydrocracker radiant tube [3].

Short-term overheating damage can occur so rapidly, using inspection as a preventive step may not always be feasible, various methods can help detect signs of overheating.

During shutdowns, visual inspections of accessible components in fired heaters and boilers can reveal deformation such as tube bulging or sagging, with further quantification using strapping and ultrasonic thickness (UT) measurements. Infrared thermography can detect localized hot spots during operation, though it is limited to line-of- sight

Thermocouples can monitor temperatures but may miss localized issues. During shutdowns, refractory damage inspections can offer clues about overheating, while Field Metallurgical Replication (FMR) can assess creep damage and estimate remaining life. Additionally, boroscopic visual testing (VT) can detect long-term caustic corrosion from steam blanketing, though certain ultrasonic techniques may be limited in specific cases, such as finned tubes [3].

3.5. Case Study Damage Analysis of Catalytic Reformer Heater Tubes

3.5.1. Process Description of The Reforming Unit

The unit operates a catalytic reforming process featuring four reactor beds with progressively increasing inlet temperatures. The lead reactors are optimized with a smaller amount of catalyst and lower hydrogen requirements, facilitating the dehydrogenation of naphtha into aromatics. In contrast, the lag reactors are equipped with more catalyst and higher hydrogen content, reducing catalyst coking rates. Naphtha is supplied from a naphtha hydrotreater stripper, filtered, and passed through a combined feed exchanger before entering the feed heater. The reactor effluent then flows through multiple re-heaters to reach the desired inlet temperatures for each reactor. This design aims to maximize the aromatics content and octane number in the final reformate product [87]. The corresponding PFD is shown in the next figure.

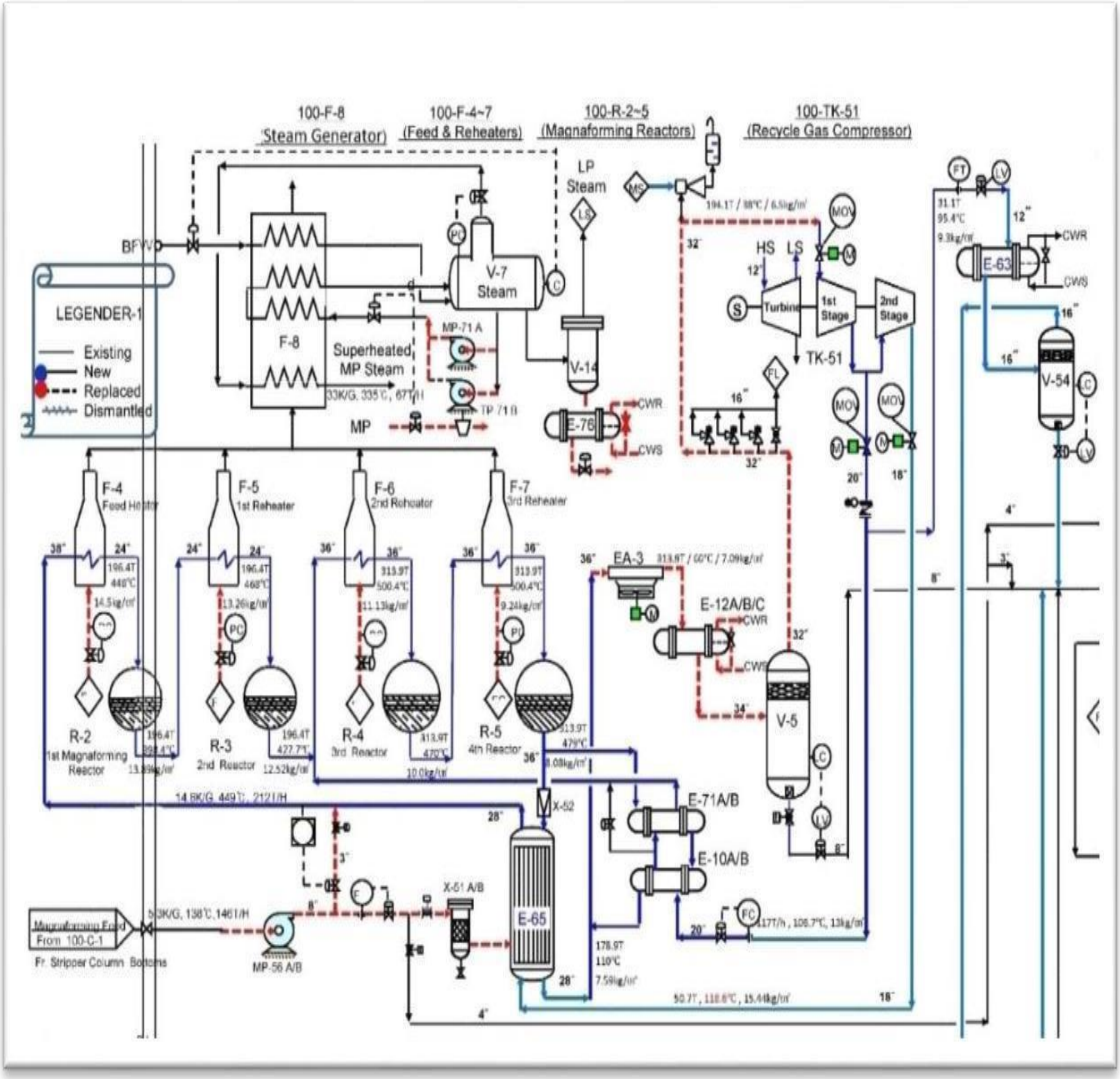


Figure 3.10: Process Flow Diagram of reforming unit [88].

3.5.1.1. Reaction Section

The Magnaforming unit is a semi-regenerative fixed-bed catalytic process that features four reactor beds, each with an increasing inlet temperature profile. The first two reactors are equipped with less catalyst, (high space velocities) than the two lag reactors and the feed fired heaters are a combined box type with common cross flow convection.

3.5.1.2. Magnaforming Feed Heaters (100-F-4/5/6/7)

The feed fired heaters are a combined box type with common cross flow convection. The heater is designed to operate on fuel gas while each burner is equipped with a gas operated pilot burner. A temperature controller is provided on the process stream side and controls heater firing for each heater. A damper is provided at the top of the heater, above the convection section to control the firebox pressure. Typically, the pressure is set at -1.3 ~ -0.25 mmH2O. The air registers at the burners are adjusted to achieve the desired airflow.

The heater is equipped with an automatic shutdown system to be activated in case of emergency. The automatic shutdown system will stop fuel to the burners and also shut down the heater. The fuel to the main burners is stopped when the fuel gas pressure is lower than a set pressure or the recycle gas flow rate is lower than a set point.

The automatic shutdown system will stop the main fuel burners or pilot fuel burners case by case also shut down the heaters. When the case that fuel gas pressure is lower than a set pressure, case of lower body pressure than a set point at Arch section, case of lower flow rate than a set point or case that lower feed charge than a set point, the fuel gas to main burners is stopped. The fuel gas to pilot burners is stopped when the pilot gas pressure is lower than a set pressure. Shutting down of pilot burner affects not only pilot burners but also main fuel burners. In this case, all burners will be stopped [89].

3.5.1.3. Description Of the Studied Equipment

The 100-F7 heater is an industrial heating equipment utilized in the reforming reaction section. It is designed to process preheated Naphtha "B," heating it to elevated temperatures for use in various process applications. The heater is engineered to run at design pressures and temperatures of 16.6 bars and 566°C, respectively. However, actual operating conditions differ, with the heater running at an operating pressure of 10.08 bars and an operating temperature of 537.6°C [89]. The selected system is illustrated in Figure 3.11.

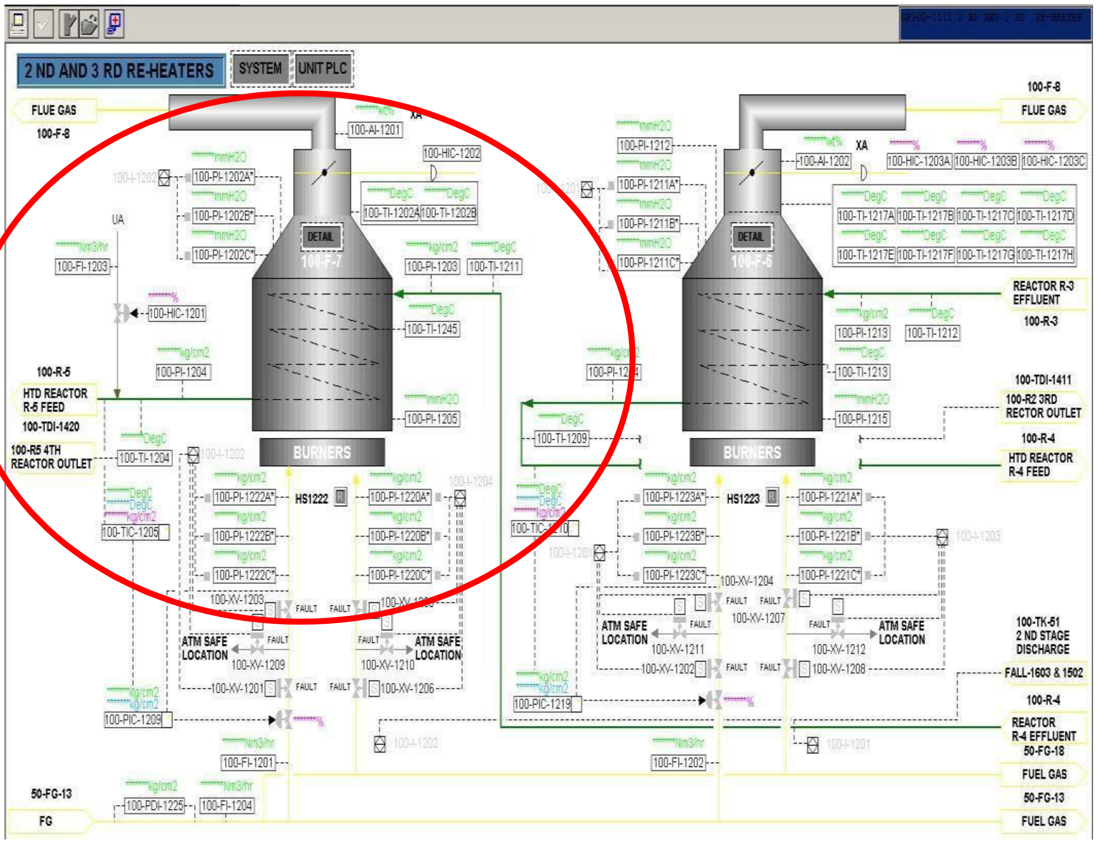


Figure 3.11: Diagram related to catalytic reformer heater [90]

The heater's casing is constructed from durable carbon steel, providing a robust outer shell. The floor is insulated with a combination of concrete and refractory bricks, ensuring excellent heat resistance and stability. For the walls and ceiling, ceramic fiber insulation is used, which offers high thermal efficiency and minimizes heat loss. The heater's internal tubes are designed to withstand the intense heat generated, enhancing the system's overall performance and safety.

The heater is constructed from Chrome-Molybdenum alloy, specifically grade A335 P22, chosen for its suitability in high-temperature and high-pressure environments. Chrome-Moly alloys, commonly known as "P-grade" materials, derive their properties from Molybdenum (Mo) and Chromium (Cr), with over 17 grades available, the most popular being P5, P9, P11, P22, and P91. Chromium enhances tensile strength, elasticity, and hardness at ambient temperatures, which is vital for resisting oxidation under intense heat. Molybdenum contributes to improved hardness, reduced brittleness, and greater yield strength, as well as increased thermal resistance.

To enhance durability, the heater includes a 1.6 mm corrosion allowance, ensuring material resilience and prolonging operational life by safeguarding against corrosive damage.

The heater is designed with 54 passes, meaning the preheated naphtha fluid makes 54 traverses through the tubes, maximizing heat transfer. Given the heater's demanding conditions, stringent standards and specialized materials were chosen to ensure the reformer’s tubes exhibit optimal mechanical properties, corrosion resistance, and structural integrity, as detailed in Table 3.2.

Table 3.2: Tube material and heater operating conditions of the 100-F7 [87].

Equipment	100-F7	
Type	Box (ARBOR)	
service	Heating (H2+HC vapor)	
operation	Temp. (°C)	537.6
	Press. (kg/cm2)	10.08
Design	Temp. (°C)	566
	Press. (kg/cm2)	16.6/F.V.
Tube material	Position	Vertical coil (suspended)
	Material	A 335 P22
	Diameters	Ø 4"
	Thickness	Sch 40
Exposed Surface Area (m^2)	398,2	
Number of Passes	54	
Useful Tube Length (mm)	20550	
Corrosion Allowance (mm)	1.6	
Burners	Number	16
	Position	floor
	Supplier	J-ZINK
Type of Fuel	Fuel gas	

3.5.2 Damage Analysis Methodology

Numerous inspection techniques indispensable to evaluating the heater tubes condition, as each method provides valuable insights into different aspects of tube integrity. It is critical to apply a comprehensive approach, as no single technique is capable of detecting all possible damage types or deterioration mechanisms. Therefore, we adopted an optimal combination of methods to ensure a thorough evaluation of the furnace tubes' condition.

Our process began with a visual inspection, which allowed us to directly observe the external condition of the tubes. This inspection serves as the first step in identifying visible signs of damage, such as corrosion, cracking, or physical wear on the surface of the tubes, which may be indicative of underlying issues. However, this method alone cannot detect internal or microscopic damage, necessitating further testing.

To gain deeper insights into the material properties and internal changes within the tubes, we employed energy dispersive spectrometry (EDS). This method was employed to examine scale fragment samples collected from the tubes. EDS allowed us to examine the microstructure and of the scale, providing critical information about the types of corrosion products, material degradation, or contamination present on the tube surfaces. This method is particularly useful for detecting chemical changes that could lead to further damage if left unchecked.

In addition, we conducted metallographic examination using replica testing. This technique allows for a closer look at the material's microstructure and helps detect issues that might not be observable to the naked eye. It is particularly useful for identifying cracks, corrosion, or other forms of material degradation that could affect the tube's integrity.

We also performed hardness testing to assess the mechanical strength of the tubes. Hardness testing measures the material's resistance to deformation, providing valuable data on its ability to withstand mechanical stresses during operation. A decrease in hardness often correlates with material degradation. This test is a critical indicator of whether the tubes can continue to perform safely under the demanding conditions of the furnace.

To further assess the structural integrity of the tubes, we measured the tubes OD. This measurement facilitated the assessment of the bulging rate, a key indicator of any deformations. Bulging often signals the development of internal pressure or thermal stresses, which could compromise the tube's structural strength. Identifying these deformations early on is crucial for preventing catastrophic failures during operation

A summary of these methodological steps is presented in Figure 3.12, illustrating the systematic approach we used to evaluate the tubes' condition.

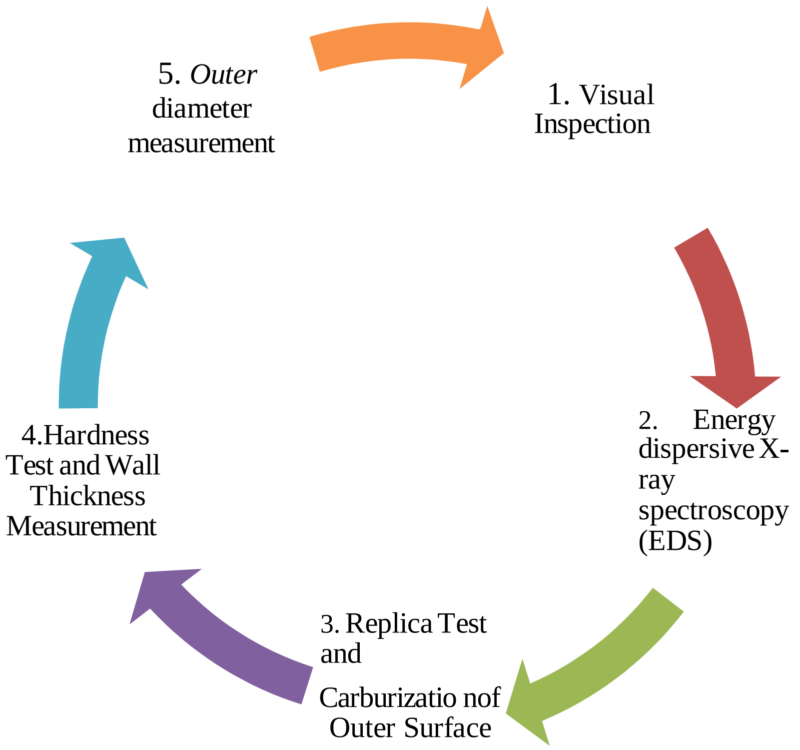


Figure 3.12: Methodology steps [1].

- Visual Inspection

Visual inspection is essential for identifying deterioration, defects, and potential weaknesses in tubes and structural components. Tubes need to be examined for bulges, sagging, bowing, discoloration, or leaks, as hot spots may indicate flame impingement and improper alignment may suggest damaged supports. Structural components, such as tube supports visible through inspection ports, should be examined to ensure they are intact, and external tube suspension systems and compensating devices should undergo routine inspection. Initial inspection of heaters in an “as opened” condition can reveal scaling, indicating areas affected by corrosion, mechanical damages, or failure of internals.

- Energy Dispersive X-Ray Spectroscopy

EDS is a widely utilized analytical method for determining the composition of solid materials, particularly in the chemical analysis of nanoparticles [91]. This method works by detecting characteristic X-rays emitted by each element in a sample, which are unique to that element [92]. EDS is commonly integrated with Scanning Electron Microscopy (SEM) [93], enabling the precise detection and measurement of X-ray emissions from prepared nanoparticles across different wavelengths with a photon energy-sensitive detector.

These characteristic emissions allow for accurate and detailed analysis of the nanoparticles' elemental composition [94].

- Replica testing

An alternative method for inspecting corrosion is the replica technique, which is also useful for evaluating carburization on the outer surface. This method entails creating a replica of the metal surface to analyze and identify any corrosion indications. A thin layer of material, such as plastic, is applied to the surface and carefully removed, producing a replica. This technique can reveal corrosion types, such as pitting or crevice corrosion, which might not be visible to the naked eye. The replica technique is a non-invasive sampling method that captures and preserves the surface structure of the metallurgical specimen as a negative relief on a plastic film [95].

The replica technique is commonly utilized to assess degradation and determine the remaining useful life of materials. It allows for the identification of damage initiation and its severity, which might not be detected through other non-invasive inspection methods. According to ASTM (Designation E 1351-01), this method provides insight into the degradation level of equipment, the residual life remaining, and the causes of damage initiation.

Replica testing involves several key steps:

- Surface Preparation: This begins with grinding, polishing, and etching to reveal the material's microstructure. In-service components often have corrosion, oxidation, or decarburized layers that must be removed using portable grinding and polishing units.
- Preparation of the Metallic Surface: The surface is mechanically polished according to modified field methods to ensure it is free of deformations, scratches, or defects. Decarburization can be detected and monitored during this process. Chemical etching is then performed following established practices, and the surface quality is checked with portable microscopes. After etching, the area is cleaned to avoid contamination.
- Replication Technique: A replica is created by applying a plastic film, wetted with a solvent like acetone or methyl acetate, to the prepared surface. The film is pressed onto the surface to ensure adherence. Alternatively, a rubber-based compound can be used. The replica should be prepared immediately after surface preparation to minimize oxidation. Once the film dries, it is removed, mounted on a slide for analysis, and protected from damage. The Replica testing key steps are represented in the following figure.

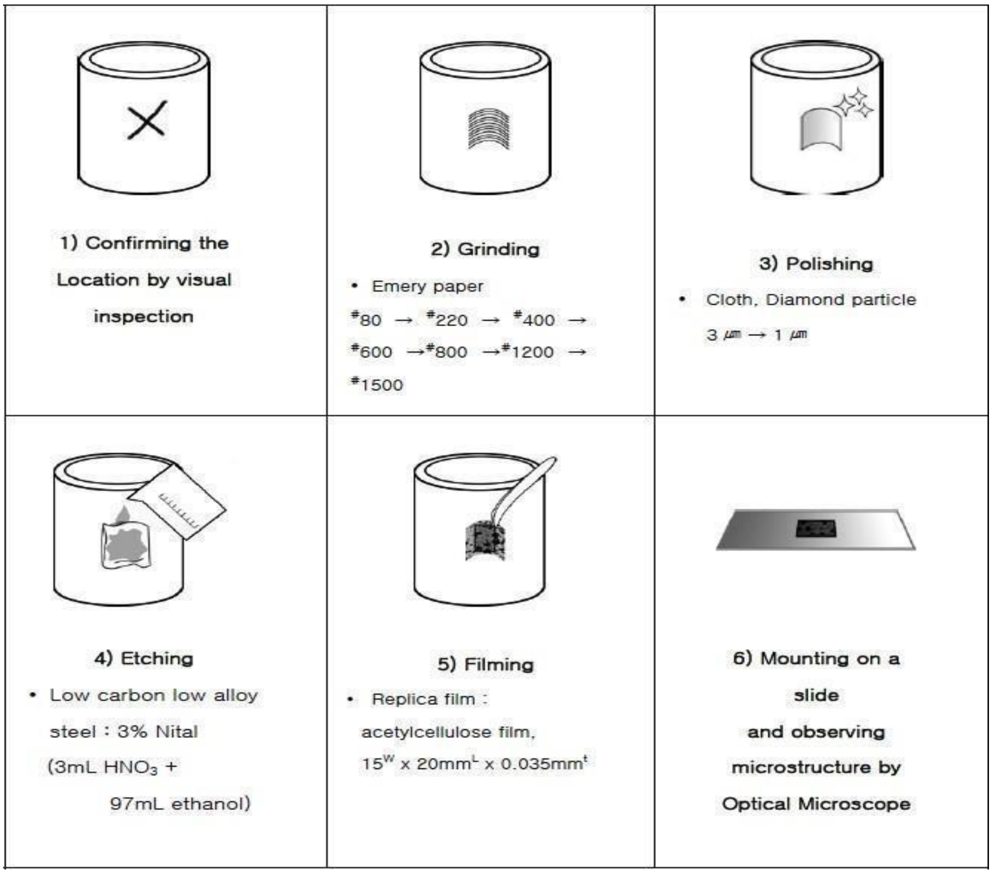


Figure 3.13: Replica method steps [95].

In this method the evaluation is carried out by analyzing the changes in the microstructure and the condition of damage revealed by the microstructure replica of the surface being examined. The degradation is classified into different grades (A to F), as outlined in Table 3.3.

Table 3.3: Evaluation of a degree of degradation

Grade	Condition	Residual life	Condition
A	Early stage	100%	Recheck after 5 years
B	Progress step between A and C	80%	Recheck after 3 years
C	Intergrade	60%	Recheck after 2years
D	Progress step between C and E	40%	Recheck after 2years
E	The last period	20%	Recheck in a year Decision repair or replacement time
F	Destruction	0%	Immediately repair or replacement

- Hardness Test and Wall thickness measurement

Ultrasonic thickness gauging is a widely used non-destructive test technique for measuring the thickness of a material from one side. It is fast, reliable, and versatile. The principle of ultrasonic wave in the thickness measurement is similar to that of optical wave. The ultrasonic wave pulses transmitted by the probe will be reflected back, while they reach the interfaces. The thickness of the object is determined by precisely measuring the time the ultrasonic wave travels in the object.

- Outer diameter measurement

Measuring the outer diameter is an essential technique for corrosion inspection, enabling the determination of bulging rates and identification of any changes in the heater tube's diameter. A reduction in diameter can indicate corrosion and suggest potential weakening of the tube structure.

Each of these inspections and testing methods contributes valuable data to the overall assessment of the furnace tubes' condition. By combining visual inspections, chemical analyses, metallographic evaluations, hardness testing, and dimensional measurements, we ensured a comprehensive evaluation of the tubes' mechanical integrity and suitability for continued use.

3.5.3 Results and Discussion

3.5.3.1 Visual inspection

A detailed VI showed that the radiant tubes had formed substantial scale layers, a clear indication of prolonged exposure to thermal oxidation. Furthermore, signs of fragmentation were observed on the tube surfaces, suggesting advanced material degradation. These conditions, which are critical to the structural integrity and performance of the tubes, were documented through photographs taken from multiple sections of the fired heater. The images, presented in Figure 3.14, offers a thorough overview of the severity and distribution of the scaling and fragmentation across the radiant heater tubes.

Figure 3.14: the inspected radiant tubes.

3.5.3.2. Energy Dispersive X-Ray Spectroscopy

Figure 3.15 displays samples collected from the studied equipment. These samples highlight the effects of prolonged exposure to high-temperature conditions. Sample A represents the outer surface of the scale, whereas Sample B corresponds to the inner surface. To further investigate the material composition of these samples, energy-dispersive X-ray spectra were obtained. The results of this detailed analysis are presented in Figures 3.16, 3.17, 3.18, and 3.19, offering valuable insights into the elemental distribution and chemical characteristics of the scale layers.

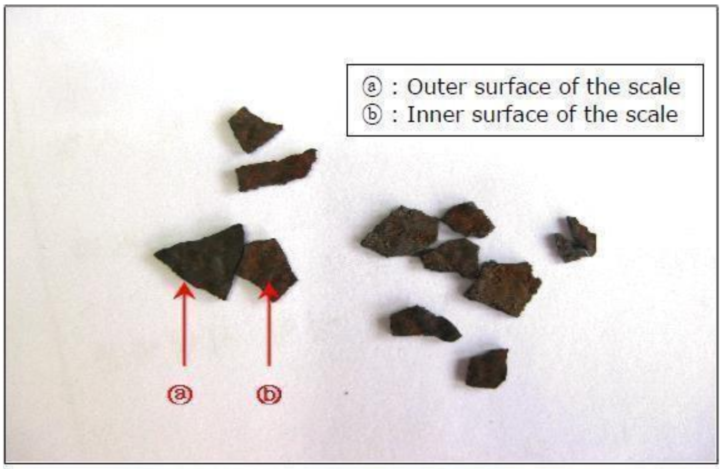


Figure 3. 15: Dark scale fragment samples taken from the heater tube

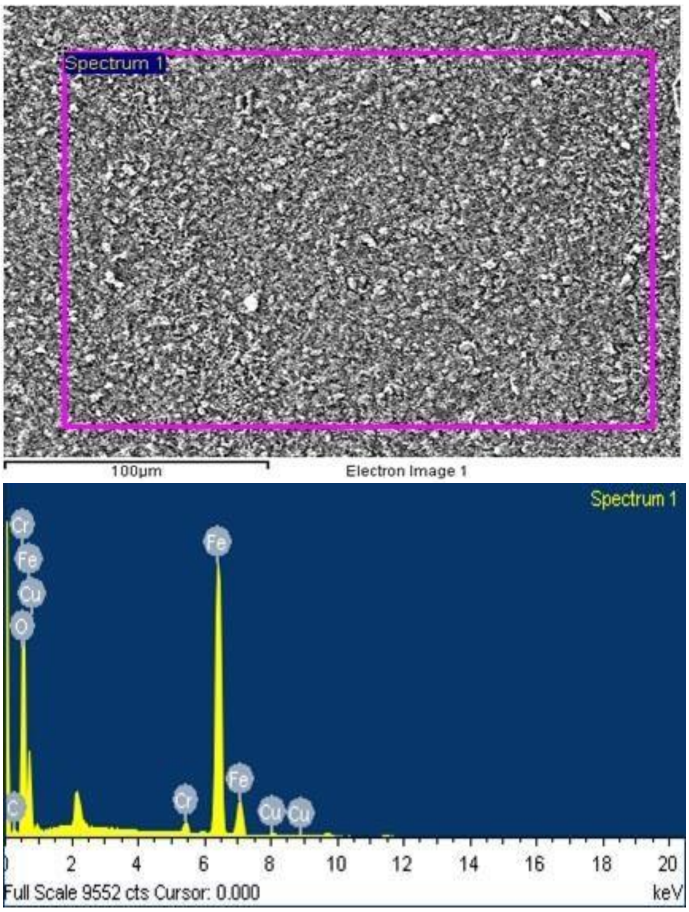


Figure 3.16: EDS results from sample A of spectrum 1

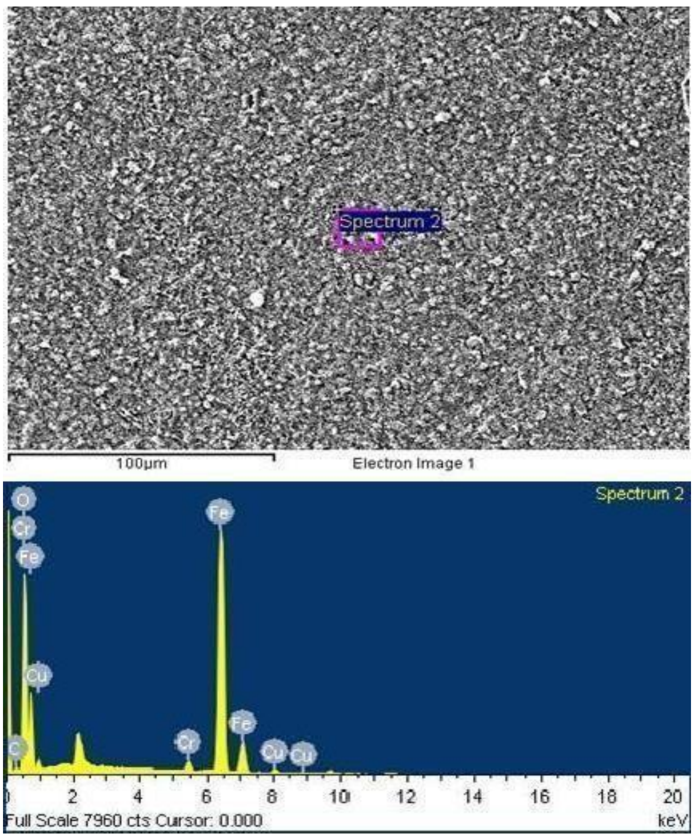


Figure 3.17: EDS results from sample A of spectrum 2

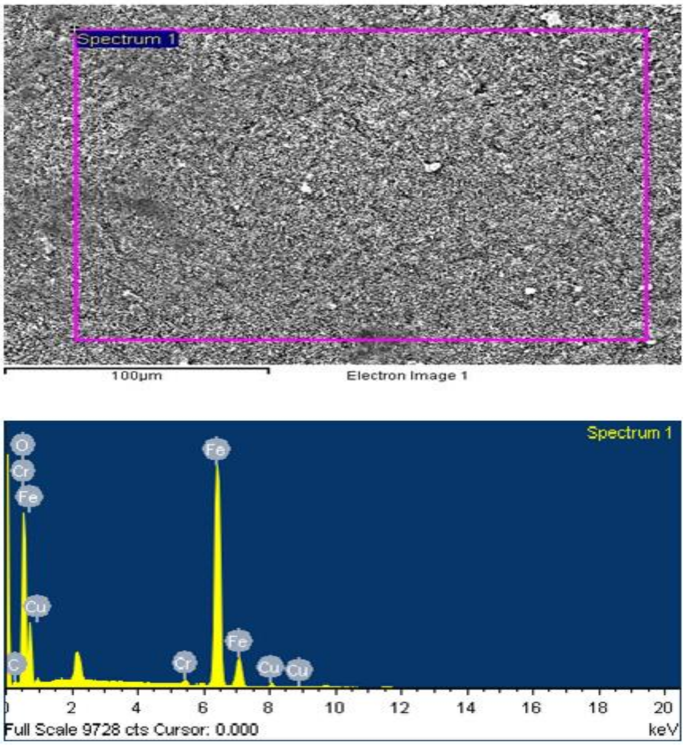


Figure 3.18: EDS results from sample B of spectrum 1

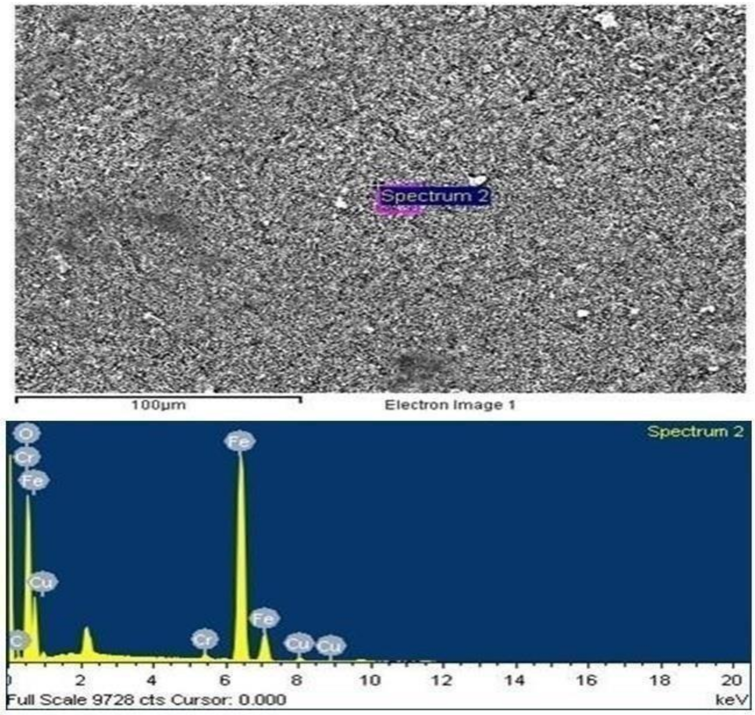


Figure 3.19 EDS results from sample B of spectrum 2.

Tables 3.4, 3.5, 3.6, and 3.7 present the outcomes of the spectral data analysis, detailing the chemical composition of Samples A and B.

Table 3.4: Chemical composition of samples A of spectrum 1

Element	Spectrum 1	
	Weight %	Atomic %
C	2.64	6.83
O	28.07	54.57
Cr	1.72	1.03
Fe	66.54	37.06
Cu	1.04	0.51
Totals	100	

Table 3.5: Chemical composition ofsamples A of spectrum 2

Element	Spectrum 2	
	Weight %	Atomic %
C	2.78	7.16
O	28.32	54.74
Cr	1.56	0.93
Fe	65.69	36.37
Cu	1.64	0.80
Totals	100	

Table 3.6: Chemical composition of samples B of spectrum 1

Element	**Spectrum 1**	
	Weight %	Atomic %
C	2.82	7.32
O	27.68	53.95
Cr	0.99	0.59
Fe	66.87	37.33
Cu	1.73	0.80
Totals	100	

Table 3.7: Chemical composition of samples B of spectrum 2

Element	**Spectrum 2**	
	Weight %	Atomic %
C	2.44	6.34
O	28.15	54.97
Cr	0.91	0.55
Fe	66.77	37.33
Cu	1.63	0.85
Totals	100	

The EDS analysis of samples “a” and “b” identified five key elements: carbon, oxygen, chromium, iron, and copper.

Iron was the dominant element, constituting 66.54% to 66.77% of the mass, consistent with ferritic alloy steel.

Oxygen, at around 28%, was the second most abundant, likely due to the oxide layer formed during high-temperature exposure.

Carbon content in sample “a” was higher than expected, suggesting potential contamination or processing variations, while the other samples had lower carbon values.

Chromium and copper levels were also lower than the ASTM standard, possibly indicating uneven alloy distribution or surface contamination, which could impact material performance.

3.5.3.3 Replica Test and Carburization

The microstructures presented in Figures 3.20 and 3.21 highlight the degree of degradation and carburization in the heater.

Figure 3.20: Microstructure of the tube A-37

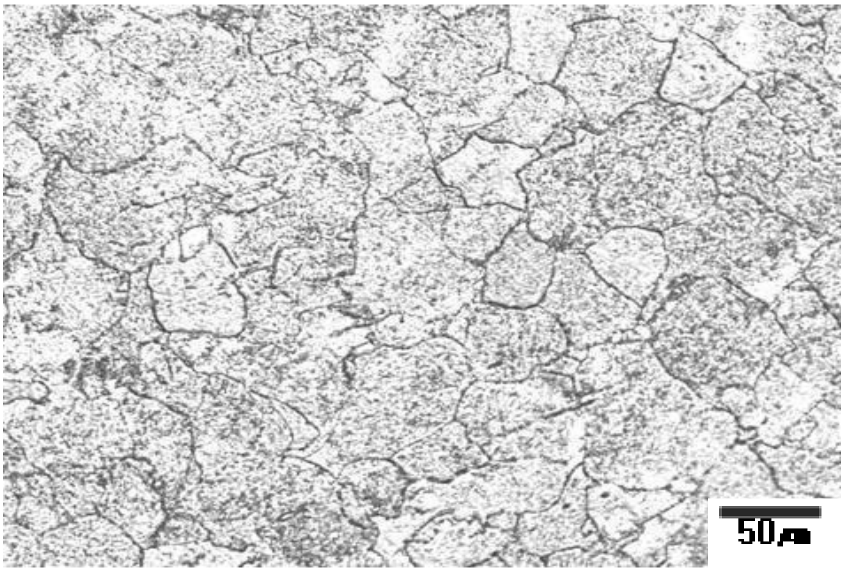


Figure 3.21: Replica test results of the tube B-37

The microstructure analysis of the heater tubes indicates varying degrees of degradation. Tube A-37 exhibits transformed large spheroidal Fe_3C carbide precipitates, with coarsened carbides along the grain boundaries, and its degradation is evaluated as grade D. Tube B-37, on the other hand, displays a mixture of ferrite and pearlite phases, with Fe_3C carbides decomposed into smaller particles and precipitated along the grain boundaries, resulting in a degradation grade of C. For both tubes, no creep cavities, micro cracks, inclusions, or segregation were detected, and neither tube shows evidence of carburization. Overall, the radiant heater tubes are not carburized, with degradation levels categorized as grade C and D, and an estimated lifespan of 40 - 60%.

3.5.3.4. Hardness Test and Wall Thickness Measurements

The results of the hardness and wall thickness measurements are summarized in Table 3.8. Over the past three years, the measured thickness of the heater tubes was 4.72 mm, 4.70 mm, and 4.69 mm, respectively, indicating a slight decrease, with the current thickness averaging around 4.70 mm.

Hardness measurements for the same period were 113 HB, 117 HB, and 124 HB. these values confirm that the tubes remain within the with the ASTM standard's limits (171 HB) based on these results we can consider that the current wall thickness operation is deemed safe.

Table 3.8: Hardness and wall thickness measurement test results

Tube No.	Wall Thickness (mm) (Design Ave. 6.02)	Hardness (HB.) (ASTM A335 Gr. P22Spec.171HB.)
A-8	5.04	143
A-17	5.46	128
A-26	4.44	123
A-35	4.72	137
A-37	5.38	126
A-43	5.05	126
A-50	4.20	130
B-8	4.70	122
B-17	4.18	131
B-26	4.89	124
B-35	4.97	131
B-37	4.09	109
B-43	4.36	123
B-50	4.24	124
Avg.	4.69	127 HB.

3.5.3.5. Outer Diameter

Visual inspection revealed no evidence of bulged tubes, and the measured outer diameter confirmed that the bulging rate was within the acceptable error range of ± 1%. Therefore, the OD of the heater tubes in all inspected areas is considered normal according to the results outlines in table 3.9.

Table 3.9: Outer diameter results of the heater tube

Location			Results			
Item	Tube No.	Replica No.	0°(mm)	Bulging Rate %	90°(mm)	Bulging Rate, %
100-F-7	A37	R14	113.30	-0.87	112.65	-1.44
	B37	R15	112.70	-1.40	113.00	-1.14

3.5.4. Overall Results and Discussion

Each inspection technique comes with its own boundaries and unlikely to locate t all types of damage. Relying solely on a single method increases the risk of overlooking certain issues. To address this, we have implemented an enhanced blend of inspection methods to guarantee a thorough assessment of the furnace tubes. This integrated approach minimizes the constraints of each individual method, offering more precise and complete outcomes.

The chromium content in Chrome-Moly alloys forms a protective oxide layer that enhances resistance to external oxidation. However, this layer can deteriorate over time due to severe thermal cycling or exposure to environments with fluctuating oxygen levels.

EDS analysis revealed the presence of copper, suggesting its penetration during combustion and confirming pure thermal oxidation. Replica test results showed no evidence of carbonization or creep in the heater tubes. Mechanical property evaluations, including hardness and wall thickness measurements, confirmed compliance with the required specifications and ruled out signs of carburization or metal dusting.

Additionally, visual inspection detected no bulged tubes, and measurements of the outer diameter indicated that the bulging rate remained within the acceptable margin. This confirms that the outer diameter of the heater tubes is within normal parameters and provides no indication of creep formation.

The findings of this study indicate that thermal oxidation is the primary cause of damage to the radiant heater tubes. Experimental results demonstrate that the tube was exposed to excessive temperatures, resulting in corrosion of the external surface. The combination of high temperature and excess oxygen in the atmosphere accelerated oxidation along the entire length of the tube. This process can be further exacerbated by over-firing or internal fouling of the tubes. Under these conditions, oxide scale accumulates on the heater tubes, which reduces efficiency and increases the risk of tube failure. The accumulation of scale acts as an insulator, impeding heat transfer and raising the surface temperature of the tubes, thereby decreasing thermal efficiency.

3.5.5. Recommendations

Based on the findings of the study, the following prioritized recommendations are proposed to mitigate the risk of thermal oxidation and prevent similar damage:

1. Apply Thermal Coatings (TBC): Coat the internal surface of heater tubes with thermal coatings to reduce fouling and minimize internal deposits. This improves heat transfer efficiency and mitigates conditions that could accelerate external oxidation.
2. Install Selective Catalytic Reduction (SCR): Enhance the combustion system by implementing SCR technology to improve combustion efficiency and reduce hazardous byproducts.

3. Maintain Recommended Temperature Levels: Monitor and control furnace temperatures to prevent excessive heat exposure. Regularly inspect and adjust temperature within the manufacturer's specified limits.

4. Remove oxide scale buildup through regular cleaning of the heater tubes to maintain efficiency and reduce the risk of tube failure. Specialized cleaning equipment or chemicals can be used for this purpose.

5. Monitor and Control Oxygen Levels: Continuously monitor atmospheric oxygen levels to prevent excessive oxygen from contributing to tube oxidation.

6. Conduct Risk-Based Inspections (RBI): Perform RBI studies for the heater to identify potential risks and enhance their reliability and safety.

7. Prevent Over-Firing: Monitor fuel consumption and adjust burners to avoid over- firing, which can exacerbate thermal damage.

8. Implement a Corrosion Monitoring Program: Conduct regular inspections including visual checks, use of thermal imaging infrared cameras, replica testing, and corrosion assessments, to detect early indicators of damage and implement preventive measures

9. Train Operating Personnel: Regularly train staff on correct operational protocols, monitoring strategies and procedures to minimize corrosion risks and extend heater lifespan.

By following these recommendations, the risk of thermal oxidation can be significantly reduced, enhancing the safety, efficiency, and lifespan of the reformer heater system. This proactive approach ensures the system's reliability while preparing it for long-term operation.

3.5.6. Conclusion

We have offered in this chapter a comprehensive description of the various damage mechanisms that can occur in catalytic reforming heaters. Understanding damage mechanisms is crucial for conducting POF analyses, selecting appropriate inspection intervals, locations, and techniques, and making informed decisions.

A study on the reformer heater tubes has highlighted external thermal oxidation as a primary damage mechanism. This oxidation, driven by high-temperature exposure and oxygen-rich environments, compromises the integrity and longevity of the heater tubes. To mitigate the effects of thermal oxidation, a multi-faceted approach has been recommended. Key strategies include the application of advanced protective coatings like thermal barrier coatings (TBC) and aluminizing, optimizing furnace operation to control temperature and oxygen levels, and implementing rigorous inspection and maintenance programs. These measures are designed to reduce oxidation rates, preserve tube wall thickness, and enhance the overall reliability of the heater system. In addition to these preventative measures, the study recommends advanced engineering solutions such as the use of low hydrogen welding techniques, installation of radiant tube shields, and the potential use of higher alloy grades for improved oxidation and creep resistance, implementation of RBI study to establish a well-defined inspection plan rooted in risk assessment in other to reduce the identified damage mechanisms, this is what will be addressed in Chapter 4.

Chapter 4

Application of the RBI approach on the f-07 reformer heater tubes

4.1. Introduction

An effective Process Safety Management (PSM) system significantly reduces risks in process plants, while a Risk-Based Inspection (RBI) study evaluates how management systems maintain mechanical integrity. By integrating data from equipment, process details, Process Hazard Analysis (PHA), and incident investigations, the RBI analysis is strengthened. Conversely, RBI enhances the PSM program by refining inspection plans and focusing on high-risk areas, leading to a more robust inspection program that minimizes equipment failures and ensures compliance with safety regulations [11].

The RBI method is a valuable tool for developing targeted inspection plans in industries. Cited in numerous studies, RBI supports decision-making by integrating critical factors like equipment reliability, safety, health, environmental impact, and financial considerations [96, 97, 98].

This chapter clarifies the RBI approach, emphasizing the probability and consequences of failure in processes per API 580 standard. It also explores the practical application of this risk-based approach in heater systems through a case study. This study identifies high-risk areas and implements appropriate inspection measures, analyzing specific situations that increase failure risks and their potential impacts on operational safety and productivity.

The chapter demonstrates the value of the risk-based approach in preventing incidents and minimizing disruptions within the heater. It emphasizes informed decision-making based on objective risk assessments. The case studies highlight essential inspection process steps, and the results are analyzed to showcase the effectiveness of this proactive risk management strategy.

4.2. Risk-Based Inspections Approach

The RBI methodology assesses the risk level of equipment by considering two key factors the POF and the COF. The POF refers to the likelihood that a piece of equipment will fail, while the COF focuses on the impact of such a failure event.

RBI is becoming an increasingly popular approach for inspecting and managing pressurized equipment in large petrochemical plants. It involves a thorough analysis of potential damage mechanisms, failure modes, and a risk assessment and ranking of the equipment under evaluation, RBI enables the identification of helps to identify key issues and weaknesses in the equipment. Based on these insights, an effective inspection program can be developed. This approach helps mitigate risks to an acceptable level by applying appropriate inspection methods and risk-reduction measures, ensuring equipment safety, reducing operational costs, and optimizing inspection strategies for pressurized equipment [11, 99, 100].

4.2.1. RBI benefits and capabilities

Risk-based inspection reduces overall risks for facilities and equipment by providing a clear understanding and measurement of risk, making it a powerful tool for managing key elements in a process plant.

RBI has the ability to assess current inspection plans to set priorities, guide future decision-making, and evaluate operational changes that impact equipment integrity. It identifies critical risk factors that might otherwise be missed and helps establish the most cost-effective inspection levels, balancing these against risk reduction. Additionally, RBI incorporates "acceptable risk" levels into its assessments.

The risk associated with each piece of equipment is first assessed. This includes analyzing how inspection techniques and process monitoring are effective at minimizing risk. Figure 4.1 represents stylized curves that shows difference between risk with typical inspection plan and risk using RBI and an optimized inspection program.

- The upper curve represents a standard inspection program. Initially, risk is high without inspection. As inspection efforts increase, risk decreases significantly, but after a certain point, further inspections offer diminishing returns and could even increase risk if invasive techniques cause damage.
- The lower curve shows the potential benefit of an effective RBI program. By focusing inspection on higher-risk equipment and reducing attention on lower-risk items, RBI can achieve greater risk reduction with the same or even fewer inspection resources [11, 101].

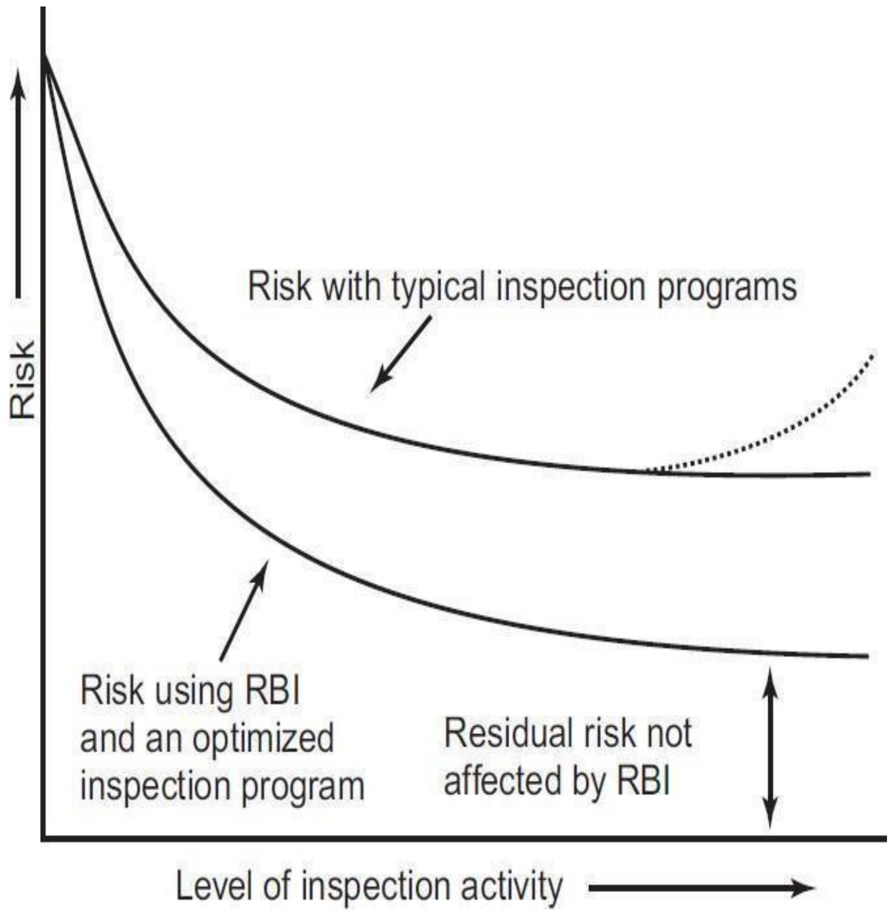


Figure 4.1: Management of Risk Using RBI [11].

An RBI program optimizes inspections by evaluating each available inspection method's cost-effectiveness and focusing resources on higher-risk equipment. This targeted approach improves overall risk reduction without unnecessary or excessive inspections, leading to more efficient resource allocation [11].

4.2.2. Equipment Included in RBI

The RBI encompasses a variety of equipment types and their associated components. These include pressure vessels, process piping, storage tanks, and rotating equipment with pressure-containing components. Additionally, it covers boilers and heaters, specifically the pressurized components, as well as heat exchangers, including shells, floating heads, channels, and bundles. Pressure-relief devices are also included within the scope of RBI assessments [11, 101].

4.2.3. Types of RBI Assessment

The RBI Risk assessment can be conducted using qualitative, quantitative, or semi-quantitative techniques. The choice of method is influenced by various factors such as the assessment objectives, data quality and accessibility, resource availability, previous risk assessments, and time limitations.

4.2.4. RBI Planning Process

According to API 580 the RBI, process encompasses six key steps, represented in the following figure.

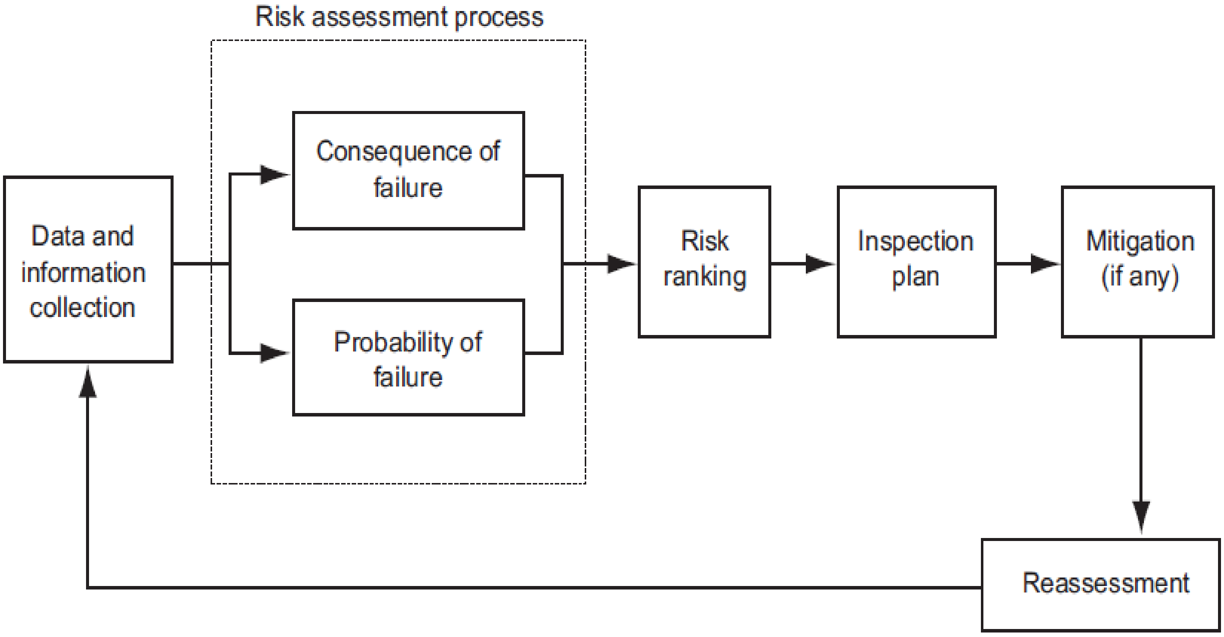


Figure 4.2: RBI Planning Process [3].

4.3. Application of RBI using VAIL-Plant software case study: Catalytic reforming heater tubes.

The implementation of the RBI study is a key recommendation previously outlined in our article to enhance maintenance strategies and risk management. This study specifically targets the reformer heater system, thoroughly detailed in Section 3.6.1.3, with a focus on identifying high-risk areas and optimizing inspection intervals to prevent failures.

4.3.1. VAIL Plant Software Description

The VAIL-Plant Software, developed as part of VELOSI's Risk-Based Inspection (RBI) services, is a powerful tool designed to streamline and enhance risk management processes. It helps prioritize equipment by ranking risks and using a risk matrix, making it easier to identify key degradation mechanisms that drive risk. The software evaluates the probability of failure and the potential consequences for each piece of equipment, considering factors like personnel safety, environmental impact, production loss, and material damage in both ignited and un-ignited leak scenarios. It also takes into account how changes in process conditions and materials might affect risk and the overall inspection strategy. The software goes a step further by assessing the impact of inspection effectiveness and frequency on risk over time. It enables the generation of detailed inspection guidelines and plans, tailored to specific engineering measures, and offers tools for managing inspection history. Additionally, it supports man-hour resource planning for both on-stream and off-stream inspections, ensuring a comprehensive, efficient approach to equipment management and risk mitigation.

Using of RBI software “Vail-Plant " as a dynamic tool for producing an effective inspection plan based on the component criticality or risk, leading to Improve the inspection effectiveness by accurate determining of How, Where, When, What to inspect, optimization of turnaround inspections and increase the reliability and availability overall the pressurized components [102].

4.3.2. Methodology Adopted To Perform The RBI Study

The RBI methodology adopted for the heater is semi-quantitative. It is in compliance with the API RP 580 standard. The figure 4.3 summarizes the methodology adopted for the RBI assessment process.

Figure 4.3: RBI assessment process [101].

4.3.2.1. Collection Of Engineering Data

The data collected for RBI study include but not limited to material selection diagram, P&ID, mechanical drawing, corrosion design basis, inspection reports, operation parameters, and failure records.

Data Validation was done specifically for this study, to collect the required information for update each component data as the following:

- Basic data: include construction data such design pressure, design temperature, minimum allowable design temperature…etc.
- Progressive data: collected from anomaly tracking sheet, process change, inspection reports, corrosion monitoring, cathodic protection measurements…etc.

4.3.2.1.1. Defining Corrosion Rate

For age-related degradation, corrosion rates are estimated to predict future damage. Ideally, these rates are derived from inspection data and supported by corrosion models from degradation modules. If inspection data is unavailable, analysis relies on corrosion monitoring data (e.g., Coupon and Probe) and generic data from similar plants, Degradation Modules, or literature. Figure 4.4 presents the flow scheme for selecting the corrosion rate (Selected Corrosion Rate or SCR) for Remnant Life assessment. Corrosion rates are essential for forecasting defect progression and determining when the Probability of Failure (POF) limit will be reached.

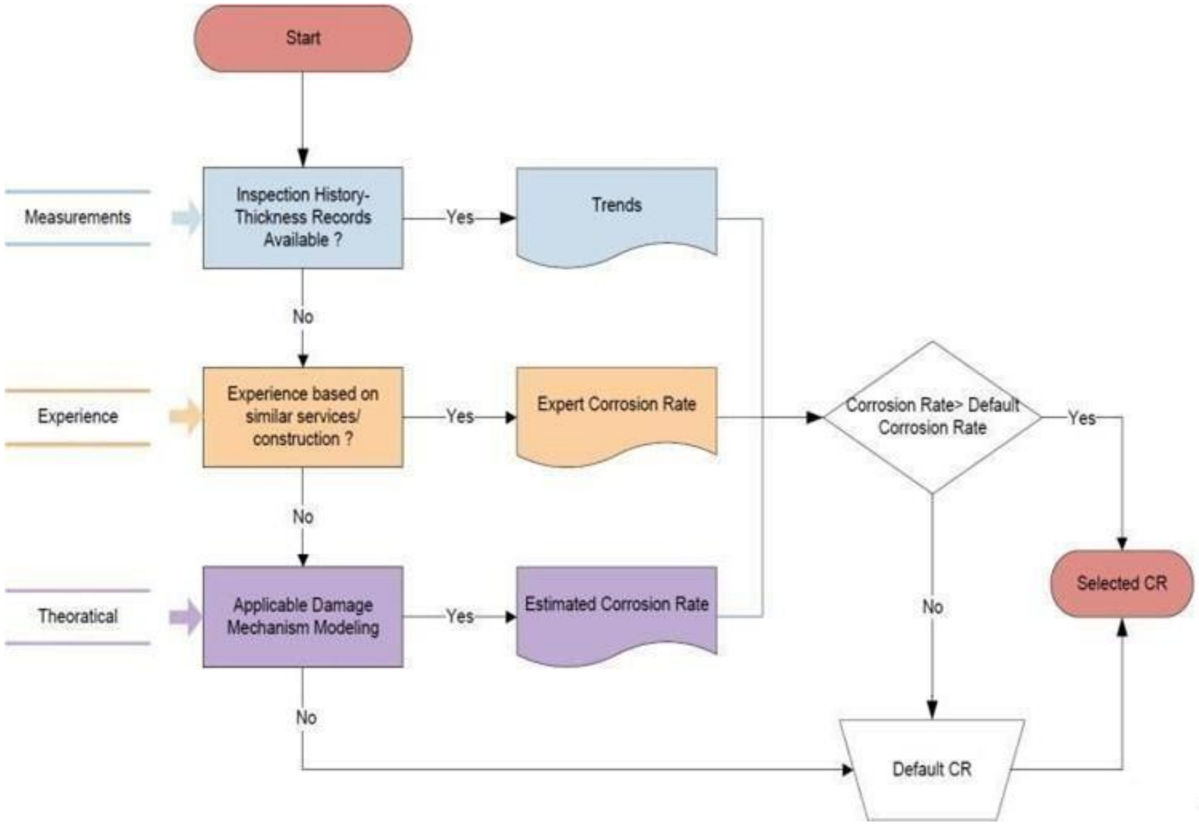


Figure 4.4: Flow chart for corrosion rates illustration [101].

Design Corrosion Rates are calculated using corrosion allowance and design life values. Measured Corrosion Rates rely on actual history and thickness measurement records. Expert Corrosion Rates are derived from personnel experience with similar services and constructions, while Estimated Corrosion Rates are based on modeling anticipated damage mechanisms.

- Measured Corrosion Rates

From the available thickness measurement results, corrosion rates and remnant life calculation for piping systems are made per API 570 as under:

a) Formula for Long term maximum measured corrosion rate calculation:

$$\boldsymbol{Corrosion\ rate\ (LT)} = \frac{Tintial - Tactual}{Time\ (years) between\ T\ initial\ and\ Tactual} \qquad (4.1)$$

Whereas:

- T initial refers to the thickness (inch or mm), measured at the same location as the initial measurement taken during installation or when a new corrosion rate environment begins.
- T actual denotes the current thickness, measured during the inspection at a specific location or component [101, 103].

b) Formula for Short-term maximum measured corrosion rate calculation:

$$\boldsymbol{Corrsion\,rate(ST)} = \frac{Tprevious - Tactual}{Time\ \ (years)\ between\ T\ initial\ and\ T\ actual} \quad (4.2)$$

Whereas:

- T previous refers to the thickness, in inches (inch or mm), measured at the same location as T actual during one or more previous inspections.
- T actual is the current thickness, measured at the time of the inspection for a specific location or component [103].

- Estimated Corrosion Rate

The VAIL Plant PEMS module offers built-in tools for estimating corrosion rates across various degradation mechanisms. Using the ECR form, users can identify key factors influencing corrosion rates. If no measured data is available, the module enables estimation of corrosion rates and calculates remnant life based on these estimates.

- Design Corrosion Rate

Design Corrosion Rate (D.C.R.) has been calculated on the basis of design corrosion allowance and the design life of a system often considered as 25 years. The DCR ins calculated as follow:

$$Design\ Corrosion\ Rate\ (mpy\ ) = \frac{design\ corrosion\ allowance}{design\ life} \quad (4.3)$$

- Expert Corrosion Rate

The "Expert Corrosion Rate" is based on historical data or data from similar equipment. It is generally conservative, resulting in higher estimated corrosion rates. [93, 95].

4.3.2.1.2. Remnant Life Calculation

Remnant life will be assessed using historical thickness monitoring results. Velosi conducts two types of remnant life assessments: long-term and short-term. The remnant life is calculated as follows:

$$Remnant\ life\ (years) = \frac{Tactual - \ Trequired}{Corrosion\ rate\ (inches\ or\ mm\ per\ year)} \quad (4.4)$$

Where:

- T actual refers to the thickness measured during the inspection at a specific location.
- T required represents the necessary thickness at the same location or component, calculated using design formulas, prior to considering the corrosion allowance and manufacturer's tolerances. [101, 103].

In practice a two-step approach is followed where first is checked whether the design corrosion allowance (DCA) is consumed and only when this has occurred the second step is to define the real future corrosion allowance (FCA), based on the difference between the last measured wall thickness and the minimum required wall thickness as per the design code [101].

Where:

- FCA is Future Corrosion Allowance
- DCA is Design Corrosion Allowance

- T_{min} measured is the minimum measured thickness from inspection
- T_{min} required is the minimum required thickness as per design requirements.

4.3.2.2. Identification of Damage Mechanisms

Damage mechanisms are identified in line with API RP 571, with Velosi's global expertise used to assign degradation mechanisms, aiding in the development of corrosion circuits and inspection plans.

4.3.2.3. Probability of Failure Assessment

The POF is determined by assessing the relevant damage mechanisms and modes for the system involved in the study. This calculation relies on a questionnaire that varies with each damage mechanism. Tabulated below are the various questionnaires and their corresponding POF categories for every damage mechanism; the full questionnaire is provided in Appendix 7.

The POF is classified into 5 classes: "Low", "Medium", "Medium High», «High", and "Very High" and will be assessed for each degradation. The probability categories that will be used for POF assessment are described in table 4.1.

Table 4.1: Probability of failure classes.

Probability Category	Possible Qualitative Risk	Failure Probability/Frequency
1	Extremely Rare	>30years
2	Extremely Improbable	10 -30 years
3	Very Improbable	3 – 10 years
4	Improbable	1– 3 years
5	Probable	<1years

If multiple degradation mechanisms are applicable, the highest Probabilityo of Failure score will be used to assess the overall risk. Figure 4.5 illustrates the flowchart for assessing the probability of failure.

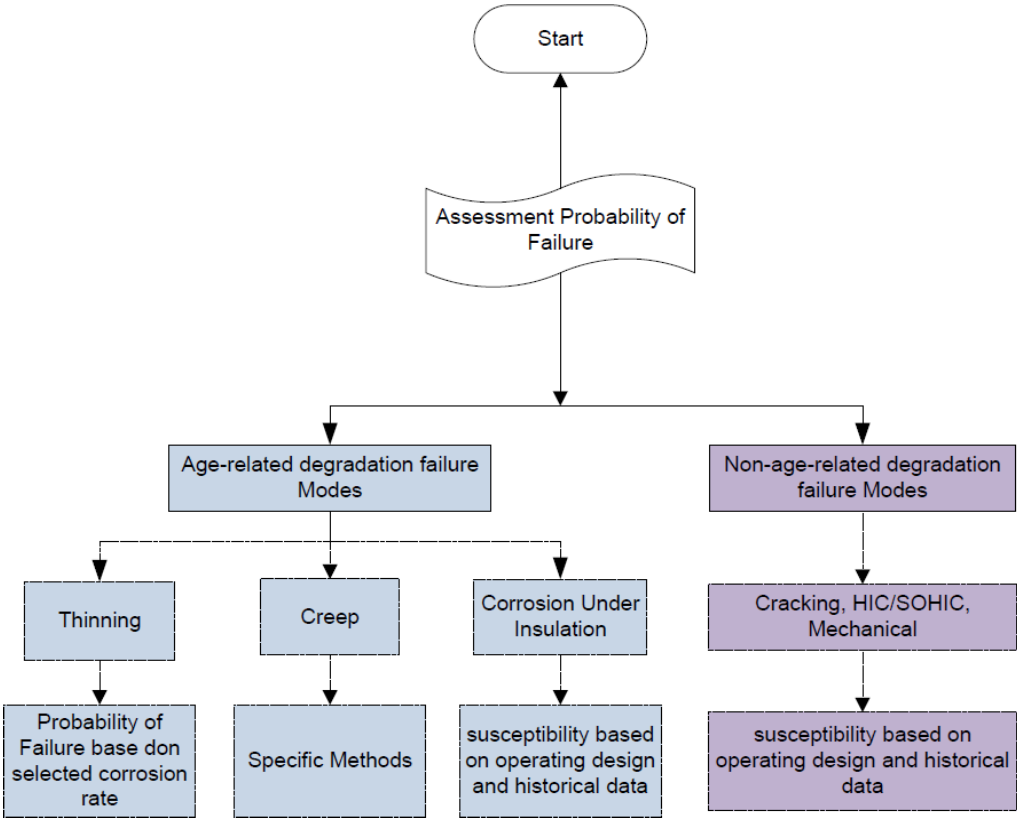


Figure 4.5: Schematic for evaluating the POF [101].

- For age-related (trendable) degradation, the Inspection Interval Factor, derived from the combination of Criticality and Confidence Ratings, is multiplied by Remnant Life to establish the maximum inspection interval. Remnant Life is calculated based on wall loss mechanisms, using actual and minimum allowable wall thicknesses along with the established corrosion rate.

- In contrast, for non-age-related (random) degradation mechanisms, estimating Remnant Life is typically not feasible, as this type of degradation depends heavily on process conditions and often occurs outside the integrity operating window. Consequently, establishing a time-dependent corrosion or degradation rate is challenging. Careful monitoring and control of relevant process parameters are essential to manage these degradation types. The Criticality and Confidence Ratings help assess whether safe operation can be maintained through monitoring and opportunistic inspections or if a more detailed analysis is necessary.

4.3.2.4. Consequence of Failure (COF) Assessment

The assessment of failure consequences for equipment considers safety, environmental, and business impacts. A top-down approach utilizing detailed questionnaires and relevant process and equipment data will be employed for classifying consequences. Failures are categorized into five classes A, B, C, D, and E aligned with the risk matrix in API RP 581 Part 1, where Class A represents the lowest consequences and Class E signifies the highest severity. For details on the questionnaire, please refer to appendix 8,9,10. The figure 4.6 represents the flow chart for assessment of consequence of failure.

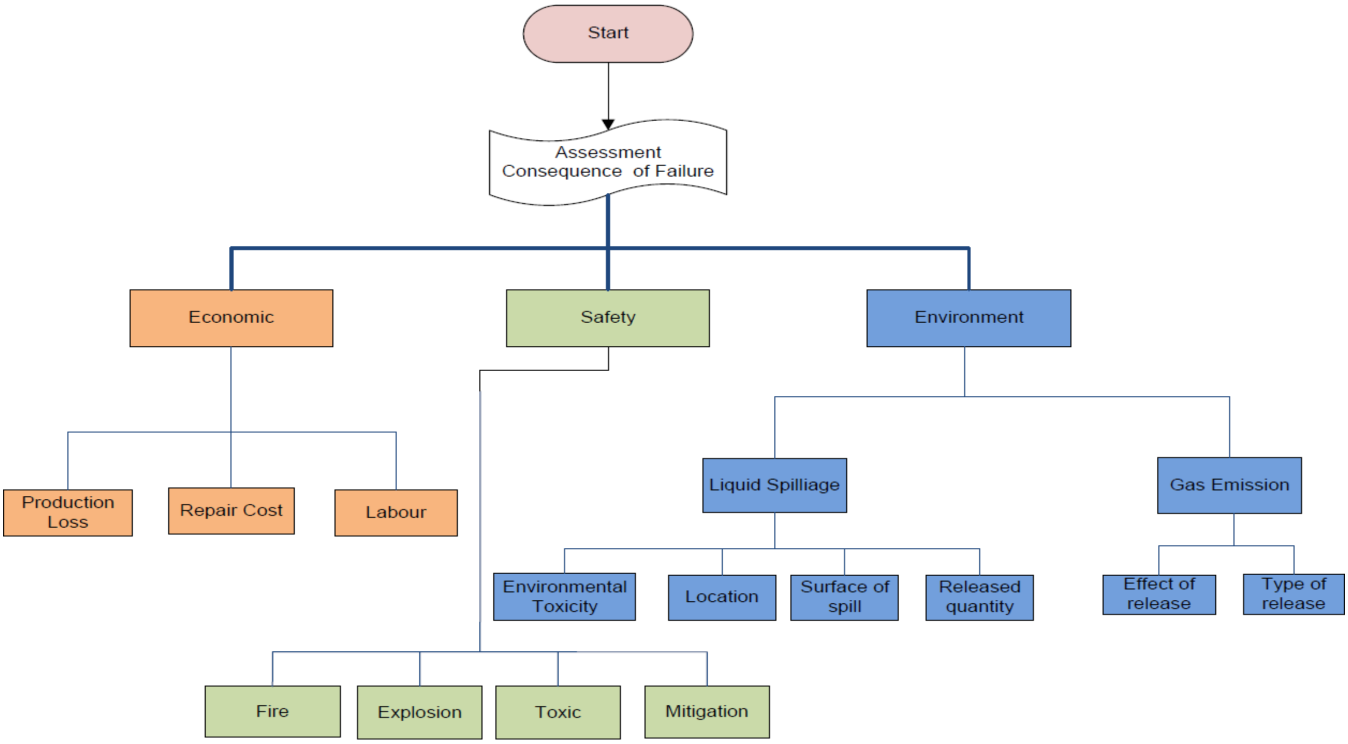


Figure 4.6: Flow chart for evaluating the COF [101].

The consequence categories those will be used for COF assessment are economic, safety and environment.

4.3.2.4.1. Economic Consequences

Economic consequences, one of the three key categories in risk assessment, focus on the financial impact of a failure on assets and production. This includes costs for equipment repair or replacement, labor, and materials. Additional costs may arise from lost revenue due to production shutdowns, reduced margins from off-spec products or lower throughput, and reprocessing expenses. Any potential fines, such as those for excessive flaring or noise violations, should also be considered where applicable.

The economic questionnaire used for COF Business Assessment considers the three main cost elements, production loss, repair costs and labour costs. The Consequence classes are described in table 4.2.

Table 4.2 Ranking for Business Consequence.

Criteria	Qualitative Ranking	Consequence Category
Loss<100,000USD	Moderate	A
Loss100,000–250,000USD	Serious	B
Loss250,000 – 1,000,000 USD	Major	C
Loss1,000,000 – 5,000,000 USD	Catastrophic	D
Loss>5,000,000 USD	Disastrous	E

4.3.2.4.2. Health/Safety Consequences

Safety consequences are divided into three categories: fire, explosion, and toxicity.

- Fire: Consequences are estimated based on flammability and the quantity released.
- Explosion: Consequences consider two risks vapor Cloud Explosion (VCE) potential (involving flammable clouds and congested areas) and the mass of vapor released.
- Toxicity: Consequences depend on toxicity levels and concentration.

Equipment failures in industries involving hazardous substances, high pressures, or temperatures can lead to health and safety risks, causing injuries from thermal, toxic, or impact effects. In assessing consequences, two mitigating factors are critical: the frequency and duration of personnel exposure in the hazardous zone and the potential for averting a hazardous event. Table 4.3 ranks safety consequences accordingly, and additional details are included in the questionnaire in Appendix 10.

Table 4.3 Ranking of Safety Consequence.

Criteria	Qualitative Ranking	Consequence Category
Insignificant	Moderate	A
Slight/Minor Injury	Serious	B
Major Injury	Major	C
Single Fatality or Permanent Total Disability	Catastrophic	D
Multiple Fatalities	Disastrous	E

The most significant COF would be considered for the overall assessment.

4.3.2.4.3. Environmental Consequences

Environmental consequences are increasingly significant in risk management and fall under two main categories of environmental damage:

1. Liquid Spillage: Spills can lead to soil and water pollution. Severity is determined by combining environmental toxicity, the spill quantity, and the location's sensitivity. Two additional factors can increase the consequence class: whether the spill escapes containment and if it reaches groundwater or external surfaces. The key parameters are:
    - Environmental Toxicity
    - Released Quantity
    - Location Sensitivity
    - Spill Surface
2. Gas Emission: Typically, less severe than liquid spills, gas emissions are capped at a "localized effect" severity. They may result from containment failure or flaring. Considerations include:
    - Type of Release (amount and harmfulness)
    - Effect of Release (whether it causes complaints or requires reporting)

Environmental consequence estimation is detailed in Appendix 9, with Table 4.4's matrix providing a framework for determining the environmental consequence class.

Table 4.4: Qualitative Ranking for Environmental Consequence.

Criteria	Qualitative Ranking	Consequence Category
Insignificant effect (<100liters)	Moderate	A
Slight/ Min or effect (100–1000liters)	Serious	B
Local effect (1000 –10,000 liters)	Major	C
Major effect (10,000 –16,000 liters)	Catastrophic	D
Massive effect (>16,000liters)	Disastrous	E

4.3.2.5. Risk Assessment per Degradation Mechanism

Two factors are used to define criticality: The Probability of Failure (POF) and the Consequences of Failure (COF), presented in 5 x 5 risk matrix as presented in table 4.5. The selected risk ranking is high, medium-high, medium and low.

Table 4.5: Risk Matrix.

POF Category			Risk				
5	<1years		MH	MH	MH	H	H
4	1–3 years		M	M	MH	MH	H
3	3–10years		L	L	M	MH	H
2	10-30years		L	L	M	M	MH
1	>30years		L	L	M	M	MH
Economy			Moderate Disturbance in operation (<100K USD)	Serious Damage in operation (100–250 KUSD)	Major Damage in operation (250– 1000 KUSD)	Catastrophic Damage in operation (1000– 5000 K USD)	Disastrous Damage in operation (>5000 KUSD)
Safety			Moderate	Serious	Major	Catastrophic	Disastrous
Environment			Moderate Effect(<100L)	Serious Effect (100L –1000L)	Major Effect (1000L–10000L)	Catastrophic Effect (10000L – 16000L)	Disastrous Effect (>16000L)
COF			A	B	C	D	E

4.3.2.6. Assignment of Inspection Effectiveness

The confidence rating indicates the level of certainty in the prediction of degradation and shall be assessed against each degradation mechanism. Better confidence yields longer inspection interval and the factor to assess.

The confidence levels are:

- Stability, predictability of degradation
- Number and quality of previous inspections
- Process stability

4.3.2.7. Inspection Plan

The paramount portion of RBI output is generating an inspection plan, which will provide guidelines on the following:

- What to inspect: selecting equipment, components, and sections.
- Why to inspect: to consider the most dominant damage mechanisms.
- Where to inspect: potential locations of inspection based on credible damage mechanisms.
- How to inspect: proper selection of NDE method based on damage group.
- When to inspect: determining inspection due date and interval. Figure 4.7 represents the development of Inspection Plan [101].

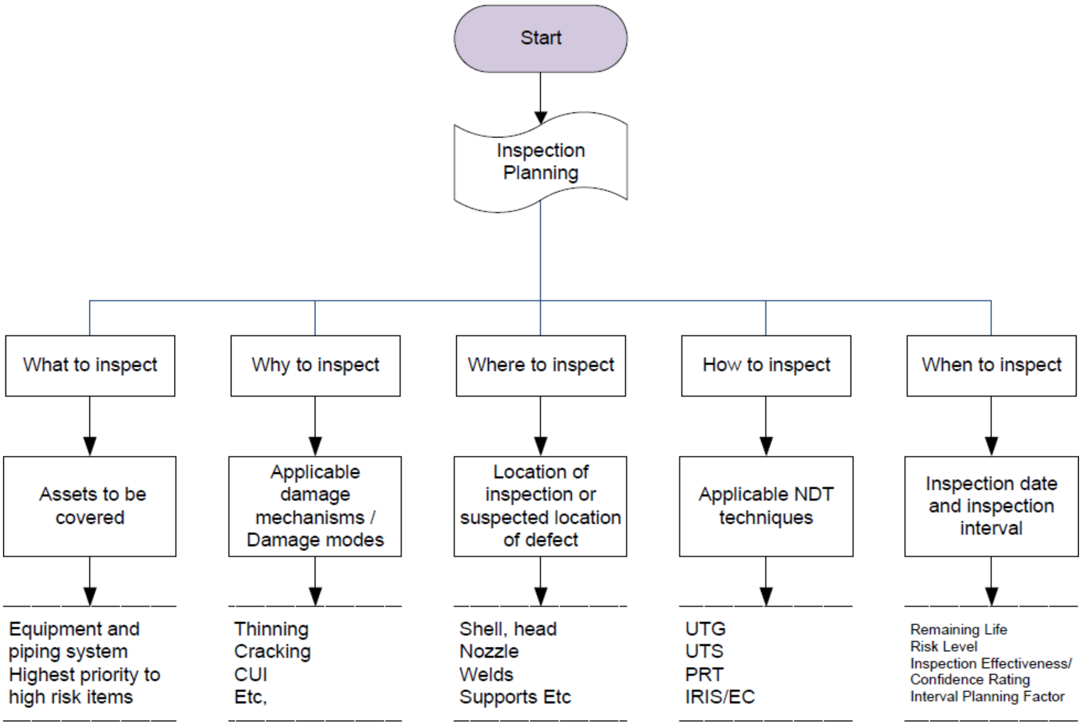


Figure 4.7: Development of Inspection Plan [101].

4.3.2.7.1. Assessment of Inspection Intervals

Inspection intervals shall be calculated semi-quantitatively, depending on the calculated remaining life of the equipment founded on selected corrosion rate and the interval factor, which is determined by the criticality and the confidence rating.

Typically, the maximum inspection interval for a piece of equipment is determined by multiplying the Inspection Interval Factor (IF) by the calculated remaining life of the item. The semi-quantitative RBI method varies the IF from 0.1 to 0.8, based on a risk and confidence assessment, as describe in Table 4.6.

Table 4.6: Confidence rating effect on inspection interval factor

Interval Factor		Confidence rating				
		Very Low	Low	Medium	High	Very High
Risk	High	0.1	0.2	0.3	0.4	0.5
	Medium High	0.2	0.3	0.4	0.5	0.6
	Medium	0.3	0.4	0.5	0.6	0.7
	Low	0.4	0.4	0.6	0.7	0.8

4.3.2.7.2. Determining the Confidence Factor

The rating represents the confidence in the degradation rate for the age-related damage mechanisms and the level of susceptibility for non-age-related damage mechanisms.

The degradation rate and the level of susceptibility shall be used to determine the Probability of Failure (POF) and can rely on design, modeling, inspection data, or expert opinion.

A higher confidence helps to extend the inspection interval for age-related damage mechanisms or to reduce the monitoring requirements for non-age-related damage mechanisms, while a lower confidence has the opposite effect.

Three key points shall be considered for assessing confidence:

1. Manageability and stability of the damage mechanisms.
2. Reliability of process and corrosion monitoring data.
3. Reliability of inspection data.

- Reliability of Inspection Data

The reliability of inspection data is related both to the effectiveness and the number of inspections.

- A 'positive' answer means that inspection activities equivalent to three or more Category B inspections have been carried out for the given equipment.
- A 'Not sure' response shall be given for inspection activities equivalent to two Category B inspections.
- A 'Negative' answer shall be given for inspections equivalent to one or fewer Category B inspections.

The questionnaire needs to be completed for each damage mechanism. The answers to the questions will be scored as shown in Table 4.7.

Table 4.7: Determining the Confidence Rating

Confidence factor parameters	Positive	Not sure	Negative
Manageability and stability of the damage mechanism	+0.1	0	-0.1
Reliability of process and corrosion monitoring data	+0.1	0	-0.1
Reliability of inspection data	+0.1	0	-0.1

The scores are then mathematically summed to determine the total confidence rating, which is limited to a maximum of 0.2 as shown in Table 4.8.

Table 4.8: Confidence Factor Categories

Category	Score
Very High	+0.2
High	+0.1
Medium	0
Low	-0.1
Very Low	-0.2

- Reliability of process and corrosion monitoring data

Process parameters and corrosion rates shall be considered reliably monitored when the right equipment, sampling, and data analysis are used.

The reliable process parameters monitoring shall ensure regular collection of data relevant to the damage mechanism, which usually includes temperature, pH, concentration of corrosive substances, dissolved/suspended solids, and flow velocity.

The reliable corrosion monitoring shall ensure application of suitable corrosion monitoring techniques with sufficient coverage and frequency.

- Manageability and stability of the damage mechanisms

A damage mechanism shall be considered managed if adequate methods are applied to reduce the degradation rate to a tolerable level (e.g., corrosion inhibition or proper material selection).

A damage mechanism shall be considered stable when it remains constant over time and the degradation rate does not change drastically with relatively small changes in process conditions.

4.3.3. RBI Results

4.3.3.1. Collection of Engineering Data

To perform an RBI analysis, we start with a systematic collection and review of critical documents to establish a foundation for evaluating potential risks associated with the catalytic reforming heater. Here's the list of required documents:

- Process Descriptions / Design Basis.
- Process Flow Diagrams (PFDs): Including flow, mass balances, and stream data.
- Piping Instrumentation Diagrams (PIDs).
- Equipment Data Sheets: Both process and mechanical.
- Equipment Mechanical Drawings.
- Inspection History Data.

❖ Corrosion rate

The corrosion rate is calculated by the software based on the equation 4.1 described in section 4.3.2.1.1 considering T initial is 6.02 mm and T actual is 4.09 mm the corrosion rate will be:

$$CR\ (LT) = 0.0553\ mm/year$$

- Remnant life calculation

The remaining life of the heater is calculated using Equation 4.4 from Section 4.3.2.1.2, starting with the determination of the minimum required thickness based on design standards. According to API 530, the minimum required thickness, $T_{min\ required}$, is 5.3 mm [104]. Considering the corrosion allowance of 1.6 mm, we can determine the adjusted required thickness.
The current minimum measured thickness, $T_{min\ measured}$, is 4.09 mm, which will help us evaluate the heater's remaining lifespan. To calculate the T required we have the equation 4.5.

$$T\ required = T\ min\ required - CA \quad (4.5)$$

$$T\ required = 3.7\text{mm}$$

Consequently, the calculation of the remnant life is:

$$RL = \frac{4.09 - 3.7}{0.0553}$$

$$RL = 7.05\ years$$

To conduct the study, we first created a tag, which is: C1-07 (the part concerned by the study). Regarding the furnace, it is divided into three parts: the inlet header, the radiant tubes, and the outlet header. We take the example of the radiant tube section, which is the most vulnerable and most exposed to the flame. Below, you will find the collected engineering data. The same step has been carried out for the inlet and outlet headers. Figure 4.8 shows the inserted engineering data within the software.

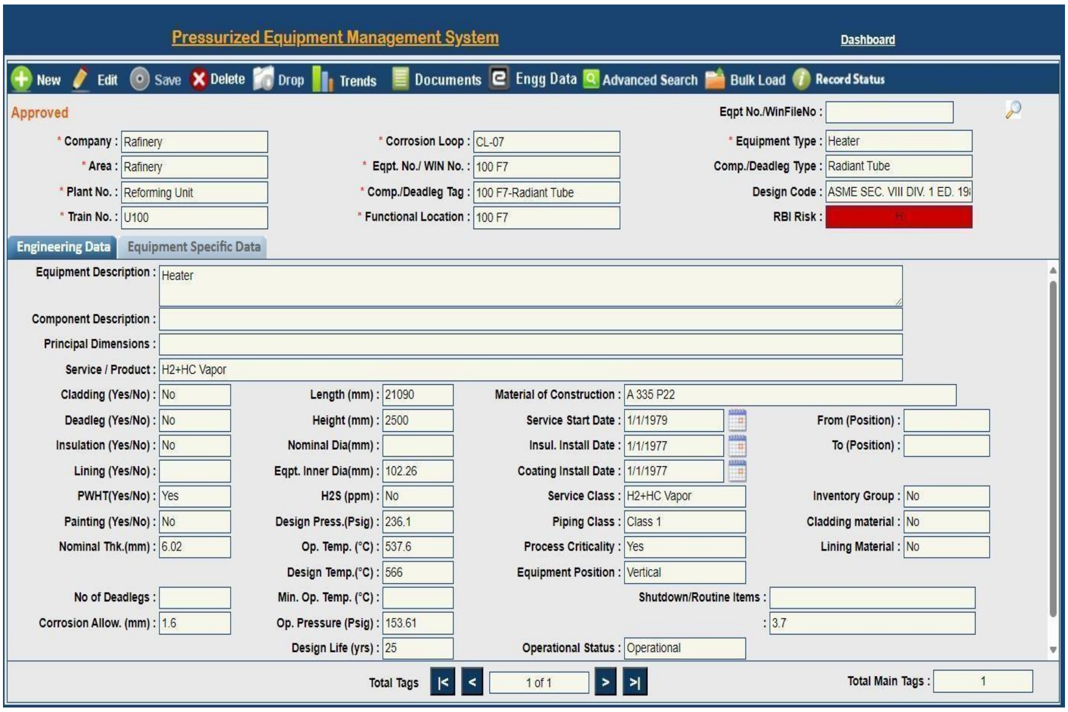


Figure 4.8: collected engineering data.

4.3.3.2 Damage Mechanisms Identification

The next step in our study is to identify the damage mechanisms likely to occur and pose a threat to the equipment. We identified seven damage mechanisms, referring to API 571 and API 573. As part of this listed in table 4.9.

Table 4.9: the identified damage mechanisms

Sr. No.	API 571 DM Code	Damage Mechanism Description
1	3	Creep/ Stress rupture
2	30	Short Term Overheating /Stress rupture
3	46	Refractory Damage
4	11	Oxidation
5	59	Metal Dusting
6	10	High-temperature Hydrogen Attack
7	24	Carburization
9	34	Spheroidization (Softening)

Those damage mechanisms are previously described in chapter 3 section 3.5. The figure 4.9 represents the credible damage mechanisms inserted into the software and their damage groups.

Figure 4.9: Identified damage mechanisms and their damage groups.

4.3.3.3 POF Assessment

In this step, we will identify the probability of failure for each damage mechanism. The POF is then ranked from 1 to 5 according to either corrosion rate or susceptibility rating of damage mechanisms. Appendix 7 provide various questionnaires and their corresponding POF categories for every damage mechanism

4.3.3.3.1 POF Assessment for Thermal Fatigue

- Creep/ Stress rupture

Creep is assessed based questionnaire provided in Appendix 7 and the replica test results

- The replica test results (see Appendix 5) revealing a completely ferritic, polyhedral structure on the external wall of the heater tube, along with total decarburization and the presence of small oxide particles, indicate significant long-term exposure to high temperatures and potential creep damage mechanisms.
- According to API 571, the creep temperature threshold for 2.25Cr-1Mo steel is 425°C, while the operating temperature of 537.6°C places the tube well within the creep range.

These findings suggest a high susceptibility to creep damage, with the advanced decarburization further confirming that the tube's structural integrity has been considerably weakened.

- Short Term Overheating /Stress rupture

The susceptibility to both creep and short-term overheating/stress rupture is high, but they are distinct damage mechanisms with different time frames. Creep occurs gradually over long-term exposure to elevated temperatures, like the current operating condition of 537.6°C, which exceeds the creep threshold for 2.25Cr-1Mo steel. Over time, this leads to slow deformation and weakening of the material under constant stress.

In contrast, short-term overheating happens quickly when there is a sudden spike in temperature, causing immediate stress rupture if the material is weakened. Given that, the heater tubes already show thermal softening with a hardness of 98.6 HB (see appendix 5), their ability to withstand rapid temperature increases is compromised. This means that while creep weakens the material over time, a sudden overheating event could lead to immediate stress rupture due to the reduced tensile strength, making short- term overheating more likely to cause failure first. Both mechanisms are related in that creep degrades the material, increasing its susceptibility to stress rupture under short-term overheating.

- Refractory damage

The observation of refractory damage during the visual inspection suggests that the heater tubes are exposed to conditions that can compromise the insulation and protective properties of the refractory lining. The susceptibility to refractory damage is considered high.

The heater now operating beyond its intended 25-year design life, the ceramic fiber lining is likely to experience a gradual loss of its chemical and physical properties. The compromised integrity of the lining increases heat exposure to the heater tubes, thereby heightening the risks of creep, oxidation, and metal dusting.

Based on these results the probability of failure falls into category 4 shown in figure 4.10.

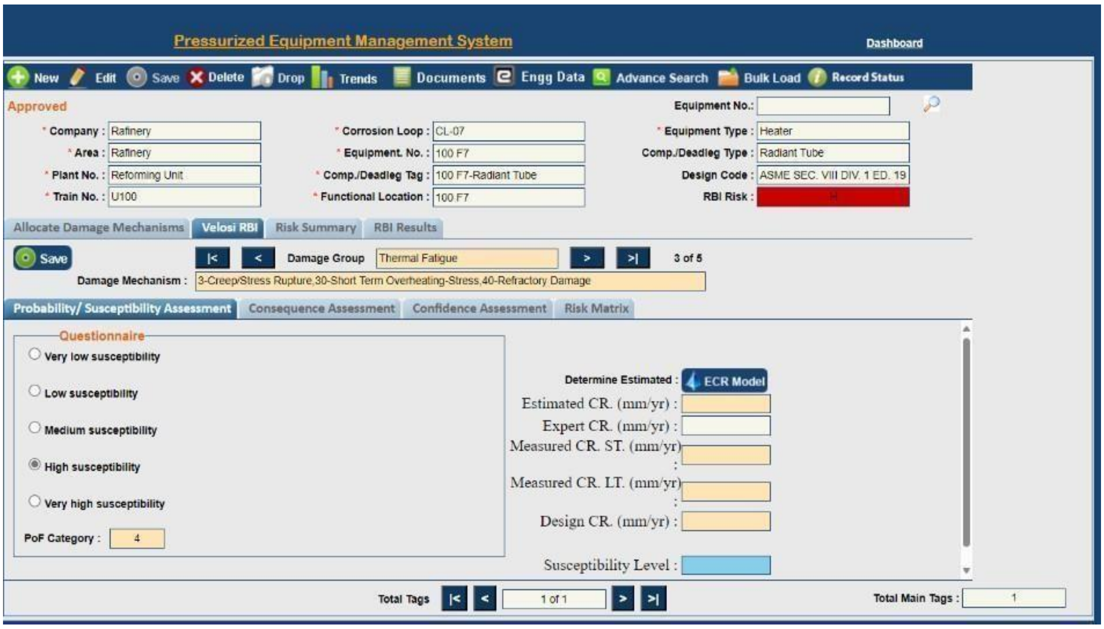


Figure 4.10: POF assessment for thermal fatigue damage mode.

4.3.3.3.2 POF Assessment for Thinning

To estimate the POF due to thinning (oxidation and metal dusting), we need to determine the design DCR using the equation 4.6

$$DCR(mm) = \frac{Corrossion\ allowance\ (mm)}{Design\ life\ (years)} \qquad (4.6)$$

- Corrosion allowance (CA) = 1.6 mm
- Design life set at 25 years

Using the equation 4.6, we obtain:

DCR = 0.064mm/year

MCR= 0.0553mm/year

To determine the probability of failure, we need to answer the questionnaire found in the appendix 7.

Based on the obtained result, the probability of failure falls into category 2 because the current corrosion rate is as per design. POF assessment for thinning damage mode is illustrated in figure 4.11.

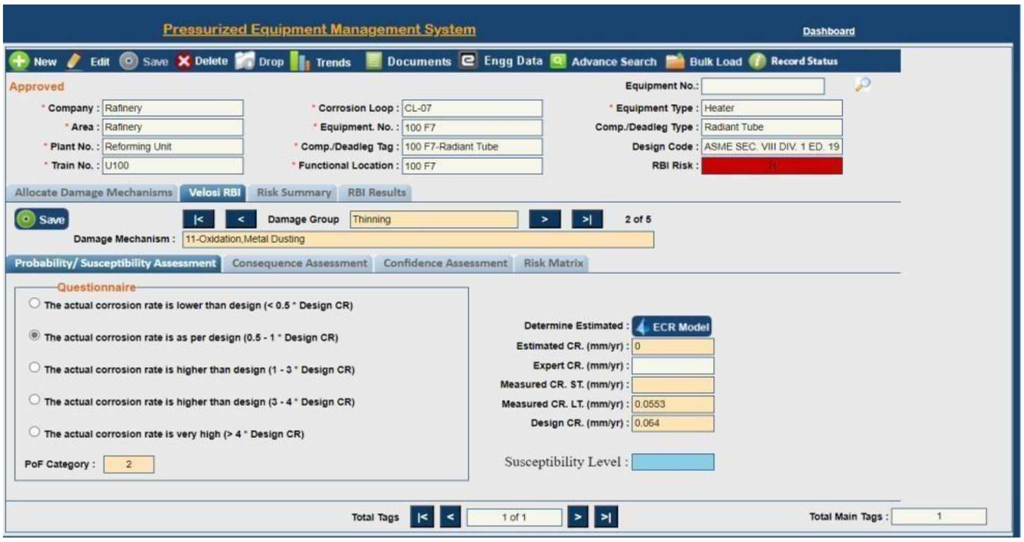


Figure 4.11: POF assessment for thinning damage mode.

The inspection results reveal concerning signs of oxidation and metal dusting, both of which contribute to the deterioration of the heater tubes. The presence of small oxide particles indicates significant oxidation due to prolonged exposure to high temperatures (537.6°C), which can lead to thinning of the tube walls. This oxidation process compromises the material's structural integrity by forming a thick oxide layer that weakens the metal and promotes material loss, ultimately reducing the tubes' ability to withstand internal pressures.

4.3.3.3.3 POF Assessment for HTHA

Based on the Nelson Curves (figure 4.12) from API 941, the susceptibility of 2.25 Cr-1Mo heater tubes to HTHA at a hydrogen partial pressure of 7.23 bars and a temperature of 537.6°C is considered low. The Nelson Curves show that for 2.25Cr-1Mo steel, the threshold for HTHA typically occurs at hydrogen pressures between 13 and 17 bars at this temperature range.

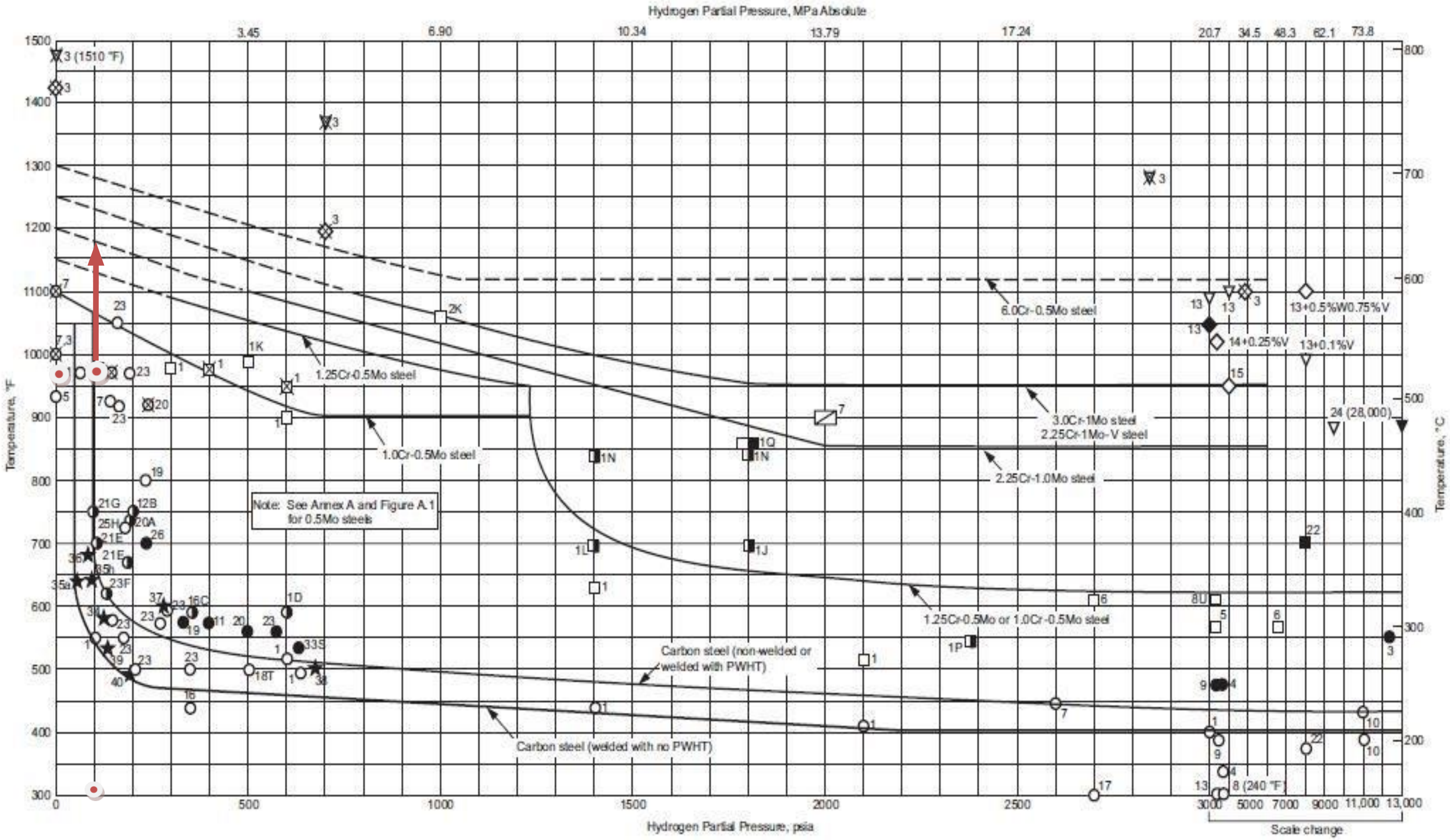


Figure 4.12: Nelson curve [105].

Since the partial pressure in our case is below this threshold, the risk of HTHA is minimal, also referring to the figure 4.13 provided in API 581 that indicates four levels of HTHA susceptibility rankings for Cr-Mo Low Alloy Steels we can identify our operational conditions ranging from 100°F below the curve up to the previous susceptibility area.

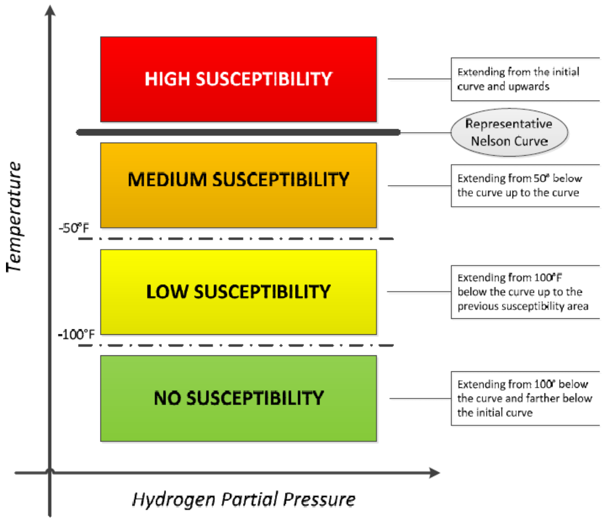


Figure 4.13: HTHA susceptibility classifications as per API 581 [100].

This positioning categorizes us within the low susceptibility zone, indicating that the risk of HTHA is minimal. Figure 4.14 shows the selected susceptibility that falls into category 2.

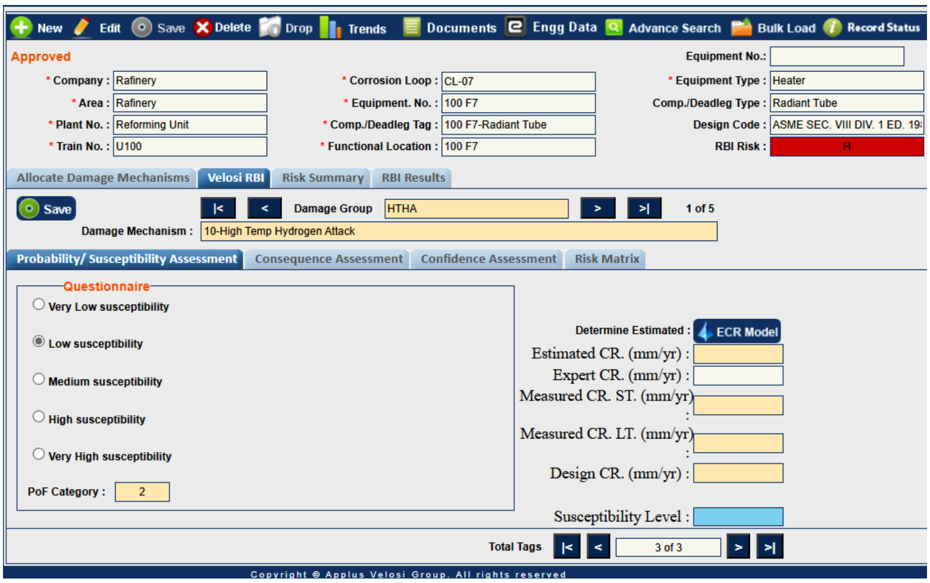


Figure 4.14: POF assessment for HTHA damage mode.

4.3.3.3.4 POF Assessment for Cracking

Based on the inspection results, the susceptibility to carburization damage is considered low. The presence of a fully ferritic microstructure and signs of total decarburization indicate that the material is losing carbon rather than absorbing it, which points to an environment not conducive to carburization. Although the tubes are operating at high temperatures (537.6°C), there is no evidence of a carbon-rich atmosphere that would typically lead to carburization. Additionally, the hardness measurement of 98.6 HB suggests thermal softening rather than hardening, which would be expected if carburization were occurring. Therefore, carburization is not a major concern in this case, and the susceptibility remains low. Figure 4.15 shows the selected susceptibility that falls into category 2.

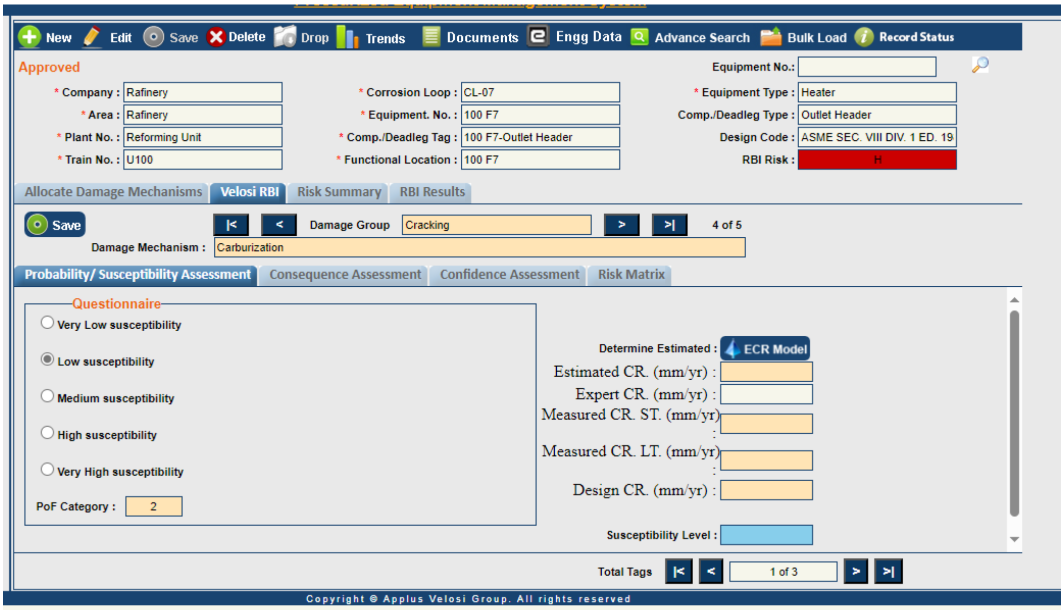


Figure 4.15: POF assessment for cracking damage mode.

4.3.3.3.5 POF Assessment for Spheroidization (Softening)

We estimate the susceptibility to softening as high based on the hardness measurement of 98.6 HB, which indicates a significant loss of strength. This hardness is well below the standard range for 2.25Cr-1Mo tubes, typically 170-210 HB, pointing to considerable softening of the material. The lower hardness reflects a major reduction in tensile strength, meaning the tube is now much weaker and less capable of handling the high temperatures and stresses in the heater. With the operating temperature at 537.6°C, above the 425°C creep threshold, the reduced strength further increases the likelihood of creep and long-term deformation. Therefore, the significant drop in hardness strongly suggests a high susceptibility to softening and related damage. The probability of failure falls into category 4 indicated in figure 4.16.

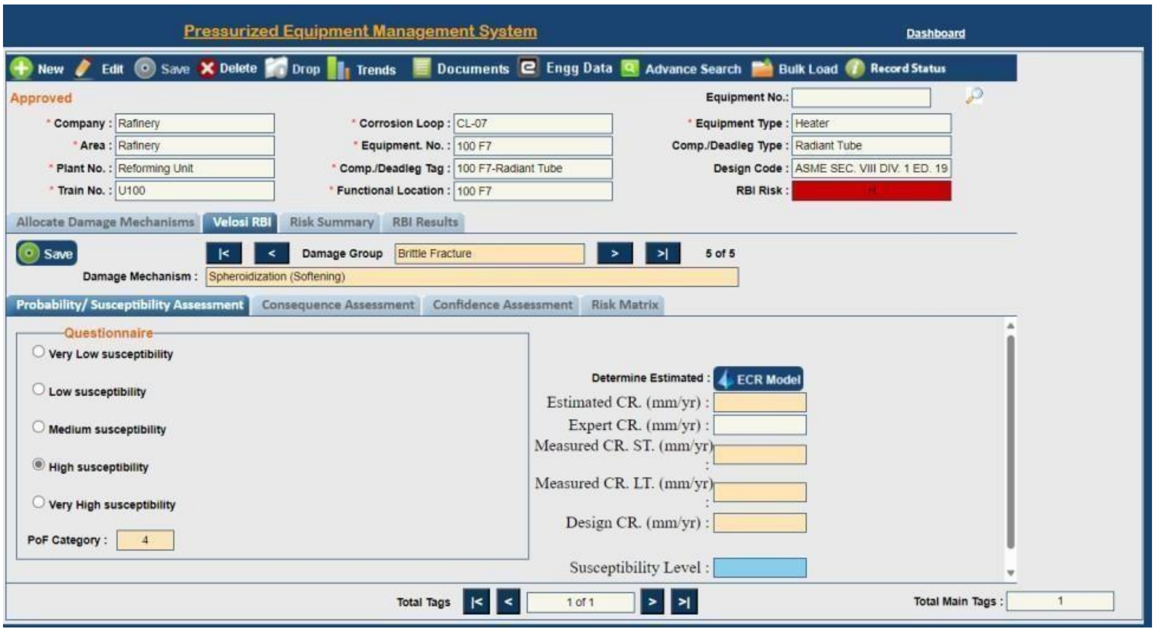


Figure 4.16: POF assessment for softening damage.

4.3.3.4 COF assessment

To assess the consequence of failure, we collaborated closely with the maintenance, finance, and safety department to estimate the probability of consequences for each damage mechanism.

4.3.3.4.1 COF Assessment for thermal fatigue

- Economy

Thermal fatigue, HTHA, cracking, and
brittle fracture, share a similar economic impact estimation.

We calculated that a shutdown would last approximately 312 hours, during which the unit, producing 156 m³ per hour (or 117 tons, given the naphtha density of 0.75), would incur a production loss valued at 1,489,837,752 DZD (around 11,165,856 USD), based on a per ton price of 40,813 DZD. The repair costs, covering material purchases and labor, are estimated at 16,885,654 DZD (or about 126000 USD). Therefore, the total cost of this failure, combining production losses and repair expenses, reaches approximately 1,506,723,406 DZD, equivalent to 11,377,968 USD. Based on these results the economic COF falls into category E shown in figure 4.17.

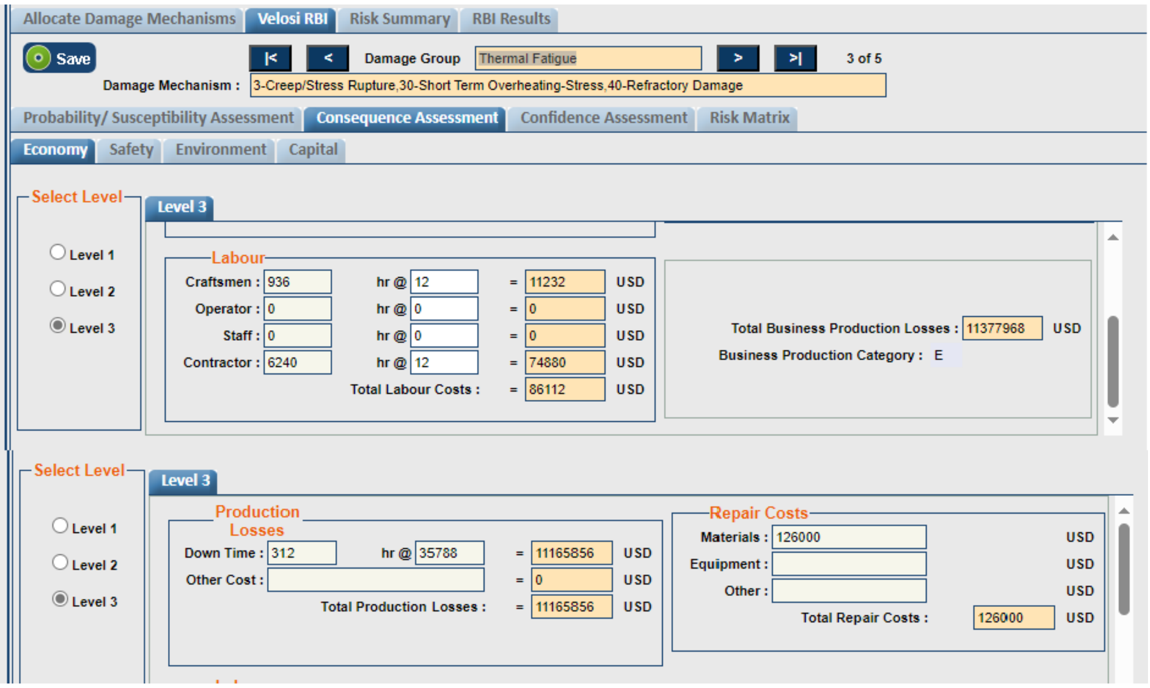


Figure 4.17: Economy consequence assessment for thermal fatigue.

- Safety

In estimating safety risks, we considered the impacts of fire, explosion, and toxicity.

For cracks, a fire scenario is expected, with high flammability, and the estimated release quantity is less than 500 kg. This places the risk in category B.

In the case of rupture, an explosion is anticipated due to gas accumulation in the combustion chamber, with a vapor cloud explosion (VCE) probability rated as medium. The release quantity for this scenario is estimated between 50 and 500 kg, placing it in category D.

For toxicity, the estimated risk level is medium across all studied damage mechanisms, with concentrations less than 10000 ppm for thermal fatigue, which aligns with category B.

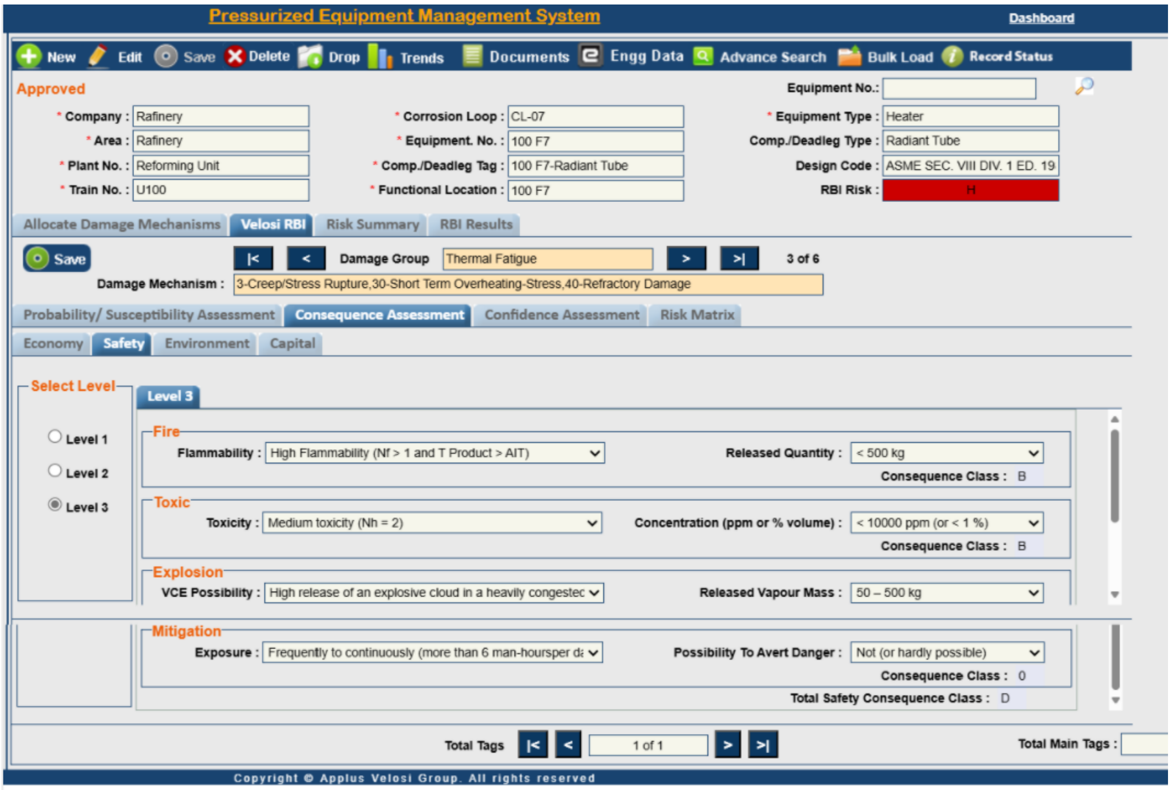


Figure 4.18: Safety consequence assessment for thermal fatigue.

- Mitigation effectiveness is estimated for all damage mechanisms at 0 based on an exposure level ranging from frequent to continuous, and the possibility of averting danger, which is hardly to avert danger. Based in these results the total safety consequence class is for thermal fatigue is D illustrated in figure 4.18.

- Environment

Two primary parameters for environmental damage are considered: liquid spillage and gas emissions. In our case, gas emissions may occur given that the product is in a gaseous state. For thermal fatigue, the release type is classified as small and harmful, with an effect level estimated at 2. This assessment places thermal fatigue in category B shown in figure 4.19.

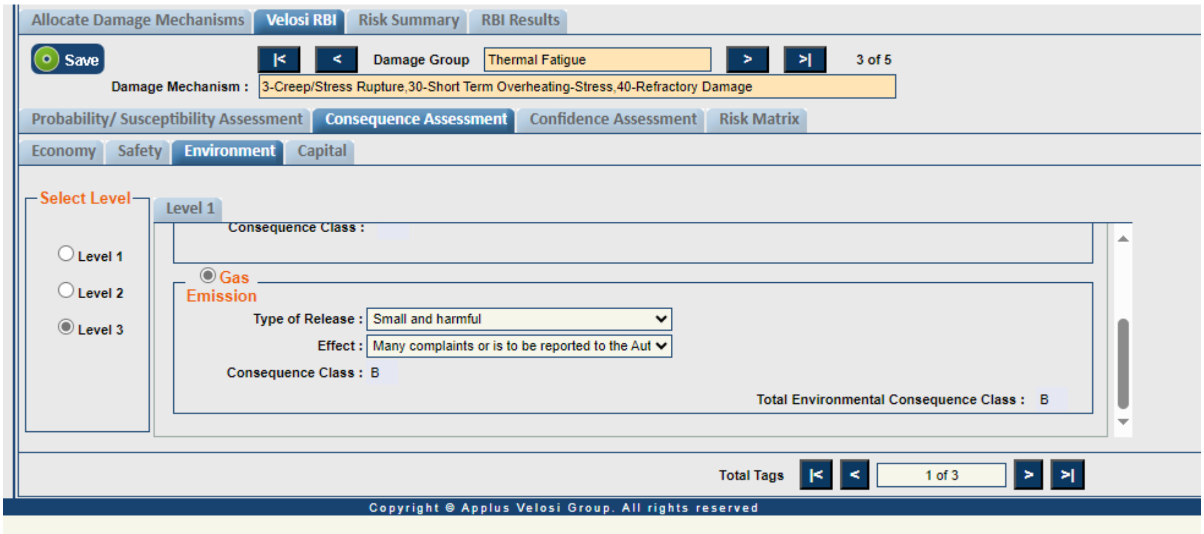


Figure 4.19: Environmental consequence assessment for thermal fatigue.

4.3.3.4.2 Thinning

- Economy

As we said before the HTHA, cracking, and brittle fracture, share similar economic impact estimation.

For thinning, we estimated a shutdown duration of 168 hours, during which production losses would total 6,012,384 USD. The cost of material repairs, focused on repair work rather than replacement, is estimated at 42,000 USD, while labor expenses amount to 46,368 USD. Consequently, the overall economic impact of a thinning-related shutdown reaches 6,100,752 USD. the overall economic COF falls into category E Illustrated in figure 4.20.

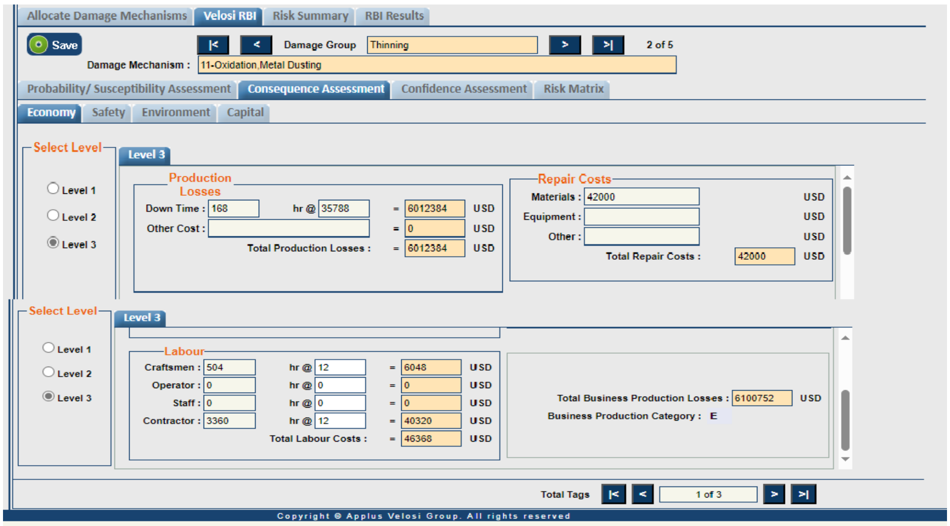


Figure 4.20: Economy consequence assessment for thinning.

- Safety

  - For the thinning a fire scenario is expected, with high flammability, and the estimated release quantity is < 500 kg.
  - the estimated risk level is medium across all studied damage mechanisms, with concentrations less than 1000 ppm for thinning, which aligns with category A. This places the risk in category B shown in figure 4.21.

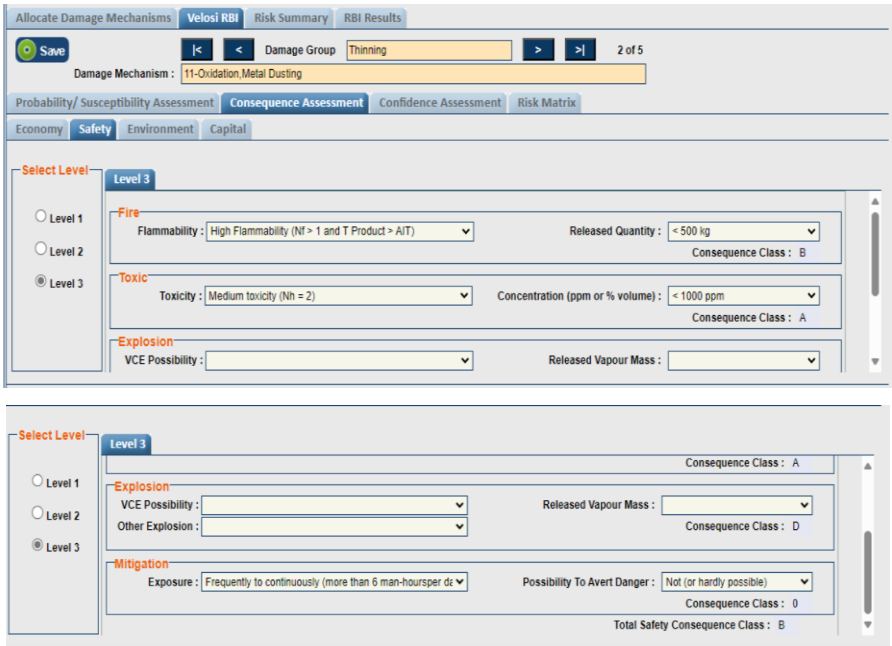


Figure 4.21: Safety consequence assessment for thinning.

  - Mitigation effectiveness is estimated for all damage mechanisms at 0.

- Environment

For Thinning, the release type is classified as small and harmful, with an effect level estimated at 2. This assessment places thinning in category B shown in 4.22.

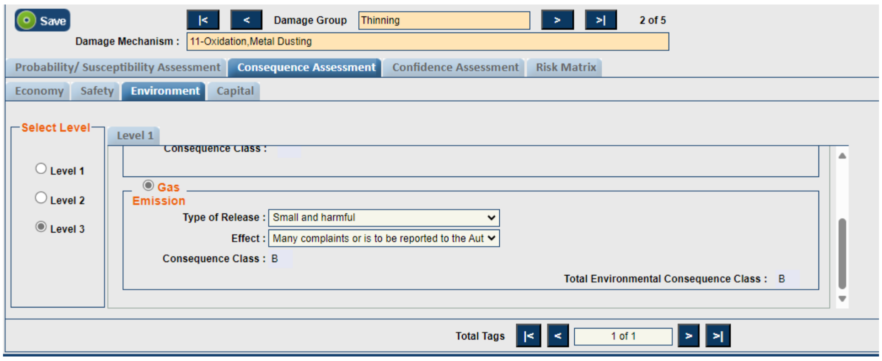


Figure 4.22: environmental consequence assessment for thinning.

4.3.3.4.3 COF Assessment for HTHA

- Economy

HTHA, thermal fatigue cracking, and brittle fracture, shares a similar economic impact estimation which is category E (described in 4.3.3.4.1).

- Safety
  - For HTHA, a fire scenario is expected, with high flammability, and the estimated release quantity is less than 500 kg. This places the risk in category B illustrated in figure 4.23.

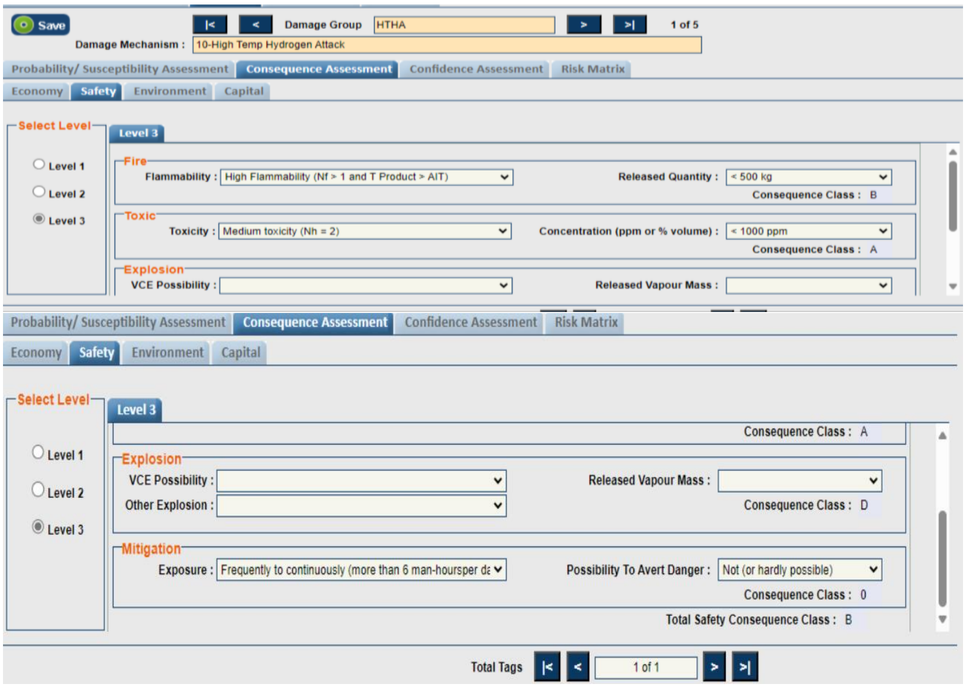


Figure 4.23: Safety consequence assessment for HTHA.

- Toxicity and mitigation ratings, classified as Category A and 0, respectively.

- Environment

For HTHA, the release type is classified as small and harmful (category 2), with an effect level estimated at 2. This assessment places HTHA in category B illustrated in figure 4.24.

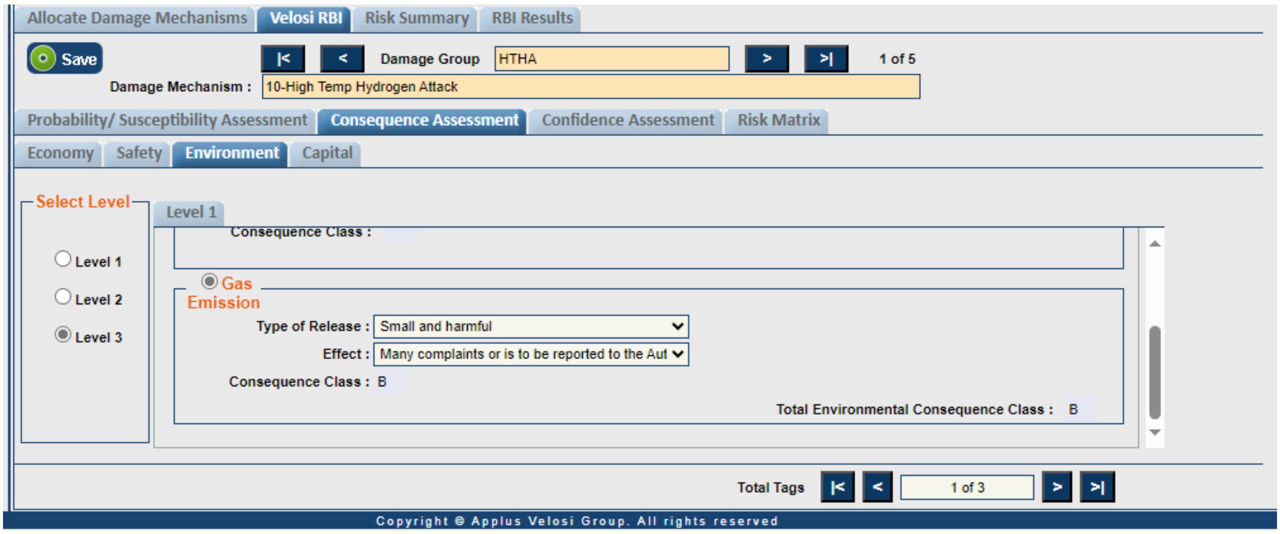


Figure 4.24: Environmental consequence assessment for HTHA.

4.3.3.4.4 COF assessment for cracking

- Economy

The cracking, HTHA, thermal fatigue, and brittle fracture, share a similar economic impact estimation which is category E described in 4.3.3.4.1

- Safety
  - For cracking, a fire scenario is expected, with high flammability, and the estimated release quantity is less than 500 kg, and explosion scenario with released quantity between 50 and 500 kg. This places the risk in category D.
  - Toxicity is classified class B
  - Mitigation ratings is 0.

The total safety consequence class will be D illustrated in figure 4.25.

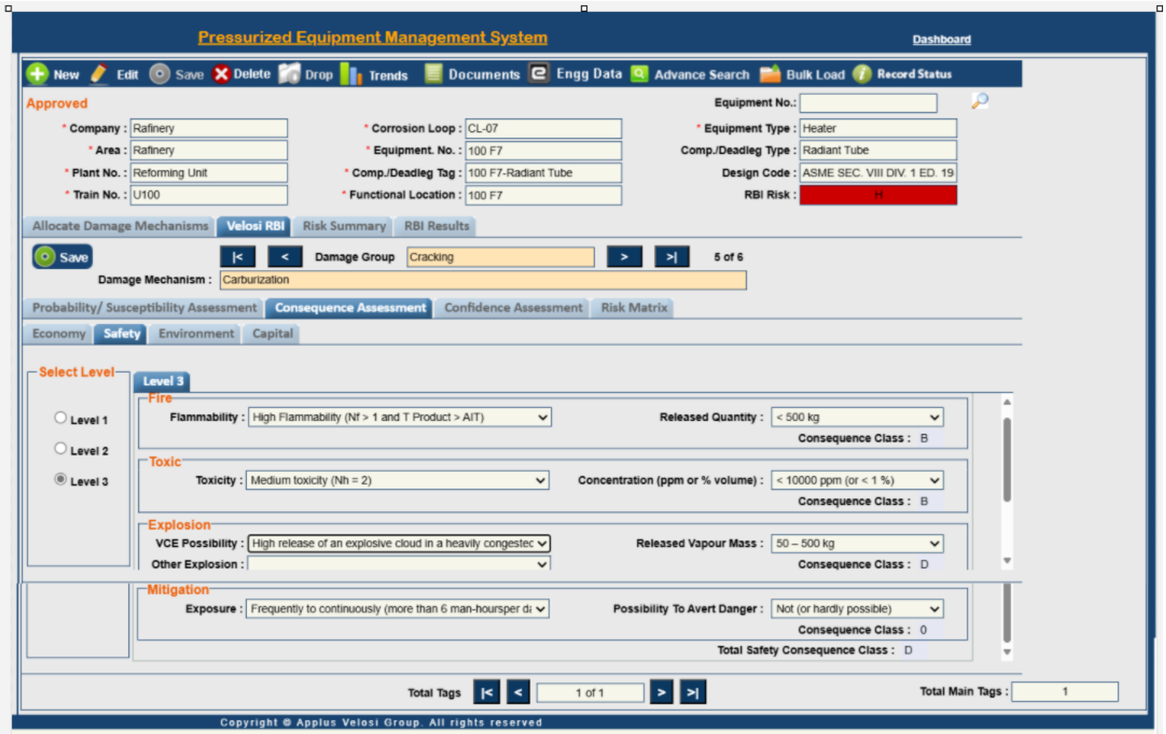


Figure 4.25: Safety consequence assessment for cracking.

- Environment

For cracking, the release type is classified as small and harmful (category 3), with an effect level estimated at 2. This assessment places cracking in category B illustrated in figure 4.26.

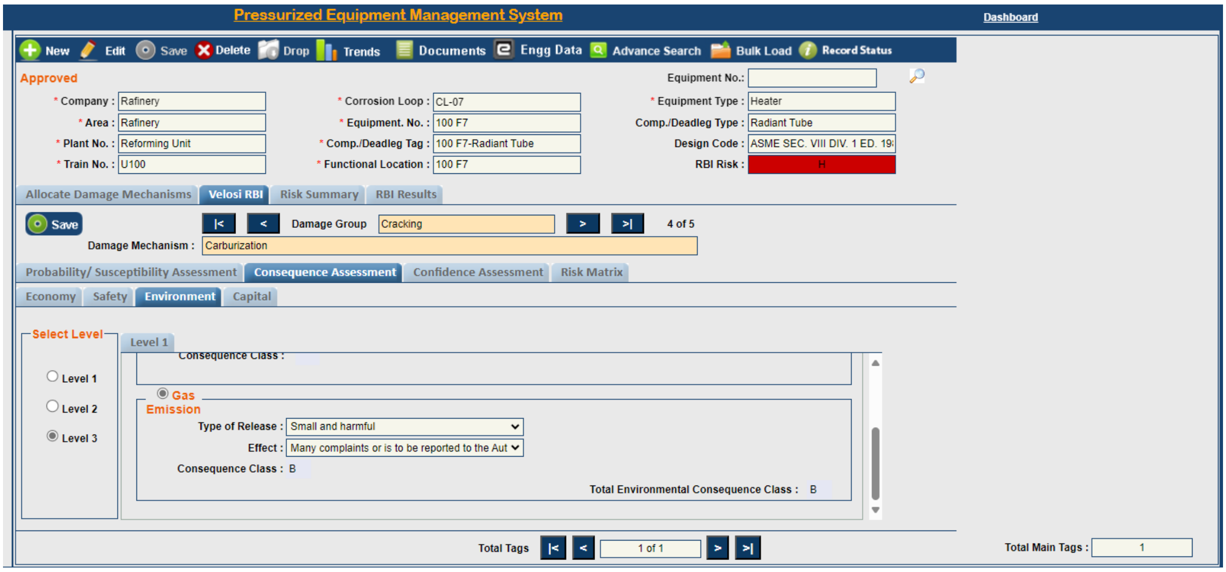


Figure 4.26: Environmental consequence assessment for cracking.

4.3.3.4.5. COF Assessment for Brittle Fracture

- Economy

Brittle fracture, HTHA, thermal fatigue, and cracking, share a similar economic impact estimation which is category E described in 4.3.3.4.1

- Safety
  - For brittle fracture, a fire scenario is expected, with high flammability, and the estimated release quantity is less than 500 kg. This places the risk in Category B.
  - In the case of rupture, an explosion is anticipated due to gas accumulation in the combustion chamber, with a vapor cloud explosion (VCE) probability rated as high (level 4). The release quantity for this scenario is estimated between 50 and 500 kg, placing it in Category D.

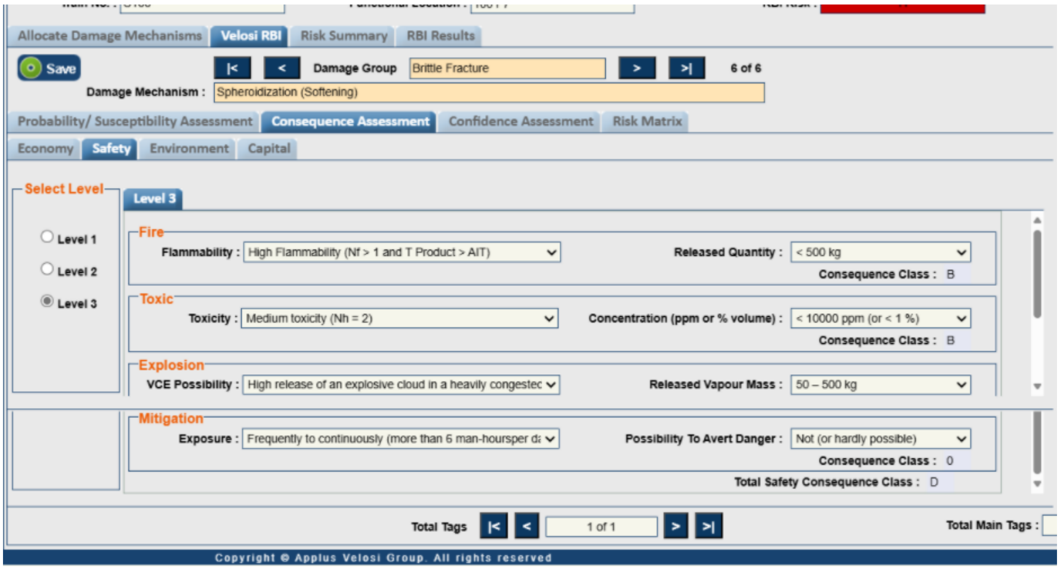


Figure 4.27: Safety consequence assessment for brittle fracture.

  - toxicity and mitigation ratings, classified as Category B and 0, respectively.
  - The total safety consequence class will be D illustrated in figure 4.27.

- Environment
  - For brittle fracture, the release type is classified as small and harmful (category 2), with an effect level estimated at 2. This assessment places brittle fracture in Category B shown in figure 4.28.

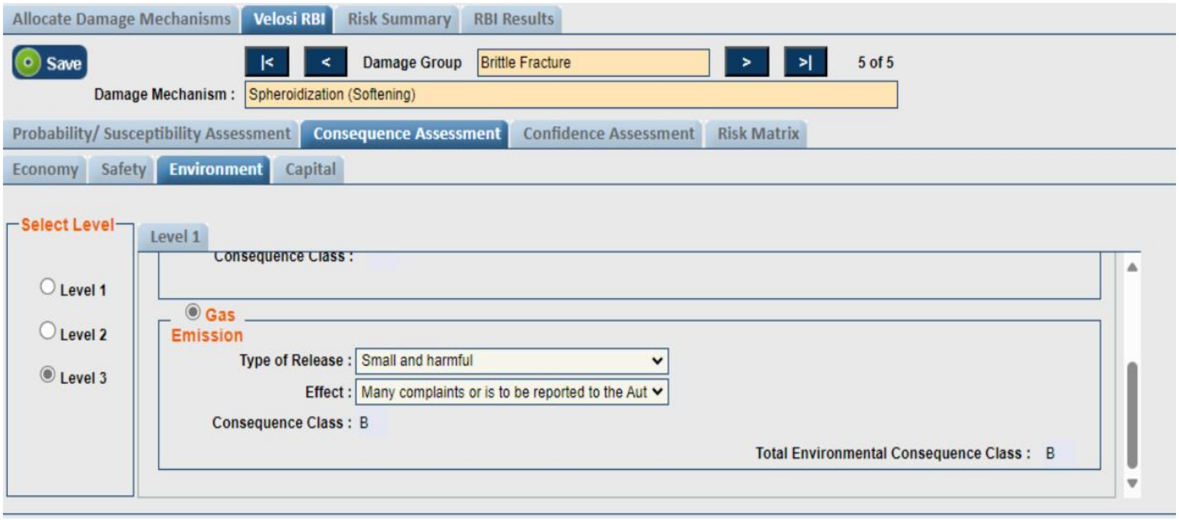
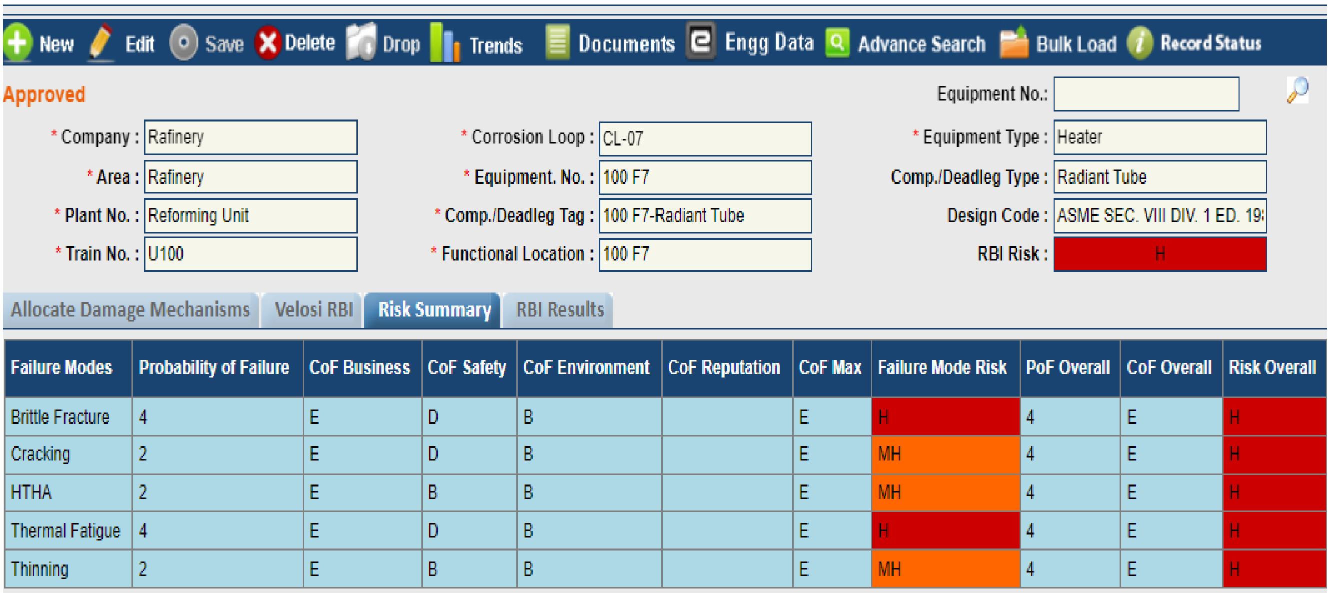


Figure 4.28: Environmental consequence assessment for brittle fracture.

4.3.3.5. Risk Assessment Results

Figure 4.29 shows a risk summary related to radiant heater tubes, illustrating the risk levels for each mode of failure associated with each damage mechanism, along with the overall risk.



Failure Modes	Probability of Failure	CoF Business	CoF Safety	CoF Environment	CoF Reputation	CoF Max	Failure Mode Risk	PoF Overall	CoF Overall	Risk Overall
Brittle Fracture	4	E	D	B		E	H	4	E	H
Cracking	2	E	D	B		E	MH	4	E	H
HTHA	2	E	B	B		E	MH	4	E	H
Thermal Fatigue	4	E	D	B		E	H	4	E	H
Thinning	2	E	B	B		E	MH	4	E	H

Figure 4.29: Radiant tube risk summary.

4.3.3.6 Assignment of Inspection Effectiveness

The assignment of inspection effectiveness is carried out by calculating the confidence rating based on a questionnaire previously listed in section 4.3.2.7.3. The results indicate a low confidence rating for all damage mechanisms due to the lack and unreliability of data related to the heater's inspection figure 4.30 represents the confidence assessment.

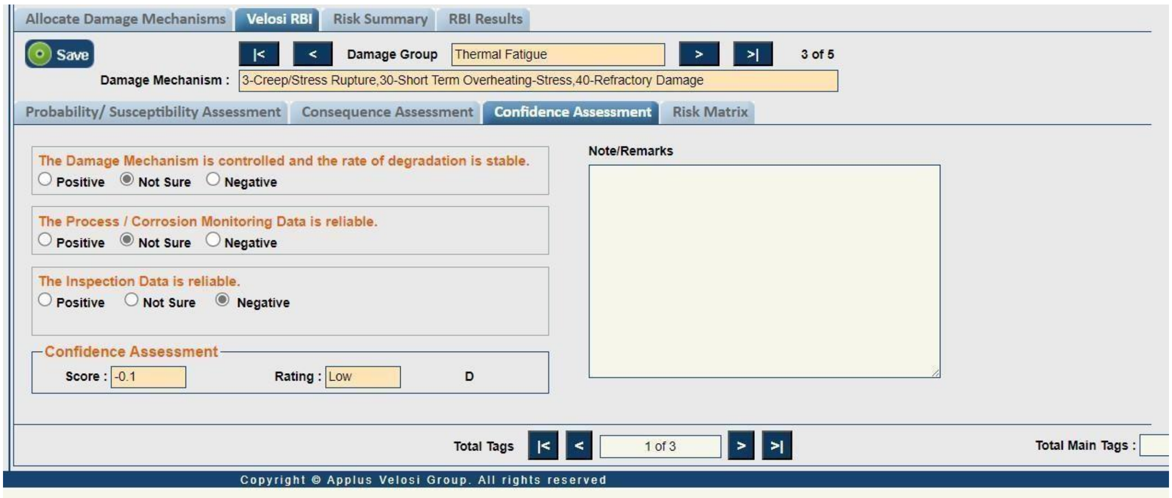


Figure 4.30: Confidence assessment.

4.3.3.7 Inspection Plan

The software calculates the next inspection interval by analyzing prior data needed for the assessment like historical corrosion rates, and remaining life. Based on this analysis, it has set the inspection interval at 1.41074 years displayed in figure 4.31, determining the optimal frequency for evaluating the equipment to maintain safe operations. Using this interval, the software predicts the next inspection date as October 27, 2024.

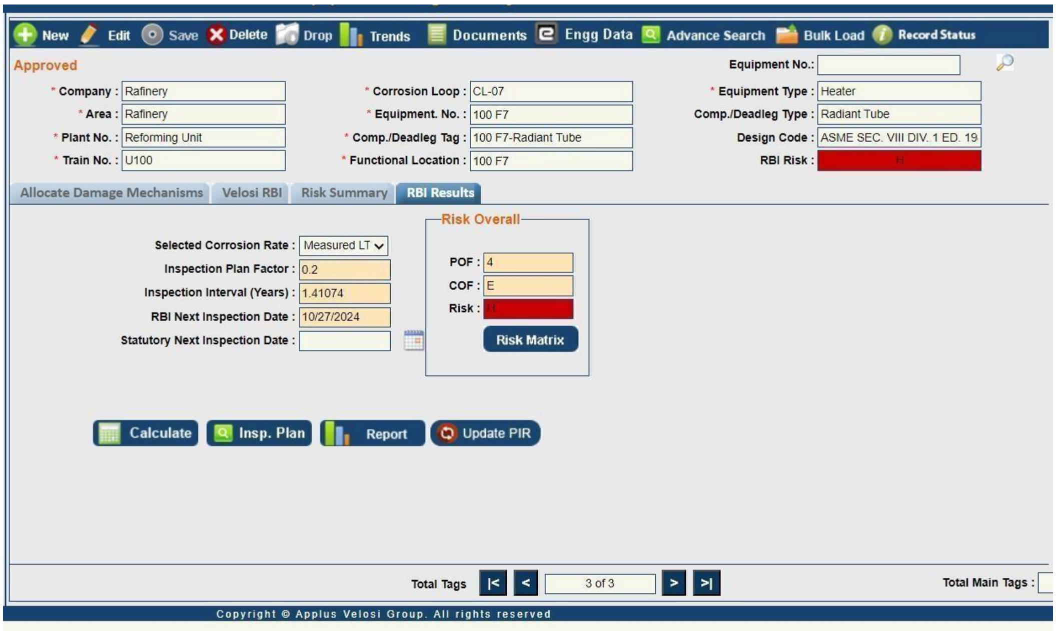


Figure 4.31: Overall risk result for the RBI study.

Based on the assessment, the risk classification for this equipment is deemed high, placing it in the red zone. This classification highlights the urgent need for attention and reinforces the importance of adhering to the specified inspection interval to mitigate potential issues.

4.3.4 RBI Results

The criticality rating for radiant tubes is predominantly High (H), placing it in the red zone. This high criticality rating results from the combined effects of high POF, severe COF ratings, and the presence of multiple damage parameters, which threatens the integrity of the furnace and leads to loss of containment.

- The POF for the radiant tubes is predominantly rated at four across multiple damage mechanisms, indicating a high likelihood of failure. The presence of multiple high-risk mechanisms HTHA, brittle fracture, and thermal fatigue, significantly elevates this probability. This high PoF underscores the tubes' vulnerability and justifies the need for proactive risk management measures.
- The COF ratings for the radiant tubes are particularly high . An "E" rating in Business signifies that the failure of these tubes would lead to substantial financial losses due to downtime, repair costs, and potential damage to nearby components. In terms of Safety, an "D" rating is critical, indicating severe potential harm to personnel in the event of a failure. Given the operational pressures and temperatures, a failure could release high-temperature gases, posing life-threatening risks.

Figure 4.32 represents the asset summary, which encapsulates the results of the assessment for each damage mechanism. This summary provides a comprehensive overview, highlighting the critical insights gathered from the evaluation. It allows for a thorough understanding of the risks associated with each mechanism, enabling stakeholders to prioritize inspection and maintenance efforts effectively, by illustrating the potential impacts and corresponding criticality ratings.

VAIL-PLANT (Integrity Management System)

Asset Passport Summary

Equipment Engineering Data Summary (What To Inspect)

WIN File/Eqpt. No	100 F7	Minimum Temp.(*c)		Corrosion Loop	CL-07	Service Start Date	01/01/1979
Functional Location	100 F7	Eqpt. Inner Dia (mm	102.26	Inventory Group	No	Coating Install Date	01/01/1977
Equipment Type	Heater	Eqpt. Position	Vertical	Plant Number	Reforming Unit	Insulation Inst.Date	01/01/1977
Service	H2+HC Vapor	Furnished Thk. (mm	6.02	Train Number	U100	Painting (Y/N)	No
Op./Pressure (psi)	141.66	Length (mm)		Material Of Const	A 335 P22	Insulation (Y/N)	No
Op./Temperature (°c	490.00	CA (mm)	1.60	PWHT (Y/N)	Yes	Lining (Y/N)	
Design Press. (psi)	160.72	Design Code	ASME SEC. VIII DIV. 1 ED. 1988 AD. 1999	Cladding (Y/N)	No	Type Of Support	
Design Temp. (°c)	545.00			Cladding Material	No	Lining Material	No

VELOSI Semi-Quantitative RBI

PoF Overall	4
CoF Overall	E
Risk Ranking	H

Low	0
Medium	0
Medium High	10
High	6

CoF

POF		A	B	C	D	E
5	<1 years	0	0	0	0	0
4	1 – 3 years	0	0	0	0	6
3	3 – 10 years	0	0	0	0	0
2	10 - 30 years	0	0	0	0	9
1	>30 years	0	0	0	0	1

Safety	Moderate	Serious	Major	Catastrophic	Disastrous
Environment	Moderate Effect (<100L)	Serious Effect (100L – 1000L)	Major Effect (1000L – 10000L)	Catastrophic Effect (10000L – 16000L)	Disastrous Effect (>16000L)
Economy	Moderate Disturbance in operation (<100 K USD)	Serious Damage in operation (100 – 250 K USD)	Major Damage in operation (250 – 1000 K USD)	Catastrophic Damage in operation (1000 – 5000 K USD)	Disastrous Damage in operation (>5000 K USD)
Capital	Slight Effect <=0.1 mil	Minor Effect 0.1 - 0.2 mil	Local Effect 0.2 - 0.5 mil	Major Effect 0.5 - 1.0 mil	Massive Effect > 1.0 mil

ComponentTagNo	ComponentType	Damage Mechanism	PoF	COF Business	COF Safety	COF Environment	COF Maximum	Criticality Rating
100 F7-Outlet Header	Outlet Header	Thinning	2	E	B	B	E	MH
100 F7-Radiant Tube	Radiant Tube	HTHA	2	E	B	B	E	MH
100 F7-Radiant Tube	Radiant Tube	Cracking	2	E	D	B	E	MH
100 F7-Radiant Tube	Radiant Tube	Brittle Fracture	4	E	D	B	E	H
100 F7-Radiant Tube	Radiant Tube	Thermal Fatigue	4	E	D	B	E	H
100 F7-Outlet Header	Outlet Header	Brittle Fracture	4	E	D	B	E	H
100 F7-Radiant Tube	Radiant Tube	Cracking	2	E	D	B	E	MH
100 F7-Radiant Tube	Radiant Tube	Thinning	2	E	B	B	E	MH
100 F7-Inlet Header	Inlet Header	Thermal Fatigue	4	E	D	B	E	H
100 F7-Inlet Header	Inlet Header	Thinning	2	E	B	B	E	MH
100 F7-Inlet Header	Inlet Header	Brittle Fracture	4	E	D	B	E	H
100 F7-Inlet Header	Inlet Header	Cracking	2	E	D	B	E	MH
100 F7-Outlet Header	Outlet Header	HTHA	2	E	B	B	E	MH
100 F7-Outlet Header	Outlet Header	Thermal Fatigue	4	E	D	B	E	H
100 F7-Inlet Header	Inlet Header	HTHA	2	E	B	B	E	MH
100 F7-Outlet	Outlet Header	Cracking	2	E	D	B	E	MH

Component Details

Component Tag #	Component Type	Op./Pressure (psi)	Op./Temperature (*c)	Design Press. (psi)	Design Temp. (*c)	Material Of Const	PWHT (Y/N)
100 F7-Outlet Header	Outlet Header	141.66	490.00	160.72	545.00	A 335 P22	Yes
100 F7-Inlet Header	Inlet Header	143.94	453.00	169.11	499.00	A 335 P22	Yes
100 F7-Radiant Tube	Radiant Tube	153.61	537.60	236.10	566.00	A 335 P22	Yes

Equipment Description: Heater

Figure 4.32: asset passport summary.

The inspection Planning - PIR (Inspection Type, When to Inspect, How to Inspect) for the heater tubes is detailed and closely corresponds to the insights gained from our RBI result in table 4.10.

Table 4.10: Inspection Planning - PIR (Inspection Type, When to Inspect, How to Inspect)

PIR	Operation No	Operation Code	Operation Description	Insp Interval	Unit	Last Insp Date	RBI Next Insp. Date	NDT Resources	Duration (hours)
100 F7-SD	10	VI	100% Internal Visual Inspection of Radiant, convection, casing (insulation/refractory, support, clips, fire brick, burners, roof hangers, thermo couples, damper, stack…ect)	1.4	Years	03/01/2023	27/10/2024	Inspector	2
100 F7-SD	20	U T S	Full continuously UT Scan Shall be done All-around circumference 100mm wide in the straight tube for the radiant coils at two intermediate levels. and at circumference of the elbows.	1.4	Years	03/01/2023	27/10/2024	Inspector	4
100 F7-SD	50	P R T	PRT to assess tube wall thickness and detect the presence and thickness of internal coke deposits.	1.4	Years		27/10/2024	Inspector	2
100 F7-SD	60	UTG Nozzle	UTG at Nozzles >2" (as per Annex 1)	1.4	Years	03/01/2023	27/10/2024	Inspector	2
100 F7-SD	80	MT /PT	Magnetic particle / dye penetrant test should be performed at attachment welds of tube skin thermocouple, tube hanger, and tube support	1.4	Years		27/10/2024	Inspector	3
100 F7-SD	100	Metallography test	10% of welds and all hotspots, selection of the weld and base materials shall be done after visual inspection and NDE	1.4	Years		27/10/2024	Inspector	4
100 F7-SD	130	HT	Hardness testing of ferritic heater tubes at location where severe overheat can be expected and should be chosen after visual inspection	1.4	Years		27/10/2024	Inspector	2
100 F7-SD	120	Dimensional test	Dimensional control of tubes for bowing, bulging sagging using flashlight, narrow tape and calibrated tube gauges "pass-fail'	1.4	Years		27/10/2024	Inspector	2

100 F7-SD	140	PT	10% hangers and supports / tube welds	1.4	Years		27/10/2024	Inspector	3
100 F7-SD	150	VI External	100% External visual inspection of casing, firebox, header box, explosion doors, ladders, stairs, platforms, walkways, foundations, steel and structural supports, anchor bolts, auxiliary equipment, grounding connections, insulation /coating and external metal surfaces.	1.4	Years		27/10/2024	Inspector	4
100 F7-SD	160	UTG External	on piping at inlet /outlet headers, outlet of convection and radiant zones taken at 3,6,9 &12 O'clock positions	1.4	Years		27/10/2024	Inspector	5
100 F7-SD	170	Infrared thermal camera	Infrared thermal scanning to determine local tube metal temperatures and hot spots in the areas not covered by skin thermocouples heater casing for identifying hot spots due to refractory damage and cracks and stacks for indication of failure of internal liner	6	Months		27/04/2024	Inspector	6

A 100% internal visual inspection of the radiant and convection sections, along with the casing, is crucial to identify any immediate visual defects or signs of degradation. The implementation of a full circumferential ultrasonic thickness (UTS) scan, covering a 100 mm wide area, ensures accurate monitoring of wall thickness, which is essential given the risk of thinning due to thermal fatigue and creep. Additionally, the use of Positive Material Identification (PRT) will further facilitate the assessment of material integrity by measuring the presence and thickness of potential degradation areas. For critical attachment welds, magnetic particle and dye penetrant tests (MT/PT) will be performed to detect any surface cracks, ensuring that weld integrity is maintained. The metallography test on 10% of the welds, particularly at hotspots, allows for a deeper understanding of material properties and potential failure points. Hardness testing (HT) at locations prone to severe overheating is vital, as it provides insight into the mechanical properties of ferritic heater tubes, which may be adversely affected by prolonged exposure to high temperatures. Dimensional control checks for bowing, bulging, and sagging will utilize flashlight inspections at 10% of the hangers and supports, ensuring that structural integrity is upheld. Finally, the 100% external visual inspection of the casing, firebox, header box, and explosion doors, complemented by ultrasonic gauging on inlet and outlet headers and infrared thermal scanning, allows for the identification of thermal anomalies and overall condition assessment. Together, these inspection strategies address the critical findings from our RBI analysis, supporting proactive maintenance and enhancing the reliability of the heater tubes. The inspection test plan (ITP)of the heater is provided in appendix 11 and 12.

Conclusion

In this chapter, we thoroughly explored the implementation of the RBI method, employing a semi-quantitative approach facilitated by the VELOSI software. This advanced tool allowed us to systematically identify and analyze various deterioration mechanisms, evaluate the likelihood and potential impact of each, and ultimately develop a robust and comprehensive inspection plan tailored to the specific needs of the catalytic reformer heater. Additionally, we formulated a targeted action plan aimed at mitigating the risks associated with these deterioration mechanisms.

The RBI assessment underscores a high probability of failure due to thermal fatigue, thinning, and softening, with the heater tubes showing advanced signs of degradation. The

COF analysis highlights significant economic impacts, particularly for prolonged shutdowns required for repair, while safety risks tied to fire, explosions, and toxicity remain moderate. Environmental impacts are relatively low but warrant attention to prevent emissions from prolonged operation.

The findings of our analysis revealed that the radiant tubes are subjected to several high-risk damage mechanisms, significantly increasing their vulnerability to failure. Consequently, based on these critical results, the inspection interval for the heater cannot be extended to the original 36 months. RBI analysis has set an optimized inspection interval of 1.41 years, with the next check scheduled for October 27, 2024, to uphold heater safety and longevity by focusing on critical degradation risks like thermal fatigue, creep, and brittle fracture. The planned 100% internal visual inspection of the radiant tubes will allow us to detect early deterioration signs and respond proactively. The ultrasonic thickness scan (UTS) will provide precise wall thickness measurements, focusing on areas susceptible to fatigue and creep, helping us track material loss over time. Complementing this, Positive Material Identification (PMI) will verify material composition in potential degradation zones, while MT/PT testing on attachment welds will identify surface cracks that could compromise weld integrity. By incorporating metallographic analysis on 10% of welds at high-risk points, we can assess microstructural stability and potential failure areas. Hardness testing at overheating-prone spots will offer valuable data on mechanical properties, supporting long- term durability in high-temperature conditions.

Additionally, dimensional control checks on hangers and supports will ensure structural alignment, detecting bowing or sagging. The 100% external inspection, enhanced by ultrasonic gauging on headers and infrared thermal scanning, will identify thermal anomalies and verify unit condition. Together, these strategies provide a robust, data-driven inspection framework, ensuring proactive maintenance and strengthening operational reliability based on the findings from our RBI study.

Following the planned inspections, it is essential to review and update the RBI study to maintain ongoing safety and integrity.

General conclusion

The safe operation of fixed pressurized equipment is essential in the oil and gas industry, where even minor lapses in equipment integrity can lead to catastrophic incidents. By implementing a risk management approach grounded in Process Safety Management (PSM) principles, organizations can proactively identify hazards, evaluate risks, and put preventative measures in place. PSM, particularly the Asset Integrity and Reliability element, plays a pivotal role in safeguarding operations through systematic inspections, testing, maintenance, and repairs, thus preventing failures that could lead to hazardous events.

Maintaining asset integrity is of critical importance. Equipment failures are often identified as key contributing factors in many past accidents and incidents. Consequently, maintenance plays a vital role in ensuring the reliability of these assets.

Our study on the catalytic reforming furnace has provided valuable insights into the operational integrity of the reforming unit. By employing a comprehensive methodology that includes various inspection techniques visual assessments, microstructure observations, metallographic analyses, and mechanical properties testing we have identified critical degradation factors impacting the heater tubes.

This damage analysis conducted on the reformer heater tube, detailed in Chapter 3, reveals that thermal oxidation is the primary mechanism responsible for tube deterioration. This analysis highlights that excessive operating temperatures, combined with elevated oxygen levels in the atmosphere, significantly accelerate external surface corrosion along the tube's length. These conditions result in the formation of oxide scale, which acts as an insulator, reducing heat transfer efficiency, raising tube surface temperatures, and diminishing overall thermal performance. Further observations show that operating beyond recommended conditions, such as over-firing and internal fouling, worsens the oxidation process. The accumulation of oxide scale not only impedes thermal efficiency but also heightens the risk of tube failure, compromising both operational reliability and safety.

The significant oxidation and scaling observed on the outer surfaces, driven by operating conditions that exceeded recommended levels, underscore the importance of vigilant monitoring and maintenance practices. The findings emphasize the necessity of understanding the underlying processes leading to deterioration, which is vital for implementing effective mitigation strategies. Among the recommendations put forth, the implementation of an RBI study stands out as a key measure to enhance safety and reliability.

Proper planning of an inspection program is crucial at an industrial level. RBI serves as an integrity management tool, using the inspection plan as a key deliverable. This process focuses on risk assessment and management, aiming to prevent equipment failure in pressure vessels within oil and gas processing facilities.

In our study, we concentrated on the integrity of the heater tubes, implementing an RBI study using a semi-quantitative approach. We highlighted the essential role of the reformer heater integrity as the central focus of our analysis. Our primary question was: How can we optimally ensure the reliability, performance, and safety of industrial equipment using an RBI approach to maximize resource efficiency and reduce the potential risks of major incidents.

Our analysis indicates that the radiant tubes are exposed to multiple high-risk damage mechanisms (thermal fatigue, HTHA and brittle fracture), significantly increasing their susceptibility to failure. Given these critical findings, it is essential to respect the inspection interval, as extending it to the initial 36 months could compromise the integrity of the heater, with inspections otherwise due by October 2024. Adhering to the recommended interval helps ensure that potential issues are identified and addressed promptly, safeguarding both operational safety and equipment reliability. Therefore, following the planned inspections, the RBI study for this heater should be thoroughly reviewed and updated to uphold stringent safety and performance standards.

In conclusion, the adoption of the Risk-Based Inspection (RBI) approach has led to optimized resource management, reduced risks of major incidents, and ensured the reliability and safety of industrial equipment. We strongly recommend the broader implementation of RBI, particularly in Algeria where its use remains limited, as an effective method to guarantee the reliability and integrity of equipment in the oil and gas sector, while enhancing both safety and operational efficiency.

Bibliography

[1] Dib K., ZennirY., Bounezour H., Bouasla S. (2023). Oxidation Damage Analysis of Ferritic Alloy Steel Heater Tubes in Catalytic Reforming Unit, International Journal of Heat and Technology, 42(2), 390-398. https://doi.org/10.18280/ijht.420204

[2] American Petroleum Institute. (2021). API Recommended Practice 573: Inspection of Fired Boilers and Heaters, (4th ed., 129 pages). API Publishing Services.

[3] American Petroleum Institute. (2020). API recommended practice 571: Damage mechanisms affecting fixed equipment in the refining industry, (3rd ed., 376 pages). API Publishing Services.

[4] Viswanathan, R. (1989). Damage mechanisms and life assessment of high-temperature components book, (1st ed., 440 pages). ASM International. https://doi.org/10.31399/asm.tb.dmlahtc.9781627083409

[5] Khan, F. I., Sadiq, R., & Haddara, M. M. (2004). Risk-based maintenance (RBM): A new approach for process plant inspection and maintenance. Process Safety Progress, 23(4), 252-265. https://doi.org/10.1002/prs.10010

[6] Hertzberg, R. W., Vinci, R. P., & Hertzberg, J. L. (2014). Deformation and fracture mechanics of engineering materials book, (5th ed., 755 pages).John Wiley & Sons.

[7] Maurice, S., Oran, T. (2013). Pressure Vessels Field Manual, Common Operating Problems and Practical Solutions Book, (1st ed., 498 pages). Elsevier. https://doi.org/10.1016/C2011-0-08042-0

[8] Matthews, C. (2001). Engineers' guide to pressure equipment book: The pocket reference, (1st ed., 388 pages). Professional Engineering Publishing Limited. https://doi.org/10.31399/asm.tb.dmlahtc.9781627083409

[9] International Organization for Standardization., International Electrotechnical Commission., Institute of Electrical and Electronics Engineers . (2015). ISO/IEC/IEEE 15288: Systems and software engineering — System life cycle processes, (1st ed., 108 pages).ISO/IEC/IEEE.

[10] American National Standards Institute., American Society of Safety Engineers. (2011). Z690.3-2011: American national standard, risk assessment techniques, (1st ed., 116 pages).ANSI/ASSE.

[11] American Petroleum Institute. (2016). API Recommended Practice 580: Risk-based inspection (3rd ed., 94 pages). API Publishing Services.

[12] Dekkers, R. (2017). Applied system theory book, , (2nd ed., 315 pages), Springer International Publishing .https://doi.org/10.1007/978-3-319-57526-1.

[13] International Organization for Standardization. (2016). ISO 14224: Petroleum, petrochemical and natural gas industries — Collection and exchange of reliability and maintenance data for equipment, (3rd ed., 272 pages). ISO.

[14] American Society of Mechanical Engineers. (2007). ASME Boiler and Pressure Vessel Code,

Section VIII, Division 1: Rules for construction of pressure vessels (1st ed., 1,855 p). ASME International.

[15] Occupational Safety and Health Administration (OSHA). (2023). 29 CFR 1910: Occupational safety and health standards. U.S. Department of Labor. Available at: https://www.osha.gov/laws-regs/regulations/standardnumber/1910. (Accessed September 2024).

[16] International Organization for Standardization . (2009). ISO 31000 Standard: Risk management — Guidelines, (1st ed., 24pages), ISO.

[17] British Standards Institution. (2007). BS OHSAS 18001:2007: Occupational health and safety management systems – Requirements, (2nd ed., 34 pages). BSI.

[18] International Organization for Standardization. (2018). ISO 26262-1: Road vehicles — Functional safety — Part 1, (2nd ed., 13 pages). ISO.

[19] International Electrotechnical Commission. (2010). IEC 61508: Functional safety of electrical/electronic/programmable electronic safety-related systems (2nd ed., 127 pages). IEC.

[20] American Petroleum Institute. (2016). API Recommended Practice 570: Piping Inspection Code: In-service Inspection, Rating, Repair, and Alteration of Piping Systems, (4th ed., 90 pages). API Publishing Services.

[21] International Organization for Standardization (ISO). (2014). ISO/IEC Guide51: Safety aspects—Guidelines for their inclusion in standards, (3rd ed., 22 pages). ISO.

[22] Department of Defense (DoD). (2012). MIL-STD-882E: Department of Defense standard practice: System safety, (5th ed., 104 pages). U.S. Department of Defense.

[23] Innal, F. (2008). Contribution to the modeling of safety instrumented systems and the evaluation of their performance: Critical analysis of IEC 61508. Ph.D thesis.

[24] Tubular Exchanger Manufacturers Association (1999). Standards of the Tubular Exchanger Manufacturers Association (8th ed., 303 pages). TEMA.

[25] American Petroleum Institute. (2015). API Standard 660: Shell-and-Tube Heat Exchangers, (9th ed., 77 pages), API Publishing Services.

[26] American Petroleum Institute. (2016). API Standard 572: Inspection of Pressure Vessels. (4th ed., 154 pages). API Publishing Services.

[27] American Petroleum Institute. (2020). API Standard 575: Inspection of Atmospheric and Low-Pressure Storage Tanks, (4th ed., 116 pages). API Publishing Services.

[28] Saudi Aramco. (2016). Engineering encyclopedia S. Aramco standard: Evaluating storage tank design and installation; storage tank types and features. Saudi Aramco.

[29] American Petroleum Institute. (2016). API Standard 620: Standard for the Design and Construction of Large, Welded, Low-Pressure Storage Tanks, (12th ed., 332 pages).API Publishing Services.

[30] American Petroleum Institute. (2020). API Standard 650: Welded Tanks for Oil Storage, (13th ed., 515 pages). API Publishing Services.

[31] Ghader, G., Liaghat, M.A., Sadeghian, A. (2011). Pressure Vessel Design, Guides & Procedures book, (1st ed., 429 pages). AbeBooks.

[32] Towler, G., & Sinnott, R. (2021). Chemical engineering designbook : Principles, practice, and economics of plant and process design, , (3rd ed., 1027 pages). Elsevier.https://doi.org/10.1016/C2019-0-02025-0.

[33] American Petroleum Institute. (2021). API Standard 560: Fired heaters for general refinery service (5th ed., 337 pages). API Publishing Services.

[34] Executive Decree No. 21-261. (2021), Pressure equipment regulation (ESP) and electrical equipment intended to be integrated into installations in the hydrocarbons sector. Official Journal of the Algerian Republic.

[35] Executive Decree No. 90-245. (1990), Article 19, Related to gas pressure equipment (APG). Official Journal of the Algerian Republic.

[36] Wintle, J., Moore, P., Henry, N., Smalley, S., &Amphlett, G. (2006). Plant ageing: Management of equipment containing hazardous fluids or pressure (Report No. RR509). Health and Safety Executive.

[37] Horrocks, P., Mansfield, D., Thomson, J., Parkerv, K., & Winter, P. (2010), Plant ageing study phase 1 report (Report No. RR823). Health and Safety Executive. Available at: https://www.hse.gov.uk/research/rrpdf/rr823.pdf. (Accessed in august 2024).

[38] De Rademaeker, E., Suter, G., Pasman, H., & Fabiano, B. (2014). A review of the past, present, and future of the European loss prevention and safety promotion in the process industries. Process Safety and Environmental Protection, 92(4), 280-291. https://doi.org/10.1016/j.psep.2014.03.007.

[39] Bonaccorsi, L., Guglielmino, E., Pino, R., Servetto, C. A., &Sili, A. (2014). Damage analysis in Fe–Cr–Ni centrifugally cast alloy tubes for reforming furnaces. Engineering Failure Analysis, 3, 65-74. https://doi.org/10.1016/j.engfailanal.2013.09.020

[40] Ray, A., Goswami, B., Kumar, S. B., Krishna, G., Roy, N., & Ray, A. K. (2015). Damage mechanism of service exposed reformer tubes in petrochemical industries. International Journal of Engineering and Technical Research, 33 (3), 454-4698. https://doi.org/10.1016/j.ijpvp.2015.10.003.

[41] Shalaby, H. M., Ravindranath, K., Tanoli, N., & Al-Wakaan, B. (2017). Failure of 321 stainless steel heater tube in heavy crude oil. Case Studies in Engineering Failure Analysis, 9, 1-8. https://doi.org/10.1016/j.csefa.2017.04.004.

[42] Sonatrach. (2022). Process safety management system reference, Central HSE Department. Sonatrach.

[43] Executive Decree No. 21-319. (2021). Specific operating permit regime for facilities and structures in hydrocarbon activities, Official Journal of the Algerian Republic.

[44] Swuste, P., van Gulijk, C., &Zwaard, W. (2010). Safety metaphors and theories: A review of the occupational safety literature of the US, UK, and The Netherlands, till the first part of the 20thcentury. Safety Science, 48(8), 1000-1018. https://doi.org/10.1016/j.ssci.2010.01.020.

[45] Robbins, S. P., & Judge, T. A. (2012). Organizational behavior book, (15thed, 720 pages).Pearson Education.

[46] Hale, A. R.,Heming, B. H.J., Carthey,J., &Kirwan, B. (1997). Modelling of safety management systems , Safety Science, 26(1–2), 121-140. https://doi.org/10.1016/S0925-7535(97)00034-9.

[47] Hammer, W. (1971). Why system safety programs can fail, NASA Government-Industry System Safety Conference, National Aeronautics and Space Administration. Available at: https://ntrs.nasa.gov/api/citations/19720018316/downloads/19720018316.pdf .(Accessed September 2024).

[48] Waring, A. (1996). Safety management systems book, (241 pages). Chapman and Hall.

[49] Thomas, M.J. (2011). A systematic review of the effectiveness of safety management systems, ATSB Transport Safety Report, (50 pages). Australian Transport Safety Bureau.

[50] Heinrich, H. W., Petersen, D., Roos, N. (1980). Industrial accident prevention book: A safety management approach (5th ed., 468 pages.). McGraw-Hill.

[51] International Organization for Standardization (ISO). (2018). ISO 45001 standard: Occupational health and safety management systems — Requirements with guidance for use, (1st ed., 41 pages). ISO.

[52] International Labour Organization. (2001). Guidelines on occupational safety and health management systems: ILO-OSH 2001. International Labour Organization.

[53] European Process Safety Centre). (2018). European Process Safety Centre - Objectives. EPSC Available at: http://epsc.be/Objectives.html.(Accessed July 2024).

[54] Theophilus, S. C., Nwankwo, C. D., Acquah-Andoh, E., Bassey, E., &Umoren, U. (2018). Integrating human factors (HF) into a process safety management system (PSMS). Process Safety Progress, 37(1), 67–85.https://doi.org/10.1002/prs.11909.

[55] Center for Chemical Process Safety (CCPS). (2016). Guidelines for risk-based process safety (RBPS) (2nd ed). American Institute of Chemical Engineers.

[56] Center for Chemical Process Safety (CCPS). (2009). Guidelines for auditing process safety management systems. Wiley.

[57] Center for Chemical Process Safety (CCPS). (2007). Risk based process safety (RBPS) guidelines. American Institute of Chemical Engineers.

[58] Sepeda, A. L. (2010). Back to basics: Understanding process safety management. American Institute of Chemical Engineers.

[59] Occupational Safety and Health Administration (OSHA). (2000). OSHA 3132: Process safety management. U.S. Department of Labor.

[60] Institution of Chemical Engineers (IChemE). (2015). ISC process safety competency - A guidance. Available at: https://www.icheme.org/media/12909/isc-competency-document-december- 2019.pdf . (Accessed in October 2024).

[61] Chizaram D.N., Stephen C.T., Andrew O.A. (2020). A comparative analysis of process safety management (PSM) systems in the process industry, Journal of Loss Prevention in the Process Industries, 66, 10417. https://doi.org/10.1016/j.jlp.2020.104171

[62] Institution of Safety and Competence (ISC). (2018), ISC process safety competency guidance (2nd ed., 28 pages), IChemE. Available at: https://www.icheme.org/media/12452/0007_18-competency_brochure-update.pdf. (Accessed in October 2024).

[63] SONATRACH. (2021). Health, safety, and environment policy of the SONATRACH Group. Central HSE Department. Sonatrach.

[64] International Organization for Standardization (ISO). (2009). ISO 31000: Risk management — Guidelines, (2nd ed., 16 pages). ISO.

[65] Dib K., Zennir Y., Bounezour H. (2024), Risk assessment of Atmospheric Column Overhead Product Drum, Algerian Journal of Signals and Systems, 9 (4), 390-398. https://doi.org/10.51485/ajss.v9i4.247

[66] Lyon, B. K., Hollcroft, B. (2012). Risk assessments – Top 10 pitfalls & tips for improvement, Professional Safety journal of the American Society of Safety Engineers, 57(12), 28–34.

[67] ANSI/ASSE/IEC/ISO 31010. (2011). Z690.3-2011: American national standard – Risk assessment techniques, (1st ed., 120 pages). ASSP.

[68] International Electrotechnical Commission (IEC). (2019), International Standard IEC 31010: Risk management — Risk assessment techniques, (2nd ed., 264 pages). IEC.

[69] Popov, G., Lyon,B.K., Hollcroft, B. (2016), Risk assessment: A practical guide to assessing operational risks book, ISBN 1118911040, (1st ed, 480 pages). Wiley.

[70] Wong, W. (2010). The risk management of safety and dependability book: A guide for directors, managers, and engineers, (1st ed, 298 pages), Wood head Publishing Limited.

[71] John, H., Jenna, M., Yoshikazu, T., Hiroshi, K., Takashi, K. (2018). A summary of the 'ALARP' principle and associated thinking, 56(2), 241-253. https://doi.org/10.1080/00223131.2018.1551814

[72] Manuele, F.A. (2014). Advanced Safety Management book: Focusing on Z10 and Serious Injury Prevention, (2nd ed., 544 pages) .Wiley.https://doi.org/10.1002/9781118840900

[73] Manuele, F.A. (2010).Acceptable risk: Time for SH&E professionals to adopt the concept Professional Safety, 55(5), 30–38.

[74] International Electrotechnical Commission (IEC). (2019). IEC EN 50126-1: Railway applications - The specification and demonstration of reliability, availability, maintainability and safety (RAMS) Part 1: Generic RAMS process. BSI.

[75] Sklet, S. (2006). Safety barriers: Definition, classification, and performance. Journal of Hazardous Materials, 19(5), 494–506. https://doi.org/10.1016/j.jlp.2005.12.004

[76] NEBOSH. (2019). International General Certificate in Occupational Health and Safetybook: IG1 Management of Health and Safety, (190 pages). NEBOSH.

[77] Justin, C., Craig, J., AnnaBelle, O., Christopher, J. (2021). The Airman's Edge Project: A Peer-Based, Injury Prevention Approach to Preventing Military Suicide, International Journal of Environmental Research and Public Health, 18(6), 3153. https://doi.org/10.3390/ijerph18063153

[78] The hierarchy of controls as an approach to visualize the impact of occupational safety and health coordination, International Journal of Environmental Research and Public Health, 19(5), 2731. https://doi.org/10.3390/ijerph19052731

[79] Ghasemi, H. (2011). High-temperature sulfidation of carbon steel heater tubes in gas condensate containing sulfur compounds. Engineering Failure Analysis, 18(3), 980-998. https://doi.org/10.1016/j.engfailanal.2010.11.017

[80] American Society of Mechanical Engineers (ASME). (2017), American National Standard, ASME PCC-3: Inspection Planning Using Risk-Based Methods (1st ed., 94 pages). ASME.

[81] American Petroleum Institute (API)., American Society of Mechanical Engineers. (2021). API 579-1/ASME FFS-1: Fitness-for-service (3rd ed., 1478 pages). API Publishing Services and ASME.

[82] American Petroleum Institute. (2018). Mechanical integrity: Fixed equipment standards & recommended practices, (36 pages). Energy API.

[83] Kucora, I., &Radovanović, L. (2014). Pyrolysis furnace tube damaging and inspection. Acta TechnicaCorviniensis – Bulletin of Engineering, 7(3), 19–24.

[84] Seung, H., Nahm, J. H., & Choi, H. J. (2003). Degradation evaluation of HK-40 steel using

electrical resistivity, International Journal of Modern Physics B. 17(8-9), 1615–1620, https://doi.org/10.1142/S021797920301940X

[85] Jakobi, J., Gommans, H. (2003). Typical failures in pyrolysis coils for ethylene cracking. Materials and Corrosion, 54(11), 881-887. https://doi.org/10.1002/maco.200303731

[86] Yashwant, R., Girish, S. (2002). In-Situ Metallography and Replication of Microstructures For Condition Assessment & Remaining Life Analysis, Microscopy and Microanalysis, 8(S02), 1332– 1333. https://doi.org/10.1017/S1431927602105095

[87] Park, K., Choi, P., Shin, H., Koh, C. (2013). Process datasheet for feed heater, 1st/2nd/3rd re- heater, steam generator, item no: 100-f-4/5/6/7/8, U100 refinery of Skikda.

[88] Park, K., Choi, P., Koh, C. (2011). Process flow diagram for reforming unit U100. Refinery of Skikda.

[89] Park, K., Choi, P., Shin, H. (2013). Operating manual ofreforming unit U100. Refinery of Skikda.

[90] DCS Graphics. (2011). Static layout printouts: Skikda refinery rehabilitation & adaptation project, refinery of Skikda.

[91] Hodoroaba, V.D. (2019). Characterization of Nanoparticles, Chapter 4.4 - Energy-dispersive X- ray spectroscopy (EDS). In Characterization of Nanoparticles, 397-417. https://doi.org/10.1016/B978- 0-12-814182-3.00021-3

[92] Scimeca, M., Bischetti, S., Lamsira, H.K., Bonfiglio, R., Bonanno, E. (2018). Energy dispersive X-ray (EDX) microanalysis: A powerful tool in biomedical research and diagnosis, European Journal of Histochemistry, 62(1), 89-99. https://doi.org/10.4081/ejh.2018.2841

[93] Rades, S., Hodoroaba, V.D., Salge, T., Wirth, T., Lobera, M.P., Labrador, R.H., Natte, K., Behnke, T., Gross, T., Unger, W.E.S. (2014). High-resolution imaging with SEM/T-SEM, EDX, and SAM as a combined methodical approach for morphological and elemental analyses of single engineered nanoparticles, 4, 49577-49587. RSC Advances. https://doi.org/10.1039/c4ra05092d

[94] Hodoroaba, V.D., Rades, S., Unger, W.E.S. (2014). Inspection of morphology and elemental imaging of single nanoparticles by high-resolution SEM/EDX in transmission mode. Surface and Interface Analysis, 46(10-11), 945-948.https://doi.org/10.1002/sia.5426

[95] American Society for Testing and Materials. (2001). Standard practice for production and evaluation of field metallographic replicas : Designation E 1351 – 01, 1, 6. ASTM international.

[96] PoulassichidT. (2009). Application of Risk Based Inspection to Offshore Facilities. United States: SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers. https://doi.org/10.2118/124539-ms.

[97] Chang M.K., Chang R.R., Shu CM., Lin K.N. (2005). Application of risk-based inspection in refinery and processing piping, Loss Prev Process, 18(4-6), 397-402. https://doi.org/10.1016/j.jlp.2005.06.036.

[98] Davood E., Hossein.C., Abdollah. (2020). A Semi-quantitative Approach Development for Risk- based Inspection in a Petrochemical Plant, Journal of Medical Sciences. 2020; 8(E):425-433. https://doi.org/10.3889/oamjms.2020.4391

[99] Viktor, N., Gunawan, D.H., Rifky, I., Seon, J.K. (2016). Risk analysis of pressure vessel with external corrosion using RBI method based on API 581. AIP Conference, 1725(1): 020052. https://doi.org/10.1063/1.4945506

[100] American Petroleum Institute. (2019). API recommended practice 581: Risk-based inspection (3rd ed., 664 pages). American Petroleum Institute.

[101] Velosi Asset Integrity Limited. (2017). Methodology for static equipment and piping system of GroupementBerkine fields. Groupement Berkine Sonatrach/Anadarco.

[102] Velosi Asset Integrity, Engineering, HSE & Software Consultants. (2022, February 28). VAIL- Plant Module - Pressurized Equipment Management System (PEMS) – Turkey. Available at: https://velosiaims.com/tr/service/softwareservices/aimsrbipems/(accessed in September 2024).

[103] American Petroleum Institute. (2014). API Standard 510: Pressure vessel inspection, Code: In- service Inspection, Rating, Repair, and Alteration (10^{th}ed., 71 pages). API Publishing Services.

[104] American Petroleum Institute. (2016), API Standard 530: Calculation of Heater-tube Thickness in Petroleum Refineries, (7^{th} ed., 264 pages). API Publishing Services.

[105] American Petroleum Institute. (2016), API Standard 941: Steels for hydrogen service at elevated temperatures and pressures in petroleum refineries and petrochemical plants, (8^{th} ed., 66 pages). API Publishing Services.

[106] Dib K., Zennir Y., Bounezour H., Bouasla S. (2022), Safety Integrity Evaluation of crude oil heater According to IEC 61508 Standard, Algerian Journal of Signals and Systems, 7 (2), 390-398. https://doi.org/10.51485/ajss.v7i2.158

Appendix 01: Process data sheet

SAMSUNG ENGINEERING	DOC. NO : 6648-0100-5-PS-DS-0005-F	REV. F	DATE : 30 Mun. 13	Sheet 5 of 7

API Standard No. 560
FIRED HEATER DATA SHEET
METRIC UNITS

	Orig.	Rev 1	Rev 2
Date:	12/12/2005		
By:	SML		
App. By:			

Service	Reactor Heaters	Equipment No.	100-F-4/5/6/7/8
Unit	Magnaformer	Plant Location	Skikda
Type	Box	No. Required	One
Owner		Reference No.	
Purchaser		Reference No.	
Vendor		Table No.	701
Date	12/12/2005	Page 3 of	4

Process Design Conditions

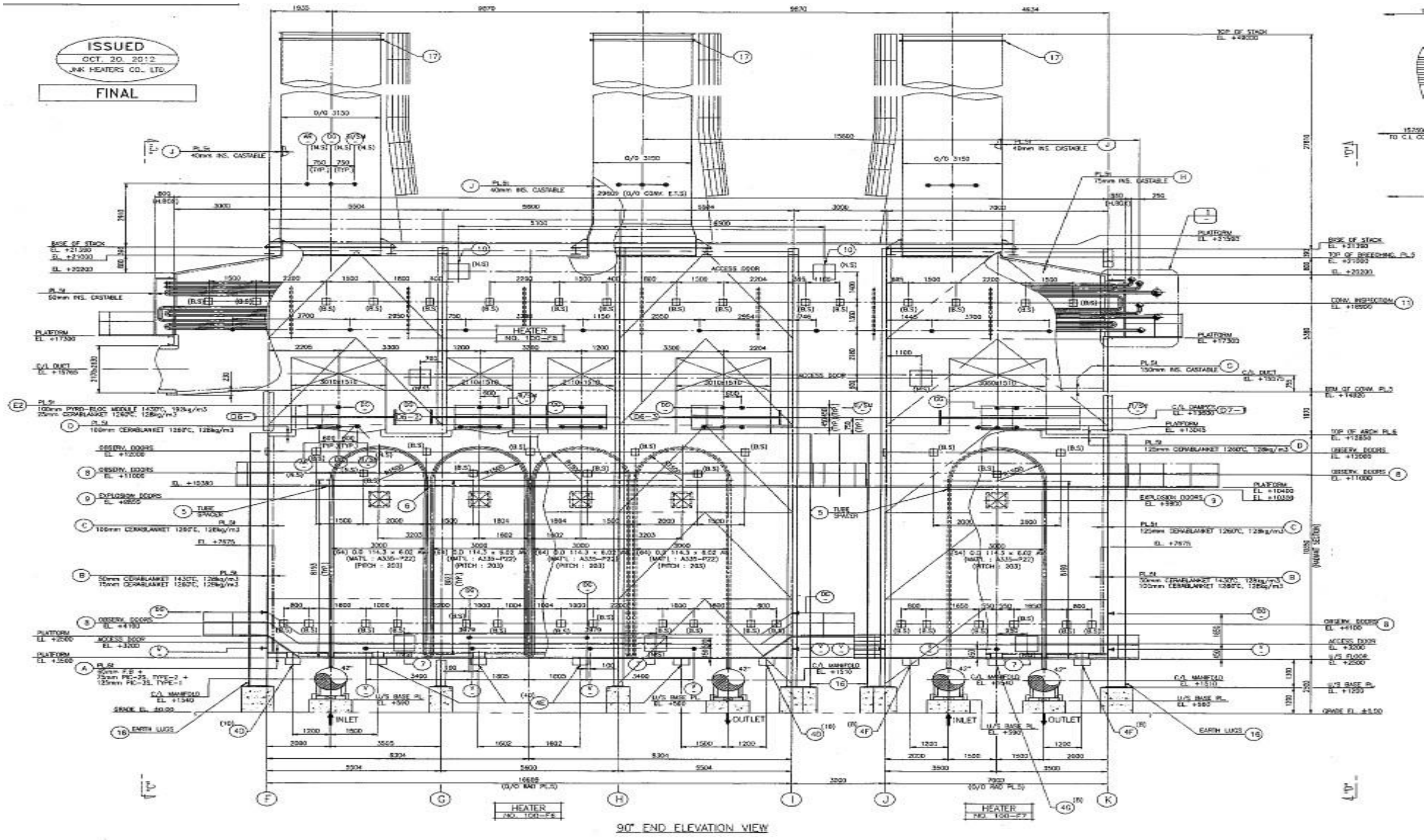
1	Total duty per heater,	MMkcal/hr	49.90	(Radiant Duty only for RA1K EOR Case)		
2	Heater section		100-F-4	100-F-5	100-F-6	100-F-7
* 3	Service		Feed Heater	1st Re-Heater	2nd Re-Heater	3rd Re-Heater
4	Heat absorption,	MMkcal/hr	2.8 (Note 6)	11.5	26.86	8.74
5	Fluid name		H2+HC	H2+HC	H2+HC	H2+HC
6	Flow Rate,	kg/h	212465	212465	345321	345321
7	Flow Rate,	m3/hr				
8	Pressure drop (allowable, clean/fouled),	kg/cm2	(1)	(1)	(1)	(1)
9	Pressure drop (calculated, clean/fouled),	kg/cm2	0.210	0.420	1.08	0.67
10	Fouling Allowance,	m^2-°C/W				
11	Thermal Conductivity of Coke/Scale,	W/m °C				
12	Average Radiant Flux Density, allowable	kcal/sq.m h				
13	Average Radiant Flux Density, Calculated	kcal/sq.m h				
14	Average Conv'tion Flux Density, allowable	kcal/sq.m h				
15	Average Conv'tion Flux Density, Calculated	kcal/sq.m h				
16	Maximum Radiant Flux Density,	kcal/sq.m h				
17	Maximum Convection Flux Density,	kcal/sq.m h				
18	Velocity limitation					
19	Maximum Allowable inside film temperature,	°C				
	Inlet Conditions :					
20	Temperature,	°C	469.7 / [454]	442.5 / [407]	458.1 / [383]	511.8 / [499]
21	Pressure,	kg/cm2 g	15.22	14.02	12.63	10.08
22	Liquid Flow,	kg/hr				
23	Vapor flow,	kg/hr	212465	212465	345321	345321
24	Gravity, liquid,					
25	Vapor molecular weight		34.00	31.60	20.65	19.75
26	Viscosity, Liquid,	Cp				
27	Viscosity, vapor,	Cp	0.028	0.027	0.026	0.027
28	Enthalpy, liquid,	Gcal/h				
29	Specific heat, vapor	Kcal/kg °C	0.857	0.845	0.936	0.972
30	Thermal conductivity, liquid,	W/m °C				
31	Thermal conductivity, vapor,	W/m °C	0.139	0.141	0.172	0.185
	Outlet Conditions :					
32	Temperature,	°C	485 / [471]	505 / [488]	537.6 / [545]	537.6 / [545]
33	Pressure,	kg/cm2 g	15.01	13.60	11.36	9.41
34	Liquid Flow,	kg/h				
35	Vapor flow,	kg/h	212465	212465	345321	345321
36	Gravity, liquid,	specific gravity at 15°C				
37	Vapor molecular weight		34.00	31.60	20.65	19.75
38	Viscosity, Liquid,	Cp				
39	Viscosity, vapor,	Cp	0.028	0.029	0.028	0.028
40	Specific heat, liquid,	Kcal/kg °C				
41	Specific heat, vapor	Kcal/kg °C	0.866	0.884	0.987	0.988
42	Thermal conductivity, liquid,	W/m °C				
43	Thermal conductivity, vapor,	W/m °C	0.142	0.153	0.190	0.191
44	Design Temperature	°C	513 / [481]	533 / [498]	566 / [555]	566 / [555]
45	Design Pressure	kg/cm2 g	16.6 / FV	16.6 / FV	16.6 / FV	16.6 / FV

Remarks and Special Requirements, Including Short-Term Operating Conditions :

46

47 Other : NOTE (1): - MAXIMUM TOTAL FURNACE PRESSURE DROP ALLOWABLE IS 2.374 kg/cm2

Appendix 02 : mechanical drawing



Appendix 03: Visual inspection results

2

Appendix 04: Replica test results

1) Introduction.

L'examen de la structure métallographique est réalisé dans le cadre d'une inspection périodique

2) Données techniques.

Donnés générales		
Numéro de série : /	Année de construction :	Constructeur :
Dimensions tube	Diamètre : 4" (114.3mm)	Longueur : / mm
Partie examinée : **Parois externe**	Matériaux : **A335 P22**	Epaisseur nominale : **6.02 mm**
☐ Isolation : /	☐ Protection contre la corrosion : /	

Conditions de calcule & de service		
Pression de calcule : **16.6 kg/cm²**	Pression de service : **10.08 kg/cm²**	Fluide externe : /
Température de calcule : **566°C**	Température de service : **537.6°C**	Fluide interne : **Chauffage (hydrogène + vapeur HC)**

3) Base de l'examen.

ISO 3057-98 : ***Non Destructive Testing – Metallographic Replica Techniques of Surface Examination.***

4) Localisation des échantillons et évaluation de la dégradation.

Elément contrôlé	Observation	Commentaire
Pipe B37	Paroi externe (hauteur 1400 mm)	Voir les interprétations en dessous des micrographies.

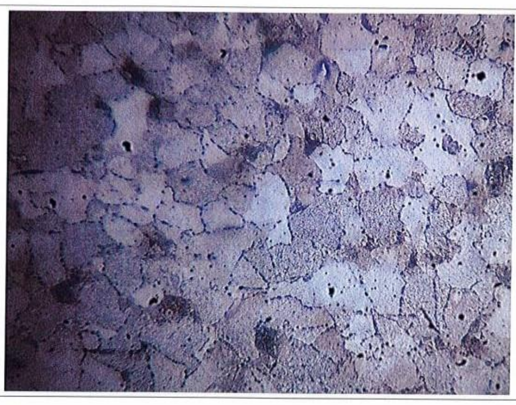
5) Conclusions :

Les résultats des répliques montrent que l'équipement peut être remis en service à condition que son suivi soit respecté dans les deux prochaines années.

ALICEF
INDUSTRIE - CERTIFICATION - ENVIRONNEMENT - FORMATION
Ex Vinçotte International Algérie s.p.a.

Rapport de contrôle par réplique métallographique

Annexe 5.4.7
Rapport n° RA210655-59
Page 2 sur 2



Micrographie de la paroi externe du pipe B37 avec les grossissements 200X
La micrographie au niveau de la paroi externe du pipe : B37, est entièrement ferritique en forme polyédrique de taille moyenne (zone de décarburation totale). Avec présence d'oxyde en forme de petites particules.

Item	Localisation	Mesures		Valeur moyenne mesurée HB
100-F7	B37	Mesure 01	98	98.6
		Mesure 02	103	
		Mesure 03	97	
		Mesure 04	100	
		Mesure 05	95	

Appendix 05: Generic Classified Damage Mechanisms as per API 571

Internal orExternal	Type of Damage	Damage Mechanism
Internal	General (Uniform) Thinning	1 Sulfidic Corrosion (Sulfidation) 4 High Temp H2/H2S 11 Oxidation 13 Sour Water Corrosion (Acidic) 17 Decarburization 24 Carburization 36 Sulfuric Acid Corrosion 37 Hydrofluoric Acid Corrosion 41 Dealloying 44 Fuel Ash Corrosion 53 Galvanic Corrosion 66 Organic Acid Corrosion 67 General Corrosion
	Localized Thinning	6 Naphthenic Acid Corrosion 7 Ammonium Bisulfide Corrosion 8 Ammonium Chloride Corrosion9 HCl Corrosion 19 Caustic Corrosion 20 Erosion/Erosion Corrosion 29 Graphite Corrosion 38 Flue Gas Dew Point Corrosion42 CO2 Corrosion 45 Amine Corrosion 50 Boiler Water/Condensate Corrosion 51 Microbiologically Induced Corrosion59 Metal Dusting 62 Phosphoric Acid Corrosion63 Phenol Corrosion 68 Under Deposit Corrosion69 Dew Point Corrosion
		49 Cooling Water Corrosion
		15 Graphitization
		26 Steam Blanketing
		27 Thermal Shock
		32 Sigma Phase/Chi Embrittlement
	Mechanical and Metallurgical Failure Mechanism	33 885F (475C) Embrittlement34 Softening (Spheroidization) 39 Dissimilar Metal Weld (DMW) Cracking
		55 Nitriding

		65 Oxygen-Enhanced Ignition and Combustion
Internal		14 Refractory Degradation
		2 Wet H2S Damage 25 Hydrogen Embrittlement
	Environmental Cracking	18 Caustic Cracking 21 Carbonate SCC 22 Amine Cracking 40 Hydrogen Stress Cracking43 Corrosion Fatigue 48 Ammonia SCC 52 Liquid Metal Embrittlement61 Sulfate SCC 64 Ethanol Stress Corrosion Cracking
	Fatigue	12 Thermal Fatigue 54 Mechanical Fatigue 56 Vibration Induced Fatigue
	Other	10 High Temperature Hydrogen Attack57 Titanium Hydriding
External	General (Uniform) Thinning	47 Atmospheric Corrosion
	Env. Cracking	23 External Chloride SCC
	Localized Thinning	46 Corrosion under Insulation (CUI)
		58 Soil Corrosion
	Other	70 UV Ray Ageing

Appendix 06 : Questionnaire & POF categories for every degradation mechanism

DAMAGE MECHANISM	QUESTIONNAIRE	POF
Internal Corrosion	The actual corrosion rate is very high (> 4 * Design CR)	5
	The actual corrosion rate is higher than design (3 - 4 * Design CR)	4
	The actual corrosion rate is higher than design (1 - 3 * Design CR)	3
	The actual corrosion rate is as per design (0.5 - 1 * Design CR)	2
	The actual corrosion rate is lower than design (< 0.5 * Design CR)	1
External Corrosion	Severe external corrosion (e.g. 60 - 120 C with high humidity and /orspray, condense, cycling conditions, damaged insulation)	4
	Serious external corrosion (e.g. -5 to 60 C or 120 - 150 C and humidclimate, damaged insulation)	3
	Minor external corrosion under normal operating conditions (< 0.05mm/yr)	2
	No foreseeable external corrosion (not insulated or > 150 C)	1
Creep	Operation in the creep range, risk of massive upsets which must bequantified in terms of remnant life	5
	Operation in the creep range, risk of major upsets which must bequantified in terms of remnant life	4
	Operation in the creep range, risk of minor upsets which must bequantified in terms of remnant life	3
	Operation in the creep range at or below design conditions	2
	No foreseeable operation in the creep range	1
Other (AR)	Very High susceptibility	5
	High susceptibility	4
	Medium susceptibility	3
	Low susceptibility	2
	Very Low susceptibility	1

Fatigue Thermal	Cyclic temperature range or delta T of two process streams greaterthan 250 C	5
	Cyclic temperature range or delta T of two process streams between200 and 250 C	4
	Cyclic temperature range or delta T of two process streams between150 and 200 C	3
	All other lines or equipment	1
Fatigue - Vibrations	Vibrating in zone 1, or nominal pipe diameter less than 50 mm and in zone 2 or 3	4
	Vibrating in zone 2, or nominal pipe diameter between 50 and 100 mm in zone 3	3
	Vibrating in zone 3	2
	No foreseeable fatigue due to vibration (zone 4 or no vibrations)	1
Stress Corrosion Cracking	Very High susceptibility	5
	High susceptibility	4
	Medium susceptibility	3
	Low susceptibility	2
	Very Low susceptibility	1
Low Temp. Embrittlement	Operating below the lower-design temperature	4
	Exceptional cool-down upsets, resulting from high rate depressurizing possible and no safeguarding to prevent (re)pressurizing	3
	Exceptional cool-down upsets, resulting from high rate depressurizing possible; (re)pressurizing prevented by safeguarding systems/ procedures	2
	Not susceptible under any foreseeable conditions	1
	Operating in the Embrittlement range and no S/D precautions	4

High Temp. Embrittlement	Design or upsets in the Embrittlement range and no S/D precautions	3
	Design and operation below the Embrittlement range or S/D precautions.	2
	Not susceptible under any foreseeable conditions	1
High Temp. Hydrogen Attack	Operating/ upset conditions above the Nelson Curve limits (API 941)	5
	Operating conditions between the Nelson Curve limit and 20 C below (API 941)	4
	Operating conditions are 20 - 50 C below the Nelson Curve limit (API 941)	3
	Operating conditions are > 50 C below the Nelson Curve limit (API 941)	2
	Material is not susceptible under any foreseeable conditions	1
Erosion	Flow velocity is much higher than design and/ or much larger amounts of solids/ droplets present	5
	Flow velocity is higher than design and/ or solids/ droplets higher than design	4
	Flow velocity is as per design, solids/ droplets loading as per design	3
	Flow velocity is less than design, solids/ droplets loading less than design	2
Other (NAR)	Very High susceptibility	5
	High susceptibility	4
	Medium susceptibility	3
	Low susceptibility	2
	Very Low susceptibility	1

Appendix 07: Economic questionnaire

Sr. No.	Cost Element	Description
1	Production loss	Deferred income (loss or downgrading of product) plus product wasted {e.g. Flared or spilled), usually calculated as margin loss plus manpower cost
2	Repair costs	The costs other than labor (but including fixed contractor costs) incurred to have the damage repaired.
3	Labour	The costs (hours) of own personnel or contractor staff on reimbursable contracts.

Total is the sum of the above three elements as given in below figure.

ELEMENT	COST
Production loss	1
Repair Cost	2
Labour	3
Total	6

Economic Consequence class: A

Appendix: 08 Environment consequences

The matrix given below is used to determine the Environmental consequence class using parameters (1) and (2). If any or both of (3) and (4) is 1 then the resultant consequence category obtained by looking up the risk matrix is moved up the COF scale by 1 category.

In case of liquid spillage

Environmental Toxicity	
1	Not harmful to environment (e.g water)
2	Harmful but not toxic (e.g most alkanes)
3	Harmful but toxic (e.g drins)

Released Quantity (or inventory)	
1	< 500 kg
2	0.5 - 5 ton
3	5 - 10 ton
4	10 - 50 ton
5	> 50 ton

	Location
0	Contamination remains inside fence
1	(Part of) contamination is outside fence
	Surface of spill
0	No chance that spilled liquids will reach outside fence surface or ground water
1	There is a possibility that spilled liquids will reach outside fence surface or ground water

Quantity	Toxicity 1	Toxicity 2	Toxicity 3
5	A	E	F
4	A	D	E
3	A	C	D
2	A	B	C
1	A	A	B

In case of gas emission

	Type of release
1	Other
2	Small and Harmful
3	Large (>1000m3) and harmful
4	Massive
5	Catastrophic

Type of Release	Effect 1	Effect 2
5	D	E
4	C	D
3	B	C
2	A	B
1	A	A

Appendix: 09 Safety Consequences

- fire

Flammability	
1	Not flammability (Nf<2) or low flammability (Nf>1 and Tproduct<Tflash)
2	Medium flammability (Nf>1 and Tflash<Tproduct<Tauto ign)
3	High flammability (Nf>1 and Tproduct>Tauto ign)
Released Quantity (Instantaneous or per hour or inventory)	
1	< 500 kg
2	0.5 - 2 ton
3	2 - 5 ton
4	5 - 10 ton
5	> 10 ton

Nf	Products
0	Sulphur Dioxide, Sodium Chloride
1	Sulphur, Ammonia
2	Diesel Fuel, Fuel Oil 1 to 6
3	Gasoline, Naphtha, Ethyl Alcohol, Petroleum Crude
4	Hydrogen, Methane, Hydrogen Sulphide

Released quantity				
	5	A	E	F
	4	A	D	E
	3	A	C	D
	2	A	B	C
	1	A	A	B
		1	2	3
			Flammability	

- Explosion

VCE possibility	
1	None; no release of an explosive cloud
2	Low; release of an explosive cloud in an open area
3	Medium; release of an explosive cloud in a medium congested area (many obstacles present)
4	High; release of an explosive cloud in a heavily congested area (many obstacles present)
Released Quantity	
1	< 50 kg
2	50 - 500 kg
3	0.5 - 5 ton
4	5 - 10 ton
5	>10 ton

Released Vapour					
	5	A	E	F	F
	4	A	D	E	F
	3	A	C	D	E
	2	A	B	C	D
	1	A	A	B	C
		1	2	3	4
			VCE Possibility		

- Toxicity

Toxicity	
1	Not toxic (Nh≤ 1) or low toxicity (Nh ≤ 3 and conc. < 100 ppm)
2	Medium toxicity (Nh= 2)
3	High toxicity (Nh = 3)
4	Extreme toxicity (Nh > 3)

Concentration (in ppm or % volume)	
1	< 1000 ppm
2	< 10000 ppm
3	1 - 5%
4	5 - 10%
5	> 10 %

Nh	Products
0	Diesel
1	Butane, Gasoline
2	CO, benzene, Ethylene Oxide
3	H_2S, chlorine, Ammonia, Sulphuric Acid, Phenol
4	Hydrogen Fluoride (HF), Hydrogen Cyanide

Concentration \ Toxicity	1	2	3	4
5	A	E	F	F
4	A	D	E	F
3	A	C	D	E
2	A	B	C	D
1	A	A	B	C

Mitigation

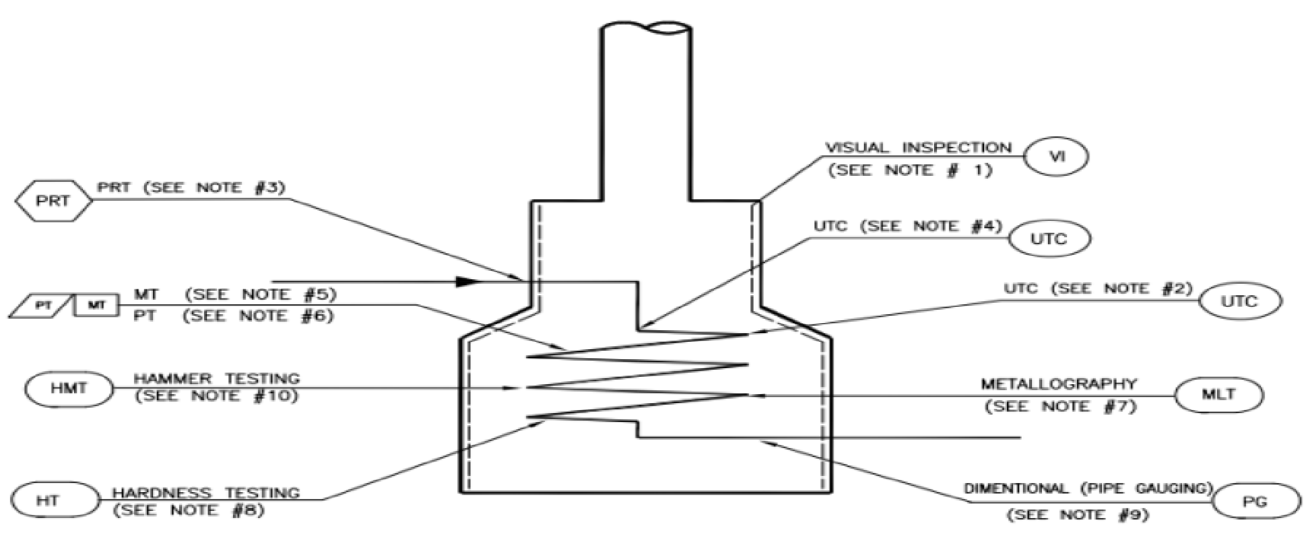
Exposure	
1	Very rare (less than 10 man-minutes per day)
2	Occasionally (less than 6 man-hours per day)
3	Frequently to continuously (more than 6 man-hours per day)

Possibility to avert danger	
1	In almost all circumstances
2	In some circumstances (more than 25% of cases)
3	Not (or hardly possible)

Possibility to avert danger \ Exposure	1	2	3
3	-1	0	0
2	-1	-1	0
1	-2	-1	-1

Appendix: 10 internal ITP's heater

CML REGISTER	NOTES FOR INSPECTORS
VI	100% Internal Visual Inspection of Radiant,convection , casing (insulation/refractory,support,clips,fire brick, burners , roof hangers, thermocouples , damaper,stack...ect)
UTG	Full continuously UT Scan Shall be done All-around circumeference 100mm wide in the staight tubefor the radiant coils at two intermediate levels. and at circumference of the elbows.
MT/PT	Magnetic particle / dye penetrant test should be preformed at attachment welds of tube skin thermocouple, tube hanger ,and tube supports
PRT	PRT to measure tube wall thickness and identify the presence and thikness of internal coke deposite
Metallography test	10% of welds and all hotspots, selection of the weld and base materials shall be done after visual inspection and NDE
HT	Hardness testing of ferritic heater tubes at location where seerve overheat can be expected and should be chosen after visual inspection
Dimensional test	Dimensional control of tubes for bowing ,bulging sagging using flashlight, narrow tape and calibrated tube gauges "pass-fail'



Prepared by:	Reviewed by:	Approved by :			
			CML MARKUP DRAWING		Sheet 2 of 5 Sheet
			Field/unit:	HBNS / OT-1 Stabilizer Heater	
			Tag No:	Heater	
			ISO/GA No	100 F7	
Integrity Specialist	Inspection Engineer	Chef sce inspection & Corrosion	P&ID No		
Date:	Date:	Date:	Drawing No:		Rev 1

Legends:

CML = corrosion monitoring location

Damage mechanism codes

3 = creep /stress rupture
12 = thermal fatigue
10 = High Temp Hydrogen Attack
40 = refractory degradation
20 = Carburization (Cracking)
23 = Spheroidization (Softening)
11 = Oxidation,Metal Dusting
54 = mechanical fatigue
56 = vibration induced fatigue
67 = general corrosion
30= Short Term Overheating-Stress
11 = oxidation
67 = general corrosion

Inspection method codes

UT = ultrasonic testing
PAUT = phased array UT
TOFD = time of flight diffraction UT
FMC = full matrix capture UT
PT = liquid penetrant test
MT = magnetic test
VT = visual testing
RT = radiographic testing
PRT = profile radiographic testing
GWUT = guided wave UT testing
PEC = pulsed eddy current
MFL = magnetic floor scan
AE = acoustic emission
APR = acoustic pulse reflectometry
ACFM = AC field measurement
FMR = field metallography replication

Access requirement codes

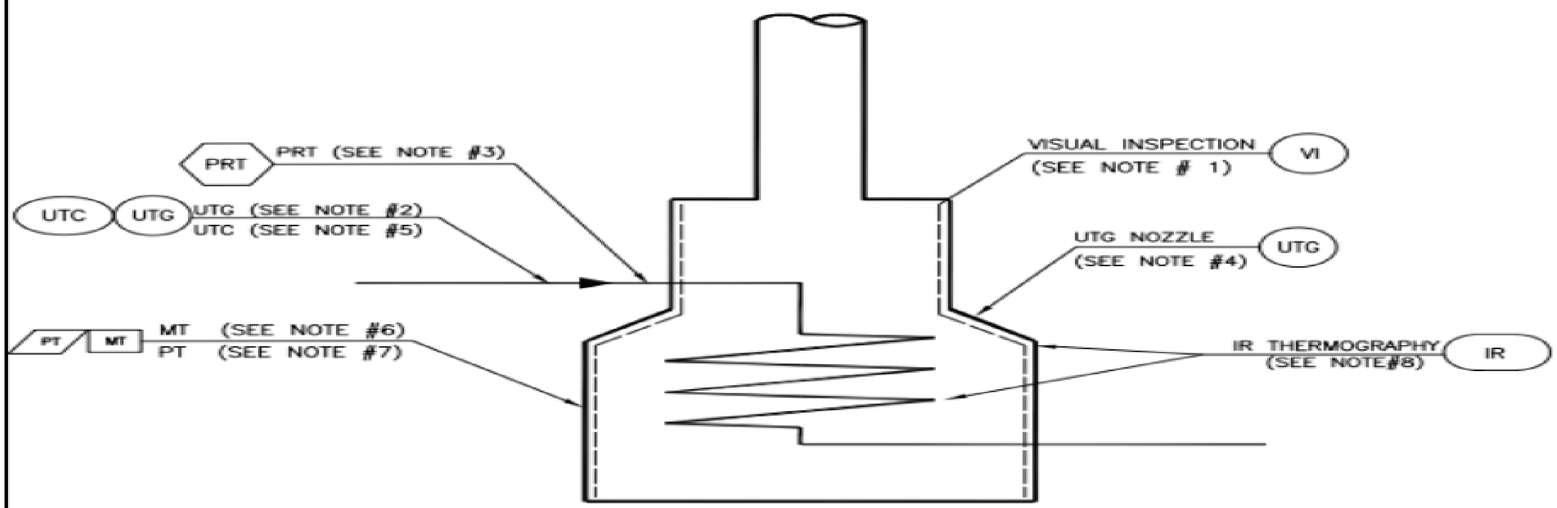
S = scaffolding
I = insulation removal
G = grating removal
P = internal packs for vessels
C = excavation
RA = rope access
D = D = Drone/crawler

Scan area codes

full area scan
spot/partial scan
full radial scan

Appendix: 11 external ITP's heater

CML REGISTER	NOTES FOR INSPECTORS
VI	100% External visual inspection of casing , firebox , header box ,explosion doors ,ladders ,stairs, platforms , walkways, foundations, steel and structural supports, anchor bolts, auxiliary equipment , grounding connections , insulation /coating and external metal surfaces
UTG	on piping at inlet /outlet headers , outlet of convection and radiant zones taken at 3,6,9 &12 O'clock positions
MT	Magnetic particle should be preformed ata attachment welds of tube skin thermocouple, tube hanger ,and tube supports
PRT	PRT to measure tube wall thickness and identify the presence and thikness of internal coke deposite
Infrared thermal camira	Infrared thermal scanning to determine local tube metal temperatures and hot spots in the areas not covered by skin thermocouples heater casing for identifying hot spots due to refractory damage and cracks and stacks for indication of failure of internal liner



Prepared by:	Reviewed by:	Approved by :		
			CML MARKUP DRAWING	Sheet 1 of 5 Sheet
			Field/unit:	Heater
			Tag No:	100 F7
			ISO/GA No	
Integrity Specialist	Inspection Engineer	Chef sce inspection & Corrosion	P&ID No	

Legends:

CML = corrosion monitoring location

Damage mechanism codes

- **3 = creep /stress rupture**
- **12 = thermal fatigue**
- **10 = High Temp Hydrogen Attack**
- **40 = refractory degradation**
- **20 = Carburization (Cracking)**
- **23 = Spheroidization (Softening)**
- **11 = Oxidation,Metal Dusting**
- **54 = mechanical fatigue**
- **56 = vibration induced fatigue**
- **67 = general corrosion**
- **30= Short Term Overheating-Stress**
- **11 = oxidation**
- **67 = general corrosion**

Inspection method codes

- UT = ultrasonic testing
- PAUT = phased array UT
- TOFD = time of flight diffraction UT
- FMC = full matrix capture UT
- PT = liquid penetrant test
- MT = magnetic test
- VT = visual testing
- RT = radiographic testing
- PRT = profile radiographic testing
- GWUT = guided wave UT testing
- PEC = pulsed eddy current
- MFL = magnetic floor scan
- AE = acoustic emission
- APR = acoustic pulse reflectometry
- ACFM = AC field measurement
- IR = infrared scan

Access requirement codes

- S = scaffolding
- I = insulation removal
- G = grating removal
- P = internal packs for vessels
- C = excavation
- RA = rope access
- D = D = Drone/crawler

Scan area codes

- ● full area scan
- ○ full radial scan
- ◉ spot/partial scan