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Implementation of risk-based inspection approach on catalytic reformer heater tubes

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ABSTRACT

This paper presents a case study on reformer heater tubes in a refinery using a Risk-Based Inspection (RBI) methodology to optimize inspection planning according to the probability and consequences of failure. The study aims to evaluate the integrity and reliability of the heater tubes by identifying the most critical degradation mechanisms affecting their performance under severe operating conditions. The assessment focused on radiant tubes exposed to high temperatures, internal pressure, cyclic thermal loading, and corrosive environments. Several damage mechanisms were analyzed, including wall thinning caused by oxidation and corrosion, thermal fatigue resulting from repeated heating and cooling cycles, and creep deformation due to long-term exposure to elevated temperatures. These degradation processes significantly affect the structural integrity and remaining life of the tubes. The RBI analysis showed that radiant tubes are subjected to high-risk damage parameters, making them highly susceptible to failure. Among the identified mechanisms, creep and thermal fatigue found to be the most critical factors influencing tube deterioration and operational risk. The calculated risk levels indicated that extending the inspection interval to 36 months would not ensure adequate safety and reliability. Based on the obtained results, an optimized inspection interval of approximately 1.41 years recommended allowing early detection of degradation and reducing the risk of unexpected failures. The proposed RBI-based strategy improves maintenance efficiency by prioritizing inspections on critical components while minimizing unnecessary inspection activities. Overall, the study demonstrates that the implementation of RBI methodology enhances refinery safety, equipment reliability, and asset integrity management. In addition, it contributes to reducing unplanned shutdowns, maintenance costs, and operational risks, ensuring safer and more efficient refinery operation.

1. INTRODUCTION

An effective Process Safety Management (PSM) system reduces operational risks, while Risk-Based Inspection (RBI) supports and evaluates mechanical integrity. By integrating equipment data, process conditions, hazard analyses, and incident findings, RBI becomes more reliable. In return, RBI strengthens PSM by optimizing inspection strategies, prioritizing high-risk areas, reducing failures, and ensuring regulatory compliance [1].

Consistent with established standards such as API 580 and API 581, and supported by previous studies e.g., Khan et al., 2004; API, 2016; Rausand, 2011 [2,3]. RBI represents a shift from conventional time-based inspection toward a more efficient risk-based strategy. Additional research Khakzad et al., 2013 highlights that incorporating probabilistic risk assessment and dynamic data further improves the reliability of inspection planning and decision-making [4].

This approach allows inspection resources to be prioritized toward high-risk components, where failure would have the most significant safety, environmental, and economic consequences. The Risk-Based Inspection (RBI) method is a valuable tool for developing targeted inspection plans in industries such as chemical, petrochemical, refinery, oil, and gas. Cited in numerous studies. RBI supports decision-making by integrating critical factors like equipment reliability, safety, health, environmental impact, and financial considerations [5-7]. Studies such as Khan and Haddara (2003) demonstrate that RBI implementation leads to a measurable reduction in failure probability and improved asset integrity management. As a result, the integration of RBI within PSM frameworks not only strengthens operational safety and equipment reliability but also ensures regulatory compliance while minimizing maintenance costs and unplanned shutdowns [8].

Risk-based inspection (RBI) is a systematic, data-driven approach designed to prevent the loss of containment in pressurized equipment by analyzing damage mechanisms and failure modes. It enhances safety and optimizes inspection strategies by focusing resources on critical equipment to maintain risks at acceptable levels. [1,9, 10]. Risk-Based Inspection (RBI) is a strategic approach that optimizes inspection planning by prioritizing equipment based on risk levels and integrity concerns. It identifies critical risk factors and selects cost-effective inspection strategies within acceptable risk limits. By evaluating both equipment risk and inspection effectiveness, RBI focuses resources on high-risk assets while reducing unnecessary efforts on low-risk items. Compared to traditional inspection methods, it improves efficiency and risk reduction without increasing inspection frequency as illustrated in Figure 1 [1,11].

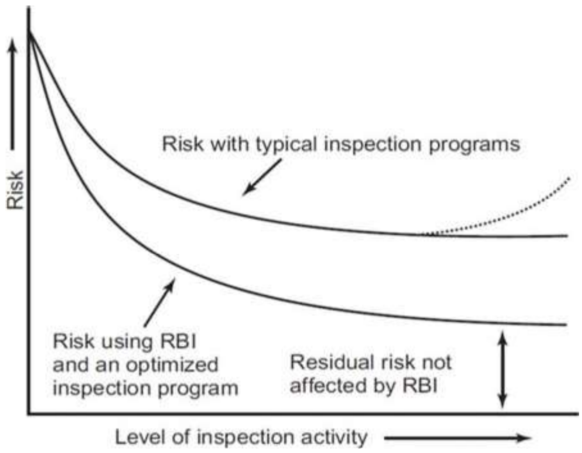

Figure 1. Management of Risk Using RBI [1].

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 [12]. 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 [2]. 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 [13]. This study focuses on the integrity and risk management of reformer heater tubes in the oil and gas industry, aiming to enhance safety and operational reliability. It reviews current maintenance and inspection practices and analyzes the main damage parameters affecting tube performance, particularly oxidation and scaling, and their influence on degradation and service life. The study further applies. Risk-Based Inspection (RBI) in line with API RP 580 to identify high-risk components, assess the likelihood and consequences of failure, and optimize inspection planning. This approach supports proactive risk control, improves decision-making for maintenance strategies, and enhances overall operational efficiency and equipment reliability.

2. DESCRIPTION OF THE HEATER

The 100-F7 heater is an industrial heating equipment utilized in the reforming reaction section designed to process preheated Naphtha "B “. The heater is engineered to run at design pressures and temperatures of 16.6 bars and 566°C, respectively. However, actual operating conditions differ, the operating pressure of 10.08 bars and an operating temperature of 537.6°C [14]. The selected system is illustrated in the Figure 2. The heater tubes are constructed from Chrome-Molybdenum alloy, specifically grade A335 P22 sch 40, chosen for its suitability in high-temperature and high-pressure environments. Tube material and heater operating conditions are illustrated in table 1.

Table 1. Tube material and heater operating conditions of the 100-F7 [15].

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
	Material	A 335 P22
	Diameters	Ø 4"
	Thickness	Sch 40
Exposed Surface Area (m²)	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	

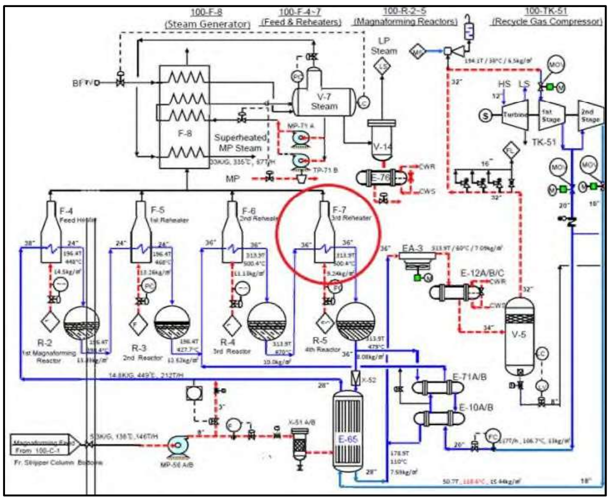

Figure 2. The 100-F7 reformer heater [16,21]

3. 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 3 summarizes the methodology adopted for the RBI assessment process.

Figure 3. RBI assessment process [1,11].

2.1 Collection of engineering data

To perform an RBI analysis, we have collected and reviewed several documents including, Process Descriptions / Design Basis, Process Flow Diagrams (PFDs), Piping & Instrumentation Diagrams (P&IDs), Equipment Data Sheets, Equipment Mechanical Drawings, Inspection History Data.

2.1.1 Defining Corrosion Rates

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. From the available thickness measurement results, corrosion rates and remnant life calculation for piping systems are made per API 570 as under the formula 1 [11, 17].

$$\text{Corrosion rate (LT)} = \frac{\text{Tintial} - \text{Tactual}}{\text{Time (years)between T initial and Tactual}} \quad (1)$$

considering T initial is 6.02 mm and Tactual is 4.09 mm the corrosion rate will be 0.0553mm/year

2.1.1.1 Design Corrosion Rate

Design Corrosion Rate (D.C.R.) has been calculated on the basis of design corrosion allowance using the formula 2.

$$Design\ Corrosion\ Rate\ (D.C.R.) = \frac{design\ corrosion\ allowance}{design\ life} \quad (2)$$

Considering the design life of a system is considered as 25 years, the design corrosion rates (mpy) against design corrosion allowance (1.6 mm) will be 0.064 mm/year.

2.1.1.2 Remaining life calculation

The remaining life of the heater is calculated using formula

$$\text{Remnant life (years)} = \frac{\text{Tactual} - \text{Trequired}}{\text{Corrosion rate (inches or mm per year)}} \quad (3)$$

starting with the determination of the minimum required thickness based on design standards. According to API 530, the minimum required thickness, Tmin required, is 5.3 mm [18]. considering the corrosion allowance of 1.6 mm, we can determine the adjusted required thickness. The current minimum measured thickness, Tmin 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.

$\text{T required} = \text{T min required} - \text{CA}$ (4), $\text{Trequired} = 3.7$ mm Consequently, the calculation of the remaining life is

$$RL = \frac{4.09 - 3.7}{0.0553} = 7.05 \text{ years}$$

2.2 Identification of damage mechanisms

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 2.

Table 2. the identified damage mechanisms [19,20,21]

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)

2.3 Probability of Failure (POF) Assessment

Criticality is defined as the combination of two parameters. The Probability to failure (POF) and the consequences of a failure (COF) presented in 5 x 5 risk matrix as presented in table 3. The selected risk ranking is high, medium-high, medium and low.

Table 3. Risk Matrix.

POF		Risk				
5	<1 year	MH	MH	MH	H	H
4	1-5 years	M	M	MH	MH	H
3	5-10 years	L	L	M	MH	H
2	10-20 years	L	L	M	M	MH
1	>20 years	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 KU SD)
Safety		Moderate	Serious	Major	Catastrophic	Disastrous
Environment		Moderate Effect(<100L)	Serious Effect (100L –1000L)	Major Effect (1000L–10000L)	Catastrophic Effect (10000L –16000L)	DisastrousEffect (>16000L)
COF		A	B	C	D	E

In this step, the probability of failure (POF) is estimated for each applicable damage mechanism and ranked from 1 to 5 based on corrosion rates or susceptibility ratings provided by the RBI software. When multiple degradation mechanisms are present, the highest POF value is used to represent the overall risk.

2.3.1 Thermal fatigue POF Assessment for:

Inspection and replica test results revealed a fully ferritic polyhedral microstructure, total decarburization, and the presence of oxide particles, indicating prolonged exposure to elevated temperatures and advanced material degradation. The heater tubes operate at 537.6 °C, well above the 425 °C creep threshold for 2.25Cr–1Mo steel [10], placing them firmly within the creep regime. The reduced hardness value (98.6 HB) further indicates thermal softening, increasing susceptibility to short-term overheating and stress rupture. These combined factors result in a high susceptibility to both creep and thermal fatigue. Additionally, visual inspection identified refractory damage, and the unit has exceeded its 25-year design life. The deterioration of the refractory lining increases heat flux to the tubes, further elevating the risks of creep, oxidation, and metal dusting. Consequently, the overall POF associated with thermal fatigue and related damage mechanisms is considered high.

2.3.2 Thinning POF Assessment for:

To estimate the probability of failure due to thinning (oxidation and metal dusting), we need to calculate the design corrosion rate (DCR) using the formula 4.

$$DCR(mm) = \frac{Corrossion\ allowance\ (mm)}{Design\ life\ (years)} \quad (4)$$

The Corrosion allowance (CA) = 1.6 mm and the Design life set at 25 years, using the equation 4.6 we obtain DCR = 0.08 mm/year and the MCR= 0.0553mm/year

Based on the obtained result, the current corrosion rate is as per design. the probability of failure falls into category 2

Inspection results indicate significant oxidation and early signs of metal dusting on the heater tubes, both caused by prolonged exposure to high operating temperatures (537.6°C). The presence of small oxide particles suggests material degradation through wall thinning and the formation of a thick oxide layer, which weakens the metal structure. This deterioration compromises the tubes' ability to withstand internal pressures

2.3.3 HTHA POF Assessment:

According to the Nelson Curves (API 941), the risk of High-Temperature Hydrogen Attack (HTHA) in the 2.25Cr-1Mo heater tubes is considered low under current operating conditions. At a hydrogen partial pressure of 7.23 bars and a temperature of 537.6°C, the tubes remain below the typical HTHA threshold for this material, which generally occurs between 13 and 17bars in this temperature range. This positioning categorizes us within the low susceptibility zone (category 2) [22]. Also referring to 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 [10].

2.3.4 Cracking POF Assessment:

Based on the inspection results, the susceptibility to carburization damage is considered low category (2), as inspection results reveal a fully ferritic microstructure and total decarburization, indicating carbon loss rather than absorption. The absence of a carbon-rich environment, despite high operating temperatures (537.6°C), and a low hardness value of 98.6 HB further support that carburization is not occurring.

2.3.5 POF Spheroidization Assessment (Softening):

We estimate the susceptibility to softening as high based on the hardness measurement of 98.6 HB (category 4), which indicates a significant loss of strength. This low hardness indicates significant softening, with the material's strength now well below the standard 2.25Cr-1Mo hardness range (170–210 HB). This softness suggests a substantial loss of tensile strength, making the tubes more vulnerable to high-temperature stress and creep.

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.

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

Thermal fatigue, high-temperature hydrogen attack (HTHA), cracking, and brittle fracture, share a similar economic impact estimation.

2.4.1 Thermal fatigue COF Assessment

The estimated shutdown duration of 312 hours results in a significant production loss of approximately 11.04 million USD, with repair costs adding another 126,000 USD, bringing the total economic impact to around 11.16 million USD, placing the economic consequence of failure (COF) in Category E. From a safety perspective, cracks could lead to fires with releases between 0.5 and 5 tones, and ruptures may result in vapor cloud explosions due to gas accumulation, both scenarios falling under Category C.

Toxicity risks are considered medium across all damage parameters, also aligning with Category C. Given the frequency of exposure and high potential for danger mitigation, the overall safety consequence class for thermal fatigue is categorized as B. Environmentally, due to the gaseous nature of the product, emissions are possible, but their scale and impact are classified as small and harmful, placing the environmental consequence of thermal fatigue in Category B.

2.4.2 Thinning COF Assessment

For the thinning damage parameter, a shutdown lasting 168 hours is estimated to result in a total economic loss of approximately 6,100,752 USD, including 6,012,384 USD in production losses, 42,000 USD in material repair costs, and 46,368 USD in labor, placing the economic consequence in Category D. The safety risk involves a potential fire scenario with high flammability and an estimated release of less than 500 kg, classifying it under Category B, while toxicity and mitigation remain consistent across all damage types, rated Category C and -1, respectively.

Environmentally, the thinning impact is considered small and harmful with a low effect level, placing it in Category A. For high-temperature hydrogen attack (HTHA), thermal fatigue cracking, and brittle fracture, the economic consequences are all classified as Category E due to high associated costs. The safety scenario for HTHA involves a fire risk with an estimated release between 0.5 and 5 tones, falling under Category C, with the same toxicity and mitigation classifications as above. Environmentally, HTHA is assessed as a small and harmful gas release (type 2) with a moderate effect, placing it in Category B.

2.4.3 Cracking COF Assessment

Cracking, along with HTHA, thermal fatigue, and brittle fracture, shares a high economic impact estimated in Category E. From a safety standpoint, cracking is expected to lead to a fire scenario with high flammability and a release quantity between 0.5 and 2 tones, placing it in Category C. Toxicity and mitigation levels are consistent across all damage parameters, classified as Category C and -1, respectively, resulting in an overall safety consequence class of Category B.

Environmentally, cracking is associated with a large and harmful gas release (Category 3) and a moderate effect level, leading to a classification of Category C.

2.4.4 Brittle fracture COF Assessment

Brittle fracture, along with HTHA, thermal fatigue, and cracking, shares a high economic impact categorized as Category E. Brittle fracture may lead to a fire scenario with high flammability and an estimated release between 0.5 and 2 tonnes, placing it in Category B. In the event of a rupture, a vapour cloud explosion (VCE) is possible due to gas accumulation in the combustion chamber, with a high probability (Level 4) and a release between 0.5 and 5 tonnes, resulting in a Category E classification. Toxicity and mitigation levels remain consistent across damage parameters, rated Category C and -1, respectively.

Based on these factors, the overall safety consequence class for brittle fracture is Category D. Environmentally, HTHA is associated with a large and harmful release (Category 3) and a moderate effect level, placing it in Category C.

2.5 Risk assessment

Figure 4 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.

Figure 4. Radiant tube risk summary logical [23]

2.6 Assignment of inspection effectiveness

The assignment of inspection effectiveness is carried out by calculating the confidence rating based on a questionnaire for each damage mechanism. 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. The answers to the questions will be scored as shown in Table 5.

Table 4. 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

Table 5. Confidence Factor Categories

Category	Score
Very High (VH)	+0.2
High(H)	+0.1
Medium(M)	0

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 30 represents the confidence assessment.

2.7 Inspection plan

The semi-quantitative RBI method varies the IF from 0.1 to 0.8, based on a risk and confidence assessment, as shown in table 6:

Table 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

The software calculates the next inspection interval by analyzing prior data on equipment risk, inspection effectiveness, historical corrosion rates, and remaining life. Based on this analysis, it has set the inspection interval at 1.41074 years displayed in figure 5, 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 5. Overall risk result for the RBI study [23]

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. RESULTS

The criticality assessment conducted for the radiant tubes revealed that these components are predominantly classified within the High (H) criticality category, positioning them in the red zone of the risk matrix. This classification reflects the severe operational risks associated with the radiant tubes and demonstrates that they represent some of the most critical components within the catalytic reformer heater. The high criticality level is the result of the combined influence of elevated Probability of Failure (PoF) values, severe Consequence of Failure (CoF) ratings, and the simultaneous presence of multiple active damage parameters acting under high-temperature operating conditions.

These combined factors significantly threaten the structural integrity of the furnace and increase the potential for loss of containment, which may adversely affect safety, production continuity, equipment reliability, and operational performance.

The Probability of Failure analysis showed that the radiant tubes are mainly assigned a PoF level of 4 for several identified degradation parameters, indicating a high likelihood of failure during operation. This elevated probability is primarily associated with the harsh service conditions experienced by the tubes, including prolonged exposure to elevated temperatures, cyclic thermal stresses, internal pressure, and aggressive process environments. Furthermore, the coexistence of several severe degradation parameters considerably increases the overall susceptibility of the tubes to failure.

Among the most critical parameters identified are High-Temperature Hydrogen Attack (HTHA), thermal fatigue, brittle fracture, thinning, creep, and softening. Each of these degradation parameters contributes differently to material deterioration and structural weakening.

HTHA represents a significant concern because prolonged exposure to high-temperature hydrogen environments may lead to decarburization and the formation of methane within the steel microstructure, ultimately reducing material strength and toughness. Thermal fatigue is another critical parameter resulting from repeated temperature fluctuations during start-up, shutdown, and operational variations, which generate cyclic stresses that promote crack initiation and propagation.

Brittle fracture presents an additional risk, particularly in areas where material toughness has deteriorated due to aging, metallurgical changes, or exposure to unfavorable operating conditions. In addition, creep damage becomes increasingly significant due to the prolonged exposure of the heater tubes to elevated temperatures over an extended service period, causing progressive deformation and loss of mechanical strength. Thinning and softening further accelerate material degradation by reducing wall thickness and decreasing hardness and load-bearing capacity.

The presence of these multiple high-risk degradation parameters acting simultaneously substantially increases the vulnerability of the radiant tubes and demonstrates that the equipment is operating under critical integrity conditions. These findings strongly justify the implementation of proactive risk management and integrity assurance measures, including enhanced inspection programs, continuous monitoring, and optimized maintenance strategies to minimize the likelihood of catastrophic failure. The Consequence of Failure evaluation also revealed very severe ratings for the radiant tubes, with several components classified under category “E” in both the Business and Safety consequence categories. In the Business category, an “E” rating indicates that failure of the radiant tubes could result in major economic consequences for the facility.

Such consequences may include prolonged production shutdowns, costly emergency repairs, replacement of damaged components, interruption of refinery operations, and significant financial losses associated with downtime and reduced production efficiency. In addition, failure of the radiant tubes could potentially damage adjacent equipment and compromise the operational reliability of the entire heater system.

From a Safety perspective, the “E” consequence rating reflects the extremely hazardous nature of a potential tube failure. Due to the high operating temperatures and pressures within the catalytic reformer heater, rupture of a radiant tube could lead to the sudden release of high-temperature hydrocarbons and process gases. Such a release may result in fire, explosion, or toxic exposure scenarios capable of causing severe injuries or fatalities to personnel working in the surrounding area. The combination of combustible materials, elevated temperatures, and pressurized conditions considerably amplifies the severity of potential accident scenarios.

Overall, the results of the RBI assessment confirm that the radiant tubes are exposed to highly critical operating conditions and multiple severe degradation parameters that significantly increase both the likelihood and consequences of failure. These findings emphasize the necessity of maintaining a rigorous inspection and monitoring strategy, supported by risk-based decision-making, to preserve equipment integrity, ensure operational reliability, minimize economic losses, and protect personnel safety throughout the remaining service life of the heater.

The table 7presents the Inspection Planning and PIR (Planned Inspection Recommendation) for the catalytic reformer heater. It summarizes the inspection activities recommended by the RBI study:

Table 7. Inspection Planning - PIR (Inspection Type, When to Inspect, How to Inspect).

Operation Code	Operation Description	Insp Interval	Last Insp Date	RBI Next Insp. Date	Duration
VI	100% Internal Visual Inspection of Radiant, convection, casing (insulation/refractory, support, clips, fire brick, burners, roof hangers, thermo couples, damper, stack…ect)	3 Years	03/01/2023	03/01/2025	2h
UTS	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.	3 Years	03/01/2023	03/01/2025	4h
PRT	PRT to measure tube wall thickness and identify the presence and thickness of internal coke deposits	3 Years		03/01/2025	2h
UTG	UTG at Nozzles >2" (as per Annex 1)	3 Years	03/01/2023	03/01/2025	2h
MT/PT	Magnetic particle / dye penetrant test should be performed at attachment welds of tube skin thermocouple, tube hanger, and tube support	3 Years		03/01/2025	3h
Metallography test	10% of welds and all hotspots, selection of the weld and base materials shall be done after visual inspection and NDE	3 Years		03/01/2025	4h
HT	Hardness testing of ferritic heater tubes at location where severe overheat can be expected and should be chosen after visual inspection	3 Years		03/01/2025	2h
Dimensional test	Dimensional control of tubes for bowing, bulging sagging using flashlight, narrow tape and calibrated tube gauges ''pass-fail'	3 Years		03/01/2025	2h
PT	10% hangers and supports / tube welds	3 Years		03/01/2025	3h
VT 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	3 Years		03/01/2025	4h
UTG External	on piping at inlet /outlet headers, outlet of convection and radiant zones taken at 3,6,9 &12 O'clock positions	3 Years		03/01/2025	5h
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		03/01/2025	6h

5. CONCLUSION

In our study, we conducted a comprehensive implementation of the Risk-Based Inspection (RBI) methodology using a semi-quantitative approach supported by the VELOSI software. This advanced tool enabled us to systematically identify and evaluate the different damage parameters affecting the catalytic reformer heater, assess their probability and consequences of failure, and establish an effective and comprehensive inspection strategy adapted to the operational conditions of the equipment. In addition, a dedicated mitigation plan was developed to reduce the risks associated with the identified degradation parameters. The RBI assessment revealed a high probability of failure mainly associated with thermal fatigue, thinning, and softening, indicating advanced degradation of the heater tubes. The consequence of failure (COF) analysis demonstrated that the most significant impacts are economic, particularly those related to extended shutdown periods and repair costs. Safety consequences related to fire, explosion, and toxicity were evaluated as moderate, while environmental impacts remained relatively limited but still require attention to avoid emissions resulting from prolonged operation. The results of the analysis confirmed that the radiant tubes are exposed to several critical damage parameters that considerably increase the likelihood of failure. Based on these findings, the original inspection interval of 36 months cannot be maintained. The RBI study optimized the inspection interval to 1.41 years, with the next inspection scheduled for October 27, 2024, to ensure the continued safety, integrity, and reliability of the heater by focusing on critical degradation risks such as thermal fatigue, creep, and brittle fracture. The proposed inspection program includes a 100% internal visual inspection of the radiant tubes to detect early signs of deterioration and enable proactive corrective actions. Ultrasonic Thickness Scanning (UTS) will provide accurate wall thickness measurements in areas susceptible to fatigue and creep, allowing effective monitoring of material loss over time. Positive Material Identification (PMI) will be carried out in critical zones to verify material composition, while Magnetic Particle Testing (MT) and Penetrant Testing (PT) on attachment welds will help identify surface defects that may compromise weld integrity. Metallographic examination on 10% of welds located at high-risk areas will be performed to evaluate microstructural stability and identify potential failure zones. Furthermore, hardness testing in overheating-prone regions will provide valuable information regarding the mechanical properties and long-term performance of the material under elevated temperatures. Dimensional inspections of hangers and supports will also be conducted to verify structural alignment and detect any bowing or sagging conditions. In addition, the external inspection program will include 100% visual examination supported by ultrasonic gauging of headers and infrared thermography to identify thermal abnormalities and evaluate the overall condition of the unit. Collectively, these inspection and monitoring techniques establish a reliable and data-driven framework for proactive maintenance, thereby enhancing operational safety and reliability based on the outcomes of the RBI study. Following the completion of the planned inspections, the RBI assessment should be reviewed and updated periodically to ensure the continuous integrity and safe operation of the heater throughout its remaining service life.

REFERENCES

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

[2] 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

[3] Rausand, M. (2011). Risk Assessment: Theory, Methods, and Applications, John Wiley & Sons.

[4] Khakzad, N., Khan, F., & Amyotte, P. (2013). Dynamic safety analysis of process systems by mapping bow-tie into Bayesian network. Process Safety and Environmental Protection, 91(1–2), 46–53. https://doi.org/10.1016/j.psep.2012.01.005

[5] 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.

[6] 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.

[7] 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

[8] Khan, F. I., & Haddara, M. M. (2003). Risk-based maintenance (RBM): a new approach for process plant maintenance. Journal of Loss Prevention in the Process Industries, 16(6), 535–544. https://doi.org/10.1016/j.jlp.2003.08.001

[9] 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

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

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

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

[13] 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.

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

[15] 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.

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

[17] American Petroleum Institute. (2014). API Standard 510: Pressure vessel inspection, Code: In-service Inspection, Rating, Repair, and Alteration (10thed., 71 pages). API Publishing Services.

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

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

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

[21] 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

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

[23] 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).