ANALYSIS OF THE ESTIMATED REMAINING SERVICE LIFE OF GAS RECTIFICATION COLUMNS

by

Marko S. JARIĆ, Sanja Z. PETRONIĆ*, Nikola J. BUDIMIR, Katarina G. ČOLIĆ, and Lazar D. JEREMIĆ

Innovation Centre of the Faculty of Mechanical Engineering in Belgrade, University of Belgrade, Belgrade, Serbia

Original scientific paper
https://doi.org/10.2298/TSCI201214083J

Gas rectification columns are process apparatuses which are very important part of each onshore plant. Sudden failure of these types of columns causes huge daily losses, while fluid leakage can be very dangerous for the people and hazardous for the environment. For that reason, a regular and correct examination of the column is of great importance for the continual process of leading. Together with the detailed examination of the column, a risk-based inspection was applied to maximize savings, both material, time, and costs. The expected remaining service life of rectification columns was also analyzed, while the corrosion rates were calculated according to the various international standards. The minimum required column wall thickness was calculated according to the most commonly used international standard and the obtained difference was analyzed. Detailed analysis of the total risks of the column due to potential failure is presented.

Key words: *gas rectification columns, corrosion rate, remaining life, thickness, risk-based inspection*

Introduction

Columns (tower) are process apparatus in which the process of enrichment of gas or liquid, depletion of gas or liquid, or fractionation of liquid takes place. The tower can be made in different varieties and sizes but common for all columns is that working mediums of different temperatures are coming in direct contact and that between them are an occurring process of heat and mass transfer. The molecules are passing from an area of higher concentration in an area of lower concentration due to the difference in concentrations, and this manner of transfer of is calling mass transfer. Usually, mass transfer is occurring from a liquid to a gas or from a gas to a liquid. In case when together with the mass transfer process heat transfer process is also occurring, these processes are often calling simultaneous transport phenomena. For the needs of increasing contact surface and to facilitate mass/heat transfer between the fluids in the column, it is necessary to install different types of trays and packing.

Raw natural gas is a naturally occurring mixture of hydrocarbon and non-hydrocarbon constituents that cannot be directly delivered to the end-users before removing undesirable components. Those undesirable components such as CO_2, H_2S, N_2, water, *etc.* can cause health issues, corrosion of process units, and poorer calorific values [1]. Therefore, raw gas should be first treated to reach the minimum quality demanded by pipe-line transmission and distribution companies.

* Corresponding author, e-mail: sanjapetronic@yahoo.com

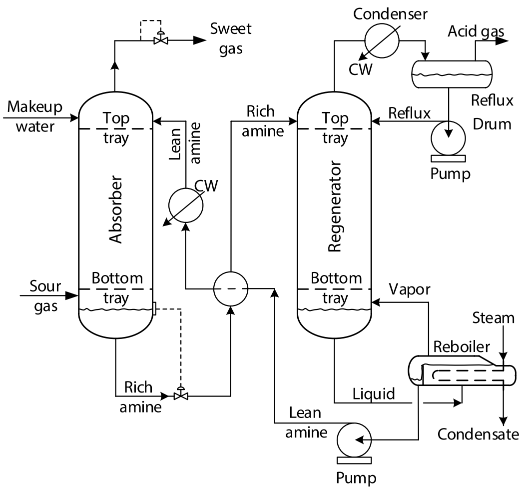

Figure 1. Typical process flow diagram of the amine unit for acid gas removal

To prevent corrosive damage to equipment and pipe-lines, gases such as CO_2 and H_2S that form acids when reacting with water must be removed. The main removal process can be based on several principles (absorption, adsorption, cryogenic, membrane*, etc.*) but the amine absorption process is the most commonly used for acid gas removal. A typical amine gas treating unit, fig. 1, consists of a gas absorber, amine regenerator, and additional equipment (heat exchangers, reboilers, pumps, pipe-lines*, etc.*) [2-4]. Almost all elements of an amine unit can be susceptible to the specific damage mechanisms known as amine corrosion and it is most commonly manifested like a general or localized corrosion that occurs principally on carbon steels or low alloy steels. This type of corrosion is not caused by amine itself, but due to dissolved acid gases CO_2 and H_2S, amine degradation products, heat stable amine salts, and other contaminants.

The regenerator reboiler and the regenerator are areas where the temperature and turbulences of the amine stream are the highest and can cause significant corrosion problems. The rich amine side of the lean/rich exchangers, hot lean amine piping, hot reach amine piping, the amine solution pumps, and the reclaimers are also areas where corrosion problems occur. Besides, faulty design, poor operating practices (higher temperatures, velocities*, etc.*) can have a significant impact on damaging mechanisms, remaining life, and reliability of equipment [5].

Corrosion is the degradation that causes loss of function of a material due to the influence of the working substance or the environment. Effects on the country's economy due to corrosion problems are huge, and financial losses due to corrosion cannot be reversed but can be minimized by controlling the corrosion management system. The model of oil and gas pipeline failure based on barrier theory shows that corrosion represents 19% of accident factors [6].

Offshore safety depends on the adopted management criteria, which affect the entire service life of the plant, including design and construction and production activities [7]. In certain circumstances, the law requires companies to make risk information available at industrial sites [8]. At the international level, the development trend of equipment inspection is risk-based inspection (RBI) – American Petroleum Institute (API), 2000. The optimal frequency of inspection is determined by the risk exposure, which can be used to avoid unacceptable risks of insufficient inspection of some cases or excessive inspection of most cases. The main goal of RBI is to make the most optimal use of limited resources for significant risks. In many practical cases, usually only 20% of the equipment represents 80% of the total risk [9]. The risk-based API methodology (RBI API) is used in the refinery and petrochemical industries to manage the overall risk of the plant and represents the process of developing an inspection scheme. This method combines the assessment of the probability of failure (POF) due to damage to the assessment of the consequences of that failure.

In most processing plants, a certain percentage of equipment poses a high risk, while another part of the equipment carries a low risk. Risk analysis of inspections also concentrates costs on high risk equipment, while much smaller funds are allocated for low risk equipment.

In this way, a balance is achieved between cost, time and safety of people and the environment. The API 581 [10] provides quantitative RBI methods for establishing an inspection program and the importance of applying the RBI method to gas rectification columns will be presented in this paper. It is firstly needed to analyze risk factors in order to effectively integrate risk evaluation, benefit evaluation and facilitate investment decision making [11]. In this paper, the inspection of gas rectification columns is presented. The corrosion rates were calculated and discussed according to different standards. A very important aspect of any pressure equipment is remaining life [12-14]. Remaining life estimation is the act of measuring and estimating the remaining lifespan of an appliance, for example, a pressure vessel in oil and gas purification units. If the remaining life of the equipment or component can be known or estimated, the field engineer can perform the necessary maintenance and be able to plan the replacement of the piece of equipment [15]. In this paper, the remaining life and RBI inspection of gas columns rectification are calculated and discussed, pointing to the importance of the safety and economy of the plant.

Technical data

The gas rectification columns, presented in fig. 2, operate at a max temperature of 100 °C and a pressure, P_s, of 7.9 MPa and contains a raw gas and 30 wt.% diethyl amine.

The mechanical design basis of the gas rectification columns is:

- fabrication date 2003,
- design Pressure 7.9 MPa,
- design temperature 100 °C,
- weld joint efficiency 0.85,
- material of construction ASTM SA 516-70,
- tensile strength 482.63 MPa,
- yield strength at 20 °C 262 MPa,
- yield strength at 100 °C 239 MPa,
- designed thickness 82.4 mm,
- corrosion allowance 6 mm,
- outside diameter (OD) 3064 mm,
- inside diameter (ID) 2900 mm, and
- length 31160 mm.

Figure 2. Gas rectification columns

Operating conditions allow aqueous conditions to occur with a localized measured corrosion rate of 0.33 mm per year.

Besides, stress corrosion cracking caused by wet H_2S is possible with low susceptibility.

Inspection history from 2018 (B effectiveness level) revealed some localized corrosion and a measured thickness of 79.2 mm.

No history of inspection for wet H_2S cracking has been conducted on these columns.

The process fluid has the following properties:

- the C_6-C_8,
- density, 1050 kg/m^3,
- the NBP 99 °C, and

– auto-ignition temperature AIT 223 °C.

The plant information for inspection planning is:

– inspection planning,
– the RBI Date 2018-05-01, and
– plan date May 1, 2020.

Inspection of gas rectification columns with the determination of corrosion rate and remaining life

Columns represent apparatus whose failure, as a rule, leads to downtime of the upstream plant and sometimes an appropriate downstream plant (oil refinery) [16]. Taking into consideration this fact, one of the main tasks in the design and construction of upstream oil and gas plants in deserts and hard-to-reach areas is to avoid potential column failures and ensure the continuity of the production process for as long as possible. The gas rectification columns were shut down for inspection in shut down 2018. The inspection covers the conditions of the external metal surfaces, protective coatings, and all other external attachments. Ladders, platforms and walkways, generally, foundation, steel support gas rectification columns were in good condition. All the anchor bolts and attached nozzles were found in good condition, good tighten, no rust and distortion observed. There was no evidence of cracking or distortion around the area of nozzles. The protective coatings of gas rectification columns were in satisfactory condition.

During the previous examination of this gas rectification column, RBI analysis has not been conducted. Also in the available literature sources, it has not been found column (tower) on which RBI analysis has been conducted, and with which this RBI analysis could be compared. Also here should be especially highlighted that only very similar gas rectificationwers can be compared (columns that have: similar dimensions, the same operating fluids and similar working parameters) in sense of the same damage mechanisms which can appear inside of the column during the operating cycle, otherwise comparison of the columns has not any valid technical sense.

The accuracy of all measured values on the column has been obtained by using a properly used calibrated ultrasonic testing UT device (A-scan-which shows the response along the path of the sound beam for a given position of the probe) and attached probes calibrated on the appropriate step wedge. Also and person (possess UT-certificate level 2) which has been conducted measuring thicknesses was certified according to the ISO 9712.

The external metal surfaces were in satisfactory condition. No evidence of external corrosion.

The inspection covers the integrity of internal metal surfaces, seam weld, nozzle weld attachment and its internal components.

Generally, internal surfaces of gas rectification columns were in satisfactory condition. Corroded areas have been observed between trays 17 and 18. The maximal depth on the damaged area is 3 mm. Also, corrosion has been observed from the opposite side of the manhole H_3, with a maximal depth of 1.8 mm. Aforementioned corrosion of the internal surface belongs to the amine corrosion damage mechanism (API 571:2011).

The internal attachment welds of gas rectification columns were in satisfactory condition. They were uniformly corroded due to the work of the apparatus in an amine environment. Amine corrosion was observed on these weld joints. Slight general corrosion of depth 0.2 mm at the shell and vertical tray support was detected in the second manhole, while the first manhole presents very slight uniform corrosion. Insulation of gas rectification columns was also in good condition. All internal attachment weld components, seam welds and components were in satisfactory condition.

The designed thickness of the absorber was 82.0 mm, and wall thickness measured after years of service is presented in fig. 3 which shows a graphical representation of the thinning of a cylindric wall.

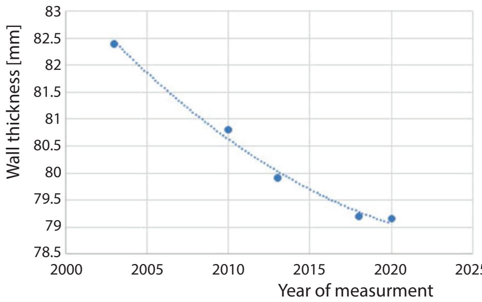

Figure 3. Graphical representation of wall thickness measured from 2003 to 2020

Wall thickness is measured in 2020 to validate the results obtained in this paper.

Thinning the cylindrical wall of columns follows an exponential distribution, noticeably slowing down in the last two years. This is in agreement that corrosion rate decreases after 20 years and at some point in time after 20 years, it becomes linear because the rate of metal loss after many years becomes equal to the rate of loss from the corrosion product layer [17]. It is expected that the corrosion rate will become linear after 20 years of service.

The corrosion rate is calculated according to ASME [18, 19] in two ways: long time corrosion rate and short time corrosion rate:

$$\text{Corrosion rate (LT)} = t_{\text{initial}} - t_{\text{actual}} \,/\text{time between } t_{\text{initial}} \text{ and } t_{\text{actual}} \text{ (years)} \tag{1}$$

$$\text{Corrosion rate (ST)} = (t_{\text{previous}} - \text{t}_{\text{actual}})/\text{time between } t_{\text{previous}} \text{ and } t_{\text{actual}} \text{ (years)} \tag{2}$$

Calculated corrosion rates are presented in tab. 1.

Table 1. Corrosion rates

Type of corrosion rate	mm per year	Time between the measured values [year]
C(LT)	0.19	17
C(LT)	0.213333	15
C(LT)	0.25	10
C(LT)	0.1625	8
C(ST)	0.271429	7
C(ST)	0.2	5
C(ST)	0.36	3
C(ST)	0.025	2

Analyzing tab. 1, it could be concluded that the short time corrosion rate is higher than the long time corrosion rate. For further calculation, the highest value of corrosion rate (0.36 mm per year) is taken as representative.

The corrosion rate has a decreasing tendency with increasing years in service.

The remaining life of the vessel (in years) shall be calculated [10]:

$$\text{Remaining life} = t_{\text{actual}} - t_{\text{required}} \,/\text{corrosion rate} \tag{3}$$

where t_{actual} [mm] is the actual thickness of a condition monitoring location (CML), measured during the most recent inspection and t_{required} [mm] – the required thickness at the same CML or component, as the tactual measurement. It is computed by the design formulas (*e.g.* pressure and structural) and does not include corrosion allowance or manufacturer's tolerances [10].

Replacing obtained results in eq. (1) remaining life for gas rectification columns is 15.72 years.

According to API 581 [10] (tab. 2, B.8.2) for following data: acid gas loading = = 0.15 mol/mol, t = 100 °C, velocity > 1.5 m/s, the corrosion rate is 0.38 mm per year, what is in line with obtained results.

According to ISO 9223 [20]: corrosion of metals and alloys. Corrosivity of atmospheres. Classification, determination and estimation (ISO, 2012) define corrosivity categories for the atmospheric environments by the first-year corrosion rate and according to fig. 3, corrosion rate in the first year is 0.29 mm per year and belongs to category CX – extreme corrosivity.

Calculating further according to ISO 9226 [21]: Corrosion of metals and alloys. Corrosivity of atmospheres. Guiding values for the corrosivity categories (CEN, 2012), the corrosion attack:

$$D\,(t) = r_{\mathrm{corr}} t^{b} \tag{4}$$

where t [years] is the exposure time, r_{corr} [μm·a^{-1}] – the corrosion rate experienced in the first year, and b – the metal-environment-specific time exponent, that depends on each metal and the particular atmospheric conditions (generally, $b < 1$):

$$r_{\mathrm{corr}} = 0.29 \text{ mm per year}$$

Long time corrosion attack, after 20 years, is calculated according to eq. (3):

$$D(t > 20) = r_{\mathrm{corr}}\,[20b + b20b^{-1}(t - 20)] \tag{5}$$

Coefficient b used in eqs. (3) and (4) is calculated (9224:2012):

$$b_a = 0.569 + \sum b_i w_i \tag{6}$$

where b_i is a multiplier for i^{th} alloying element and w_i is the mass fraction of the i^{th} alloying element.

The chemical composition of steel SA 516-70 is listed in tab. 2, and the values of a multiplier in tab. 3.

Table 2. Chemical composition of SA 516-70

Composition	C	Si	Mn	P	S	Al	Cr	Cu	Ni	Mo	Nb	Ti	V
Percentage [%]	0.10/ 0.22	0.6	1/ 1.7	0.03	0.03	0.02	0.3	0.3	0.3	0.08	0.01	0.03	0.02

Table 3. The alloying element multipliers [21]

Alloying element	C	P	S	Si	Ni	Cr	Cu
Values of multipliers	–0.084	–0.49	1.44	–0.163	–0.066	–0.124	–0.069

By replacing the values listed in tabs. 2 and 3 in eq. (6) the coefficient b for SA516-70:

$$b_a = 0.40352 \tag{7}$$

Figure 4 presents the predicted corrosion attack for 50 years calculated according to eqs. (3) and (4). The obtained results are combined in one diagram. The first-year corrosion rate is taken from fig. 3. According to fig. 4 after 17 years the corrosion attack is approximately 0.9 mm, almost half of the lost material for 17 years. After 50 years expected corrosion attack would be almost 1.7 mm which is not expected to seriously affect the pressure service or life.

The corroded surface of the manhole H_3 is presented in fig. 5(a). The maximal depth is 3 mm. Figure 5(b) presents the detail from fig. 5(a).

As per Plant Inspection Philosophy maximum interval is 2.5 years for pressure safety valve inspection which should be done by the Vendor or at a specialist repair workshop approved by the company according to [22, 23].

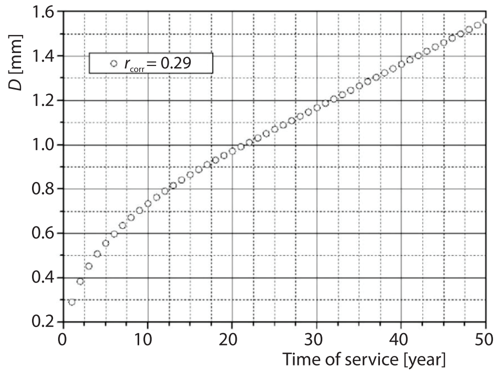

Figure 4. Corrosion attack for 50 years

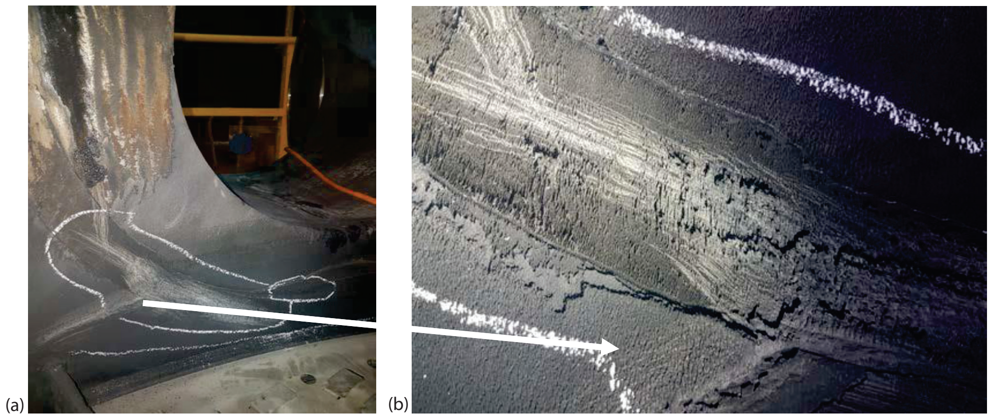

Figure 5 (a). Corroded surface of the manhole 3 (maximal depth is 3 mm) and (b) detail from fig. (a)

The RBI calculation

The RBI, proposed by the U.S. Petroleum Institute (API 580, 2016), aims to maintain the mechanical integrity of equipment items, minimizing loss of retention due to deterioration, providing mitigation or prevention measures that can be proposed to avoid plant damage and potential staff injury. The RBI API is used to identify critical cases within an institution, where necessary inspections provide the main benefit in reducing overall risk. The application of this methodology enables a significant reduction of maintenance costs and at the same time an increase in plant safety and reliability by limiting costs [24]. When observing the risk, possible consequences for the people, property, environment and reputation of the company should be considered [25].

Calculation of risk in API 581 [12] RBI involves the determination of a POF combined with the consequence of failure (COF) [10]:

$$R(t) = P(t)C(t) \tag{8}$$

The API 581RBI standard defines a failure as a leak or rupture of a pressure component, and as damage accumulates in that component during its in-service operation, the risk increases. If the risk tolerance is exceeded, effective inspection is necessary. The inspection does not reduce the risk but reduces the uncertainty for the condition of the component [10].

The POF is calculated [10]:

$$P_f(t) = g_{ff} D_f(t) F_{MS} \tag{9}$$

The risk for the presented gas rectification columns is calculated according to [10] and important results are summarized in tab. 4. The risk is calculated at the RBI date, and at plan date. The age at the RBI date is 15 years, and at plan date 18 years, while a POF at RBI date is $1.17 \cdot 10^{-3}$ and at plan date $1.6 \cdot 10^{-3}$.

Table 4. Calculation results summarized for gas absorber

	At RBI date	At plan date
Art	0.0627357	0.0751823
Inspection effectiveness category	B	B
Damage stage	1	1
Thinning factor	23	35
Cracking factor	19.66	24.3
Total damage factor	42.66	59.3
POF with inspection, failures, [year]	0.0011749	0.0016257
Final consequence area	946	946
FC_{md} – financial consequence of component damage to surrounding equipment on the unit	20951.03 €	20951.03€
FC_{affa} – financial consequence of damage	19787852.23 €	19787852.23 €
FC_{prod} – financial consequence of lost production on the unit	51100000 €	51100,000 €
FC_{inj} – financial consequence as a result of serious injury to personnel	2365000 €	2365000 €
The final financial consequence	73290250.93 €	73290250.93 €
Risk, [m^{2}year^{-1}]	86105.52 €	119146.95 €

The final consequence area is 946 m^2, and the total damage factor is 42.66 at RBI date, and 59.3 at plan date. Table 5 presents numerical values associated with POF and area-based COF categories taken from API 581 standard. In this paper, these values are taken as referent values for the iso-risk plot and risk matrix.

Table 5. Numerical values associated with POF and area-based COF categories (API 581)

Category	Probability category (1, 2)		Consequence category (3)	
	Probability range	Damage factor	Range category	Range [m^2]
1	$P_f(t) \leq 3.06 \cdot 10^{-5}$	$D_f \leq 1$	A	CA ≤ 9.29
2	$3.06 \cdot 10^{-5} < P_f(t) \leq 3.06 \cdot 10^{-4}$	$1 < D_f \leq 10$	B	9.29 < CA ≤ 92.9
3	$3.06 \cdot 10^{-4} < P_f(t) \leq 3.06 \cdot 10^{-3}$	$10 < D_f \leq 100$	C	92.9 < CA ≤ 929
4	$3.06 \cdot 10^{-3} < P_f(t) \leq 3.06 \cdot 10^{-2}$	$100 < D_f \leq 1000$	D	929 < CA ≤ 9290
5	$Pf(t) > 3.06 \cdot 10^{-2}$	$D_f > 1000$	E	CA > 9290

According to results presented in tab. 4 and categories presented in tab. 5, the gas rectification columns belong to category D-3 at RBI date – medium-high risk and D-3 at plan date – medium-high risk. The results are presented in the Iso-risk plot for the consequence area in fig. 6 and the risk matrix for the consequence area in fig. 8.

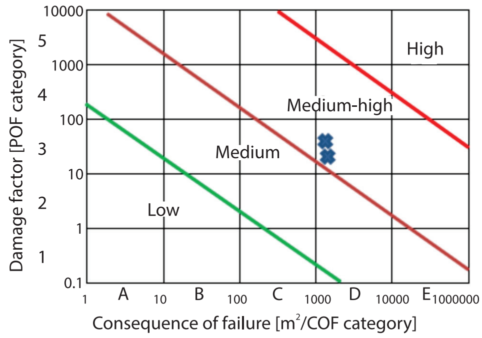

Figure 6. Iso-risk plot for the consequence area; the gas rectification columns belong to medium-high risk

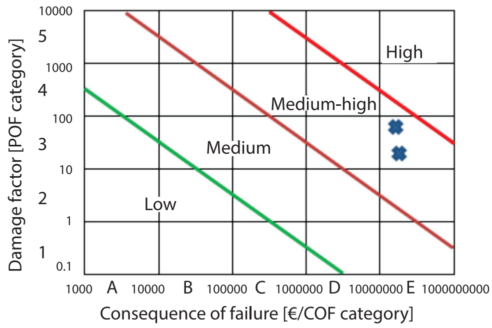

Figure 7. Iso-risk plot for financial consequence; the gas rectification columns belong to medium-high risk

Table 6 presents numerical values associated with POF and financial-based COF categories taken from API 581. According to tab. 6, the damage factor belongs to Category 3 and financial consequence (73290250.93 €) to range category E.

The risk category of gas rectification columns for financial consequences is E3 and belongs to medium-high risk. That is presented in the Iso-risk plot for financial consequences , fig. 7 and the risk matrix, fig. 8.

Figure 8 presents the balanced risk matrix for consequence area and financial consequence. The gas absorber belongs to medium-high risk.

Table 6. Numerical values associated with POF and financial-based COF categories [10]

Category	Damage factor	Range category	Consequence category range [$]
1	$D_f \leq 1$	A	FC ≤ 10000
2	$1 < D_f \leq 10$	B	10000 < FC ≤ 100000
3	$10 < D_f \leq 100$	C	100000 < FC ≤ 1000000
4	$100 < D_f \leq 1000$	D	1000000 < FC ≤ 10000000
5	$D_f > 1000$	E	FC > 10000000

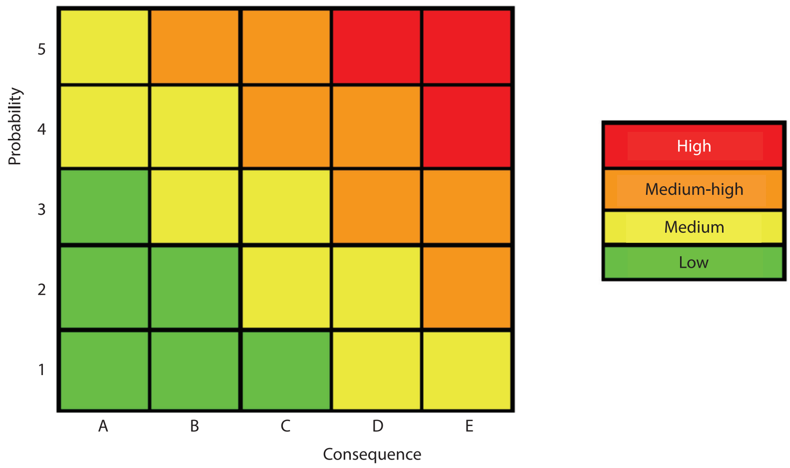

Figure 8. Balanced misk matrix for consequence area and financial consequence [5]

Conclusions

For security reasons, one of the models is the design of a plant with two parallel work units, which enable the leading of the production process (with the decreased capacity) even in the event of a column failure. However, it is necessary to perform a detailed economic analysis of the profitability of such investments, which as a rule depend on the number of surrounding oil/gas wells from which the plant is supplied with working fluids as well as their yield.

This paper presents the inspection of gas rectification columns, determination, and analysis of remaining service life, corrosion rate. The RBI inspection is applied and calculated in detail. From the presented the next could be concluded as follows.

- All of the essential sections/components of the presented rectification columns satisfy the API 510 and API 572 code requirements for maintenance inspection/examination hence, rectification columns are safe to operate until the next scheduled inspection.
- Corrosion rate is extremely high affecting the remaining life which is 18 years.
- Gas rectification columns belong to high medium risk, for both concequence area and financial concequence.

Acknowledgment

This research was financially supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia, under Contract numbers 451-03-68/2020-14/200105.

Nomenclature

b – metal-environment-specific time exponent, [–]
$C(t)$ – consequence of failure
$C(\mathrm{LT})$ – long time corrosion rate according to ASME, [mm per year]
$C(\mathrm{ST})$ – short time corrosion rate according to ASME, [mm per year]
$D(t)$ – corrosion attack, [mm]
$D_f(t)$ – damage factor, [–]
F_{MS} – management systems factor, [–]
g_{ff} – generic failure frequency, [–]
$P(t)$ – probability of failure, [–]
r_{corr} – corrosion rate according to EN 9226, [mm per year]
$R(t)$ – risk of failure according to API 581, [–]
t_{initial} – initial wall thickness, [mm]
t_{actual} – actual wall thickness, [mm]
t_{previous} – previous wall thickness, [mm]
w_i – mass fraction of the ith alloying element, [%]

References

[1] Mokhatab, S. S., *et al.*, *Handbook of Natural Gas Transmission and Processing – Principles and Practices*, 4th ed, Elsevier, Cambridge, Mass., USA, 2019
[2] Devold, H., *Oil and Gas Production Handbook – An Introduction Oil and Gas Production, Transport, Refining and Petrochemical Industry*, 3rd ed, ABB Industries, Oslo, Norway, 2013
[3] Jarić, M. S., *et al.*, Total Costs of Shell and Tube Heat Exchangers with Concentric Helical Tube Coils, *Thermal Science*, *23* (2019), 6A, pp. 3661-3673
[4] Budimir, N. J., *et al.*, Rectified Ethanol Production Cost Analysis 282, *Thermal Science*, *15* (2011), 2, pp. 281-292 [8]
[5] ***, API PR 571, Damage Mechanisms Affecting Fixed Equipment in the Refining Industry, 3rd ed, American Petroleum Institute, 2020
[6] Wang, X., Duan, Q., Improved AHP-TOPSIS Model for the Comprehensive Risk Evaluation of Oil and Gas Pipe-Lines, *Petroleum Science*, *16* (2019), Sept., pp. 1479-1492
[7] Bertolini, M., *et al.*, Development of Risk-Based Inspection and Maintenance Procedures for an Oil Refinery, *Journal of Loss Prevention in the Process Industries*, *22* (2009), 2, pp. 244-253
[8] Kamsu-Foguem, B., Information Structuring and Risk-Based Inspection for the Marineoil Pipe-Lines, *Applied Ocean Research*, *56* (2016), Mar., pp. 132-142

[9] Chang, M. G., *et al*., Application of Risk Based Inspection in Refinery and Processing Piping, *Journal of Loss Prevention in the Process Industries*, *18* (2005), 4-6, pp. 397-402
[10] ***, API 581, Risk-Based Inspection Methodology, American Petroleum Institute, 2016
[11] Li, Z. X., *et al.*, Study of Evaluation Method for the Overseas Oil and Gas Investment Based on Risk Compensation, *Petroleum Science*, *17* (2020), pp. 858-871
[12] Martic, I., *et al*., Remaining Life Determination for Pressure Vessel in a Refinery, *Structural Integrity and Life*, *16* (2016), 1, pp. 49-52
[13] Ishizaki, Y., *et al*., Remaining Life Assessment of an External Pressure Vessel in Creep Range and Inspection Findings, *Proceedings*, ASME 2017 Pressure Vessels and Piping Conference, PVP2017, Waikoloa, Hi., USA, 2017
[14] Dedov, A., *et al*., Corrosion and Life Assessment of IntrexTM Superheater Tubes in a CFB Oil Shale Boiler, *Applied Thermal Engineering*, *101* (2016), May, pp. 468-478
[15] Jayanto, S. T., *et al*., Estimating Corrosion Rate and Remaining Life of a Pressure Vessel of H_2S Absorber, *AIP Conference Proceedings*, *2097* (2019), 1, 030007
[16] Majstorović, M., Repairment of the Main Column DA-2301 in FCC, *Structural Integrity and Life*, *1* (2001), 1, pp. 47-50
[17] ***, ISO 9224, Corrosion of Metals and Alloys, Corrosivity of Atmospheres, Guiding Values for the Corrosivity Categories, CEN, 2012
[18] ***, ASME SEC VIII, Division 1, 2019 ASME Boiler and Pressure Vessel Code 2019, The American Society of Mechanical Engineers, 2019
[19] ***, ASME SEC VIII, Division 2: Alternative Rules, 2017 ASME Boiler and Pressure Vessel Code 2017, The American Society of Mechanical Engineers, 2017
[20] ***, ISO 9223, Corrosion of Metals and Alloys, Corrosivity of Atmospheres, Classification, Determination and Estimation, CEN, 2012
[21] ***, ISO 9226, Corrosion of Metals and Alloys, Corrosivity of Atmospheres, Determination of Corrosion Rate of Standard Specimens for the Evaluation of Corrosivity, CEN, 2012
[22] ***, API 510, Pressure Vessel Inspector, American Petroleum Institute, 2020
[23] ***, API 572, Inspection of Pressure Vessels, American Petroleum Institute, 2020
[24] Vianello, C., *et a*l., A Risk-Based Tool to a Support the Inspection Management in Chemical Plants, *Journal of Loss Prevention in the Process Industries*, *41* (2016), May, pp. 154-168
[25] Kirin, S., *at al*., Risk Based Analysis of RHPP Penstock Structural Integrity, *Frattura ed Integrità Strutturale*, *14* (2020), 53, pp. 345-352

Paper submitted: December 14, 2020
Paper revised: January 26, 2021
Paper accepted: January 29, 2021