A quantitative risk-based approach for assessing optimal inspection intervals of a caustic soda recovery plant: a case study

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Abstract: Inspection and maintenance activities are necessary to ensure mechanical integrity and the efficient and safe operation of systems and equipment. The management of critical assets is crucial, and it should take into consideration the inspection and testing of the equipment using proper approaches and procedures. The Risk Based Inspection (RBI), proposed by the American Petroleum Institute (API), is currently the major practical standard for the management and scheduling of in-service/on-site inspection activities in the chemical industry. In this paper, the risk-based inspection (RBI) technique, based on API 581 standard, is introduced for determining optimal inspection intervals of a caustic soda recovery plant. Using inspection data based on active major damage such as corrosion and thinning both the probability and consequence of accident have been investigated as well as the annual cost of the inspection program. The novelties lie in performing this analysis on a caustic soda recovery plant due to limited literature on this specific application and the inclusion in the proposed approach of several damage mechanisms aiming at providing a more accurate analysis. Therewith, the corresponding scenarios and outcomes of potential failures are determined, and accordingly, appropriate inspection dates and maintenance routines are proposed by considering the assumption that risk remains acceptable between two planned intervals. This paper summarizes that, as a fundamental step in the risk analysis, the RBI can be considered as suitable maintenance guidance for assessing critical equipment affected by multiple damage mechanisms providing an effective approach for inspection programs that increases plant availability and reduces unplanned shutdowns.

Keywords: RBI, Caustic Soda, Sodium Hydroxide, Risk Analysis, Production plant

I. INTRODUCTION

During the last three decades, maintenance and inspection management practices have emerged as vital and crucial aspects in all technical and industrial domains, especially in safety-critical sectors when hazardous substances are involved, since they represent the most dreadful hazard (Pasman, 2015). In this context, failures, i.e., losses of such substances, may cause accidents with severe consequences for equipment, production, humans, and environment. Therefore, suitable and specific safety measures should be implemented to avoid or reduce such issues aiming at ensuring mechanical integrity and maintaining functional assets capability. To do this, maintenance and inspection activities planning represent the foundation for effective prevention through both proper detections of degradation phenomena and scheduling of mitigating measures (Peron et al., 2022). Particularly, inspection is widely used to reduce the frequency of unexpected failures in fixed equipment such as pipe systems, tanks, and pressure vessels that are generally exposed to degradation process due to corrosion, fatigue, and mechanical damage leading to potential accidents and shut-downs (Khan and Haddara, 2003). Thus, by performing inspection, these failure mechanisms can be identified, monitored, and controlled aiming at estimating the health condition of the asset and the time to failures around its critical status (Shin and Jun, 2015). Since inspection plays a vital role in developing effective preventive measures to diagnose and detect potential failures, during time, different tools have been proposed to aid decision-makers in implementing suitable inspection planning. Historically, traditional inspection intervals were assumed to be performed at fixed-interval over the whole life of the monitored asset, or more recently, they were scheduled based on the equipment's health condition, implementing condition-based maintenance (CBM) and reliability-centered maintenance (RCM) strategies. However, since asset utilization and maintenance resources may not be optimized by a fixed-based period, to date, a new paradigm of planning strategies has emerged with the introduction of the risk-based inspection (RBI) mostly applied in chemical, petrochemical, refinery, oil, and gas industries. This methodology proposed by the American Petroleum Institute (API), is currently the major practical standard for the management and scheduling of in-service/on-site inspection activities in the chemical industry (API, 2016a, 2016b). The RBI is a risk-based approach that allows to prioritize and plan inspection programs focusing on the equipment and the related damage mechanisms. This approach encompasses the contributory factors estimation of the involved damage mechanisms and the associated consequences in terms of criticality such as safety, asset damage, environmental damage, and production stoppage aiming at defining the criteria to prioritize the inspection tasks (Khan et. al., 2004; Khan et al., 2006). Thus, it provides valid support for decision-making process on the inspection type, frequency, and extent. The performed analysis may be quantitatively, qualitatively, or semi-quantitatively, based on available data sources, aim of the analysis, processes or facilities complexity, etc… Particularly, the risk target concept for inspection planning is introduced as an expected value while, the calculated risk level is expressed as time dependent and reliant on the inspection data (Shishesaz et al., 2013). The risk concept is defined as a combination of consequences of potential failures and the likelihood that these will happen (Khan and Haddara, 2003) aiming at designing a proper plan for periodic inspections. An additional attribute when assessing risk that may be included is detectability. Indeed, it ensures that potential or actual failures can be identified with enough time before harm occurrence ensuring a significant impact on risk reduction process. Furthermore, the adoption of the RBI approach allows companies to include several key factors in the decision-making processes, such as equipment reliability safety, health, the environment, and financial issues (Eskandari et al., 2020) providing a comprehensive view to assess the asset functionally and mechanical integrity and then optimize the related operating and maintenance time scheduling (Coble et al., 2013). Over the past two decades, various studies dealing with risk-based inspection have been presented from different perspectives. A brief review of some of the frequently cited quantitative approaches for industrial application is presented here. Vinod et al. (2014) applied the RBI approach to assessing the main factors affecting the release of H_2S in a process plant. Mohamed et al. (2018) depicted a practices maturity model to aid companies in the implementation of the RBI approach. Bathia et al. (2019) presented a dynamic RBI framework applied to a sulfuric acid pipeline by real-time assessment of risk indicators based on degradation mechanisms. Abubakirov et al. (2020) performed a dynamic Bayesian network (DBN) for optimization of inspection intervals through the estimation of internal and external corrosion damage. Dabagh et al. (2022) presented a multi-objective mathematical model for self-adaptive RBI planning. Especially in practical situations and case studies, the RBI methodology has been extensively investigated in scientific literature. Song et al. (2021) focused the analysis on critical piping systems operating at high energy, temperature, and pressure. Shishesaz et al. (2013) conducted an RBI analysis on pressure vessel components in two crude oil distillation units aiming at evaluating the optimal inspection intervals. Fujiyama et al. (2004) proposed an RBI approach applied to steam turbines in power stations, while Drożyner and Veith (2002) and Tan et al. (2011) to different components of oil and gas units. Shuai et al. (2012) and Perumal (2014) proposed a case study applying the RBI methodology to crude oil tanks and an oil and gas pipeline, respectively. Dou et al. (2017) analysed a case study based on leakage risk assessment of the direct coal liquefaction process. In this work, the RBI methodology is introduced to be applied in the leakage risk assessment of a caustic soda recovery plant (Sodium hydroxide, NaOH). Particularly, the analysis has been focused on optimizing the inspection intervals of the counter-flow heat exchanger calculated considering API 581 standard. The purpose is to define the scenarios and outcomes of potential failures through the inspection data based on active major damage such as corrosion and thinning aiming at designing appropriate inspection plans and maintenance routines. The remainder of this paper is organized as follows: Section 2 presents a brief introduction to the RBI methodology; Section 3 reports the implementation of different RBI steps involved in the API 581 standard applied to a case study, as well as the achieved results including the determination of corresponding inspection strategies. Finally, the conclusions are depicted in Section 4.

II. THE RBI METHODOLOGY

A. *Risk assessment method of the RBI*

The Risk-based inspection (RBI) is a methodology for estimating the optimum inspection plan and frequency by prioritizing inspection activities for critical equipment. The base resource document is the API 581 (API, 2016b). On this basis, the risk induced by a failure is defined as the product of the Probability of Failure (PoF) and the Consequence of Failure (CoF):

$$Risk = PoF \cdot CoF$$

where PoF is a time-dependent function that increases with the gradual damage in the component due to the different damage mechanisms occurring during time. The estimation of the Probability of Failure is obtained as the product of a generic failure frequency gff, the different damage factors $D_f(t)$ that indicates the evolution over time of the active damage mechanisms on the specific equipment, and a management systems factor F_{MS}, as reported in the following equation:

$$PoF = gff \cdot D_f(t)^{tot} \cdot F_{MS}$$

The CoF is the financial consequence due to that damage. The consequences can be calculated by considering two different approaches: area-based or financial-based. The former is calculated based on the involved process and equipment operating condition. The latter is assessed by multiplying the affected area by costs per unit area and then adding this to the cost of production downtime and environmental clean-up costs. Then, a risk matrix is used to define the level of risk determined based on probability PoF against consequence CoF. Finally, the achieved risk is the outcome to determine proper inspection planning.

III. RESULTS

A. *Caustic soda recovery unit*

A Risk-based inspection approach is adopted to assess the leakage risk of a critical component as part of a caustic soda recovery unit. The schematic of the plant as well as the process flow diagram is reported in Fig. 1.

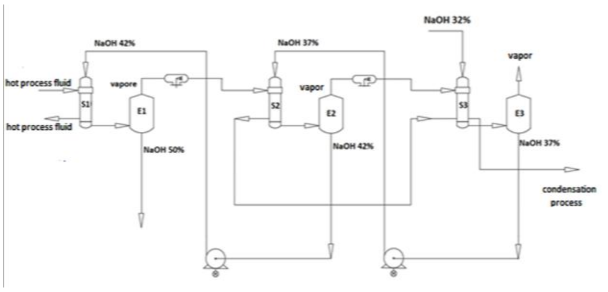


Fig. 1.Schematic of the caustic soda recovery plant.

It is based on a multi-stage evaporation plant driven by pressure and temperature gradient between the stages. In this process, the caustic soda at a low concentration is heated using steam to its boiling point in a heat exchanger. Then, when the lye, e.g. the caustic soda, reaches the evaporator, a significant amount of vapor is released as a result of water evaporation that eventually increases the soda concentration. This hot liquid is then flashed at lower pressure and the vapor so generated is used again, while the concentrated lye is removed from the last stage by a pump. In each stage of the analysed process, the concentration of caustic soda changes up to achieve a value equal to 50% (weight). Particularly, the analysis has been focused on the counter-flow heat exchanger S1 (see Fig. 1), which represents the most critical component since it operates at the highest temperature and NaOH concentration. The characteristics and operating parameters of heat exchanger S1 are shown in Table 1.

TABLE I
CHARACTERISTICS AND PROCESS OPERATING PARAMETERS

Variable	**Value**	**Variable**	**Value**
Temperature	154 °C	Density NaOH	1358 kg/m^3
Pressure	0.081 MPa	Flow rate NaOH	109233 kg/h
Diameter/Height S1	1.4/8.2 m	Concentration NaOH	42 %

In this scenario, the RBI approach provides suitable information about the damage mechanisms and related failure modes aiming at determining effective inspection and maintenance activities. Thus, the following steps are involved in applying the RBI approach:

- Data collection and equipment screening;
- Estimation of the failure consequences;
- Estimation of the failure probability;
- Risk determination;
- Inspection planning assessment.

B. *Data collection and equipment screening*

In this step, the critical components are identified and inspected, thus the basic parameters are determined, such as geometry and material, as well as the potential presence of welds is verified. Subsequently, the data related to the operating condition such as the chemical-physical and thermodynamic properties of the fluid are determined. Finally, both historical data and the manufacturer's maintenance guidelines may be used to determine additional aspects and inputs of the analysed components. The main purpose is to assess actual health condition of the equipment in terms of damage through non-destructive testing aiming at detecting potential weaknesses. Therefore, wall-thickness measurement is carried out by the implementation of specific ultra-sonic inspection, liquid penetrant, and magnetoscopic inspection are used to detect surface-breaking defects, and finally, radiography and ultrasonic testing to find evidence of cracks or other hidden internal flaws. The evaluation of the involved damage factors is essential to account for the damage mechanisms that affect the equipment. In the design of caustic soda recovery plants, laboratory tests, as well as operating experience over many years, have demonstrated that nickel and nickel alloys are the preferred materials for handling caustic solutions (Rebak, 2006). Indeed, they can be used for practically a huge range of concentrations and temperatures. However, these materials may generally be affected by stress corrosion cracking (SCC), which is a damage mechanism based on crack propagation resulting from the combined interaction of tensile stress and corrosive environment. Its occurrence in severe process environments, such as the caustic soda recovery plant, should not be ignored since SCC may result in the catastrophic failure of the equipment. This potential event may require greater attention thus, it is essential to manage the overall risk of caustic soda recovery process by focusing inspection efforts on the equipment with higher risk. Therefore, since SCC is also dependent on operating conditions, especially the corrosion rate increases with increasing temperature and concentration of the caustic soda, the choice to focus the RBI approach on the heat exchanger S1 was consistent with its critical issues. Concerning this equipment, the SCC turns out to be the predominant degradation mechanism leading to crack propagation, perforation, and external leakage and, consequently, severe damage to the unit safety. However, the corrosiveness of hazardous substances used also aggravates the thinning failure and leakage risk.

C. *Estimation of COF*

For acidic and/or caustic substances, API 581 recommends using water as a representative fluid to determine the maximum impacted area of consequences resulting from leakage. It is performed for both the equipment damage and the personnel injury consequence areas. This area is defined as the semi-circular area around the component where the released substance may be present in the form of rain and/or nebulised and therefore represents the area where personnel is subject to danger. In this specific case, the resulting consequence area for non-flammable releases of acid and caustic is determined through the following relationship for each hole:

$$CA_{inj,n}^{cont} = 0.2 \cdot a \cdot rate_n{}^{b}$$

This represents the personnel injury consequence area for continuous releases, this means that the substance flows stably at a certain rate, while parameters a and b are pressure-dependent constants associated with release duration. The parameter $rate_n$ represents the adjusted discharge rate associated with hole sizes. It is dependent on the theoretical release flow rate $flow\ rate_n$ and the adjustment factor $fact^{ID}$ that represents a reducing factor due to the presence of unit detection and isolations. In this case, its value is equal to zero.

The two expressions are reported as follows:

$$rate_n = flow\ rate_n \cdot (1 - fact^{ID})$$

$$flow\ rate_n = \frac{Cd \cdot kv_i \cdot \rho \cdot A_i}{C_1} \cdot \sqrt{\frac{2 \cdot g_c \cdot P}{\rho}}$$

Where, C_d is the discharge coefficient, k_{vi} is the viscosity correction factor, ρ is the density of caustic soda, C_1 is a conversion parameter, A_i is the hole area associated with the release hole size, g_c is the gravitational constant, and P is the pressure.

According to API 581 a set of diameters for the size of each release hole has been selected and reported in Table 2 to determine the potential range of consequences in the risk estimation. Then, the total consequence area CA_{tot} is estimated by considering the failure frequency for each hole size gff_n (see Table 2):

$$CA_{tot} = \frac{\sum_1^4 gff_n \cdot CA_n}{gff_{tot}} = 49.92\ m^2$$

Where, gff_{tot} is the failure frequency sum of individual release hole size.

TABLE II

HOLE SIZE AND AREA FOR THE RELEASE FLOW RATE ESTIMATION

D (m/inch)	**Ai (m^2)**	**rate$_n$ (kg/s)**	**gff$_i$**
Small: 0.0064 (0.25”)	$3.22\ 10^{-5}$	0.002	$8.0\ 10^{-6}$
Medium: 0.025 (1”)	0.0005	0.0038	$2.0\ 10^{-6}$
Large: 0.102 (4”)	0.0082	0.0634	$2.0\ 10^{-6}$
Rupture: 0.406 (16”)	0.1295	1.0041	$6.0\ 10^{-7}$

Concerning the financial-based CoF, the following factors should be estimated (the financial consequence of environmental clean-up is neglected in this analysis):

- Cost of equipment repair and replacement, FC_{cmd}

$$FC_{cmd} = \left(\frac{\sum_1^4 gff_n \cdot holecost_n}{gff_{tot}}\right) \cdot matcost$$

where, $holecost_n$ and $matcost$ are the equipment repair cost and material cost factor, respectively.

- Cost of damage to surrounding equipment in the affected area, FC_{affa}

On the basis of API 581, this factor is equal to zero since caustic soda is considered a non-toxic and non-flammable substance.

- Cost associated with lost production on the unit, FC_{prod}

$$FC_{prod} = \left(outage_{cmd} + outage_{affa}\right) \cdot prodcost = outage_n \cdot prodcost$$

where, $outage_{cmd}$ and $outage_{affa}$ are estimated downtimes due to repairing (i) the damage of a specific equipment and (ii) the surrounding equipment in the affected area, respectively, while $prodcost$ is the cost of lost production. In this case, according to the substance used, $outage_{affa}$ is equal to zero. Therefore, only the first factor has been determined using the formula:

$$outage_{cmd} = \left(\frac{\sum_1^4 gff_n \cdot outage_n}{gff_{tot}}\right) \cdot outage_{mult}$$

Here, $outage_n$ refers to the cost of repair for each hole and can be derived according to the values provided by API 581 (see Table 3), while $outage_{mult}$ is a multiplicative factor needed to increase the days of downtime. In the specific case of this calculation, it has been selected as equal to 1.

TABLE III

ESTIMATION OF OUTAGE$_N$ FOR EACH HOLE SIZE

D (m/inch)	**Outage$_n$**
Small: 0.0064 (0.25”)	2
Medium: 0.025 (1”)	3
Large: 0.102 (4”)	3
Rupture: 0.406 (16”)	10

- Cost associated with a serious injury to personnel, FC_{inj}

$$FC_{inj} = CA \cdot popdens \cdot injurycost$$

where, $popdens$ is the constant population density, while $injurycost$ is the cost per individual. This approach takes into consideration the above costs on both an equipment specific basis and an affected area basis. Thus, any leakage-based failure has costs associated with it, even when the release of the hazardous substance does not result in damage to other equipment in the unit or serious injury to personnel. This results in a more realistic consequences value due to a failure. Finally, the total financial consequences are achieved by using the following expression:

$$FC = FC_{cmd} + FC_{affa} + FC_{prod} + FC_{inj} + FC_{environ} = 211330\ \$$$

D. *Estimation of PoF*

The estimation of the Probability of Failure is obtained as the product of a generic failure frequency *gff*, the different damage factors $D_f(t)$, and a management systems factor F_{MS}, as reported in the following equation:

$$PoF = gff \cdot D_f(t)^{tot} \cdot F_{MS}$$

The generic failure frequency is determined by using:

$$gff = \sum_{n=1}^{4} gff_n$$

where, gff_n is referred to each release hole size (see Table 2). The damage factor $D_f(t)$ represents the factor that indicates the evolution over time of the active damage mechanisms on the specific equipment. Their estimation has been carried out on the basis of the procedures described in API 581 for the following damage mechanisms:

- Thinning D_f*_thin*
- Corrosion and cracking (external) D_f*_CC*
- Stress Corrosion Cracking (internal) D_f*_CUI-CLSCC*

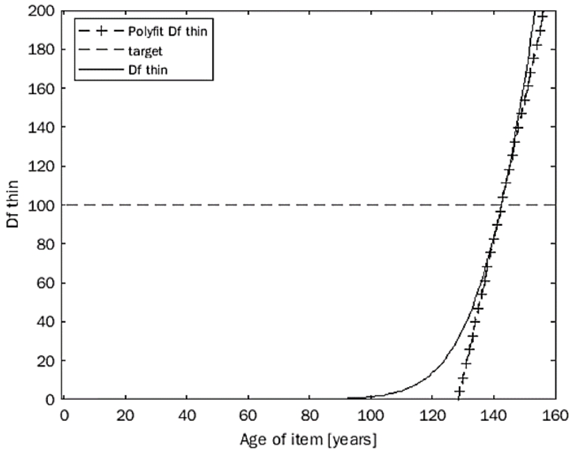


Fig. 2.Trend of the interpolation of the D_f*_thin* factor as a function of the age of the component.

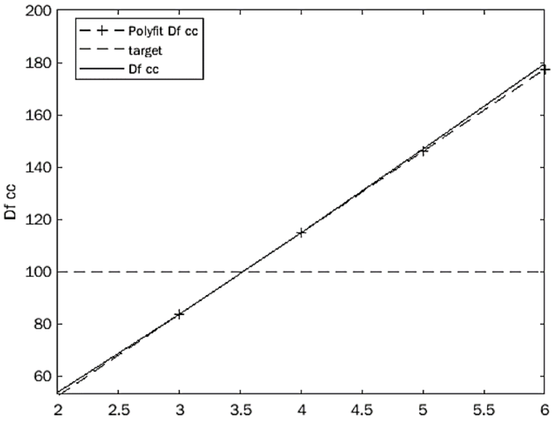


Fig. 3.Trend of the interpolation of the D_f*_CC* factor as a function of the age of the component.

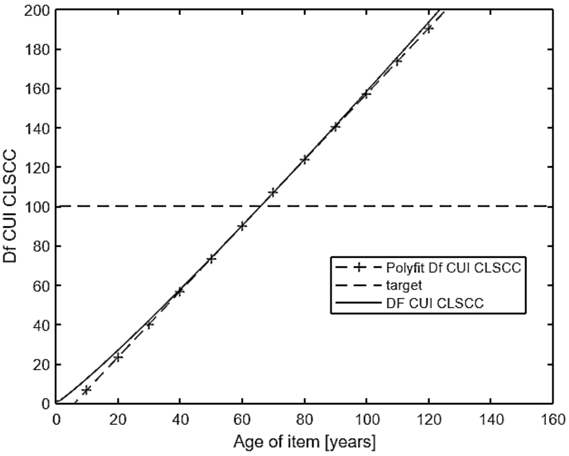


Fig. 4.Trend of the interpolation of the D_f*_CUI-CLSCC* factor as a function of the age of the component.

Each damage factor has been evaluated as a function of the age of the component considering the operative starting time point, and the year of the last inspection that took place, i.e, 2019. Thus, the trend of D_f*_thin*, D_f*_CC*, and D_f*_SCC* are reported in Figs. 2, 3, and 4, respectively. In addition, to determine an inspection date the assessment of a risk target parameter is necessary. This target value is a benchmark to trigger inspection planning that must not be exceeded. In the reported figures, the risk target based on damage factors is imposed as equal to 100 according to the literature (Siswantoro et al., 2019). To estimate the year in which the $D_f(t)$ is greater than or equal to the target value, a first-degree interpolation curve is used.

Since multiple active failure mechanisms affect the equipment, the estimation of the suitable inspection plan should be carried out by assessing the total damage factor in accordance with the following equation:

$$D_f^{tot} = \max\left(D_f^{thin}, D_f^{CUI\ CLSCC}\right) + D_f^{CC}$$

Therefore, the most critical damage factor is related to stress corrosion cracking caused by caustic soda since the equipment will reach the target value in 3.5 years. Thus, to mitigate its severe adverse effects, a maintenance inspection activity will have to be planned in mid-2022. This may be triggered through the suitable planning of testing practices such as magnetic-particle or liquid-penetrant inspection to effectively detect SCC. The factor management system FMS is a parameter that takes into consideration the probability that accumulating damage that results in leakage-based failures will be discovered in time. Thus, it accounts for the quality of the facility’s management system on the mechanical integrity of the plant equipment. On the basis of API 581, the value of FMS is imposed equal to 0.5.

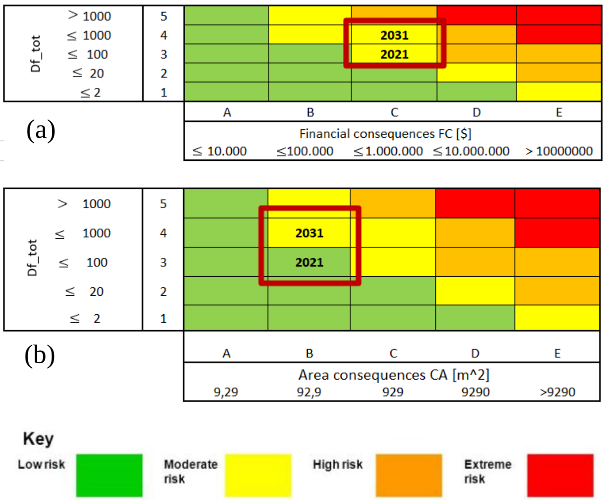
E. *Risk determination*

As said in Section 2, the estimation of the risk combines the product between the Probability (PoF) and the Consequences of the Failure (CoF). However, according to API 581, the equation of the risk can be rewritten depending on whether the CoF is expressed in terms of impact area or financial consequences.

$$R(t) = PoF \cdot CA$$

$$R(t) = PoF \cdot FC$$

Thus, according to the company's management, the analysis concerned the risk determination starting from the current year, i.e., 2021, and will cover a time horizon of 10 years. The achieved results are presented in Fig. 5 which shows the risk matrix based on impact area (5a) or in financial terms (5b), respectively. The risk matrix is an effective way of showing the distribution of risks throughout a plant since the consequence and probability categories are arranged such that the highest risk ranking is placed in the upper right-hand corner. This means that equipment placed towards the upper right-hand corner of the risk matrix will most likely take priority for inspection planning because of the highest risk. Numerical values associated with the consequence (from A to E) and probability (from 1 to 5) categories as well as the risk categories defined by colours are also shown in figure 5. The results show that the risk by 2031 will be acceptable for both risk categories. Therefore, this indicates that the predicted future risk at the planned date will not exceed the risk target thus, no inspection is recommended during the adopted plan period.



Df_tot		A	B	C	D	E
> 1000	5	🟩	🟨	🟧	🟥	🟥
≤ 1000	4	🟩	🟨	🟨 2031	🟧	🟥
≤ 100	3	🟩	🟩	🟨 2021	🟧	🟧
≤ 20	2	🟩	🟩	🟩	🟨	🟧
≤ 2	1	🟩	🟩	🟩	🟩	🟨
Financial consequences FC [$]		≤ 10.000	≤100.000	≤1.000.000	≤10.000.000	> 10000000

(a)

Df_tot		A	B	C	D	E
> 1000	5	🟩	🟨	🟧	🟥	🟥
≤ 1000	4	🟩	🟨 2031	🟨	🟧	🟥
≤ 100	3	🟩	🟩 2021	🟨	🟧	🟧
≤ 20	2	🟩	🟩	🟩	🟨	🟧
≤ 2	1	🟩	🟩	🟩	🟩	🟨
Area consequences CA [m^2]		9,29	92,9	929	9290	>9290

(b)

Key

Low risk	🟩
Moderate risk	🟨
High risk	🟧
Extreme risk	🟥

Fig. 5.Risk matrix for area-based risk (a) and Risk matrix for financial-based risk (b)

However, since the financial-based risk resides in the "moderate risk area", the future risk trend should be monitored.

F. *Inspection Planning Assessment*

According to the company's management strategy, the analysis to assess the forecast for a second inspection predicted in the future plan is carried out. To do this, the *Df(t)* due to the SCC mechanism expected in 2022 was reset since, on that date, the risk associated with this damage factor will be mitigated thanks to the first inspection. Concerning the other damage factors, their value has not been modified since their negative effects are expected over a very long-time horizon as shown in Figs. 2 and 4. Therefore, the implementation of two different types of inspections has been evaluated based on the amount of equipment surface area to be inspected. The A-type inspection involves the analysis of 100% of the surface area, while the B-type only involves 75% of the surface area resulting in less accurate but cheaper than the A-type. Moreover, an additional constraint has been defined. Indeed, the minimum time between two successive inspections is set equal to 5 years. Thus, on the basis of this consideration, the total damage *Df(t)_tot* has been determined for both types of inspections as reported in Fig. 6. In the beginning, the damage factor tends to increase up to 2022, which indicates the first inspection plan. At that time, maintenance activities will be performed to mitigate *Df(t)_tot* until a value equal to zero. Then, the damage factor referred to A-type and B-type inspections tends to increase reaching the target value in, approximately, 2035 and 2026 respectively. Hence, since B-type inspection is not compliant with the time-horizon constraint between two successive inspection plans, the A-type inspection can be considered the proper solution.

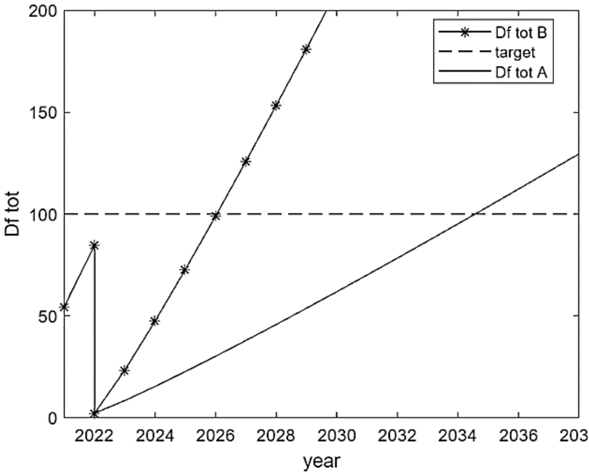


Fig. 6.Total damage factor trend

Finally, this result achieved through the RBI assessment may be used as a basis for the development of an overall inspection plan.

IV. CONCLUSIONS

In this work, the RBI approach is introduced to optimise the inspection planning of a caustic soda recovery plant on the basis of API 581 standard. Risk of failures of the critical equipment of the unit, i.e., the heat exchanger operating at the highest temperature and pressure, is assessed to identify and determine suitable intervals. The main damage mechanisms influencing the mechanical integrity and the efficient and safe operation of the equipment have been assessed. Particularly, stress corrosion cracking caused by caustic soda has been estimated as the predominant mechanism resulting in potential loss of containment. Thus, maintenance and inspection activity will be planned in the mid-2022 aiming at mitigating its severe effect. Estimation of the risk is carried out based on consequence and failure probability by considering both the maximum impacted area of consequences resulting from leakage and the related economic losses. The achieved results showed an impacted area equal to 49.92 m^2 and a financial-based consequence equal to 211330 \$. Based on the RBI analysis results, the risk matrix for area-based risk showed that the level of risk is expected to become medium over a time horizon of 10 years but still acceptable as regards safety issues. Concerning the financial-based risk, a medium level of risk is estimated to remain constant up to 2031. However, financial consequences should take priority in inspection planning to reduce the risk at the future plan date related to significative production stoppage costs. Moreover, additional analysis has been performed to design a second inspection program by considering 5 years as a time-horizon constraint between two successive inspections. Two different types of inspection practices are proposed based on the accuracy by which the component is examined. It emerged that a high degree of accuracy inspection is the most suitable solution ensuring the proper trade-off between maintenance and production stoppage costs. Finally, although the main goal was achieved, future research may aim to address some limitations of the proposed work. Indeed, the RBI methodology involves a systematic process for identifying all relevant degradation mechanisms and sites as a result of an asset-by-asset-based evaluation thus, the overall performance of the system or facility is not accounted for. Moreover, the damage mechanisms or deterioration rate of equipment are assessed by using lookup tables, assumptions, or generic data thus, they are affected by a degree of unavoidable uncertainty. Therefore, sensitive analysis or predictive machine learning algorithms may be implemented to extend the present study aiming at increasing safety and reducing the risk of an unexpected failure of the whole plant as well as the inspection and maintenance costs.

ACKNOWLEDGMENTS

The authors would like to acknowledge the SARAS Industrial Engineering & Services Group which provided the opportunity to conduct this research. The research would not have been possible without the extensive participation and collaboration of Ing. Cozza R. and the involved company employees.

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