Fitness for Service and Reliability of Materials for Manufacturing Components Intended for Demanding Service Conditions in the Petrochemical Industry

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ABSTRACT A methodology has been developed to quantitatively assess the suitability of use and fitness for service of candidate materials using a novel approach that includes multiple perspectives. As a case study, a carbon steel pipe has been selected for operation in the petrochemical sector. The materials studied were the following: American Petroleum Institute (API) A25, A, B, X42, X46, X52, X56, X60, X65 and X70, as well as American Society for Testing and Materials (ASTM) A-106 Gr. A, B and C. The developed model combines an analytical multiperspective approach with calculation methods based on recognized prestige standards. In the present study, the following material degradation mechanisms have been considered: generalized corrosion, fracture due to mechanical overload and high-temperature degradation. Several novel analysis elements have been incorporated into this new methodology, such as the concept of a suitability matrix and a fitness for service index. The approach allows construction of a decision diagram, and the best alternatives ordered according to the criteria and restrictions that have arisen from the analysis are obtained. Additionally, from the analysis, a series of service limitations are proposed based on the maximum hours of operation of a component. The materials ASTM A-106 Gr. A, API-A, ASTM A-106 Gr. B and API-B maintain the best balance between properties and show greater reliability versus the probability of failure due to the degradation mechanisms considered in this study. In addition, some use limitations such as critical exposure temperature have been determined for these materials (450 °C for ASTM A-106 Gr. A designation and 440 °C for API-B and ASTM A-106 Gr. B designations) to avoid the harmful effects of high-temperature operation on the material mechanical properties.

INDEX TERMS Fitness for service, high-temperature, performance, reliability, use limitations.

I. INTRODUCTION Reliability evaluation plays an important role in the design and development of any engineering system [1], [2]. Traditional material research relies on a considerable amount of trial experimental designs, which are time-consuming and costly [3]. In addition, the manufacture and operation of components in real service involves additional time-dependent factors that can influence material performance [4].

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numerous opportunities have arisen for different predictions of the behavior of equipment and materials that are currently in service using new techniques of predictive analysis and determination of reliability based on evaluation of data obtained by these new technologies.

Uncertainty stems from the assumption of a future event [7], and to identify and mitigate risks, it is crucial to have as much information as possible about the conditions and state of materials making up certain equipment in real time. Through the massive collection of information, not only is the optimization of existing technologies obtained, but it is also possible to develop innovative solutions that provide enhanced capabilities to existing industries [8].

The advancement of nondestructive testing techniques in recent years and their industrial applications provide reliable and objective information [9]. On the other hand, during the last decade, we have also seen the consolidation of several disruptive technologies, such as the Internet of Things (IoT) and scalable computing (big data), as well as the popularization of advanced data analysis (data science) and other techniques related to artificial intelligence [10].

For the analysis of this information, powerful tools capable of filtering are required to sort and analyze data to provide a methodology to support decision-making, such as those related to the selection of materials and/or behavior in service. In this regard, some recent works have described [11], [12] new systems able to recognize patterns and estimate the damage in various steels from metallographic data.

Recently, the worldwide industry has required a change of approach, moving from corrective maintenance through predictive maintenance and recently addressing prescriptive and prognosis approaches. Therefore, it is undoubtedly useful that new methods of analysis and evaluation of the suitability of materials from a combined approach allow the consideration of various mechanisms of the degradation or failure of materials, which are generalized as atmospheric corrosion, overload-induced fracture and high-temperature degradation.

Therefore, regarding these degradation and failure mechanisms, this paper aims to develop a methodology to quantitatively assess the suitability for service of standardized materials intended for use in applications in the petrochemical industry by employing a novel approach that includes multiple perspectives.

This new approach allows predicting behavior in service and therefore involves optimizing the selection of materials by establishing various limitations of use to identify optimal alternatives from a point of view based on reliability.

II. METHODOLOGY

Reliability is intended to give a measure of the probability of failure of a system [13]. To apply the probability method, considerable quantities of information or experimental data are required to construct precise probability distributions of the random inputs. Unfortunately, in many engineering applications, the experimental data are limited [14].

The reliability of a structural system may be estimated at two levels: the component level and the system level [15]. In this work, reliability is centered at the component level. Thus, a decision-making methodology involves considering that when the choice of material is limited to a list of predefined candidates, one difficulty is that the properties of different candidate materials (alternatives) may not indicate any obvious correlation in the given list [16]. Finally, the concept of fitness for service (FFS) pertains to the development of quantitative tools to evaluate the ability of existing equipment that experience one or more forms of defects and/or damage to remain in service [17].

The methodology developed in this paper for calculating reliability and fitness for service is a multiperspective approach that combines analysis with calculation methods based on recognized standards such as those issued by the American Petroleum Institute (API). The methodology for calculating the reliability and construction of the suitability matrix is shown in Fig. 1.

The presented methodology has three well-differentiated stages:

- Step 1: An evaluation using a methodology of stringency levels and a multiperspective approach is performed, with different material properties depending on the service conditions. This evaluation considers the following degradation mechanisms:
  1) Generalized corrosion and its influence
  2) Fracture due to overload
  3) Degradation of mechanical properties at high temperature

In this stage, efficiency is studied in the selection of materials (by using the methodology of stringency levels), and the probability of failure (POF) and reliability are determined in terms of the three considered degradation mechanisms.

Once the analysis considering each of the degradation mechanisms is complete, candidate materials that do not meet the required balance between properties are
TABLE 1. Operating conditions and dimensional parameters used in the calculations.

| Process variables | Value                        |
|-------------------|-----------------------------|
| Service temperature (°C) | 60-80 °C (liquid phase) up to 450 °C (steam system) |
| Fluid pressure, $P$ (MPa) | 30 |
| Fluid type         | Water                       |
| pH                | 5                           |

**External conditions**

| Condition | Value |
|-----------|-------|
| Ambient temperature (°C) | 30 |

**Dimensional characteristics of the tubing in the study**

| Parameter | Value |
|-----------|-------|
| Outer diameter, $d$ (m) | 0.2 |
| Thickness $t$ (m) | 0.025 |

**Membrane stresses calculated**

| Component | Stresses (MPa) |
|-----------|----------------|
| Longitudinal | 60 |
| Transversal | 120 |

TABLE 2. Chemical requirements of seamless pipe [18], [19].

| Designation of the material | Chemical composition (wt%) | Mechanical properties (MPa) |
|-----------------------------|-----------------------------|-----------------------------|
|                            | C   | Mn | P  | S  | Ti | $\sigma_y$ | $\sigma_U$ |
| API-A25 Cl II              | 0.21| 0.60| 0.08| 0.03| -  | 172        | 310        |
| API-A                       | 0.22| 0.90| 0.03| 0.03| -  | 207        | 331        |
| API-B                       | 0.28| 1.20| 0.03| 0.03| 0.04| 241        | 414        |
| API-X42                     | 0.28| 1.30| 0.03| 0.03| 0.04| 290        | 414        |
| API-X46                     | 0.28| 1.40| 0.03| 0.03| 0.04| 317        | 434        |
| API-X52                     | 0.28| 1.40| 0.03| 0.03| 0.04| 359        | 455        |
| API-X58                     | 0.28| 1.40| 0.03| 0.03| 0.04| 386        | 490        |
| API-X60                     | 0.28| 1.40| 0.03| 0.03| 0.04| 414        | 517        |
| API-X65                     | 0.28| 1.40| 0.03| 0.03| 0.06| 448        | 531        |
| API-X70                     | 0.28| 1.40| 0.03| 0.03| 0.06| 483        | 565        |
| ASTM A-106 Gr. A            | 0.25| 0.93| 0.035| 0.035| -  | 205        | 330        |
| ASTM A-106 Gr. B            | 0.30| 1.06| 0.035| 0.035| -  | 240        | 415        |
| ASTM A-106 Gr. C            | 0.35| 1.06| 0.035| 0.035| -  | 275        | 485        |

The materials selected for study as candidates for the manufacture of pipes intended for petrochemical industry plants are given in Table 2 along with their most important properties.

Regarding the chemical properties, as shown in Table 2, the carbon and manganese contents exhibit the most significant differences among the various materials; these elements greatly influence the mechanical properties, such as the yield stress ($\sigma_y$) and maximum tensile strength ($\sigma_U$). Thus, increasing the contents of carbon and manganese increases these parameters.

The following degradation mechanisms were selected for evaluation: general corrosion, fracture due to mechanical overload and high-temperature degradation (Table 3).

Based on the analysis of the considered degradation and failure mechanisms, Step 1 is developed according to the methodology outlined in Fig. 1 as follows.

### A. STEP 1. QUANTITATIVE EVALUATION OF PROPERTIES DEPENDING ON THE OPERATING CONDITIONS

Mechanical loading, geometric size, material properties, service conditions and environmental effects such as atmospheric corrosion are heterogeneous and time-variant. Thus, material properties may decay over time and can be presented as degradation mechanisms [22].

The evaluation of the properties of materials depending on the service conditions is a complex task that must be approached from multiple perspectives. Only this type of approach allows optimization of the combination of strength and ductility properties with a suitable profile calculation, which allows selection of an appropriate thickness that will provide component structural integrity and that is sufficient to
TABLE 4. Calculation of the ratio between the yield strength and maximum strength ($\sigma_Y/\sigma_U$), the maximum elongation at fracture ($e\%$), the stress to collapse ($\sigma_{col}$) and the safety factor ($SF$) for each of the materials according to the maximum applied membrane stress ($\sigma_t$).

| Grade   | $\sigma_Y/\sigma_U$ | $e\%$ | $\sigma_{col}$ (MPa) | $SF$ |
|---------|---------------------|-------|----------------------|------|
| A23Cl. II | 0.55                | 5.96  | 241.00               | 0.31 |
| A       | 0.63                | 5.11  | 269.00               | 0.37 |
| B       | 0.58                | 4.66  | 327.50               | 0.41 |
| X42     | 0.70                | 3.94  | 352.00               | 0.45 |
| X46     | 0.73                | 3.68  | 375.50               | 0.47 |
| X52     | 0.79                | 3.32  | 407.00               | 0.49 |
| X56     | 0.79                | 3.15  | 438.00               | 0.50 |
| X60     | 0.80                | 2.99  | 465.50               | 0.52 |
| X65     | 0.84                | 2.80  | 489.50               | 0.53 |
| X70     | 0.85                | 2.65  | 524.00               | 0.54 |
| A-106 Gr. A | 0.62             | 5.15  | 267.50               | 0.37 |
| A-106 Gr. B | 0.58             | 4.68  | 327.50               | 0.41 |
| A-106 Gr. C | 0.57             | 4.27  | 380.00               | 0.44 |

TABLE 5. Correspondence between quantitative and qualitative stringency scale levels.

| Stringency levels (Quantitative) | Qualitative correspondence with stringency level |
|----------------------------------|-----------------------------------------------|
| 1                                | Insufficient                                  |
| 2                                | Mild                                          |
| 3                                | Medium                                        |
| 4                                | Moderate                                      |
| 5                                | High (SL_max)                                 |

FIGURE 2. Balance among strength, ductility and minimum thickness.

palliate possible loss of corrosion thickness over an extended period of operation (Fig. 2).

In general, maximizing the mechanical strength involves reducing the ductility and vice versa. Therefore, it is necessary to find an optimal balance between mechanical strength and ductility. On the other hand, greater strength means reducing the resulting thickness. However, the thickness can also be increased by design considering external factors such as generalized corrosion. As is clearly well known, adequate strength with adequate ductility is essential to prevent brittle behavior [23].

Finding a balance among these three parameters (strength, ductility and minimum thickness) requires modeling to calculate the fitness for service index from the concepts of probability of failure ($POF$) and reliability ($R$) calculated in steps 2 and 3 of the methodology.

For evaluation of the mechanical strength depending on the mechanical stresses considered (Table 1), the ratio between the maximum tensile strength ($\sigma_U$) and yield strength ($\sigma_Y$) is calculated. Additionally, the maximum elongation at fracture ($e\%$) according to API SL (2018), the effort to collapse ($\sigma_{col}$) and the structural safety factor ($SF$) are calculated according to Eqs. 1 to 3, respectively.

\[ e = 1.944 \frac{\sigma_Y^{0.2}}{UTS^{0.9}} \]  
\[ \sigma = \frac{\sigma_Y + UTS}{2} \]  
\[ SF = \frac{\sigma_t}{\sigma_Y} \]

Table 4 shows the parameters calculated using Eqs. 1 to 3.

The chemical and mechanical properties indicated in Tables 2 and 4 are evaluated using an analysis by stringency levels divided into five scales, as indicated in Table 5.

The methodology for assigning $SL$ to different technological requirements has been developed depending on the type of requirement and considerations taken into account in its analysis [2], [24].

Eqs. 4 and 5 show the allocation methodology. $SL = 5.00$ is assigned to the requirement of greater value (Eq. 4):

\[ SL = 5.00 \max\{L_e(API, ASTM)\} \]  

Eq. 5 is used to calculate $SL$ of the remaining requirements for the other materials analyzed:

\[ SL = \frac{L_{e,min}}{L_e} SL_{Max} \]  

where $L_e$ corresponds to the value of the requirement to be analyzed from all {API, ASTM} and $L_{e,min}$ is the minimum value of the set.

The results of applying Eqs. 4 and 5 are presented in Table 6, wherein $SL_S$ refers to the average stringency levels obtained for the ratio ($\sigma_Y/\sigma_U$), collapse stress ($\sigma_{col}$) and structural safety factor ($SF$) and $SL_e$ defines the material ductility from the analysis of the condition of maximum elongation at fracture.

Fig. 3 shows the decrease in the requirement of elongation dependent on an increase in the strength characteristics, allowing the first constraint or boundary condition to be obtained to find a balance between the strength and ductility of the material.

Given the inverse relationship between the requirements of mechanical strength and ductility, to find a balance between
TABLE 6. Stringency levels for parameters $\sigma_U/\sigma_Y$, $\sigma_{col}$, and $SF$ and mean stringency levels of mechanical requirements ($SL_s$) and ductility requirements ($SL_e$).

| Grade designation | $SL_s(\sigma_U/\sigma_Y)$ | $SL_s(\sigma_{col})$ | $SL_s(SF)$ | $SL_s$ | $SL_e$ |
|-------------------|---------------------------|-----------------------|------------|--------|--------|
| A25               | 3.25                      | 2.30                  | 2.90       | 2.82   | 5.00   |
| A                 | 3.66                      | 2.57                  | 3.45       | 3.23   | 4.29   |
| B                 | 3.40                      | 3.13                  | 3.84       | 3.46   | 3.91   |
| X42               | 4.10                      | 3.36                  | 4.23       | 3.89   | 3.31   |
| X46               | 4.27                      | 3.58                  | 4.39       | 4.08   | 3.08   |
| X52               | 4.61                      | 3.88                  | 4.60       | 4.37   | 2.78   |
| X56               | 4.61                      | 4.18                  | 4.71       | 4.50   | 2.65   |
| X60               | 4.68                      | 4.44                  | 4.81       | 4.64   | 2.51   |
| X65               | 4.93                      | 4.67                  | 4.91       | 4.84   | 2.35   |
| X70               | 5.00                      | 5.00                  | 5.00       | 5.00   | 2.23   |
| A-106 Gr. A       | 3.63                      | 2.55                  | 3.43       | 3.20   | 4.32   |
| A-106 Gr. B       | 3.38                      | 3.13                  | 3.83       | 3.44   | 3.93   |
| A-106 Gr. C       | 3.32                      | 3.63                  | 4.12       | 3.69   | 3.58   |

After preliminary analysis of the properties of the materials, we proceed to study the influence of the material properties on the susceptibility to the degradation mechanisms considered in this work. According to the degradation mechanisms shown in Table 3, the properties of the materials are analyzed, starting with an evaluation of the corrosion resistance of each designation of standard material and its influence on the mechanical integrity of the component (a). We then study fracture due to overload (b) by cumulatively considering the loss of integrity due to corrosion. Finally, in subsection (c), an evaluation of susceptibility to high-temperature degradation is carried out.

1) EVALUATION OF RESISTANCE TO GENERAL CORROSION AND INFLUENCE ON THE MECHANICAL INTEGRITY

By using various standards, such as API RP 581 [25] and ISO 9223 [26], in this section, various estimates are carried out that allow later analysis for predictively evaluating the corrosion resistance of the materials under study and determining how this mechanism of degradation affects the mechanical integrity of the component.

Table 7 shows the estimated corrosion rate for the first year of exposure for API RP 581 [25]. The corrosion rate is calculated for the first year of exposure, where $R_{corr} = 3.81 \text{ mm/yr}$, interpolated to pH = 3 and 79 °C.

The corrosion rate estimated for the first year of exposure ($R_{corr}$) in Table 8 can be used to classify the sample into the category of C2 according to the defined scale in the ISO 9223 [26] standard.

For corrosivity category C2, we can estimate the thickness loss after the first year of exposure according to the estimates provided by the ISO 9224 [27] standard. In Table 9, the loss of thickness ($\Delta t$) is shown in $\mu$m depending on the exposure time $T_{exp}$.

The corrosion rate can be calculated according to the calculation method described in API 570 [28] using Eq. 6.

$$v_{corr} = \frac{\Delta t}{T_{exp}}$$

Thus, as estimated by API 581 [25] for corrosion from the first year (Table 7) and for durability of at least 100,000 h (11.41 years), a loss of thickness from corrosion of 4.66 mm
TABLE 7. Determination of the corrosion rate (mm/year) for the first year of exposure, depending on the PH and temperature (carbon steel), according to API RP 581 [25].

| pH  | Temperature (°C) | 38  | 52  | 79  | 93  |
|-----|-----------------|-----|-----|-----|-----|
| 0.5 | 25.37           | 25.37 | 25.37 | 25.37 | 25.37 |
| 0.8 | 22.86           | 25.37 | 25.37 | 25.37 | 25.37 |
| 1.25 | 10.16          | 25.37 | 25.37 | 25.37 | 25.37 |
| 1.75 | 5.08            | 17.78 | 25.37 | 25.37 | 25.37 |
| 2.25 | 2.54            | 7.62 | 10.16 | 14.22 | 7.11 |
| 2.75 | 1.52            | 3.30 | 5.08  | 7.11  | 5.08 |
| 3.25 | 1.02            | 1.78 | 2.54  | 3.56  | 2.54 |
| 3.75 | 0.76            | 1.27 | 2.29  | 3.18  | 1.78 |
| 4.25 | 0.51            | 1.02 | 1.78  | 2.54  | 1.78 |
| 4.75 | 0.25            | 0.76 | 1.27  | 1.78  | 0.76 |
| 5.25 | 0.18            | 0.51 | 0.76  | 1.02  | 0.51 |
| 5.75 | 0.10            | 0.38 | 0.51  | 0.76  | 0.38 |
| 6.25 | 0.08            | 0.25 | 0.38  | 0.51  | 0.25 |
| 6.80 | 0.05            | 0.13 | 0.18  | 0.25  | 0.13 |

TABLE 8. Corrosion rate after the first year of exposure ($R_{corr}$) in micrometers/year for different categories of corrosion according to ISO 9223 [26].

| Corrosivity category | Corrosion rate after the first year of exposure ($R_{corr}$) in μm/year |
|----------------------|---------------------------------------------------------------|
| C1                   | $R_{corr} \leq 1.3$                                           |
| C2                   | $1.3 < R_{corr} \leq 16$                                      |
| C3                   | $16 < R_{corr} \leq 50$                                       |
| C4                   | $50 < R_{corr} \leq 80$                                       |
| C5                   | $80 < R_{corr} \leq 200$                                      |
| CX                   | $200 < R_{corr} \leq 700$                                     |

TABLE 9. Maximum thickness loss due to corrosion from the first year of exposure [27].

| $t_{exp}$ (years) | $\Delta t$ (μm) |
|-------------------|-----------------|
| 1                 | 1.3             |
| 2                 | 1.9             |
| 5                 | 3.0             |
| 10                | 4.3             |
| 15                | 5.4             |
| 20                | 6.2             |

Thus, Eq. 9 can be used to determine the time that elapses from the start of plastic deformation ($T_{critic,collapse}$) as follows:

$$T_{critic,collapse} = \frac{t_{min} - t_{min no collapse}}{V_{corr} + R_{corr}}$$  \hspace{1cm} (9)

where $V_{corr}$ is the corrosion rate after the first year of exposure.

Table 10 shows the minimum thickness ($t_{min}$), the minimum thickness after corrosion loss ($t_{min corr}$), the thickness limit before collapse ($t_{min no collapse}$) and the maximum allowable membrane stress considering reduced thickness by corrosion ($\sigma_{t,corr}$).

Calculations made after loss of corrosion thickness allow the verification of how the resulting thickness (arising from the selection of the material) is essential to alleviate the possible effects of thickness loss due to widespread corrosion phenomena. This analysis allows assessment of whether it is worth employing a material with better mechanical resistance (at the expense of ductility) and increasing the excess thickness to avoid overstressing fracture after a possible loss of thickness due to corrosion.

For the focus on evaluating candidate materials, Fig. 6 shows a representation of the effect of the thickness loss on membrane stresses after 100,000 h of operation.

At 80 °C, for a calculated corroded thickness of 4.66 mm after 100,000 h of operation at pH = 3 (according to Table 1), materials API A25, A and B as well as materials ASTM A-106 Gr. A and ASTM Gr. B meet the requirement imposed on the maximum recommended value of elastic stress extrapolated at 80 °C for carbon steels according to API STD 530 ($\sigma_{Y,API 530,80}$). Eq. 10 shows the calculation of the probability...
of failure (POF) based on the maximum time in operation.

$$POF = \frac{1}{T_{max}}$$  \hspace{1cm} (10)

$T_{max}$ = maximum operating time (in hours) depending on the considered degradation mechanisms.

Thus, Table 11 shows the calculation of the probability of failure due to loss of thickness by corrosion and overload ($POF_{corr+overload}$) based on the critical time ($T_{critic\, collapse}$) that elapsed between the start of plastic deformation and breakage.

### 3) EVALUATION OF HIGH-TEMPERATURE STRENGTH

By extrapolating the data representing the relationship between the maximum stress before rupture ($\sigma_{U,\, max}$) as a function of temperature and the hours of operation foreseen by design ($T_{DL}$) given in API STD 530 [29], Fig. 7 illustrates that the maximum allowable stress ($\sigma_{U,\, max}$) decreases slightly faster above approximately 300 °C. Furthermore, we observe that the difference between the maximum allowable stresses ($\sigma_{U,\, max}$) for 100,000 h and 20,000 h (since they are the extremes of operation hours postulated by API STD 530) increases more rapidly above 400 °C, with a greater difference from 450-500 °C (as shown in Fig. 8). This representation was obtained by extrapolating data from API STD 530 [29] (including estimated life – $T_{DL}$ –, operating temperature – $T$ – and maximum allowable stress – $\sigma_{U,\, max}$).

Thus, it is possible to obtain the following constitutive equations, where Eqs. 11 to 14 relate the maximum allowable stress ($\sigma_{Y,\, max}$) according to API STD 530 depending on the temperature and estimated life:

$$\sigma_{Y,\, max} = 0.0027 T^2 - 3.1450 T + 919.29$$ \hspace{1cm} (11)

$$\sigma_{Y,\, max} = 0.0028 T^2 - 3.2354 T + 952.60$$ \hspace{1cm} (12)

$$\sigma_{Y,\, max} = 0.0028 T^2 - 3.3165 T + 981.54$$ \hspace{1cm} (13)

$$\sigma_{Y,\, max} = 0.0029 T^2 - 3.4547 T + 1031.60$$ \hspace{1cm} (14)

By focusing on the temperature range (temperature) where the mechanical properties are more strongly negatively affected (400-500 °C), Fig. 9 shows the maximum elastic...
stress ($\sigma_{Y \text{ max}}$) versus the estimated life ($T_{DL}$) depending on the operating temperature.

After the above analysis, an interpolation of values is performed to obtain the maximum elastic stress ($\sigma_{Y \text{ API 530}}$) allowed by API STD 530 [29] at 400-500 $^\circ$C (the temperature range in which the degradation is more accelerated). This analysis allows a comparison of the maximum stresses until rupture ($\sigma_{U \text{, max}}$) calculated for each material with $\sigma_{Y \text{ API 530}}$. Thus, the critical exposure temperature ($CET$) of each material can be determined.

In Table 12, several color codes are defined for use in the estimation matrix (Fig. 10) for the $CET$.

Table 13 shows the critical exposure temperature ($CET$), time in operation by design ($T_{DL}$) and probability of failure due to high-temperature degradation ($POF_T$).

**TABLE 13.** Critical exposure temperature ($CET$), time in operation by design at 450 $^\circ$C ($T_{DL}$) and probability of failure due to high-temperature degradation ($POF_T$).

| Material | CET  ($^\circ$C) | $T_{DL}$ (years) $\forall$ | $POF_T$ |
|----------|-----------------|---------------------------|----------|
| A        | 450             | 11.42                     | 0.09     |
| B        | 440             | 11.42                     | 0.15     |
| X42      | 430             | 2.28                      | 0.44     |
| X46      | 410             | 2.28                      | 0.44     |
| A-106 Gr. A | 450   | 11.42                     | 0.09     |
| A-106 Gr. B | 440   | 11.42                     | 0.15     |
| A-106 Gr. C | 420   | 2.28                      | 0.44     |

**TABLE 14.** Probability of failure associated with corrosion and overload ($POF_{corr+overload}$) and with high-temperature degradation ($POF_T$), along with the total probability ($POF_{total}$), reliability ($R$) and inverse of the mean stringency level of mechanical strength ($SL_s$) and ductility ($SL_e$).

| Material | $POF_{corr+overload}$ | $POF_T$ | $POF_{total}$ | Reliability ($R$) | $2 / SL_s + SL_e$ |
|----------|------------------------|----------|----------------|-------------------|-------------------|
| A        | 0.11                   | 0.09     | 0.20           | 0.80              | 0.27              |
| B        | 0.12                   | 0.15     | 0.27           | 0.73              | 0.27              |
| X42      | 0.18                   | 0.44     | 0.62           | 0.38              | 0.28              |
| X46      | 0.20                   | 0.44     | 0.64           | 0.36              | 0.28              |
| A-106 Gr. A | 0.11   | 0.09                     | 0.20     | 0.80              | 0.27              |
| A-106 Gr. B | 0.12   | 0.15                     | 0.27     | 0.73              | 0.27              |
| A-106 Gr. C | 0.14   | 0.44                     | 0.58     | 0.42              | 0.28              |

**B. STEP 2. CONSTRUCTION OF THE SUITABILITY MATRIX**

The reliability ($R$) in relation to the probability of failure ($POF$) of a component, equipment or system can be obtained from Eq. 15.

$$R = 1 - POF$$  \hspace{1cm} (15)$$

The focus of this article includes the novel element of the construction of a suitability matrix and the calculation of the fitness for service ($FFS_i$) index (Fig. 1) of the materials selected for study, which are shown later in this section. The concept of the suitability matrix for reliability is based on the quantification of the probability of failure, and the stringency of the technological requirements of the materials has an important influence on the service performance and service life of components manufactured with these materials. The probability of failure ($POF$) is calculated from Eq. 16.

$$POF = POF_{corr+overload} + POF_T$$  \hspace{1cm} (16)$$

Table 14 shows the probability of failure associated with corrosion and overload ($POF_{corr+overload}$) and with high-temperature degradation ($POF_T$), together with the total probability ($POF_{total}$), reliability ($R$) and inverse of the mean value ($2/SL_s + SL_e$) of the stringency levels of mechanical strength ($SL_s$) and ductility ($SL_e$).

The data obtained represent the probability of complete failure ($POF_{total}$) versus reliability ($R$) for each of the candidate materials (Fig. 11).

In addition, the data obtained allow us to build the suitability matrix (Fig. 12).

As shown in Fig. 12, the stringency levels of the requirements used along with $POF$ allow us to construct the suitability matrix that defines a relative position that can be used for the elaboration of tailored-made inspection and testing plans for predictive maintenance, allowing us to achieve a reliability target with minimum inspection and manufacturing costs [30], [31]. This analysis shows that the best alternatives are the materials ASTM A-106 Gr. A and API-A (high qualitative reliability) and ASTM A-106 Gr. B and API-B (mean qualitative reliability). Thus, materials API X42 and X46 are discarded at this stage. Low-carbon steels should exhibit ductile behavior [32] balanced with mechanical strength.
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III. RESULTS

The increasing complexity of engineering systems and their working environments enhances the importance of operational reliability throughout a lifecycle [33], [34]. Therefore, the best alternatives correspond to the standard materials API-A and B and ASTM A-106 Gr. A and Gr. B. A comparative study (Step 3) - in which the durability of the material is included - is performed. Moreover, some limitations in service that arise upon application of the methodology are described.

A. STEP 3. ANALYTICAL DETERMINATION OF THE FITNESS FOR SERVICE INDEX (FFSI) BASED ON DURABILITY AND ESTIMATION OF SERVICE LIMITATIONS

In step 3, the fitness for service index (FFSI) for candidate materials (Fig. 13) can be estimated using Eq. 17.

$$\text{FFSI} = SL \cdot R$$  \hspace{1cm} (17)

In view of the results, the highest values of FFSI are obtained for the materials API-A and ASTM A-106 Gr. A. On the other hand, Table 15 shows some restrictions arising from the analysis and defines exclusion parameters to be considered in the analysis.

After determining the candidate materials with better characteristics, upon application of the exclusion criteria, Table 16 defines a series of parameters (and an optimization strategy) for the order of selection of materials that meet the criteria shown in Table 15.

With the results shown in Tables 15 and 16, a selection diagram (Fig. 14) can be made using the main groups of materials.
criteria used in the analysis in this work (evaluation according to stringency levels, assessment of the susceptibility to loss of integrity due to corrosion, chemical composition restrictions and evaluation of the reliability and estimated life at high temperature). Thus, a selection is made based on the fulfillment of all criteria.

As Fig. 14 shows, the materials that meet the criteria for exclusion are the following: ASTM A-106 Gr. A and B and API-B. After obtaining the best alternatives, an assessment of the restrictions recommended by continuous use is performed. The maximum recommended continuous use temperature ($RuT$) is calculated (Fig. 15) by setting the maximum temperature ($CET$) for which $\sigma_{col} > \sigma_{U,\text{max}}$ according to API STD 530 [29]. Thus, a long-term reliability analysis based on corrosion and high-temperature performance is conducted [35].

To avoid degradation of the mechanical properties at high temperature and to obtain a higher durability for 100,000 h, the temperature should be limited to 260 °C for ASTM A-106 Gr. A and 230 °C for API-B and ASTM A-106 Gr. B.

Finally, Table 17 summarizes the order of selection of materials with use limitations depending on the temperature and considering the effects of corrosion damage and possible over stress.

| Order of Selection | Materials | Limitations of use |
|-------------------|-----------|--------------------|
| 1°                | ASTM A-106 Gr. A | $RuT$ (°C), $T_{M}^{\text{max}}$ (years) at $T = 450$ °C |
| 2°                | ASTM A-106 Gr. B | 230 6.85 |
| 3°                | API-B      | 230 6.85 |

**IV. CONCLUSIONS**

In the new methodology developed in this work, several new elements have been incorporated, such as the concept of the suitability matrix and the fitness for service index ($FFS_i$), allowing a multiperspective approach to find the optimal solution to arduous material selection tasks in the petrochemical industry.

The approach allows a decision diagram to be built and establishes an order of selection along with several limitations of service in accordance with the maximum hours of operation of the component.

API materials A and B as well as materials ASTM A-106 Gr. A and Gr. B have higher reliability and suitability for service regarding the degradation mechanisms discussed in addition to an adequate balance between mechanical properties (mechanical strength and ductility).

However, considering the restrictions extracted from the analysis, the selected materials are API-B, ASTM A-106 Gr A and Gr. B since the API-A material would not meet the constraint (no. 2) that imposes a limit for the maximum carbon and manganese content (to maintain a balance between strength and ductility associated with the influence of the chemical composition on mechanical properties).

The maximum use limitations for the chosen materials are as follows: a critical exposure temperature ($CET$) equal to 450 °C for the material ASTM A-106 Gr. A and 440 °C for both API-B and ASTM A-106 Gr. B. On the other hand, maximum continuous use temperature ($RuT$) values have been established as 260 °C for ASTM A-106 Gr. A and 230 °C for API-B and ASTM A-106 Gr. B.

In the future, this new development can be applied as a decision algorithm within a framework of analysis based on the massive data collection obtained using sensor-based technologies (IoT), allowing the reliability of equipment and systems in the petrochemical sector to be improved.

**LIST OF SYMBOLS AND ABBREVIATIONS**

- **API**: American Petroleum Institute
- **ASTM**: American Society for Testing and Materials
- **CET**: Critical exposure temperature (%)
- **$\sigma_{col}$**: Maximum elongation at fracture (%)
- **$D$**: Ductility
- **$\sigma_{U,\text{max}}$**: Critical yield strength (MPa)
- **$T_{M}^{\text{max}}$**: Maximum hours of operation
- **$T_{M}$**: Maximum temperature (°C)
- **$T_{M}^{\text{max}}$**: Maximum temperature (°C)

**TABLE 17. Order of selection for the best alternative material with use limitations depending on the temperature and considering the effects of corrosion damage and possible overload.**
**IoT** | Internet of Things
---|---
**FFS** | Fitness for service
**FFS<sub>i</sub>** | Fitness for service index
**L<sub>e</sub>** | Value of the requirement to analyze from the set {API, ASTM}
**L<sub>e,min</sub>** | Minimum value from the set {API, ASTM}
**MS** | Mechanical strength
**P** | Design pressure
**POF** | Probability of failure
**POF<sub>corr + overload</sub>** | Probability of failure due to corrosion and overload
**POF<sub>T,max</sub>** | Probability of failure due to degradation of the material at high temperature
**POF<sub>total</sub>** | Probability of failure due to corrosion and overload and high-temperature degradation
**R** | Reliability of the analyzed material with respect to the application
**R<sub>d</sub>** | Inner radius (<i>R</i><sub>d</sub>) plus half the thickness (<i>t</i>). Typically, this is applied in piping and pressure vessel calculations using membrane stress theory.
**<i>R</i><sub>corr</sub>** | Corrosion rate during the first year of exposure
**<i>RuT</i>** | Recommended mean temperature for continuous use
**Δ<i>t</i>** | Thickness loss
**SF** | Safety factor for each material depending on the mechanical stresses applied
**SL** | Stringency level
**SL<sub>max</sub>** | Maximum stringency level in the scale defined (5 points)
**SL<sub>s</sub>** | Stringency level for strength properties
**SL<sub>e</sub>** | Stringency level for ductility properties
**t** | Mean thickness
**<i>t</i><sub>min</sub>** | Minimum thickness to prevent plastic deformation
**<i>t</i><sub>min,corr</sub>** | Thickness after the loss due to corrosion
**<i>t</i><sub>min,no collapse</sub>** | Thickness limit before collapse
**<i>T</i><sub>critic,collapse</sub>** | Time to collapse after plastic deformation begins
**<i>T</i><sub>DL</sub>** | Expected operating lifetime determined by design (considering degradation at high temperature)
**<i>T</i><sub>DL,Tmax</sub>** | Expected operating lifetime determined by design at 450 °C
**<i>T</i><sub>max</sub>** | Maximum operation time (depending on the mechanisms of degradation)
**<i>V</i><sub>corr</sub>** | Corrosion rate after the first year of exposure
**<i>σ</i><sub>col</sub>** | Maximum effort allowed before collapse
**<i>σ</i><sub>c,corr</sub>** | Maximum membrane stress after loss of thickness due to corrosion

| **<i>σ</i><sub>Y API 530</sub>** | Maximum elastic stress at a temperature <i>T</i> according to API STD 530
| **<i>σ</i><sub>Y API 530,80</sub>** | Maximum elastic stress at 80 °C according to API STD 530
| **ψ** | Outer diameter of pipe
| **<i>σ</i><sub>U</sub>** | Ultimate tensile strength
| **<i>σ</i><sub>U,max</sub>** | Maximum allowable rupture stress
| **<i>σ</i><sub>Y</sub>** | Yield point
| **<i>σ</i><sub>Y,max</sub>** | Maximum allowable elastic stress (to prevent plastic deformation)

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