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RELIABILITY ASPECTS OF CORROSION IN OIL STORAGE TANKS

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ABSTRACT

Storage tanks are critical elements within oil facilities not because of their failure rate, but because of their critical function and the high environmental consequences when they fail. The presented analysis allows determining the probability of failure of storage tanks considering the most probable failure scenarios of this equipment. The utilized methodology considers the uncertainties associated with material degradation mechanism such as general corrosion, pitting and cracking induced by corrosion.

The analytical formulations of the time dependant degradation of the isolated mechanisms and the system conformed by the conjunction of them are considered. Obtained results allow determining the contribution of the individual scenarios in the system reliability.

Additionally, the probability of failure results and the maintenance cost are used to determine the optimum inspection time based on minimum costs criterion.

INTRODUCTION

This paper presents the results of a research conducted on Risk based Inspection of Aboveground Storage Tanks (AST). This equipment is a critical element within refineries and oil facilities not because of it failure rate, but because of their critical function and the high environmental consequences when they fail. In general AST have a very low failure rate, but the increasing age of the existing population raises their likelihood to fail, threatening with sudden spilling or gradual leaks, that could end in disastrous fires, environmental pollution, and/or contamination of underground waters. A high percentage of the world drinking water is groundwater and many refineries and tanks facilities are located relatively close to populated areas [1-3].

Over the last decade the threat of massive contamination due to catastrophic failure of aging tanks is a major concern. The American Petroleum Institute in a 1994 study revealed that 85% of U.S. refineries have groundwater contamination caused by AST systems [4].

Many of the early welded storage tanks were fabricated according to codes that allowed incomplete root penetration up to 1/3 the wall thickness furthermore in the past the inspections techniques were not as sophisticated as nowadays letting welding defect to pass undetected during post-fabrication inspections [5]. Many of these tanks are still operating and decommissioning them is not practical. Implementing an appropriate risk based inspection plan can lead to take appropriate actions before catastrophic scenarios occur.

A probabilistic analysis is conducted to assess the chance of failure considering several scenarios. The different elements that interact with the tank are considered.

Additionally, the optimum inspection time is determined based on a lowest cost criterion aiming to optimize the inspection frequencies. These guidelines will supplement operators to select an appropriate strategy for preventing, detecting, and controlling tanks failures.

THE AST SYSTEM

The AST system includes the equipment, the structure, the organization, procedures, and the environments.

The equipment and structure includes the tank, piping connections, loading and unloading system, and accessory equipment.

The organization includes all those people involved directly or indirectly in the management and operation and the equipments. These elements are; the refinery management, the product storage management, the tank owner (person assign to this tank farm), the inspection and maintenance people and the operator that deal with the filling and emptying of the unit.

Procedures constitute all those practices written or informal utilized during the operation, inspection, and maintenance routines of the tanks.

The environments refer to all external, internal and social elements that interact with the other elements in the system; wind, temperature, noise, motivation to work, etc [6].

Figure 1 shows a scheme of the different elements that interact within the tank AST system.

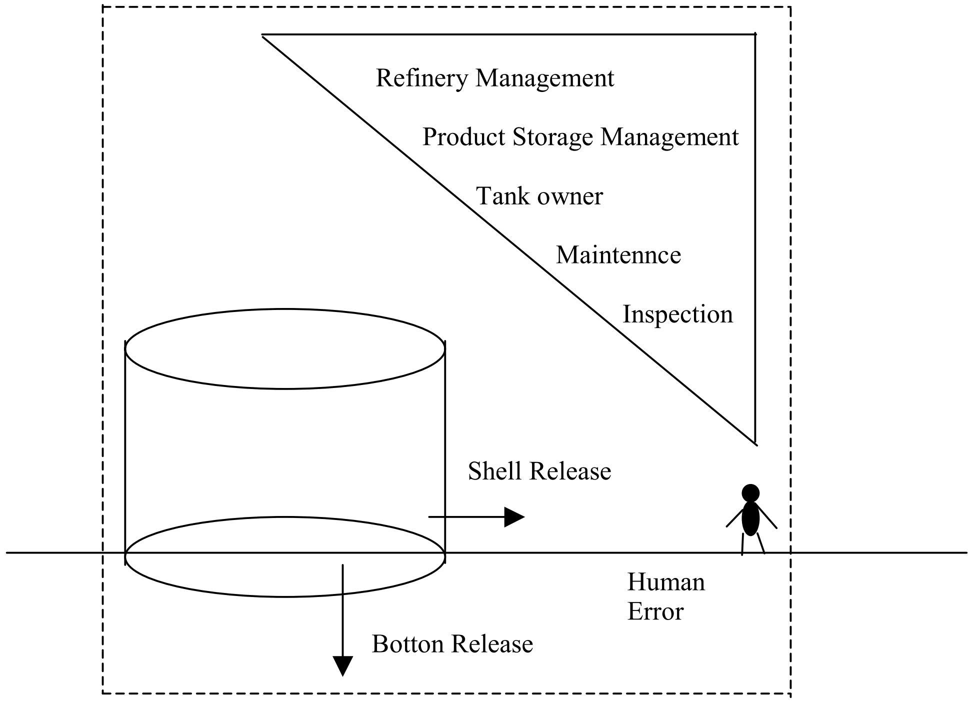

Figure 1. AST System Boundaries

FAILURE MECHANISMS

Storage tanks are subjected to several material degradations. The rate or degree of each one of these mechanisms will depend on each site particular conditions, say; environmental, tank coating or corrosion protection, maintenance procedure, etc.

Slow releases from a tank can occur from several sources: the bottom, the shell, or a tank appurtenance [7,8]. A tank release involves a loss of product through the tank, loss of production, human lives and environment damage, and may be the result of several causes: Intrinsic; say, material failures and natural disasters or Extrinsic; Human and Organization Malfunctions.

The most common failure mechanism is AST is ***corrosion***. In general tank floor is the most susceptible element to this type of degradation.

Corrosion is a complex electro-chemical-mechanical process that is a function of the stored product, the external surrounding media and the control measure to mitigate the phenomenon [9,10]. Thus, the corrosion rate varies from site to site and from tank to tank. Primary corrosion rate determining parameters in AST include temperature, product composition (water content, pH), coating and cathodic protection of the exposed surface.

Brittle failure experienced in tanks is consistence with the general dependence of material toughness on temperature (i .e. Carbon steel-toughness generally decreases as the temperature is decreased). It has been observed that the fracture toughness can be quite low even at temperatures above 60˚F.

Other Failure mechanisms that could initiate or speed the corrosion phenomenon are Human and Organization Errors [11]. For instance; change of tank service without ensuring that the tank is designed to accommodate the new conditions (change of the product stored, temperature), inadequate coating or inappropriate cathodic protection system, lack of appropriate post-repair inspection to prevent weld defects, etc [12-14].

Human Errors are an inevitable part of all human actions, they add a considerable degree of uncertainty to design and construction activities. Surveys indicate that human error is a dominant cause of failures in the engineering practice [6,15]. Any activity that involves human intervention is subject to the results of human influences. The following are task influences that have both positive and negative impacts of varying degrees (see figure 2) [16]:

- The system operators
- The organizations that they work for
- The procedures; formal and informal
- The structures and equipment (hardware) involved
- The environments (external, internal, social) in which the tasks occur
- The interfaces between the above five elements

The scenarios covered in this study are: (1) Tank bottom failure due to general corrosion and pitting, (2) Release due to Shell Cracking Induced by Corrosion, (3) Rapid Shell Failure due to HOE.

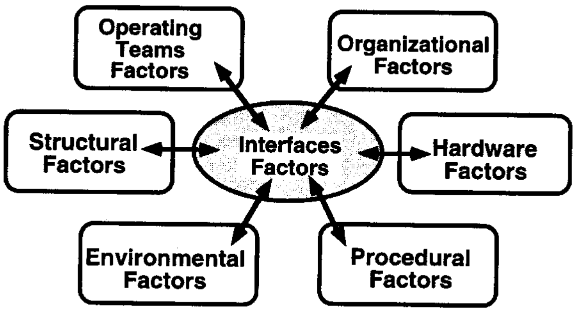

Figure 2. Factor that Influence Human Errors

RELIABILITY FORMULATION OF THE CORROSION MECHANISM

Although the basic electro-mechanic theory of the corrosion process is well understood, accurate mechanistic corrosion models capable of predicting corrosion rates for common metals under a variety of environmental conditions do not exist [9].

No model at present can quantitatively predict the formation and incubation time to pits. Even though, the corrosion process has become better understood, it is not possible to make accurate predictions of corrosion initiation and growth rates in most commonly uncounted environments, chiefly because of lack of data. Furthermore, in most situations requiring corrosion estimates, the necessary environmental data upon which theoretical calculations depend, are either uncertain or unavailable. Nevertheless, decisions must be made that depend on the outcome of the corrosion process [17].

In the past several researcher have developed models for different application to assess probabilistically corrosion problems on carbon steel tanks. Yanamoto (1996) carried out probabilistic analysis of ship hulls; B.F [9]. Lyon performed probabilistic estimations of corrosion on carbon steel nuclear waste drums. Masaru Saku utilized stochastic Finite Element for the evaluation of Storage tank including seismic loads.

Yanamoto and Ikegami modeled the loss of effectiveness of coating considering that the life of coating was a random variable governed by a normal distribution [18]. The generation of pitting points was considered by modeling a transition time, defined as the duration between the times when the coating becomes ineffective and when a pitting point is generated. The transition time was represented by an exponential distribution, although justification for this was not given either.

A model to predict corrosion progress in a storage tank should be function of time and must consider the following [19-21]:

- Loss of effectiveness of anti-corrosion coating
- Progress of general corrosion
- Generation of a pitting point
- Progress of pitting corrosion
- Lack of effectiveness of cathodic protection

A suitable method for calculating the minimum acceptable bottom thickness for the tank bottom is the following [22]:

$$MRT = T_o - t * \left(S_t P_r + UP_r\right) \quad \textbf{(1)}$$

Where:
MRT: Minimum Remaining thickness (inches)
t: Evaluation period of time (years)
T_o: current thickness (inches)
S_tP_r: Maximum corrosion rate on the top side (inches/year)
UP_r: Maximum corrosion rate on the bottom side (inches/year)

In general, the corrosion rate can be split into two general corrosion and pitting corrosion:

$$S_t P_r = P_p C_r + G_p C_r \quad \textbf{(2)}$$

$$UP_r = P_g C_r + G_g C_r \quad \textbf{(3)}$$

Where:
P_pC_r: Pitting rate product side
G_pC_r: General corrosion rate product side
P_gC_r: Pitting rate soil side
G_gC_r: General corrosion rate soil side

The number and growth of pits can be modeled as follows:

$$N\_Pits = K_1 * t^2 \quad \textbf{(4)}$$

$$Pits\_Grows = K_2 * t^n \quad \textbf{(5)}$$

The pit grows rate will determine the likelihood of leakage, and the number of pits the severity of the consequence [23]. Thus, the pitting rate for the ground and product side can be expressed as:

$P_gC_r = K_{1g} * t^n$ and $P_gC_r = K_{1p} * t^n$ respectively.

A coating coefficient (A) is introduced to account for the effectiveness of the coating. This coefficient represents the time (years) that the coating material provides suitable corrosion protection.

In order to account for the effectiveness of the cathodic protection system, a factor (B) is introduced in the equation. The coefficient B vary from 0 to 1, being 1 when the cathodic protection is 100% effective, say no corrosion is expected in the soil side, and 0 when there is no cathodic protection.

Introducing the above-mentioned factors, equation (1) can be expressed as:

$$MRT(t) = T_0 - t * \begin{bmatrix} A * \left(G_p C_r + K_{1p} * t^n\right) + \\ (1-B) * (G_g C_r + K_{1g} * t^n) \end{bmatrix} \quad \textbf{(6)}$$

The coefficient of coating wear can be expressed as a function of the coating effective time as follows:

$$A = \left(1 - \frac{T_c}{t}\right) \quad \textbf{(7)}$$

where T_c correspond to the coating effective time.
A limit state function for the metal loss due to corrosion can be express as follows:

$$\mathrm{G(t)} = MAT - MRT(t) \quad \textbf{(8)}$$

$$G(t) = MAT - T_0 + t * \begin{bmatrix} \left(1 - \frac{T_c}{t}\right) * \\ \left(G_p C_r + K_{1p} * t\right) + \\ (1 - B) * (G_g C_r + \\ K_{1g} * t\ ) \end{bmatrix} \quad \textbf{(9)}$$

Where MAT is the minimum allowance thickness. MAT represent the Minimum Allowed Thickness, and can be expressed as a deterministic value (0.1 inches) according to Reference [22]. The rest of the variables T_o, T_c, G_pC_r, K_{1p}, G_gC_r and K_{1g} can be treated as independent random variables, and the probability of failure is given by:

$$\mathrm{Pf} = \mathrm{P(G(t)<0)} \quad \textbf{(10)}$$

The Pf is determined through de reliability index (β), which can obtained using the First Order Second-Moment method. The reliability index calculated this way depends only on the means and standard deviation of the random variables [15,24].

Thus, for a limit state function f the form:

$$g(x_1, x_{2,....} x_n) = a_0 + a_1 X_1 + a_2 X_2 + ...a_n X_n \quad \textbf{(11)}$$

$$\beta = \frac{a_0 + \sum_{i=1}^{n} a_i * \mu * X_i}{\sqrt{\sum_{i=1}^{n} (a_i * \sigma * X_i)^2}} \quad \textbf{(12)}$$

RELIABILITY FORMULATION OF CRACK GROWTH ANALYSIS

The Fracture mechanic approach considers that an initial flaw is present in a stressed zone, and the fact that not every material flaw can be detected by the inspection methods. The initial flaws correspond to those defects smaller that the minimum detectable tolerance or those undetected by the inspector or those left in the material because considered harmless [25,26].

Initial flaws can potentially grow due to pitting corrosion and lead to a lead to a crack like failure. These flaws might be located near the wall-floor joint, in welds or in the welds. The maximum principal stresses, and the stress concentration in the joint, establish the local stresses. Residual stresses product of the welding process are present during the process of crack initiation, but once the crack develops, plastic deformation around the crack tip relaxes the residual stresses [27].

In a fracture, mechanics approach the Limit state function can be expressed as [28]:

$$G(t) = K_c - K_i \quad \textbf{(13)}$$

K_i is determine as a function of local crack free stress (σ_l), the crack shape (γ) and the flaw size (a) as follows:

$$K_i = \gamma * \sigma_l * \sqrt{\pi * a} \quad \textbf{(14)}$$

Where γ is a geometric factor that depends on the crack shape, and the proximity of the crack to reach the thickness of the component. In this analysis the cracks were idealized as semi-elliptical. The principal stresses in the tank wall can be determined utilizing the theory of thin cylinders. In the bottom tank course, the maximum principal stresses is located a few inches above the shell to bottom joint, and it is normally determined using finite element analysis. An approximation of the principal stress value at this zone is the following:

$$\sigma = \frac{\gamma * h * D}{4 * t} * SCF \quad \textbf{(15)}$$

Where SCF represent the stress concentration factor in the shell to floor joint.

For a semi-elliptical crack (see Figure 3) the shape factor is represented by the following equation:

$$\gamma = \frac{\left[1 + 0.12 * \left(1 - \frac{a}{b}\right)\right] *}{\sqrt{2 * \frac{t}{\pi * a} * tan\left(\pi * \frac{a}{2 * t}\right)}} \quad \textbf{(16)}$$

Where a and b are the characteristic parameters of the crack.

Substituting the above expressions in equation (14), we have:

$$K_i = \left[1 + 0.12 * \left(1 - \frac{a}{b}\right)\right] * \sqrt{2 * \frac{t}{\pi * a} * tan\left(\pi * \frac{a}{2 * t}\right)} * \frac{\gamma * h * D}{4 * t} * SCF * \sqrt{\pi * a} \quad \textbf{(17)}$$

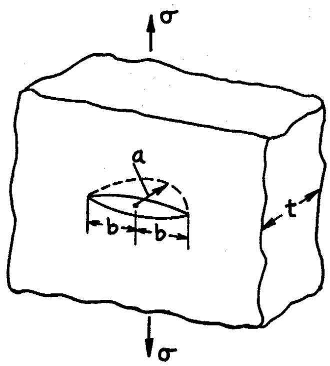

Figure 3. Characterization of a part-trough wall crack

Substituting K_i in equation (13) we have:

$$G(t) = K_c - \left[1 + 0.12 * \left(1 - \frac{a}{b}\right)\right] * \sqrt{2 * \frac{t}{\pi * a} * tan\left(\pi * \frac{a}{2 * t}\right)} * \frac{\gamma * h * D}{4 * t} * SCF * \sqrt{\pi * a} \quad \textbf{(18)}$$

K_C, a, b, t and h can be treated as random and independent variable, while γ, and SCF are consider to have little variation, thus, considered as deterministic variable, and the probability of failure is given by equation 10.

LIKELIHOOD OF RAPID SHELL FAILURE DUE TO HOE

This scenario considers a rapid shell failure due to a human malfunction. In order to assess the likelihood of occurrence of this scenario, human related tasks have been identified in the four life cycle parts of the system: design, construction, maintenance and operation [1,20,29-32].

The probability of failure is the likelihood of not developing the four quality attributes: Durability, Safety, Compatibility and Serviceability, leading to the above describe scenario.

In order to assess qualitatively the likelihood of developing this scenario, a mean failure frequency has to be selected, based on previous experience of similar failures. This mean rate is adjusted to the particular case study through the use of performance shaping factors. These factors can result in an increase or decrease in the mean rates of human errors.

In order to determine the likelihood factor, first, the partial likelihood factor within each the life cycle stages are grouped together to obtain each life cycle stage likelihood factor (LF) [33-36]:

Design LF = $f_1*f_2*f_3*....*f_n$ **(19)**

Construction LF = $f_1*f_2*f_3*....*f_n$ **(20)**

Operation LF = $f_1*f_2*f_3*....*f_n$ **(21)**

Maintenance Lf = $f_1*f_2*f_3*....*f_n$ **(22)**

Where f_1 to f_n are the different factors that define each cycle life stage.

Tables 1 to 4 show a questionnaire and performance-shaping factor, to correct the mean likelihood of a Rapid shell failure due to HOE. The likelihood factors are obtained using equations (19) to (22).

The Total Likelihood factor is obtained combining the four life cycle stages.

Scenario LF = Design LF* Construction LF* Operation LF* Maintenance LF **(23)**

Table 1. Performance shaping factor during the design stage (Scenario 5)

Design stage	LF
Designed acc. API 650	
Yes	1
Unknown	1.6
Coating	
Accord. SSPC or equivalent	1
Unknown	1.4

Table 2. Performance Shaping factor during the Fabrication stage (Scenario 5)

Fabrication/Installation stage	LF
Welds performed by	
Certified Welder	1
Unknown source	1.6
Post-Weld Inspection	
Inspected by authorized company	1
Unknown source	1.4
No Inspection	2

Table 3. Performance Shaping factor during the Operation stage (Scenario 5)

Operation stage	LF
Procedures	
Written - key steps highlighted	0.8
Acc. API RP 750	1
Exist by they are not formals	1.2
No written procedures	2
Operator expertise	
Formal - documented training program	1
Informal on the job	2
No training	3

Table 4. Performance shaping factor during the maintenance stage (Scenario 5)

Maintenance stage	LF
Repairs, reconstruction acc API 653	
Yes + after maintenance check list	0.8
Yes	1
No	2

AST SYSTEM

Typically, the term system is applied to an assembly of components whose state depends on the states of its components. Often the components of a system are physical elements. For example, a whole refinery plant, which include components consisting of pumps, valves, and one or more vessels. However, more generally, the components of a system need not be physical elements. For example, a simple beam with several failure modes in flexure, shear and torsion is a system with three components. Mathematical expressions describing the failure states in flexure, shear and torsion represent the components of the system. On the other hand, a frame structure can be treated as a component if one considers only a single failure mode, e.g., the exceedance of a critical response above a safe threshold.

Using the techniques presented earlier, we can analyze individual members in the context of structural reliability. However, when considering system reliability, it is important to recognize that the failure of a single component mayor may not mean failure of the structure. Consequently, the reliability of an individual member may not be representative of the reliability of the entire structural system.

The components of a system may have single or multiple states. In this work, it was assumed that the individual components, as well as, the system as a whole have only two possible states: the state of survival and the state of failure.

In reality, most structures cannot be classified as either series or parallel. They may not fail when a single member fails, but they can fail before all members fail.

A series system is sometimes referred to as a weakest link system because failure of the system corresponds to failure of the weakest element in the system. Assuming that all elements are statistical independents, we can calculate the probability of failure of a series system as follows:

$$P_f = 1 - P\left[(R_1 > q_1) \cap (R_2 > q_2) \cap .....(R_n > q_n)\right]$$

$$P_f = 1 - \prod_{i=1}^{n} \left[1 - P_{f_i}\right] \qquad \textbf{(24)}$$

The lower bound is the probability of failure when all elements are fully correlated (correlation coefficient = 1). If they are fully correlated, then all elements will tend to fail when one fails, thus, the probability of failure will correspond to the largest probability of failure among the constituent elements. The upper bound is the probability of failure when all elements are uncorrelated.

OPTIMUM SERVICE INTERVAL

The service interval is the time period until the tank has to be next taken out of service for cleaning, inspection, and maintenance. In general, the tank bottom is the limiting factor for service interval is ASTs [37].

The majority of ASTs in the petroleum industry are constructed using steel bottom plate ranging in thickness from 1/4 in. (6.4 mm) to 3/8 in. (9.5 mil). Due to corrosion, both internal and external, the service interval of a tank bottom is limited. Tanks owners have been a keen interest in extending the service interval of their tanks. The cost of cleaning large diameter storage tanks can easily reach tens of thousands of dollars. In addition, the temporary loss of storage volume or plant operating issues (in the case of an oil refinery) can be extremely costly. Added to these factors are the risk of environmental damage caused by leaking tanks and the high cost of environmental cleanup.

Risk Based Inspection is about identifying, and prioritizing risks [38]. In nearly every situation, once risks have been identified, alternate opportunities are available to reduce them. On the other hand, nearly all-major commercial losses have been the result of failure to understand or manage risks.

The RBI methodology provides the basis for managing risk by making an informed decision on inspection frequency and level of detail. In most plants, a large percent of the total unit risk will be concentrated in a relatively small percent of the equipment items. With an RBI program in place, inspections will continue to be conducted as defined in existing working documents, but priorities and frequencies will be guided by the RBI procedure.

The optimum inspection time is that, which provides the minimum total cost per unit of time [39,40]. The optimum inspection/replacement interval time depends on the cost of an unplanned outage, schedule maintenance and the tank failure rate.

The planned, unplanned and total costs can be expressed by:

S(t)=Ps(t) x CPR **(25)**

$$F(t)= Pf(t) \times CUR \quad \textbf{(26)}$$

$$TC(t)= F(t)+S(t) \quad \textbf{(27)}$$

Where:
S(t): Risk to succeed - Cost of not inspecting/repairing
Ps(t): Probability of Success
CPR: Cost or consequences of a Plan Inspection/Repair
F(t): Failure risk - Cost of Inspecting/Repairing
Ps(t): Probability of Failure
CUR: Cost or Consequences of an Unplanned Inspection/Repair
TC(t): Total cost

Figure 6 shows a scheme of the optimum inspection time evaluation.

CASE STUDY

In order to validate the above stated methodology a 35 years old 35 feet diameter Diesel tank was evaluated [41,42], the floor and shell thickness means and Standard Deviations were calculated based on the available inspection information. The corrosion rate mean and standard deviation were calculated combining the statistical data of two different inspections.

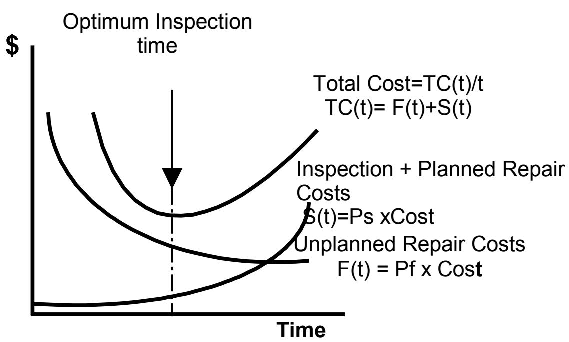

Figure 4. Scheme of the Optimum Inspection Time

General corrosion rate mean was 3.94 Mils/year and the Coefficient of variation was 0.2. The pitting corrosion rate was estimated as two times the general corrosion rate, where the coefficient n and K_2 of the equation 5 are set to 1 and 2 respectively. According to this assumption the pitting rate is 7.88 Mils/year. These rates were also used for the shell courses due to lack of more detailed information.

Scenario 1 - Slow Release Due to Tank Bottom Corrosion: This scenario consists of a progressive floor wear, where the general corrosion rate is known and the pitting rates are estimated based on equation 5. The limit state function is based on the total metal loss proposed in equation 16 of this paper.

The variables t_c can be estimated based on the experience of the operators. For this case study the factor t_c was set to be:

$\mu_{tc} = 10$ year

C.O.V = 0.4

Since there is no information of cathodic protection, the coefficient B is set to 0 (No cathodic protection).

Table 5 shows a summary of the results of β and Pf(t). The probability of failure is very low for inter-inspection times below 10 years but increases rapidly for inter-inspection times above 15 years.

Table 5. Probability of failure of the Tank Floor

Time	β	Pf(t)
5	6.02	8.78×10^{-10}
10	2.93	1.70×10^{-3}
15	1.55	0.06
20	0.82	0.208
25	0.36	0.36

Scenario 2 -Release Due to Shell Cracking Induced by Corrosion: The initial flaw size considered in the analysis was considered to be 1 mm (0.04 in) with a coefficient of variation of 0.1. These initial flaws are considered to grow because of pitting corrosion.

The analysis considers that these flaws might be located near the shell-floor joint or in the welds. The higher local stress in this area is determined by the hoop stress or by the axial stress, incremented by the stress concentration factor (stress next to the floor to shell joint).

The limit state function was defined as stated by equation 11, where K_i is a function of σ, γ and the flaw size (a), and the critic flaw size (K_c) was determined from reference #.

The internal general and pitting corrosion rates were assumed to be the same as those utilized in the previous scenario.

Table 6 shows a summary of the results. The probability of failure is very low for inter-inspection times below 15 years but increases rapidly for inter-inspection times above 20 years.

Scenario 3 - Rapid Shell Failure: According to the API the mean failure frequency of having a tank catastrophic failure is 2.0×10^{-5} failures a year.

In order to customize the given failure likelihood, the likelihood factor of Table 1 to 4 and equation 19 to 22 were utilized. For this case study, fabrication and operation have the higher likelihood factors. After multiplying the mean failure frequency by the likelihood factors, the likelihood of occurrence of this scenario was 2.9×10^{-5}.

Table 6. Probability of Failure at the Shell to Floor joint

Time	β	Pf(t)
5	5.51	8.71×10^{-9}
10	4.29	4.54×10^{-6}
15	3.05	6.48×10^{-4}
20	1.84	0.022
25	0.69	0.20

PROBABILITY OF FAILURE OF THE SYSTEM

The system contains a sequence of uncorrelated series element (failure modes or scenarios). The Probability of failure of Scenarios 1 and 2 are time dependant, but the corresponding of scenario 3 is fixed, and only depend on the quality assurance practices implemented by the refinery management.

The results of the probability of failure of each scenario and the system are shown in Figure 5. These results shows that for short inter-inspections period (<6 years), scenario 3 has the higher contribution to the probability of failure of the system, but for longer inter-inspection periods (>15 years), scenario 1 gives a higher contribution.

OPTIMUM INSPECTION TIME

In order to assess the optimum inspection time, both the probability of failure and the cost (consequences) information is utilized. The optimum replacement interval depends on the replacement costs for an unplanned outage, planned shutdown, probability of success and the probability of failure. These costs are shown in the following table, which can be plotted to arrive at the minimum interval.

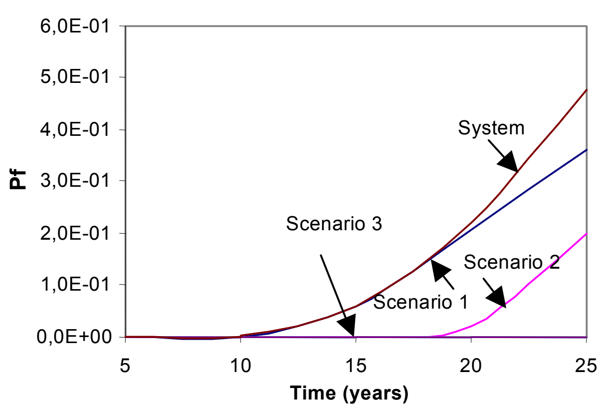

Figure 5. Probability of failure of the tank system

The consequence (costs) considered for this study were the following:

A tank overfill will have a clean-up cost of $10,000.

Release though any tank fitting will have a remediation cost of $20,000.

Any spill though the tank floor will have clean-up/remediation cost of $500.000.

A tank catastrophic failure will have a cost of tank replacement ($2,000,000) + clean-up/remediation costs.

The cost of a planned Tank floor repair is $200,000.

The cost of an unplanned Tank floor repair is $300,000.

Base on the above stated assumption the consequences of each scenario were estimated as follows:

Scenario 1. Release Due to Tank Bottom Corrosion:
Total cost = $300.000 + $500.000 =$800.000

Scenario 2. Release Due to Shell Cracking Induced by Corrosion
Total Cost =$500.000 + $2,000,000 = 2,500,000

Scenario 3 - Overfill Releases/Spill Through Tank Vents
Total Cost =$10.000

Scenario 4 - Slow Release Though Tank Fitting or Pressure Release System
Total Cost =$20.000

Scenario 5 - Rapid Shell Failure – Collapse
Total Cost =$500.000 + $2,000,000 = 2,200,000

Scenario 1. Release Due to Tank Bottom Corrosion:
Planned maintenance cost: $200,000
Unplanned Maintenance + Spill remediation cost = $300.000 + $500.000 =$800.000

The optimum inspection time corresponds to the lowest total cost per unit of time, and it was found to be 16 years for scenario 1. Table 7 shows the total costs for this scenario.

CONCLUSIONS

The utilized methodology permit to use the Corrosion rate based on the knowledge of influence factors: like level of corrosion protection, soil condition and product corrosive characteristic. It also allows accounting for the uncertainties associated with the above. It has been stated in previous studies that floor corrosion is the main factor that limits the mean time between failures. However, under special circumstances, brittle fracture can threaten the useful life of the tank. Human and Organization Factors can be of a high significance depending on the facility particular conditions.

Additionally, the likelihood of failure due to HOE can be tailor to any particular facility through the evaluation of the shaping factors.

Contrary to scenarios 1 and 2, were the probability of failure is time dependant, the probability of failure leading to this scenario 3 does not depend on time, but on the quality assurance procedures developed by the refinery management.

Table 7. Total cost for scenario 1

Time (Years)	Pf(t)	Unplanned Maintenance Risk	Ps(t)	Plan Maintenance Risk	Total cost	Total Cost/time
1	0.00	0.0	1.00	200.0	200	200.00
5	0.00	0.0	1.00	200.0	200	40.00
10	0.00	1.4	1.00	199.7	201	20.10
11	0.01	4.1	0.99	199.0	203	18.46
12	0.01	9.6	0.99	197.6	207	17.27
13	0.02	18.4	0.98	195.4	214	16.45
14	0.04	31.2	0.96	192.2	223	15.96
15	0.06	48.0	0.94	188.0	236	15.73
16	***0.09***	***68.0***	***0.92***	***183.0***	***251***	***15.69***
17	0.11	91.2	0.89	177.2	268	15.79
18	0.14	115.2	0.86	171.2	286	15.91
19	0.18	140.8	0.82	164.8	306	16.08
20	0.21	166.4	0.79	158.4	325	16.24
25	0.36	287.2	0.64	128.2	415	16.62
30	0.48	382.4	0.52	104.4	487	16.23

The analysis of the system allows showing the contribution of every component in the final result in the global probability of failure.

It is important to keep in mind that this tool is only a guide for management decision, and NOT a final pronouncement formula. It is responsibility of the evaluator the judgment of the input data and the interpretation of the results.

From the particular evaluation:

The probability of having a leak due to floor corrosion is higher that the probability of having a failure due to shell cracks. This result is sustained for very long times up to 30 years.

The probability of having a shell fracture leading to a catastrophic failure is very low even for long periods (20 years). This fact is in accordance with the standard API 653, which state that if large initial defect are not present or in the absence of any stress raiser, the likelihood of catastrophic shell failure is very low.

It was observed that for short forecast times human and Organization factors have higher relative Risk, bur for longer times (beyond 15 years) floor corrosion lead the risk scale.

The Optimum Inspection time was 16 years (minimum total cost per unit of time), which is higher that the Inspection interval of 10 years recommended by the standard API 653 representing a tremendous amount of saving for the owner.

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