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# Assessment of the Perforation Risk for Atmospheric Storage Tanks Containing Solvents

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The assessment of the integrity of the atmospheric storage tanks is needed to prevent releases of hazardous materials. In particular, the control of the localised losses of thickness, due to pitting or other phenomena, is essential for the bottom of the storage tanks, because these could lead to the perforation of the plates and leakages of materials with severe environmental consequences. Different techniques are available for the integrity measurement, but they always require the tanks is out of service, therefore, it has to be empty and reclaimed. Measurements can be repeated only after some years of further service. Nevertheless, the estimation of the perforation probability is important to assess the risk of major accidents as well as the environmental risk, associated with possible leakages. Unfortunately, discrete thickness measurements cannot determine with certainty the maximum corrosion depth of the bottom, where the materials usually exhibit localised corrosion in the form of pits. For this reason, to assess the perforation probability of the storage tank, a probabilistic approach based on the extreme value theory must be used. This work describes a model predicting the maximum expected damage with respect to the deterioration mechanisms affecting the bottom of the atmospheric storage tanks containing naphtha based solvents. The model is based on an analysis of the bottom damage, obtained by collecting thickness measurements. The application to a real case-study is presented.

## 1. Introduction

Corrosion of the bottom of atmospheric storage tanks is a major problem in chemical and petrochemical industries and depots. Many tanks have been in service for more than 40 years, thus, the ageing issue is of paramount concern (Milazzo and Bragatto 2019). The thicknesses of bottom floors of atmospheric storage tanks are usually measured every 10 years or more as part of the overall inspection of the tanks. The corrosion rate, which is evaluated based on the ratio of the detected minimum thickness to the usage time, is used to estimate the *Residual Useful Lifetime* ($RUL$) and plan an appropriate maintenance aimed at the prevention of leakages. Accurate measurements of the bottom integrity can only be performed when the tank is empty. During the planned stops, the entire bottom is carefully examined by means of thickness measurements. Currently, the use of the *Magnetic Flux Leakage* (MFL) technique is diffused, but the *Ultrasound Thickness Measurements* (UTM) are the most common and needed for detection in difficult points. Acoustic emissions could be useful to verify the presence of ongoing degradation for in-service tanks, however, they are absolutely complementary to direct thickness measurements.

The cost for a complete screening of the bottom is high, since the tank must be put out of service. To execute UTM, workers remain in a highly dangerous environment for a long time. Therefore, extensions of the typical inspection interval are accepted. This interval could also be reduced to ensure that the average time, before reaching unsafe conditions (with reference to the minimum thickness), is less than the time expected for the subsequent inspection. In addition to the occupational risk, the risk of major accidents has also to be accounted for as well as the environmental risk. These are associated with the release of dangerous substances due to the perforation of the bottom as a consequence of the deterioration. Unfortunately, discrete thickness measurements cannot determine with certainty the maximum corrosion depth, where the materials

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usually exhibit localised corrosion in the form of pits. Hence, to assess the perforation probability for the storage tank, a probabilistic approach combined with an analysis of the phenomenon, obtained by collecting thickness measurements, has to be applied. In this context, the use of the extreme value theory is frequent (HSE, 2002; Velázquez et al., 2009). The literature shows different applications: Joshi (1994) characterised the corrosion from UTM of the bottom of above-ground crude oil storage tanks; Shibata (1991) determined the optimal return period and predicted maximum corrosion from a Gumbel diagram; Bolzoni et al. (2006) applied probabilistic models describing the localised corrosion in oil industry; Kasai et al. (2016) combined the analysis of extreme values and the Bayesian inference to predict the maximum corrosion depth. Other studies use the stochastic approach to predict the failure probability of pipes, components, etc. (Ishikawa et al., 1982; Lee et al., 2005).
The probability of perforation of the bottom of tanks is essential to quantify the risk associated with accidental scenarios due to ageing. The assessment and management of the risk caused by equipment ageing have also been pointed by relevant European Directive (EU Council, 2012; EU Council, 2010; Laurent et al., 2021). The literature shows a limited investigation of the problems associated with tanks containing solvents based on the above approaches. Therefore, this study describes a model predicting the probability of the maximum expected damage with respect to the deterioration mechanisms that affect the bottom of the atmospheric storage tanks containing solvents. The model was developed through a statistical analysis of the bottom integrity, obtained by UTM measurements. The paper is structured as follows: Section 2 describes the approach modelling the perforation probability; Section 3 presents a case-study used to apply the approach; Section 4 gives the results; finally, Section 5 provides some conclusions.

## 2. Methodology

The extreme value theory (EVT) supports in searching the probability of the pit, having a critical depth, for a system in which the localised corrosion occurs by means of a set of $n$ measures. By referring to the set of the maximum depths, as the data grows, the distribution of the extreme values becomes insensitive and tends to some limit forms called asymptotic distributions (Berretta, 2009). These describe the behaviour of the variable corrosion depth ($x$) and are classified into 3 types according to the shape of their tails (Gumbel, 1958):

$$F_I(x) \approx \exp\left[-\exp(-x)\right] \quad \text{type I distribution} \tag{1}$$

$$F_{II}(x) \approx \exp(-x)^{-k} \quad \text{type II distribution} \tag{2}$$

$$F_{III}(x) \approx \exp\left[-(\omega - x)^k\right] \quad \text{type III distribution} \tag{3}$$

where: $k$ and $\omega$ = parameters of the distribution.

The *type I distribution* (Gumbel distribution) is used if the field of the parent distribution is unlimited at the top and the right tail of the relative density exponentially decays. As $n$ approaches $+\infty$, it is given by Eq(1). The *type II distribution* is used when the parent distribution is defined in the range $0 < x < +\infty$. Finally, the *type III distribution* is used when the parent distribution has an upper limit $\omega$. The *type II* and *III* can be transformed in the *type I* that is the most frequent used. Alternatively, a generalised extreme-value (GEV) distribution can be also used (Jenkinson, 1955):

$$F_{GEV}(x) = \exp\left\{-\left[1 + \frac{\gamma(x-\beta)}{\alpha}\right]^{1/\gamma}\right\} \qquad \gamma \cdot x \le \alpha + \beta \cdot \gamma \tag{4}$$

where: $\alpha$ = scale parameter; $\beta$ = location parameter; and $\gamma$ = shape parameter.

The $\gamma$ parameter indicates the type of distribution by the sign and the absolute value (*type I*: $\gamma = 0$; *type II*: $\gamma > 0$; *type III*: $\gamma < 0$). To understand which of the four distributions is the best fitting for the data, three additional criteria (VOSE, 2017) can be applied:

$$SIC = \ln(n) \cdot k - 2 \cdot \ln(L_{\max}) \quad \text{information criterion 1 (Schwarz criterion)} \tag{5}$$

$$AIC = \left(\frac{2 \cdot n}{n-k-1}\right) \cdot k - 2 \cdot \ln(L_{\max}) \quad \text{information criterion 2 (Akaike criterion)} \tag{6}$$

$$HQIC = 2 \cdot \ln\left[\ln(n)\right] \cdot k - 2 \cdot \ln(L_{\max}) \quad \text{information criterion 3 (Hannan and Quinn criterion)} \tag{7}$$

where: $n$ = number of observations (e.g. data values, frequencies); $k$ = number of parameters to be estimated; $2 \cdot \ln(L_{max})$ = estimation of the deviance of the model fit.

The information criteria indicate the goodness of the fitting. The rule is that the lower an information criterion, the better the fit. Therefore, the fitted distributions are ranked according to the $SIC$, $AIC$ and $HQIC$. A further check can be done by means of the $\gamma$ parameter of the GEV distribution. After the choice of the distribution type, the plot position is constructed by introducing a reduced variate ($y$), which allows the linearization of the equation (Milazzo et al., 2020). From the plot position the probability of the critical pit is determined.
The application of this approach is widespread in the corrosion context, but it is not common to find applications finalised to the quantitative risk assessment. To this scope, the critical pit depth should be the thickness of bottom plates but, as suggested by the standard EEMUA (2014) a conservative safety threshold of 2.5 mm has been assumed; therefore, the critical corrosion depth becomes the thickness of bottom plates subtracted of the threshold. Hence, the probability of corrosion higher than 5.5 mm is assumed as the probability of perforation.

## 3. Case-study

The methodology has been applied to a large fixed roof atmospheric tank, containing naphtha solvent. It is included in a Seveso site, close to a residential area, highways and railways and natural vulnerable elements, and has a maximum capacity of about 5000 $m^3$. The tank is operating since 1962; its bottom has 53 carbon steel plates, welded each other and covers about 360 $m^2$. The nominal thickness is 8 mm. The most recent inspections have been done to the 2010 and the 2017 and refer to an extensive visual inspection and a number of UTM for each plate of the bottom, i.e. 126 points in 2010 (minimum thickness = 4.7 mm) and 252 in 2017 (minimum thickness = 3.9 mm). To execute the inspection, the tank was emptied and cleaned. The main risk, caused by the bottom deterioration, is due to the potential solvent release. Beyond the risk for the workers associated with the flammability of the substance, a modest leakage could pollute the surroundings. In general, if the damage occurs at the first shell, the product certainly ends up in the containment basin and therefore a safety problem could arise due to the flammability of the substance. The release from the bottom, on the other hand, could cause infiltration into the soil, reaching any water bodies. If the damage occurs right on the gunwale, the flammability hazard cannot be excluded, but it is generally controlled through the containment basins and the area should be classified as an ATEX zone with all the necessary precautions.
The set of the maximum corrosion depths have been extracted from the UTM measures. These have been processed by means of the trial version of the software ModelRisk (VOSE, 2017) to choose the best fitting probability distribution type based on the information criteria discussed above and the $\gamma$ parameter of the GEV.

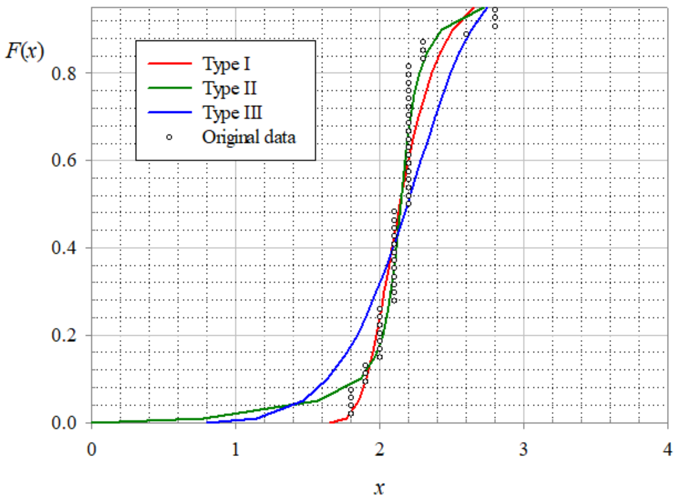
## 4. Results

### 4.1 Identification of the best-fitting extreme-value distribution

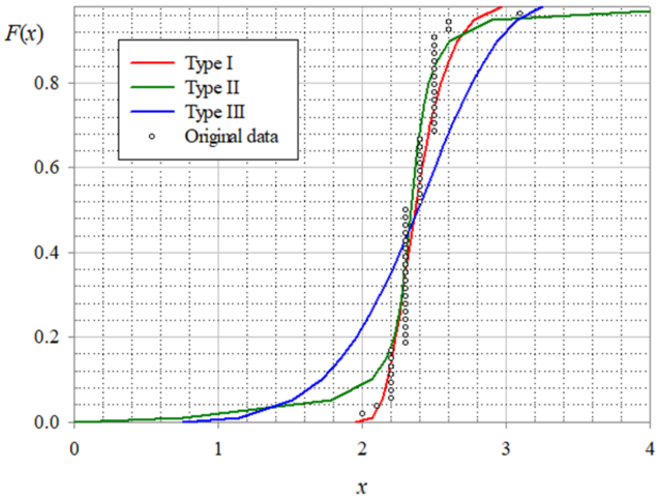
The fitting of data gave the cumulative distribution curves of Figure 1; it can be observed, the same corrosion value appears associated with different $F(x)$, this is due to the equation used to estimate $F(x)$ that account for the rank of the measure (Shibata, 1991). The original data overlaps the *type II* distribution for higher $x$ and the *type I* for lower values. The parameters of each distribution have been derived with the ModelRisk (Table 1). Given that for the GEV distribution $\gamma > 0$, the best fitting should be given by the *type II*, this is also confirmed by the information criteria as the lowest $SIC$, $AIC$ and $HQIC$ have been identified for the *type II* distribution (Table 1). The goodness of the fit by means the check of the residuals is made by means of the value of $2 \cdot \ln(L_{max})$.

*Table 1: Parameters of the distribution*

| Parameter | Type I (2010) | Type II (2010) | Type III (2010) | GEV (2010) | Type I (2017) | Type II (2017) | Type III (2017) | GEV (2017) |
|---|---|---|---|---|---|---|---|---|
| scale parameter $\alpha$ | 0.196 | 0.092 | -- | 0.192 | 0.158 | 0.088 | -- | 0.155 |
| location parameters $\beta$ | 2.068 | 2.146 | -- | 2.060 | 2.309 | 2.339 | -- | 2.301 |
| shape parameter $\gamma$ | -- | -- | -- | 0.068 | -- | -- | -- | 0.077 |
| shape parameter $k$ | -- | -- | 6.511 | -- | -- | -- | 5.745 | -- |
| scale parameter $\omega$ | -- | -- | 2.317 | -- | -- | -- | 2.542 | -- |
| $SIC$ | 4.655 | 1.028 | 43.163 | -- | - 17.872 | - 19.548 | 58.484 | -- |
| $AIC$ | 0.954 | - 2.672 | 39.462 | -- | - 21.572 | - 23.249 | 54.784 | -- |
| $HQIC$ | 2.229 | - 1.397 | 40.737 | -- | - 20.297 | - 21.973 | 56.059 | -- |




(a)




(b)

*Figure 1: Cumulative distribution curves for (a) 2010 and (b) 2017.*

### 4.2 Plot position and probability of the critical pit

Given that, the *type II* and *III* distributions can be always transformed in *type I*, to derive the plot position, the *type II* distribution has been transformed in *type I*, as suggested by Alaswed (2018). Thus, by introducing a reduced variate $y$, the Eq(9) has been used to construct the Gumbel probability plot:

$$y = \frac{x - \beta}{\alpha} \tag{8}$$

$$y = -\ln\left(\ln \frac{1}{F(y)}\right) \tag{9}$$

The set of the maximum corrosion depths at each plate has been analysed for the 2010 and 2017 and a plot $y$ vs. $x$ has been produced (Figure 2). Through regression, the parameters of the distribution have been obtained. Figures 2(a-b) show that the probability of a pit greater than or equal to 2.5 mm is 0.05 in 2010 and 0.15 in 2017. The plot position should be extended to make the analyst able to read the probability of having a pit greater than 5.5 mm (which is used as threshold value of criticality before the perforation is reached), therefore, this calculation has numerically been carried out and the resulted probabilities are $3{\cdot}10^{-12}$ in 2010 and $5{\cdot}10^{-12}$ in 2017, practically absolutely negligible values. The probabilities obtained with *type II* distribution are conservative and more accurate than those derived with the *type I*, in particular, the Gumbel distribution gives low probabilities of perforation. In Figure 2, points with corrosion depth higher than 3 mm deviate from the linear trend, this can likely be attributed to the simultaneous presence of other deterioration mechanisms, which should be investigated by using two plot positions on the same graph. The use of this approach can also incorporate the effects of time when several inspections are available, this allows making prediction about the perforation as given by Milazzo et al. (2020).

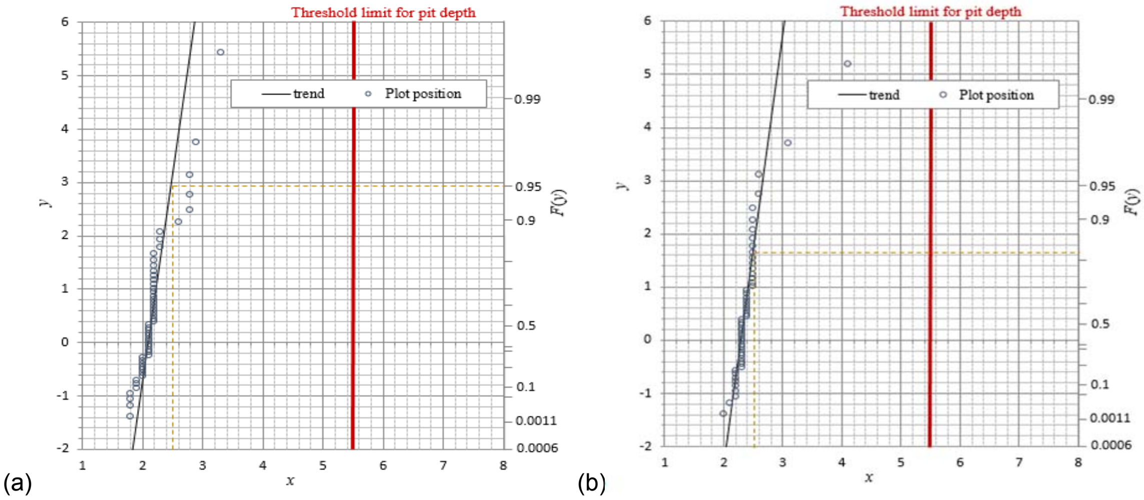



*Figure 2: (a) Plot position 2010, (b) Plot position 2017.*

### 4.3 Discussion

The distributions of the localised corrosion depths of the bottom of tanks are interpolated with various types of statistical distributions. The depth distribution depends on the mechanisms of formation and growth of pitting. A lot of work has been done to find the best way to represent localised corrosion in tank bottoms and also pipes. As mentioned above, a very strong basis was laid by Shibata (1991) that demonstrated how the double exponential Gumbel distribution was the most suitable to represent pitting. The physical and chemical foundations underlying the pitting distribution have been extensively discussed by Valor et al. (2007a), based on a number of laboratory tests. In another work, Valor et al. (2007b) reviewed 48 datasets of experimental measurements and verified that Gumbel distribution was definitely the most suitable distribution to represent the corrosion depths. This deduction contradicts with works that tried to demonstrate the non-applicability of Gumbel theory and introduced variants. Among the various attempts, Jarrah et al. (2011) proposed a much more complicated version of the distribution of extremes, i.e. the generalised lambda distribution (GLD), which was also used by Valor et al. (2013), combined with Markov chains to refine pitting modelling. A very recent work by Melcher and Ahammed (2020) demonstrated the sound physical and chemical basis behind the statistics of extremes, based on measurements performed on pipes. While the first works were based on laboratory tests, over time, data on real situations were also accumulated, in particular pipelines and tanks of fuel oil and petroleum products.

The results obtained in this work relate to a type of tank that is currently not sufficiently investigated, i.e. chemical tanks; this type, although similar to oil ones, still have noteworthy peculiarities, such as more frequent emptying and reclamation, possible use of different substances, standards of higher product quality, smaller size. The Gumbel distribution is still a good basic reference, but the result can be even better with the generalised distribution or with the *type II* distribution. In RBI studies, the assessment of the conditions concurs to determine the interval between subsequent inspections, whilst in Seveso safety management the need to adopt additional preventive measures. In particular, in the *ageing fishbone method* (Milazzo and Bragatto 2019), adopted by the Italian authorities to verify the adequacy of the ageing management in the Seveso plants, there is a "damage/defect" factor, which contributes, together with other technical and organisational factors, to the calculation of an overall ageing index. The damage/defect factor should, reasonably, consider the distribution of pitting, assigning a higher score to the distributions characterised by a higher pitting depths.

## 5. Conclusions

The study proposed the use of a probabilistic approach for the derivation of the probability of perforation of the tank, which is widespread in the corrosion context, to be applied in quantitative risk assessment. The case-study relates to a type of tank, containing solvents, that is currently not sufficiently investigated in the literature. The results show the probability of perforation is absolutely negligible, but these refers to the current use of the tank and assume a constant trend of the corrosion over the time. Nevertheless, the application provides useful information that can be utilised for the safety management, i.e. to adopt additional preventive measures, as well as to verify the adequacy of the ageing management by integrating information about the evolution of the mechanism in the prediction of the "damage/defect" factor.

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