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Evaluation of the Condition of the Bottom of the Tanks for Petroleum Products-Forecast of the Remaining Operating Life

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Corrosion rate measurements in the tank enable us to develop a new model for predicting the remaining operating period of the tank. The empirical model for the study of bottom plate thicknesses and corrosion pits is more conservative than the standard linear model, as it considers the autocatalytic nature of the corrosion process. We used the double exponential distribution of maximum values (Gumbel's) to evaluate the maximum depth of pits, and the double exponential distribution of minimum values to evaluate the minimum values of the plate thickness. A comparison of the values of the parameters obtained using linear extrapolation and exponential models indicates the unreliability of linear extrapolation, since disregarding dynamic processes underestimates the actual rate of corrosion.
Keywords: pitting, storage tank bottom, time-dependent reliability, corrosion model

Highlights

- *The class of tank bottom metal plates can significantly affect on the prediction of the remaining operating period of the tank.*
- *Improving the reliability of measurements of the condition of the tank bottom by statistical analysis of extreme values.*
- *New model for predicting the remaining operating period of the tank.*
- *Improving the reliability of the remaining tank operating period prediction model using actually calculated tank bottom corrosion rates.*
- *The proposed model is more reliable than the established models and is consistent with the actual consequences of tank bottom corrosion.*

0 INTRODUCTION

When storing fuels in tanks, complete bottom tightness must be ensured. A potential fuel spill can result in ecological and economic damage. From long-standing monitoring of the condition of the internal surfaces of the tanks it follows that the presence of water makes the internal surfaces of the tanks the most congested. The presence of aqueous solutions at the bottom of the tank, in addition to general corrosion, allows the development of more problematic forms of local corrosion such as pitting and microbiological corrosion. Pitting may also appear independently from microbiological corrosion. Rapid progression of local forms of corrosion can lead to premature failure of the tank bottom, especially if adequate anti-corrosion protection system is not provided on surfaces contacting petroleum products. The combination of local corrosion and the absence of anti-corrosion protection system resulted in leaking of tank bottom constructed of nominal 8 mm carbon steel plates after 6 years of tank operation.

During the regular periodic inspections of the tanks, it is necessary to reliably assess the progress of corrosion in the future operating period. The generally established methodology for predicting the remaining operational life of the tank bottom is based on non-destructive measurements of the thickness of the bottom plate with magnetic flux, ultrasound and measurements of the depth of corrosion damage with mechanical measures [1]. The corrosion rate is estimated from the measurements based on extrapolation to the previously known or initial condition of the tank bottom. The most unfavorable measured values, such as the minimum measured bottom plate thickness or the maximum measured depth of corrosion damage, are taken into account in the assessment. Construction of tank bottom must be also taken in account. In our case of double bottom tanks, with vacuumed interspace between bottoms, corrosion is limited to surfaces contacting petroleum products. In single bottom tanks can additional corrosion also occur from outside contacting soil or concrete.

Corrosion rates estimated in this way are usually of the order of 0.1 mm/year to 0.2 mm/year [2] and [3]. This is significantly less than experience and data show us about the possible rates of pitting (0.5 mm/year to 1.5 mm/year) or microbiological corrosion (0.5 mm/year to 2 mm/year) [2] and [3]. Therefore, the estimates of measurements carried out in accordance with standard methodology [1], significantly

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*Corr. Author's Address: Jožef Stefan International Postgraduate School, Slovenia, ales.povse@petrol.si underestimate the actual rate of corrosion progression in the presence of local form of corrosion.

One of the reasons for the unreliability of the standard corrosion prediction model is the lack of measurements of tank bottom plate thickness, as only a limited number of measurements are usually available. For this purpose, a statistical methodology of extreme values was developed for laboratory measurements during simulations of actual corrosion on objects. This, based on the hypothesis that the statistical distribution of measurements is the same on all parts of the surface, enables the evaluation of extreme values for the minimum bottom plate thickness or the maximum depth of corrosion damage. This approach improves the reliability of the corrosion progression prediction compared to the standard linear model.

The reliability of the prediction of the remaining service life of the tank bottom depends on the reliability of the assessment of the existing condition, the assessment of the corrosion rate and the adequacy of the model for the evaluation of the course of the corrosion rate. A linear model of corrosion progression with a constant corrosion rate is established in the technical regulations [1]. This is based on the lowest measured bottom plate thickness and an estimate of the corrosion rate based on a linear extrapolation to the previously known condition of the tank bottom. More reliable approach is use of extreme value estimates, again with linear extrapolation to a known initial state [4]. In case of accumulated data (databases), as is case for marine ships, prediction of thickness loss and corrosion rates can be estimated with statistical models [5] to [11]. In case of above ground storage tanks, in best case (but usually not), we have plate thickness measurements from previous tank inspection.

Laboratory monitoring of corrosion processes has shown that the progression of corrosion can be described, depending on the nature of the corrosion, with two empirical models for passivation and active dissolution of steel. Laboratory empirical models are based on a large number of plate thickness measurements over at least three-time intervals, which are then correlated in an empirical model. In reality, however, this type of data is not available to us [12].

Long inspections intervals, currently lasting at least every 10 years, tank design and design imperfections, stored fuels and their quality, frequency of drainage, refill intervals, micro location of tank, cathodic protection of external tank bottoms contacting concrete foundations are some main factors which influence corrosion rates on internal surfaces of bottoms. During tank inspections we discovered significant differences on neighboring tanks of the same construction, age, design and stored fuel, probably due to variations of fuel quality. These are some main reasons, why laboratory simulations of internal tank exposure, progress of corrosion rates through time may significantly differ from reality and cannot be used for a reliable prediction for the remaining service life.

In our previous work, we performed established electrochemical measurements (anodic polarization) in the studied tank before replacing the upper tank bottom. Measured spots plates were cut out and tank measurements verified in controlled laboratory conditions [13].

Replacing the bottom plates of the tank allowed us to measure the actual corrosion rates, while we were able to use the laboratory empirical model for active steel dissolution [13]. The empirical parameters of the model were evaluated based on extreme values of ultrasonic measurements of bottom plate thickness, pit depth and measured corrosion rates. The obtained corrosion progression model allowed us to predict the remaining service life of the tank bottom significantly more reliably compared to the standard linear model [1]. The results of our model were consistent with the observed actual condition of the reservoir bottom plates.

1 EXPERIMENT

Measurements of bottom plate thickness and pit depth were made at the bottom of an above-ground, double bottom tank for the storage of petroleum products with a volume of 55,000 m^3. The tank was built in 2006 [14] and [15]. After six years of operation, a bottom leak was detected. The measurements in the tank were carried out before the bottom plates were replaced. Corrosion was limited to surfaces contacting petroleum products.

1.1 Measurements of the Remaining Bottom Plate Thickness

Measurements of the remaining bottom plate thickness (Tables 1 and 3) were carried out with an Elcometer 204 Steel Ultrasonic Thickness Gauge, in accordance with the standard SIST EN 14127 [16]. The meter has a measuring range from 0.63 mm to 199.99 mm and a resolution of 0.01 mm and a reliability of ±2 %.

From 12 to 18 measurements were performed on each of the eleven measuring spots, in size approximately 1.5 m × 1.5 m. The nominal thickness

Table 1. *Bottom plate thickness measured by ultrasound [mm]*

No	Measurement point										
	1	2	3	4	5	6	7	8	9	10	11
1	9.27	8.24	8.43	8.56	8.97	8.42	8.55	8.21	8.50	7.70	8.12
2	9.61	8.21	8.69	8.16	9.04	9.03	8.52	8.13	8.93	7.92	6.08
3	9.32	8.26	8.41	8.54	8.78	8.77	8.57	8.37	8.60	8.29	6.54
4	9.25	8.25	8.72	8.65	8.83	8.45	7.30	8.47	8.35	8.90	5.58
5	9.49	8.22	8.56	8.21	8.61	8.40	8.26	8.64	8.72	8.16	6.30
6	8.66	8.26	8.72	8.27	9.03	8.56	8.40	8.15	8.88	8.08	7.98
7	8.77	8.22	8.56	8.53	8.86	8.59	8.28	8.23	8.57	7.20	8.89
8	9.22	8.23	8.56	8.50	8.73	8.68	8.20	8.33	8.58	7.67	5.93
9	8.74	8.23	8.39	8.57	8.73	8.63	8.70	8.66	8.69	7.66	8.01
10	9.28	8.28	8.78	8.33	8.58	8.60	8.62	8.58	8.72	8.77	6.65
11	8.70	8.23	8.40	8.17	8.97	8.61	8.51	8.18	8.67	7.19	5.96
12	8.75	8.29	8.69	8.48	8.93	8.63	8.66	8.32	8.67	7.93	6.15
13	9.02	8.27	8.58	8.34	8.68	8.30		8.11	8.70	7.64	5.77
14	8.66	8.24	8.76	8.53	8.80	8.37		8.26	7.49	7.81	7.57
15	8.61	8.28	8.50	8.89	8.60			8.51	8.60	7.48	7.52
16	8.63	8.26	8.49					8.32		7.20	
17	9.31										
18	8.62										

of the tank bottom plate was 8 mm. According to the standard **[17]**, for class C, a tolerance of 0 mm to +1.4 mm is allowed. Due to the inclination of the bottom towards the center of the tank, corrosion loads are greatest in the middle of the tank, where we have the water phase zone **[2]**, **[3]**, **[18]**, and **[19]**. A decrease in bottom plate thickness towards the center of the tank is expected.

1.2 Corrosion Pits Depth Measurements

Corrosion pits depths (Tables 2 and 4) were measured with a KS Tools digital depth gauge 300.0550 with a measurement range of 0 mm to 40 mm and a measurement uncertainty of ± 0.01 mm, the diameter of the needle was 2 mm.

We performed 14 to 18 measurements at eleven measurement spots, in size approximately 1.5 m × 1.5 m. The deepest pit of 3.45 mm was measured at the measuring point number 11. Comparable to ultrasonic measurements, the depth of pits increases towards the center of the tank bottom.

1.3 Calculations and Evaluations of Measurements

From the extreme values of spot measurement series, we compiled an empirical cumulative distribution using the average ranking method **[12]**. This is optimized non-linearly with a selected statistical distribution **[12]** and **[20]**. The series of corrosion rates (Table 5) was evaluated with a normal distribution **[12]**, **[13]**, and **[20]**. Extreme values of the pit depth (Table 4) and the remaining thickness of the bottom plates (Table 3) were evaluated with double exponential distributions of minimum and maximum values. The optimized empirical cumulative distributions allow us to estimate the maximum corrosion rate, the lowest residual thickness, and the deepest ulcers at the bottom of the tank (Table 6), with a chosen confidence of 99 % or return interval 100 with assumption that determined cumulative distributions are valid over all internal surfaces of upper tank bottom **[12]**.

Corrosion is an electrochemical process for which the exponential model (kinetics of chemical reactions) applies **[5]**, **[7]** to **[12]**:

$$x - a_0 = k(t - t_i)^n, \tag{1}$$

where x is pit depth, t_i time at which local corrosion occurs, a_0 initial value of pit depth, k and n empirical kinetic constants.

Derivation of Eq. (1) over time gives us the corrosion rate (v_{corr}):

$$v_{corr} = \left(\frac{dx}{dt}\right)_t = nk(t - t_i)^{n-1}. \tag{2}$$

Empirical kinetic constants (k, n) are calculated from the combination of Eqs. (1) and (2).

Table 2. *Pit depths [mm]*

No	Measurement point										
	1	2	3	4	5	6	7	8	9	10	11
1	0.84	0.08	1.47	0.60	0.06	0.13	1.19	1.71	0.03	2.98	2.61
2	0.56	0.20	1.86	0.84	0.12	0.07	0.41	0.19	0.00	2.62	3.16
3	0.88	0.06	3.26	1.89	0.07	0.22	0.55	1.50	0.05	0.94	2.69
4	0.55	0.11	1.20	1.12	0.05	0.09	0.96	1.39	0.09	1.36	2.09
5	0.61	0.07	1.52	1.51	0.09	0.16	0.35	0.87	0.03	2.44	2.63
6	0.91	0.17	1.43	1.70	0.05	0.07	0.47	0.67	0.04	1.91	2.58
7	0.85	0.10	1.47	0.97	0.05	0.33	0.51	1.06	0.05	2.42	2.86
8	1.48	0.14	1.75	0.52	0.04	0.07	0.91	1.49	0.13	2.54	2.73
9	0.71	0.14	1.87	2.25	0.31	0.00	1.30	1.31	0.13	2.29	2.95
10	0.71	0.03	1.18	2.50	0.33	0.09	1.06	0.85	0.08	0.85	3.31
11	0.83	0.17	1.54	1.20	0.32	0.03	0.82	0.45	0.09	1.17	3.41
12	0.63	0.00	1.89	2.34	0.06	0.39	1.21	0.99	0.13	2.63	2.93
13	0.58	0.16	2.70	1.52	0.20	0.15	0.98	2.12	0.01	1.98	3.45
14	0.70	0.14	1.32	2.19	0.21	0.19	0.49	2.52	0.20	2.02	2.95
15	0.76	0.18	0.70	2.41	0.24	0.07		2.27	0.09	2.36	2.63
16	0.79	0.07	1.51	2.40	0.26			1.58	0.08	2.32	
17	0.45	0.11	1.30	2.34	0.41			2.43	0.12		
18		0.08	1.30								

$$n = \left(\frac{dx}{dt}\right)_t \frac{\left(t - t_i\right)}{\left(x - a_0\right)}, \tag{3}$$

$$k = \frac{\left(x - a_0\right)}{\left(t - t_i\right)^n} = \frac{1}{n}\left(\frac{dx}{dt}\right)_t \left(t - t_i\right)^{1-n}. \tag{4}$$

For new plates are initial pit depths (a_0) zero. In absence of intermediate measurements, we assumed that initial time (t_i) for occurrences of local corrosion is also zero, which is valid in worst case scenario – immediate formation of pits.

The quality of the correlation is evaluated with the coefficient of determination [20]:

$$R^2 = 1 - \frac{\sum_{I=1}^{n}\left[F_{eks}\left(x\right) - F_{mod}\left(x_i\right)\right]^2}{\sum_{I=1}^{n}\left[F_{eks}\left(x_i\right) - \overline{F_{eks}}\right]^2}, \tag{5}$$

where R^2 is coefficient of determination, $F_{eks}(x_i)$ empirical cumulative distribution of measurements, $F_{mod}(x_i)$ selected theoretical cumulative distribution and $\overline{F_{eks}}$ average value of empirical cumulative distribution of measurements.

2 RESULTS

Optimization of empirical cumulative distributions significantly improved coefficient of determination for both double exponential distributions and slightly for normal distribution. Extreme values were calculated from optimized empirical cumulative distributions for 99 % confidence (Table 6), where and are location and scale parameters (Eq. (6) and (7)), mean and standard deviation for normal distribution, coefficient of determination (Eq. (5)) and estimated extreme value. Statistically estimated extreme values in comparison to measured extreme values are more conservative and presented a more reliable state of tank bottom in worst case scenario – bottom leakage.

2.1 Evaluation of the Remaining Operating Time of the Tank Bottom

Corrosion damage can be roughly divided into two groups: uniform and local corrosion. Uniform corrosion results in a general reduction in bottom plate thickness. Localized corrosion causes corrosion damage in the form of pits and cracks.

The condition of the tank bottom, from the corrosion point of view, is evaluated by the remaining thickness of the bottom plate and the depth of the pits. Evaluating the time dependence of bottom plate thickness or pit depth requires at least two sets of measurements at different time periods. In practice, the problem of corrosion is only encountered during the prescribed periodical inspection of the condition of the tank. We do not have intermediate measurements, so a linear extrapolation of the rate determination to the new state of the tank is used to predict the remaining operating time of the tank. Most

Table 3. *Recapitulation of minimum bottom plate thicknesses [mm]*

Measurement spot	1	2	3	4	5	6	7	8	9	10	11
Number of measurements	18	16	16	15	15	14	12	16	15	16	15
Average thickness [mm]	9.00	8.25	8.58	8.45	8.81	8.57	8.38	8.34	8.58	7.85	6.87
Mean thickness [mm]	8.90	8.25	8.56	8.50	8.80	8.60	8.52	8.32	8.67	7.76	6.54
Standard deviation [mm]	0.34	0.02	0.13	0.2	0.16	0.19	0.38	0.18	0.33	0.51	1.05
Minimum measured thickness [mm]	8.61	8.21	8.39	8.16	8.58	8.30	7.30	8.11	7.49	7.19	5.58

Table 4. *Recapitulation of maximum depth of corrosion pits [mm]*

Measurement spot	1	2	3	4	5	6	7	8	9	10	11
Number of measurements	17	18	18	17	17	15	14	17	17	16	15
Average pit depth [mm]	0.76	0.11	1.63	1.66	0.17	0.14	0.80	1.38	0.08	2.05	2.87
Mean pit depth [mm]	0.71	0.11	1.49	1.70	0.12	0.09	0.87	1.39	0.08	2.31	2.86
Standard deviation [mm]	0.23	0.06	0.58	0.69	0.12	0.11	0.33	0.68	0.05	0.64	0.36
Maximum measured pit depth [mm]	1.48	0.20	3.26	2.50	0.41	0.39	1.30	2.52	0.20	2.98	3.45

Table 5. *Corrosion rates in the tank [mm/year] [4]*

Measurement spot	1	2	3	4	5	6	7	8	9	10	11
Corrosion rate	0.33	0.35	0.82	0.37	1.34	0.91	0.93	1.15	1.15	1.59	1.17

Table 6. *Optimisation and estimation of extreme values for pit depth, plate thickness and corrosion rate with 99 % confidence*

Distribution	Pit depth		Plate thickness		Corrosion rates	
	Double exponential of max.		Double exponential of min.		Normal	
	Theoretical	Optimised	Theoretical	Optimised	Theoretical	Optimised
$\lambda(\mu^{(*)})$ [mm]	1.1125	1.0165	7.9060	8.2588	0.9191	0.9399
$a/(\sigma^{(*)})$ [mm]	1.0026	1.5104	0.6931	0.6323	0.4218	0.5183
R^2 [-]	0.758	0.937	0.869	0.928	0.938	0.945
x [mm]	5.7	8.50	4.7	5.1	1.9	2.1

Table 7. *Empirical model parameters calculation for active dissolution – Eq. (1), and Figs. (3), (4) and (5)*

Time [years]	Pit Depth		Plate thickness			
	Measured	Estimated	Measured / (1)nominal Class C		Estimated / (1)nominal Class C	
0			8.0 mm(1)	9.4 mm(1)	8.0 mm(1)	9.4 mm(1)
7	3.5 mm	8.5 mm	5.6 mm		5.1 mm	
Empirical calculated parameters for Eq. (1):						
n	4.3420	1.7624	6.1901	3.9215	5.1655	3.4837
k	0.0007386	0.2754	0.00001421	0.001854	0.0001250	0.004891

of material is lost due to uniform corrosion. Local corrosion represents only small portion of overall loss but presents major threat for tank bottom tightness due to significantly higher corrosion rates. Local corrosion rates, with time, can vary from decreasing (passivation) to increasing (active dissolution). In absence of localized corrosion, linear extrapolation to initial known state of tank bottom may provide good corrosion rate estimate. But in case of presence of local corrosion, even one pit is enough for loss of tank bottom tightness. For evaluation of remaining service life, model for active dissolution is more appropriate. [1], [4], [12], and [21] to [23].

2.2 Estimate Bottom Plate Thickness

The plate thickness on the bottom was evaluated using a double exponential distribution of the minimum values [12].

A double exponential distribution of minimum values was used to estimate the thickness of the bottom plate:

$$F_{-I}\left(x\right)=1-\exp\left[-\exp\left(\frac{x-\lambda}{\alpha}\right)\right], \qquad (6)$$

where $F_{-I}(x)$ is the cumulative distribution function of the minimum values, the location parameter, and is the distribution width parameter.

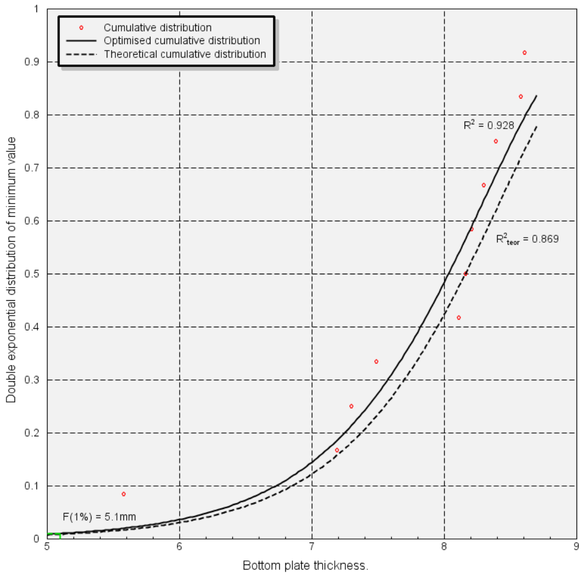

Fig. 1. *Estimate of minimum bottom plate thickness*

The measured minimum values for each measurement spots were subjected to empirical cumulative distribution using the average ranking method. This was optimized as double exponential distribution of minimum values, using the Newton-Raphson algorithm (Fig. 1). The minimum bottom plate thickness 5.1 mm (with 99 % confidence) was estimated from an optimized double exponential cumulative distribution of minimum values.

2.3 Evaluation of the Maximum Depth of Pits

The pit depths on the bottom were evaluated using a double exponential distribution of the maximum values [12].

We used (Gumbel's) distribution to evaluate the maximum depth of pits:

$$F_{I}\left(x\right)=\exp\left[-\exp\left(-\frac{x-\lambda}{\alpha}\right)\right], \qquad (7)$$

where $F_{-I}(x)$ is the cumulative distribution function of maximum values, λ is the location parameter, α is the distribution width parameter.

The maximum measured depths for each measurement site were subjected to empirical cumulative distribution using the average ranking method. This was optimized as double exponential distribution of maximum values with the Newton-Raphson algorithm (Fig. 2). The maximum pit depth 8.5 mm (with 99 % confidence) was estimated from the optimized double exponential cumulative distribution of maximum values.

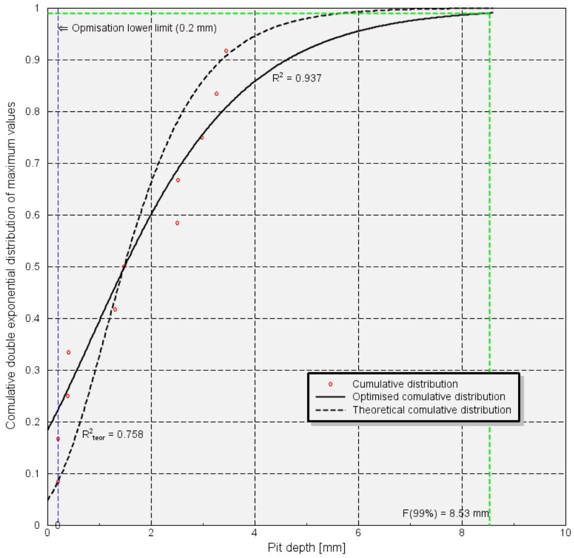

Fig. 2. *Evaluation of the maximum depth of pits*

3 DISCUSSION

The definition of time models for the evaluation of the remaining operating life of the bottom of the tanks requires the implementation of many series of measurements of corrosion parameters (plate thickness, depth of pits) after different time periods of operation, which are usually not available or have not been carried out. Therefore, linear extrapolation is used to predict the remaining service life of tank bottoms. In the past, the relatively poor reliability of linear extrapolation of corrosion parameters led to the development of statistical methods for the evaluation of extreme values, which allowed us to make more reliable estimates of the remaining service life. The statistics of extreme values allow us to more conservatively predict critical corrosion parameters, such as the minimum bottom plate thickness and the maximum depth of pits [12]. Especially in case of local corrosion presence.

Evaluating corrosion rate allowed us to use a real-time model to predict the remaining service life of the tank. Compared to linearly extrapolated time models, exponential time models allow for a more reliable prediction of the remaining operating life of the tank.

In our case, the estimation of corrosion rate, based on the linear extrapolation of bottom plate thicknesses, to the initial design state, was in the range from 0.6 mm/year to 0.7 mm/year. The rate of corrosion in the linear extrapolation of pit depths was in the range of 0.5 mm/year to 1.2 mm/year.

Estimated rate of corrosion (2.1 mm/year) from empirical normal distribution and even max. measured corrosion rate (1.6 mm/year) are significantly higher than estimation with linear extrapolation. Even with additional 1.4 mm from upper allowed initial thickness of plates, we failed to estimate actual corrosion rates in tank, with linear extrapolation of extreme values. Therefore, we are of the opinion that from the point of view of predicting the remaining operating life of the tank, empirical model for active dissolution [12] is a better solution.

3.1 Prediction of the Remaining Operating Life of a Tank Bottom

The established and prescribed way of predicting the remaining operating life of the tank bottom is based on linear extrapolation of the established tank condition [4], and [24]. The rate of corrosion is evaluated linearly, based on comparison with previous measurements of bottom plate thickness and depth of pits or to the initial design state. When evaluating the state of the tank bottom, estimated extreme statistical values [4], [12], [21], [22], and [25] are conservatively used instead of direct measurements.

To predict the remaining operating life, in addition to the condition assessment, an assessment of the corrosion rate based on transient measurements or even the condition of the initial design of the tank bottom is essential. The long intervals between prescribed periodical inspections (10 years or more) and the high costs associated with carrying out inspections practically make it impossible for us to carry out more frequent condition measurements.

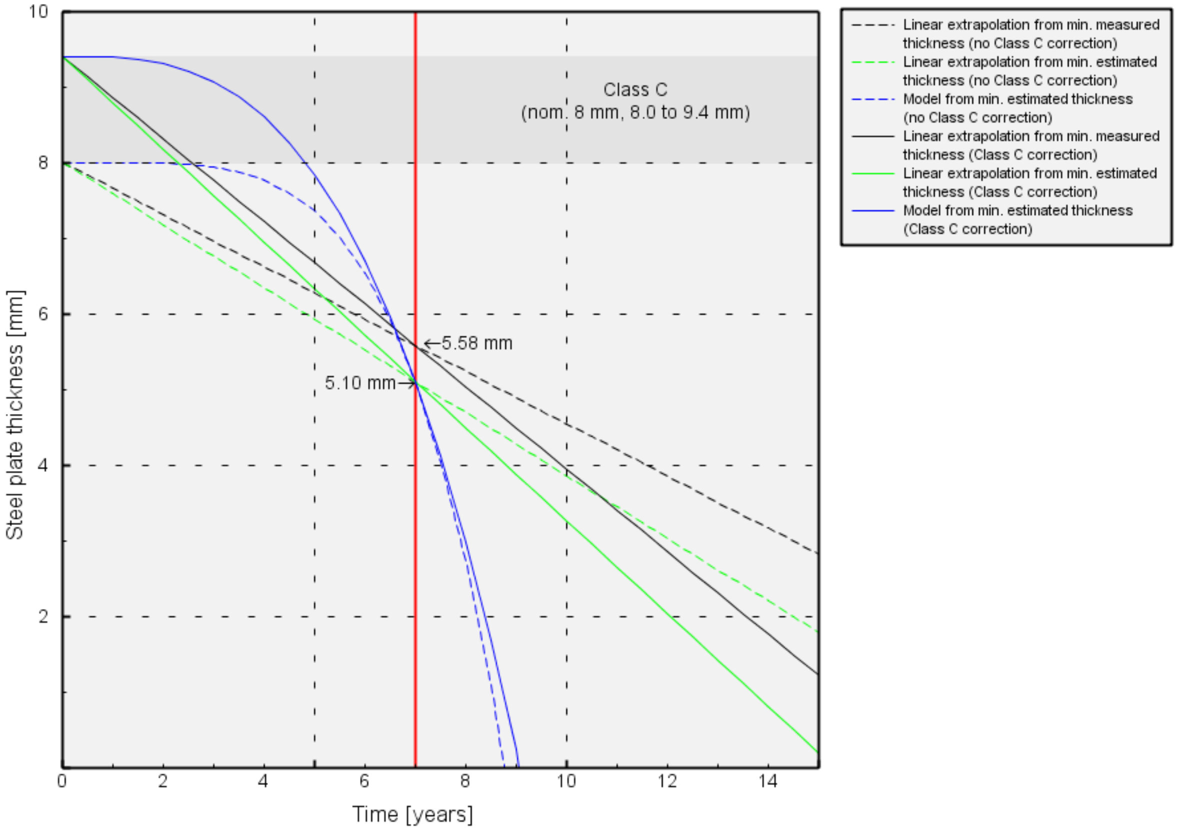

Fig. 3. *Prediction of service life from ultrasonic bottom plate thickness measurements: Comparison of empirical model (Eq. (1)) with established linear extrapolation model, based on minimal measured and minimal estimated plate thickness to initial state; Effect of Class C plate thickness tolerances on service life is also presented*

The problem of predicting the remaining operating life is therefore only encountered when corrosion is discovered at the bottom of the tank.

The material for bottom plate is standardized into classes that, among other things, define thickness tolerances. The most demanding class "C" according to EN 10029 **[17]** is usually used for the bottom of the tanks, which does not allow negative deviations from the nominal plate thickness. However, it allows limited positive deviations. In the case of our tank bottom, plate with a nominal thickness of 8 mm was used, which allows a maximum thickness of 9.4 mm.

In the case where the initial state of the bottom plate is defined only nominally, when evaluating the corrosion rate, we are confronted with the designed state, where the thickness of the bottom plate is defined in the interval between the nominal and the maximum permissible thickness of the bottom plate. In our case, the projected bottom plate thickness is between 8 mm and 9.4 mm. There is a significant difference between the corrosion rates estimated based on the nominal and the maximum allowable thickness (Fig. 3). For example, depending on plate thickness interval, corrosion rates (9.4 mm to 5.1 mm) per 7 years or (8.0 mm to 5.1 mm) per 7 years. Even much greater than the difference in estimated corrosion rates between the minimum measured and the minimum statistically estimated bottom plate thickness.

The reliability of the corrosion rate estimation when intermediate measurements are not available can also be strongly influenced by the time of corrosion initiation. The later the time of initiation, the higher the corrosion rate. When evaluating the rate of corrosion based on measurements of the depth of corrosion damage, the influence of thickness tolerances for the bottom plate class does not apply, since there are no corrosion pits at the start of operation. The influence of the bottom plate class is shown in the prediction of the remaining service life, since the exceeded nominal thickness of the bottom plate cannot reliably predict failure.

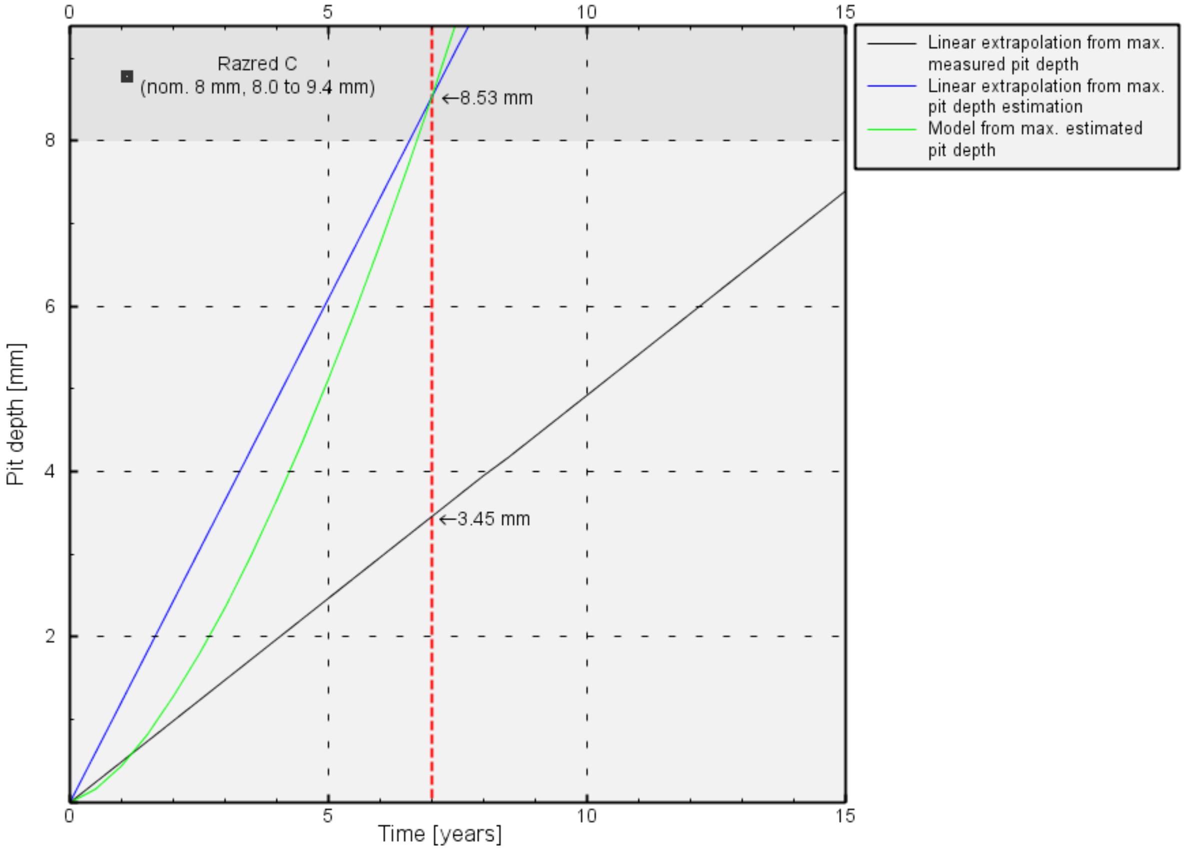

Fig. 4. *Prediction of operating life based on corrosion pit depth measurements: Comparison of empirical model (Eq. (1)) with established linear extrapolation model, based on maximal measured and maximal estimated pit depth to initial state*

The linear corrosion prediction is also strongly influenced by the initiation time of local corrosion. From the point of view of the linear prediction of the corrosion rate, based on the designed state, due to the lack of knowledge of the initiation time, we underestimated the corrosion rate.

Linear predictions of the remaining operating life of the tank bottom, in the absence of intermediate measurements of the tank condition, are not reliable.

When evaluating the measurements with the double statistic of extreme values, we found an interesting difference between ultrasound and pit depth measurements. The difference between the measured and estimated extreme values is significantly higher and thus more conservative when measuring the depth of pits than when measuring the bottom plate thickness (Figs. 3 and 4).

Evaluating the rate of corrosion in conjunction with an assessment of the condition of the tank allows us to use the empirical model (Eq. (1), Table 7) to predict the remaining service life of the tank bottom. Unreliability of the initial plate thickness and unknown initiation time only affect the shape of the empirical model curves for plate thickness, (Figs. 3 and 4).

With the empirical model of bottom plate thicknesses (Fig. 3), the unreliability of initial plate thickness is reflected in significantly smaller differences compared to linear models. The empirical model that considers the minimum initial bottom plate thickness is more conservative compared to the model that considers the maximum allowable thickness, due to higher value of parameter . Curve shape parameters are significantly above value 1. Corrosion rates (Eq. (2)) increase through time. Parameter is corrosion rate constant rather than corrosion rate as in linear approximations of empirical model in Eq. (1).

The exponential model for pit depth is more conservative compared to the linear model, but the difference is significantly smaller compared to

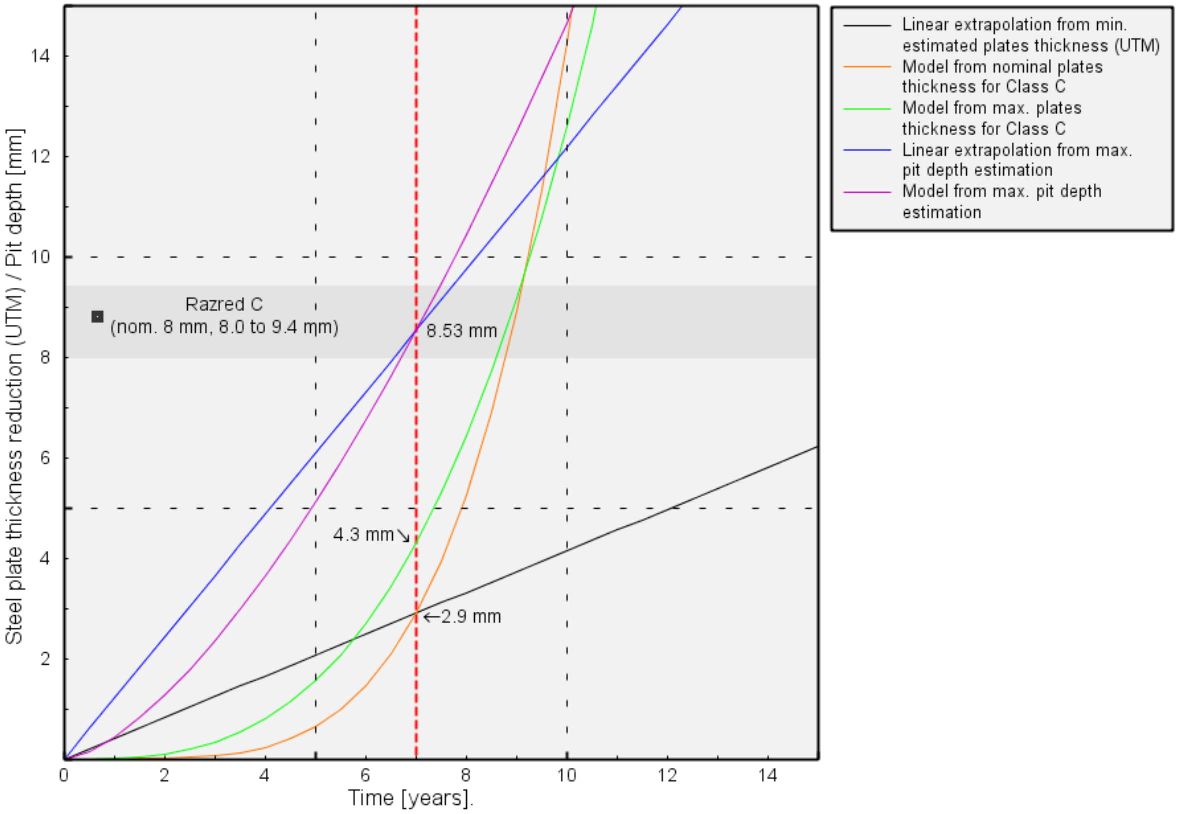

Fig. 5. *Comparison of models for predicting the remaining service life of the tank bottom: Informative comparison of empirical models (Eq. (1)) for pit depth and plate thickness measurements; For direct comparison of reliability, steel plate thickness reduction is calculated as difference between initial plate state and empirical model for plate thickness (red and green curve); Additional lines for linear extrapolation, based on statistically estimated values for maximal pit depth and minimal plate thickness are added*

models for bottom plate thickness based on ultrasound measurements.

Reliable comparison of bottom plate thickness model with pit depth models is not possible (Fig. 5). Ultrasonic measurements on the uneven surface of the bottom plate give us the thickness between the apparent plane in the pit profile and the bottom surface of the bottom plate. Initial interval of plate thickness prevents any reliable estimation of uniform corrosion. Pit depth measurements do not consider thickness loss due to uniform corrosion and are limited by the diameter of the depth gauge needle.

Depth of pits or the thinning of the bottom plate at which the bottom of the tank fails is equal to the nominal thickness of the bottom plate. The exception is the empirical models, which considers the initial thickness of plates 9.4 mm (Fig. 5). In our case, after seven years of operation of the tank, we were faced with a leak in the bottom of the tank, which is also confirmed by the statistical analysis of the depth of the pits.

4 CONCLUSION

In the experiment, we compared different models for predicting the remaining operational life of the tank bottom. Conventional linear time models for predicting the remaining operating life of the tank bottom **[4]**, and **[24]** are not reliable in the case of local forms of corrosion.

Empirical model in Eq. (1) enables us to make better predictions of the remaining operational life of the tank bottom, which require the implementation of several series of measurements of the tank's condition during its operational period. In practice, data on the state of the tank bottom within the legally prescribed inspection intervals are not available to us. Therefore, the use of an exponential model to predict the remaining operating life based on the actual state of the tank bottom is not possible.

The exponential model of pit depths increase is more conservative than the linear model. The bottom plate thickness measurements, even after extreme values analysis, fail to predict tank bottom failure as the minimum estimated bottom plate thickness was 5.1 mm. The reason for this is probably related to the geometry of the probe of the ultrasonic meter and the rugged topography of the bottom plate surfaces.

When determining the condition of the bottom of the tank with ultrasound, the performance of reliable measurements requires additional grinding of the bottom plate surfaces to the depth of the pit, otherwise the measurement is not reliable due to the relatively large surface area of the measuring probe. Therefore, models for predicting the remaining service life of the tank bottom based on ultrasonic measurements (without grinding) of bottom plate thicknesses fail in case of local corrosion. The assessment of the remaining service life based on measurements of the depth of pits is more reliable and faster in the case of local corrosion, as it does not require additional preparation of the bottom plate surface for measurements.

In the water phase, the presence of salts or micro-organisms results in significantly higher corrosion rates than would be expected from the values published in the literature **[2]**, **[3]**, **[26]**, **[27]**. This confirms the established requirement for adequate service and anti-corrosion protection of tank bottoms **[28]**, **[29]**, and **[30]**.

Some empirical cumulative distributions obtained in other tanks showed bi-modal distribution patterns, when we observed different types of local corrosion on separate parts of bottom. Further studies will be focused on possible influence of type of corrosion on empirical distributions to improve estimation of extreme pit depths.

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