Improving the API 653 Corrosion Rate Methodology

For API 653 Tank Bottoms

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Abstract

The integrity of flat bottom petroleum storage tanks is critical to all stakeholders including the public. Setting the intervals too short results in inefficient use of resources and unnecessary costs as well as unnecessary vapor emissions and personnel entries to confined spaces and exposure to hazards, while setting them too long increases the potential for leaking tanks and damage to the environment. Therefore, setting internal inspection intervals for petroleum storage tanks is a critical function of API Standard 653[1] in which all stakeholders depend on the best reasonable methodology to set the time for these intervals.

API Standard 653 was published by the American Petroleum Institute in 1991. This standard has drastically reduced tank bottom leaks and other types of tank failures and has been a model for other standards development organizations throughout the world in the attempt to reign in environmental damage from petroleum storage facilities. It truly is one of the great standards that protects all stakeholders from the problems of petroleum pollution in petroleum facilities, however, it can be improved.

The claim in this paper is that the API 653 5th edition methodology for estimating corrosion rate lives of tank bottoms is flawed in a very specific regime; in this regime it is not logical and is not technically defensible. It also has a serious error in setting the internal inspection intervals that leads to systematic bottom corrosion penetration through the bottom thickness, if the linear corrosion rate (LCR) model holds.

While LCR may not be the best model nor the most accurate, it is what the entire industry uses in general for determining penetration rates of corrosion and is accepted in all industry standards throughout the world. In this paper we demonstrate why the API 653 methodology should be corrected. We also show a few minor changes that correct these problems.

To balance our perspective, there is no question that API 653 has vastly improved the performance of aboveground petroleum storage tanks and has eliminated the vast majority of leaking tanks. However, it turns out that API 653 is excessively conservative by a factor of 2 to 4 in predicting corrosion rate lives for tank bottoms when the topside corrosion rate is greater than the bottom side corrosion rate. On the other hand, it can cause tank bottoms to leak for years.

[1] Attach1 653 Reqts.pdf: API 653 5th ed, Nov 2014, Addendum 2, May 2020. Relevant Section 4.4 Tank Bottom Evaluation is reproduced here.

This paper shows the specific conditions under which this happens. More importantly, this paper shows[2] that this problem is easy to fix. At the end of this paper under commentary, compelling reasons to modify API 653 are given so that it can be an even better standard than it has been.

Overview

There are whole engineering disciplines devoted to materials and corrosion. The field is vast because there is an unlimited combination of materials and chemical environments. In petroleum storage tank work, a major focus is on the bottom corrosion of flat bottom tanks. These are typically 6 mm or ¼ inch thick, although some may be thicker. The corrosion problem may seem simple since there is a limited list of materials (usually mild carbon steel such as A36), conditions of the ground acting to corrode the underside, and conditions of the upper side acted on by the petroleum products. Yet, in spite of the reduced scope of material-environmental conditions, the factors affecting corrosion of tank bottoms seems unlimited.

A critical parameter of maintaining tank bottom integrity is setting the operating interval. Tanks are taken out of service as little as possible due to the high costs of cleaning and gas freeing the tank, as well as the pollution the removal from service causes. There is an optimal interval which is to make sure that tank bottoms do not hole through from corrosion but also are not taken out of service too soon. Calculating operating intervals based on the estimated corrosion rate of tank bottoms is important for tank owners/operators if they want to run efficient and competitive tank and terminal facilities. The operating interval is defined as the time between the current internal inspection and the next internal inspection. Internal inspections are of most interest because the inspection requires that the tank be cleaned and gas freed so that inspectors can safely enter the tank and perform detailed visual and other kinds of examinations. While setting the operating interval for the first run of a new tank bottom is governed by other criteria, the first and subsequent internal inspection are governed by the corrosion rate principles discussed in this paper.

API 653 ¶3.9 provides some guidance about how to estimate corrosion rates and has rules for computing the corrosion rate life of tanks as shown by its definition of corrosion rate:

> **3.9**
> **corrosion rate**
> The total metal loss divided by the period of time over which the metal loss occurred.

This definition represents the common industry definition of a linear corrosion rate (LCR) model. Corrosion can be non-linear. However, non-linear methods are more difficult to apply, and little tank industry work has been applied to understanding corrosion rates of tank bottoms. Hence, the tank industry normally and exclusively uses the LCR method of computing and predicting corrosion rates. The specific language from the 5th edition API 653 is shown in Appendix 1.

Although the definition above is reasonable, the algorithm given in API 653 for computing operating intervals and determining corrosion rates is not. Note that we call the methodology of API 653 an algorithm because there is no technical basis for it. *The algorithm is complex, confusing, lacks*

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[2] Attach 2 Markup.pdf: Markup showing specific changes to correct API 653.

transparency, and is not technically defensible. So why do its methods for corrosion rate determination persist? The viability of prescriptive rules and guidelines depends on whether the methods can be shown to work well. Unfortunately, there is no data and no formal studies to show it does or does not work well. The long cycle time of internal inspections makes getting the answer to the question as to how well API 653 works at preventing tank bottom leaks even more difficult. What we do know[3] is that there is some small fraction of tanks where corrosion holes have penetrated tank bottoms.

The Problem Defined

> CRA (corrosion rate algorithm) is the API 653 methodology for determining tank bottom corrosion rate life.
>
> LCR (linear corrosion rate) is the linear corrosion rate model which is the standard model.

The first step in deciphering the methodology of API 653 is to examine the language used to describe the process. This language is reproduced in Appendix 1 and coded with 3 notes highlighting the problems. The first point to be made is that although the statement "An acceptable method for calculating the minimum acceptable bottom thickness for the entire bottom or portions thereof is …". While this is not prescriptive virtually all company apply the method in ¶4.4.5.

In describing the problems we need to distinguish between what we refer to as CRA (*corrosion rate algorithm)* to distinguish it from the LCR (linear corrosion rate) method. That is because we believe the API 653 algorithm does not accurately reflect the reality of corrosion on the tank bottom and does not even hold up to its own definition of corrosion rate.

API 653 introduces the CRA ¶4.4.5 as

$$MRT = \min(RT_{bc}, RT_{ip}) - O_r \left(StP_r + UP_r \right)$$

And the definition of these symbols is shown in Appendix 1:

The equation can be rearranged to $O_r = \dfrac{\min(RT_{bc,} RT_{ip}) - MRT}{StP_r + UP_r}$ which is simply a rearrangement of the form $\text{rate (mils/year)} = \dfrac{\text{distance}\left(\text{mils}\right)}{\text{time}\left(\text{years}\right)}$ to the form $\text{time}\left(\text{years}\right) = \dfrac{\text{distance}\left(\text{mils}\right)}{\text{rate}\left(\text{mils / year}\right)}$. In this case, O_r is the time; $\min\left(RT_{bc}, RT_{ip}\right) - MRT$ is the distance; and $StP_r + UP_r$ is the rate.

[3] In one case study of a large company with over 500 tanks we found that 8 – 10 percent of the tanks that were inspected had bottom corrosion holes. In another large company we found less than 1 - 2 percent with bottom corrosion holes. Other anecdotal information comes from inspectors with boots on the ground who can attest to what proportion of tanks have holes in them. The numbers will be qualified by condition, company, type of service, etc.

There are 3 issues with Appendix 1 and they are notated 1, 2 and 3.

Issue 1: The language is ambiguous. Is StP_r based on the corroded bottom without repairs indicated by "corrosion not repaired" or is it based on corrosion not repaired but excluding repaired corrosion. Most inspectors would take the second interpretation. However, we illustrate the first interpretation throughout this presentation because it is simpler to convey the concepts and because the bottom failure rate is less than with the other interpretation. Therefore we will assume that the corrosion on the topside follows the LCR model.

Issue 2: The bottom side corrosion rate UP_r is calculated using the minimum repaired thickness *after* repairs. This thickness does not consider metal lost to corrosion. It is arbitrary and based on what is called the *repair-to thickness*. The tank could be repaired to any desired thickness, and this rate would be calculated from that value. This calculated rate has no relation to the real corrosion of the tank on the bottom side nor corrosion data collected from inspection.

Issue 3: The total implied corrosion rate is $StP_r + UP_r$. This is excessively conservative. Because the two deepest corrosion pits on the top and bottom side will virtually never be positioned such that they are lined up at exactly the same spot on the bottom; this estimate is always conservative. Note that if there is predominantly only top side or soil side corrosion, then the conservatism of the denominator is not significant. But the conservatism is maximized when the topside and bottomside corrosion rates are approximately equal.

Nomenclature

Here is an explanation of the symbols and nomenclature used in this paper. Some of them are from API 653, and some new ones are introduced for alternative calculations or simplification.

- RT_{ip}, the remaining thickness from topside, after repairs
- RT_{bc}, the remaining thickness from bottomside, after repairs
- StP_r, the maximum rate of corrosion not repaired on the top side
- UP_r, the maximum rate of corrosion on the bottom side. API 653 CRA specifies using the "minimum remaining thickness *after* repairs" (emphasis added).
- MRT, the minimum remaining thickness at the end of interval O_r
- O_r, the in-service interval of operation/years to next internal inspection or CRA interval

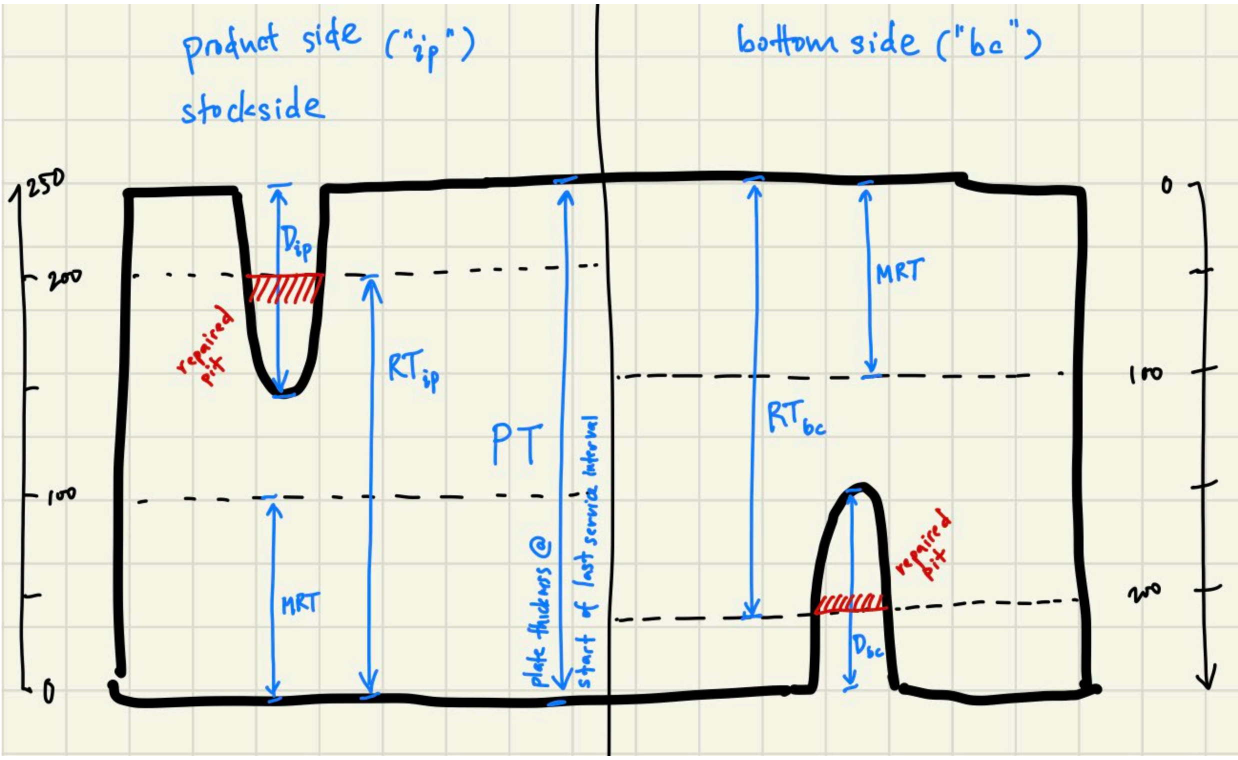

Figure 1 Diagram for CRA and LCR

- D, the maximum corrosion pit depth, measured from plate thickness. It is the maximum of D_{ip} and D_{bc}, which are the greatest pit depths for the top and bottom side, respectively.
- PT, the plate thickness at the beginning of the previous service interval – the original bottom thickness for the second inspection or the repair/patch thickness for subsequent generations of inspections
- RT, the remaining thickness after repairs. $min\left(RT_{ip}, RT_{bc}\right)$
- T, the time that the corroded, pitted, or thinned plate has been in service since the previous internal inspection/since it was installed
- r^*, the maximum corrosion rate computed with LCR, using thickness not considering repairs
- O^*, the operating interval computed with LCR

Typically, tank bottoms have the following properties (and this baseline will be assumed for this paper and the examples presented throughout):

- The bottom plate thickness at installation PT is typically 250 mils.
- The repair-to thickness will typically be from 175 - 200 mils. RT_{ip}, RT_{bc}, and PT may often be set to this if the bottom has corroded past 200 mils when repairs to the tank bottom are made.
- The desired minimum remaining thickness after the operating interval MRT is typically 100 mils.
- The operating interval O_r typically has a maximum limit of 20 years, or 30 years with a release prevention barrier. This is a limit set by API 653 ¶5 6.4.2 – the tank must be inspected by this

time limit, even if the corrosion rate is low and the bottom is not expected to corrode through by this time.

Corrosion Rate Calculations

Recall the API 653 ¶3.9 definition of corrosion rate:

3.9
corrosion rate
The total metal loss divided by the period of time over which the metal loss occurred.

Simply put, it makes sense for the corrosion rate (more specifically the linear corrosion rate, LCR) to be defined as

$$corrosion\,\mathrm{rate}(mils/year) = \frac{\mathrm{metal\ loss}(\mathrm{mils})}{\mathrm{time}(years)}$$

However, the amount of metal loss varies throughout the surface of the tank bottom. There is some general corrosion (metal loss throughout the entire regions or large surface areas) and more localized corrosion in the form of deeper pits. The chief concern is corrosion hole leakage through the bottom, and so the corrosion rate calculation uses the greatest pit depth. So, the corrosion rate should be

$$r^* = \frac{D}{T} = \max\left(\frac{D_{ip}}{T}, \frac{D_{bc}}{T}\right)$$

It is appropriate to use the worst of the top or bottom side pit depths, as the tank bottom can corrode from either side. It is unlikely, however, that it would have localized corrosion at the same spot on both sides, so the rates are not summed in LCR.

The CRA uses two corrosion rates StP_r and UP_r, which are the top and bottom side corrosion rates, respectively. These are summed in the CRA.

As indicated earlier for communication reasons, we are taking the first interpretation of the language to mean that StP_r is calculated just like the LCR: $StP_r = D_{ip}/T = r_{ip}^*$. However, UP_r is not. As noted earlier, it is calculated from the thickness *after* repairs. API 653 ¶4.4.5.1 states ". . . to calculate corrosion rate [UP_r], use the minimum remaining thickness after repairs. Assume a linear rate based on the age of the tanks." Thus, the pit depth D_{bc} is not used. Instead, it uses the minimum remaining thickness *after* repairs.

$$UP_r = \frac{PT - RT_{bc}}{T}$$

Note that PT and T are set values based on the construction of the tank and the previous inspection interval duration, and RT_{bc} can be set by the tank owner depending on their chosen repair-to thickness. This "corrosion rate" is not dependent at all upon the actual corrosion of the bottom side.

Operating Interval Calculations

The inspection interval O_r is determined in API 653 ¶6.4.2.1 for the initial inspection interval after installation/refurbishment, and in ¶6.4.2.2 for subsequent inspection intervals. The initial inspection interval is set by the design of the tank, as there are no corrosion observations made yet that could be used to predict corrosion in the future. However, the subsequent inspection intervals are to be determined by use of the measured corrosion rate and the desired minimum remaining thickness, with a maximum limit of 20 years (or 30 years with a release prevention barrier).

From the corrosion rate calculations, we would expect the O_r calculation to be simple. Firstly,

$$\text{corrosion rate}\left(\text{mils / year}\right) = \frac{\text{metal loss}\left(\text{mils}\right)}{\text{time}\left(\text{years}\right)}$$

then,

$$\text{predicted interval}\left(\text{years}\right) = \frac{\text{current thickness}\left(\text{mils}\right) - \text{desired remaining thickness}\left(\text{mils}\right)}{\text{corrosion rate}\left(\text{mils / year}\right)}$$

Using the LCR method (identified by the *), the expected calculation for the LCR operating interval O^* is:

$$r^* = \frac{D}{T}$$

$$O^* = \frac{RT - MRT}{r^*}$$

API 653, however, refers to ¶4.4.5, which is ostensibly an equation to calculate MRT. However, it is used to calculate the operating interval O_r.

$$O_r = \frac{\min(RT_{bc,} RT_{ip}) - MRT}{StP_r + UP_r}$$

While StP_r uses the top side linear corrosion rate, recall that $UP_r = \frac{PT - RT_{bc}}{T}$. PT and T are set values, but RT_{bc} can be changed by changing the repair-to thickness after the inspection. Thus, the "true" LCR bottom side corrosion rate, which is calculated from the bottom side corrosion pit depth, can be effectively ignored. Instead, the after-repair UP_r value is used instead.

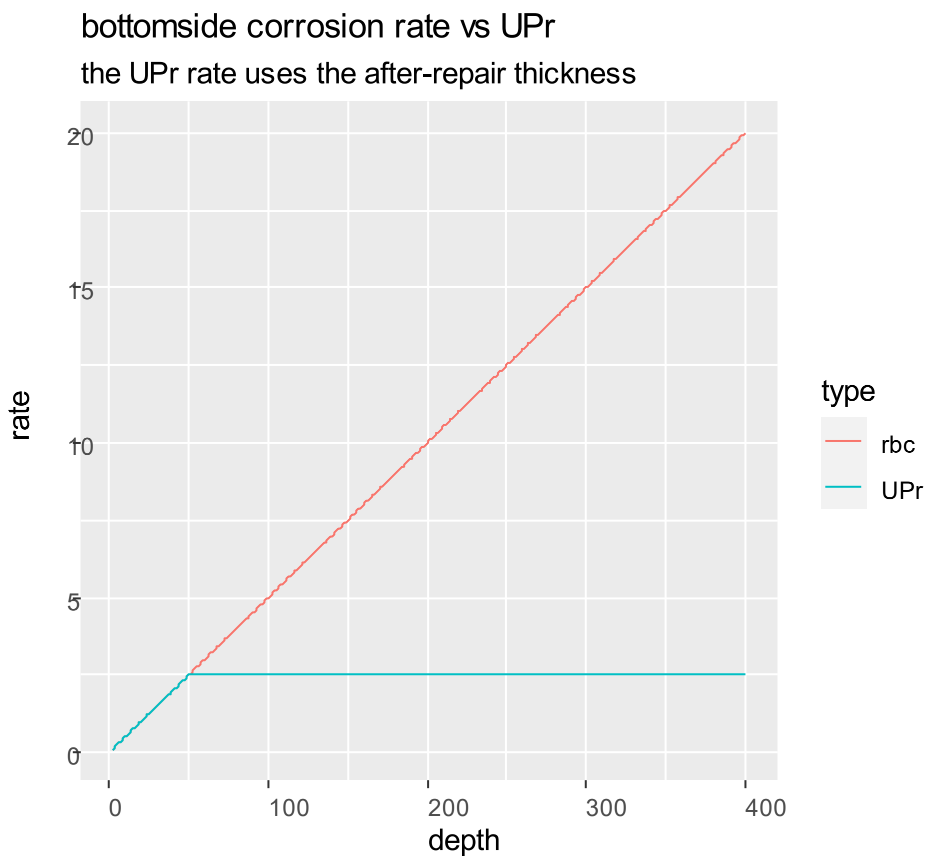

Figure 2 LCR red line, CRA blue line

Figure 2 shows how the LCR corrosion rate and UP_r diverge. The x-axis is the greatest bottom side pit depth in mils and the y-axis is the calculated corrosion rate in mils/year. “rbc” refers to r_{bc}, the LCR bottom side corrosion rate, while “UPr” is UP_r, the CRA bottom side corrosion rate. The assumption made in the chart is that the tank bottom has an original thickness of 250 mils and will be repaired to 200 mils if any pits result in plate thicknesses less than 200 mils.

If there were negligible top side corrosion and an MRT of 100 mils, the resulting LCR and CRA operating intervals could be compared as in Figure 3, where the x-axis is the greatest bottom side pit depth in mils and the y-axis is the calculated operating interval. There is a maximum of 20 or 30 years, by API 653-5 ¶6.4.2.2, so both curves would have a maximum of 20 years. However, starting at a maximum pit depth of 100 mils and increasing, the CRA rate calculation would result in a grossly unconservative estimate of the operating interval.

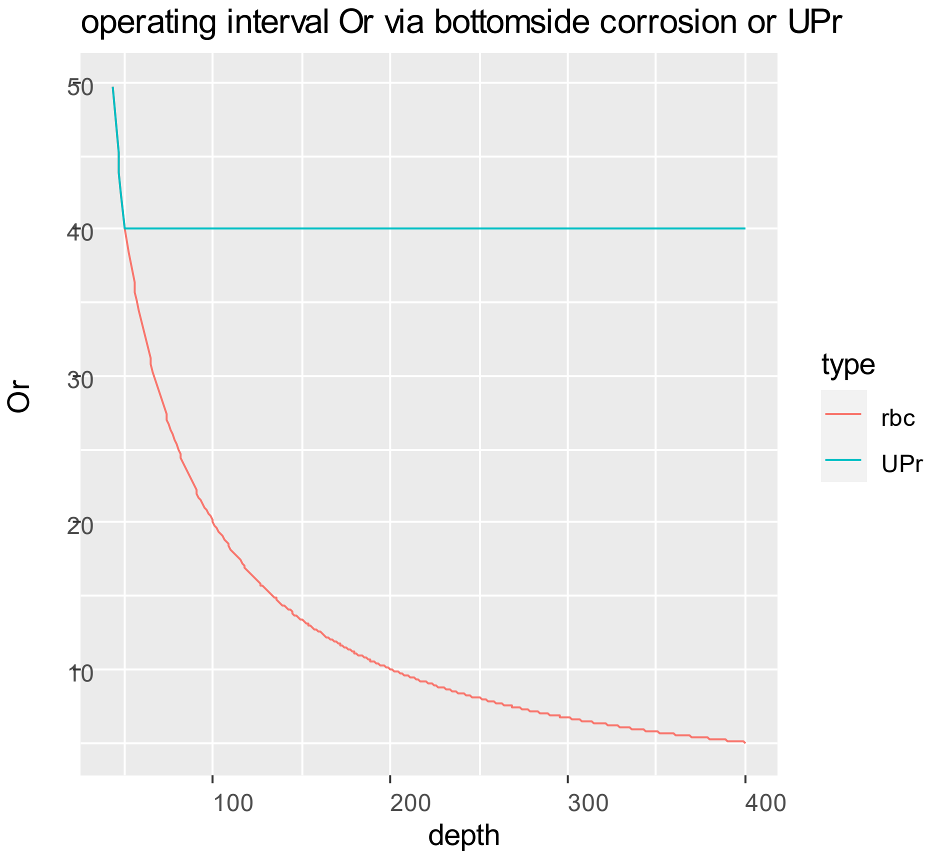

Figure 3 Red line LCR, Blue line CRA

Cases where CRA cause systematic tank bottom failures

Since the actual bottom side corrosion rate is ignored, it is possible that the CRA operating interval calculation may be incorrect. If the CRA operating interval O_r is greater than the LCR calculated interval O^*, corrosion will eat into the minimum remaining thickness MRT by the time the O_r elapses. If the values differ greatly, it is even possible that the tank bottom will form a through-hole and leak for years. It seems the use of an MRT and the summation of top and bottom side corrosion is to be a source of conservatism, to counteract the unconservative use of the after-repair corrosion rate UP_r – however, API 653 does not make it clear just how conservative or unconservative this is.

Let us compare the CRA operating interval calculation with the LCR interval calculation.

$$O^* = (RT - MRT) / r^*$$

$$O_r = (RT - MRT) / (StP_r + UP_r)$$

Let's define the time to leakage T_L. This is O^* when MRT is set to 0.

$$T_L = RT / r^*$$

If $O_r < T_L$, then the tank has not leaked by the next inspection; however, if $O_r \geq T_L$, then the tank has leaked by the next inspection. $O_r \leq T_L$ is the same as $O_r / T_L \leq 1$. Manipulating the interval ratio based on CRA and LCR:

$$O_r / T_L = \frac{(RT - MRT)/(StP_r + UP_r)}{RT / r^*}$$

$$O_r / T_L = \frac{(RT - MRT) r^*}{(StP_r + UP_r) RT}$$

$$O_r / T_L = \left(\frac{RT - MRT}{RT}\right)\left(\frac{r^*}{StP_r + UP_r}\right)$$

$$= \left(1 - \frac{MRT}{RT}\right) F \text{ where}$$

$$F = \left(\frac{r^*}{StP_r + UP_r}\right)$$

For the first inspection after installation, the repair-to thickness is assumed to be 200 mils and the MRT is set to 100 mils thus $\frac{RT - MRT}{RT} = \frac{1}{2}$ for the first of the subsequent inspection intervals.

The right term *F* requires further investigation. r^*, in this case, would be the greater of the top and bottom side corrosion rates before repairs.

$$r^* = max\left(r_{ip}^*, r_{bc}^*\right)$$

Note that $r_{ip}^* = StP_r$, since CRA uses the linear corrosion rate calculated *before* repairs. But in CRA r_{bc}^* is greater than or equal to UP_r, as UP_r is calculated from thicknesses *after* repairs, and the pit depths after repairs would only be less than or equal to the pit depths before repairs.

There are two possible cases for the factor $F = r^* / (StP_r + UP_r)$:

Case 1 Topside Corrosion Rate Higher than Underside Rate

$$\boxed{St\,\mathrm{Pr} = r^* = r_{ip}^* \geq r_{bc}^*}$$

In this case, the topside corrosion rate governs the corrosion rate life (operating interval) because the topiside corrosion rate is greater than the bottomside corrosion rate.

$$\frac{O_r}{T_L} = \left(\frac{RT - MRT}{RT}\right)\left(\frac{r^*}{StP_r + UP_r}\right)$$

$$= \frac{1}{2} F \text{ where}$$

$$F = \left(\frac{r^*}{StP_r + UP_r}\right)$$

But $\frac{r^*}{StP_r + UP_r} = \frac{r_{ip}^*}{r_{ip}^* + UP_r / r_{ip}^*} = \frac{1}{1 + UP_r / r_{ip}^*}$ so that $0 \le UP_r / r_{ip}^* \le 1$ and therefore *F* is bounded between ½ and 1. Since $\frac{1}{2} \le F \le 1$ and $\frac{O_r}{T_L} = \frac{1}{2} F \ge 1$ for failure, this implies that $\frac{1}{4} \le \frac{O_r}{T_L} \le \frac{1}{2}$.

The two important conclusions are when the topside corrosion rate is greater than the bottomside corrosion rate:

- The tank will not leak under the CRA methodology.
- The safety factor from the CRA ranges from 2 to 4 times what the LCR model predicts and therefore CRA is highly conservative.

Case 2 Bottomside Corrosion Rate Greater than Topside

$$\boxed{r^* = r_{bc}^* > r_{ip}^*}$$

$$F = \frac{r_{bc}^*}{r_{ip}^* + UP_r} = \frac{1}{\frac{r_{ip}^*}{r_{bc}^*} + \frac{UP_r}{r_{bc}^*}} = \frac{1}{R + f}$$

Then $R = \frac{r_{ip}^*}{r_{bc}^*}$ and $0 \le R \le 1$

$$f = UP_r / r_{bc}^* \text{ where } 0 \le f \le 1$$

We defined the *corrosion rate ratio* as $R = \frac{r_{ip}^*}{r_{bc}^*}$ and $0 \le R \le 1$.

To aid in our analysis, we define a *corrosion scaling factor* as $f = {UP_r}/{r_{bc}^*}$ where $0 \le f \le 1$.

Factor *f,* the CRA *corrosion scaling factor*, scales the underside corrosion rate down from r_{bc}^*. When it is 0 then there is no calculated CRA corrosion (i.e. $UP_r = 0 \neq r_{bc}^*$) but when it is 1.0 then it is the same as LCR (i.e. $r_{bc}^* = UP_r$).

Factor *f* could only be 0 if the repair to thickness were brought up to the original nominal thickness or the plate thickness from the prior out-of-service condition (no one would ever do this as this would effectively be a new bottom and these particular rules in API 653 would not apply). Realistic values of the repair to thickness used to calculate UP_r typically range from 175 to 200 mils.

Going back to the operating intervals ratio for RT = 200 and MRT = 100,

$$\begin{aligned}\frac{O_r}{T_L} &= \left(\frac{RT - MRT}{RT}\right)\left(\frac{r^*}{StP_r + UP_r}\right) \\ &= \left(\frac{200-100}{200}\right)F \\ &= \left(\frac{1}{2}\right)F\end{aligned}$$

Leakage occurs when the ratio exceeds 1:

$$\frac{O_r}{T_L} = \left(\frac{1}{2}\right)\frac{1}{R+f} > 1$$

$$F = \frac{1}{R+f} > 2$$

$$R + f < {1}/{2}$$

The other requirement for failure is that the bottomside LCR corrosion rate must corrode through the remaining thickness before the operating interval (assuming RT = 200 mils and O_r = 20 years, this would be a corrosion rate of 10 mpy.).

> When the bottomside corrosion rate is greater than the topside corrosion rate, an early leak of the bottom occurs if both of the below are true:
> - Corrosion rate exceeds 10 mpy.
> - The sum of corrosion rate ratio R and scaling factor *f* is less than ½.

Examples

Consider the following example:

In this example, the tank was installed 20 years ago, with a 250 mil bottom. Since then, it has had negligible pitting on the top side but a 210 mil pit on the bottom side. The bottom is being repaired to 200 mils. The MRT is 100 mils.

- The “true” corrosion rate, $r^* = r_{bc}$ is 210 mils/20 years = 10.5 mils/yr.
- The safe operating interval is $O^* = (200 - 100)/10.5$ = 9.52 years. It would corrode through the entire 200 mils in $T_L = 200/10.5$ = 19.04 years.

The tank engineer now calculates the second operating interval:

- The tank bottom thickness was previously 250 mils. The bottom is being repaired to 200 mils so UP_r is only (250 mils - 200 mil)/20 yrs = 2.5 mils/yr.
- The operating interval calculated from CRA is (200 – 100)/(0 + 2.5) = 40 yrs. CRA has a maximum of 20 years, so the operating interval is set to 20 years.

The tank’s next inspection is in 20 years, but it will corrode into the MRT in only 9.52 years into this interval and will hole-through at 19.04 years. There will be an approximate 1-year period where the tank bottom is leaking.

Below are 3 more examples illustrating the criteria factors F and the failure ratio.
In EX1 we have failure because $f + R = 0.42$ and the failure ratio is $O_r / T_L = 1.2$ In EX2 we have reversed the topside and bottomside corrosion rates. The value of $f + R = 5.17$ which exceeds ½ so no failure. The failure ratio is also greater than 1. In EX3 there is no failure in spite of the $f + R = 0.39$ and the failure ratio of 1.3. Failure does not occur because the CRA cap on the interval of 20 years occurs before the time to failure at 22.2 years.

			EX1	EX2	EX3
			Simulation inputs		
yrs	Or Cap	653 cap on interval	20	20	20
yrs	Icap	max cap on internal inspection interval	20	20	20
yrs	Iprev	previous interval	20	20	20
mils	PT	plate thickness previous interval or when new	250	250	250
mils	RT	min remaining thickness or repair-to thickness	200	200	200
mils	MRT	min remaining thickness at end of next interval	100	100	100
mpy	rip	topside LCR corrosion rate	3	13	1
mpy	rbc	bottomside LCR corrosion rate	13	3	9
mils	PT-RT	max bottom pit depth used by CRA for Upr	50.0	50.0	50.0
mpy	max(rip,rbc)	max of topside or bottomside corrosion rate	13	13	9
mils	Dip	deepest topside pit	60.0	260.0	20.0
mils	Dbc	deepest bottomside pit	260.0	60.0	180.0
	(RT-MRT)/RT		0.5	0.5	0.5
mpy	StPr	topside corrosion rate (LCR = CRA)	3.0	13.0	1.0
mpy	Upr	bottomside corrosion rate per CRA	2.5	2.5	2.5
yrs	Or	ACR operating interval wo cap	18.2	6.5	28.6
yrs	TL	Time to leak	15.4	15.4	22.2
	f	CRA corrosion scaling factor	0.19	0.83	0.28
	R	factor (corrosion rate ratio)	0.23	4.33	0.11
	f+R	when < 1/2 failure	0.42	5.17	0.39
	Or/TL	failure ratio	1.2	0.4	1.3
	Status	OK or failure	failure	OK	OK

Plots Describing the Above Analysis

Although Figure 4 is provided to show the region where CRA is unconservative and when the tank will fail (i.e. leakage), it is cast in terms of the corrosion rate ratio R and the scaling factor *f* and does not provide ready intuition about the problem.

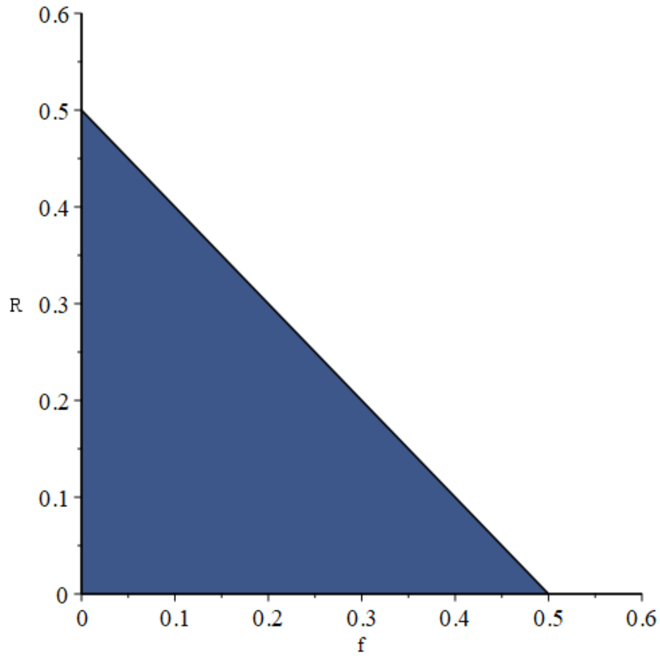

Figure 4 Boundary of leakage based on R and f

A more understandable plot (Figure 5) shows where the CRA algorithm leads to systematic failure based on the corrosion rates of the topside and bottomside and the relationship of the deepest bottomside pit to the repair thickness (i.e. f). Note that for RT=200 a corrosion rate of 10 mpy is required to penetrate RT. However, above that rate the shaded boundary shows that the topside corrosion rate can be greater than 0 but must be less than r_{be}^*. The slope of the bounding line is ½ so that for $r_{be}^* > 10$ mpy the bounding line allows for internal corrosion to range $0 \le r_{ip}^* \le \frac{1}{2} r_{bc}^*$ as shown by the shading.

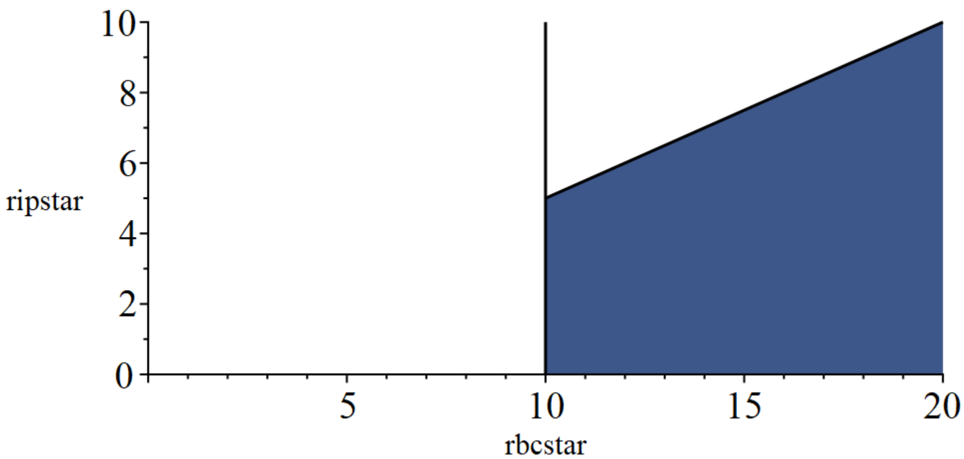

Figure 5 Bounding corrosion rates for bottom failure (shaded area is failure). Ripstar is LCR topside corrosion rate. Rbcstar is bottom side LCR corrosion rate. In this plot f ranges from 0 to 1 (unrealistic)

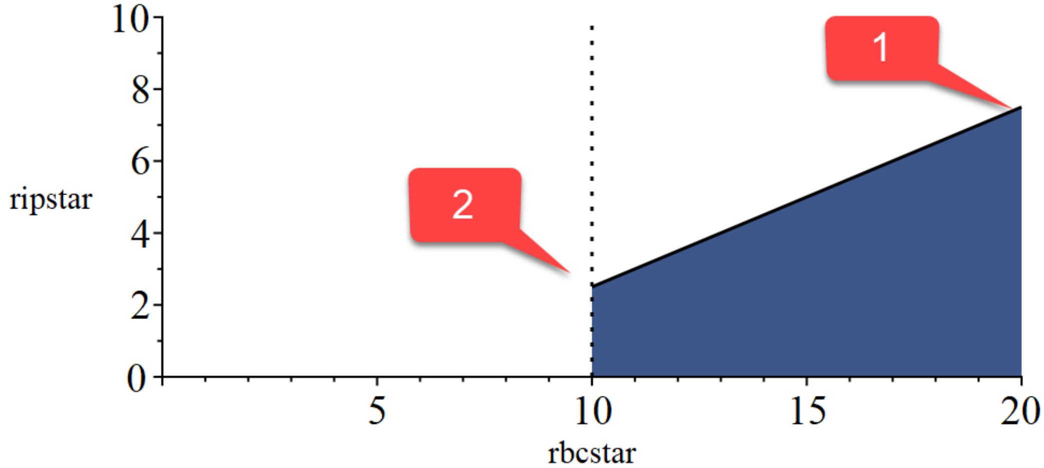

Figure 6 Shading shows leakage region in the CRA methodology. Realistic region where f ranges from 0.125 to 0.25.

In Figure 5 the line had a slope of ½ since $R + f < {}^{1}\!/_{2}$ and for f=0 the maximum corrosion rate ratio R=1/2. However, f is not really zero because no one would ever use a repair-to a thickness equal to the previous interval plate thickness.

The next question is "how is the bounding slope derived?"

For point 1 in Figure 6, we assume a 200 mil repair-to thickness RT and a bottomside corrosion rate of 20 mpy over 20 years, the theoretical corrosion depth would be 400 mils. This gives us the upper bound on f.

$$R = \frac{r_{ip}^*}{r_{bc}^*} = \frac{1}{2} - f$$

But $f = \frac{50}{400} = 0.125$ and therefore $R = 0.5 - 0.125 = 0.375$ and the y-coordinate is $0.375 \times 20 = 7.5$ mils. The 50mils is from the depth of corrosion to the RT or the original plate thickness (250) less the repair to thickness (200). The 400 mils are the depth that would have occurred in 20 years under the LCR model.

To obtain point 2 and hence the bounding slope we have $f = \frac{50}{200} = .25 \Rightarrow R = 0.5 - 0.25 = 0.25$.

Therefore, for point 2 with $r_{ip}^* = .25 r_{bc}^* = 0.25 \times 10 = 2.5$ which is the y coordinate for point 1.

The slope of the line is $\frac{7.5 - 2.5}{20 - 10} = 0.5$. The equation of the sloped bounding line can be found to be

$$\boxed{r_{ip}^* = \frac{1}{2} r_{bc}^* - 2.5, r_{bc}^* \geq 10}.$$

The slope and bounds for the vulnerable region are shown in the plots have been verified by simulations which show in Figure 7 as the bright, sloped red line.

Here is a short thought experiment: consider if corrosion rates for all API 653 tanks randomly varied from 0 to 20 mpy for both the topside and bottomside. The area of 400 (20 x 20) spanning the entirety of this range of corrosion rates would represent the total population of tanks. The area under the bounding curve is 50. The ratio of areas in this case 12.5% - that would be the percentage of failures that occur as a result of using CRA. While this is just a crude estimate and there are other values for variables that could be assigned to the CRA, it shows that the failure envelope is definitely not negligeable but is likely to be substantially larger than 1%. This alone is a compelling reason to correct CRA to the LCR methodology.

Simulations

Using simple calculations like the example above, we have simulated hundreds of thousands of cases varying the topside and bottomside corrosion rates and computing both the CRA life or LCR life or time to leakage (respectively O_r and O_r^*) and plotted the envelope where CRA yields leaking and non-leaking tank bottoms.

This is illustrated in Figure 7, with a simulation of varied combinations of top and bottom corrosion rates[4]. The x- and y-axes are the bottom and top side corrosion rates r_{bc} and r_{ip}, respectively, in mils/year. The color at each (x,y) coordinate is a function of $T_L - O_r$. If $T_L - O_r > 0$, then the tank bottom will not leak before the interval O_r elapses. If $T_L - O_r < 0$, then the tank bottom will leak before the interval O_r elapses. The red line illustrates the break-point $T_L - O_r = 0$. The bottom-right region under the bounding line is the region where the CRA calculation fails.

[4] Assumptions made in the simulation: previous thickness PT of 250 mils, repair-to thickness RT of 200 mils, minimum remaining thickness MRT of 100 mils. Both the time to leakage T_L and the API CRA operating interval O_r are capped at 20 years.

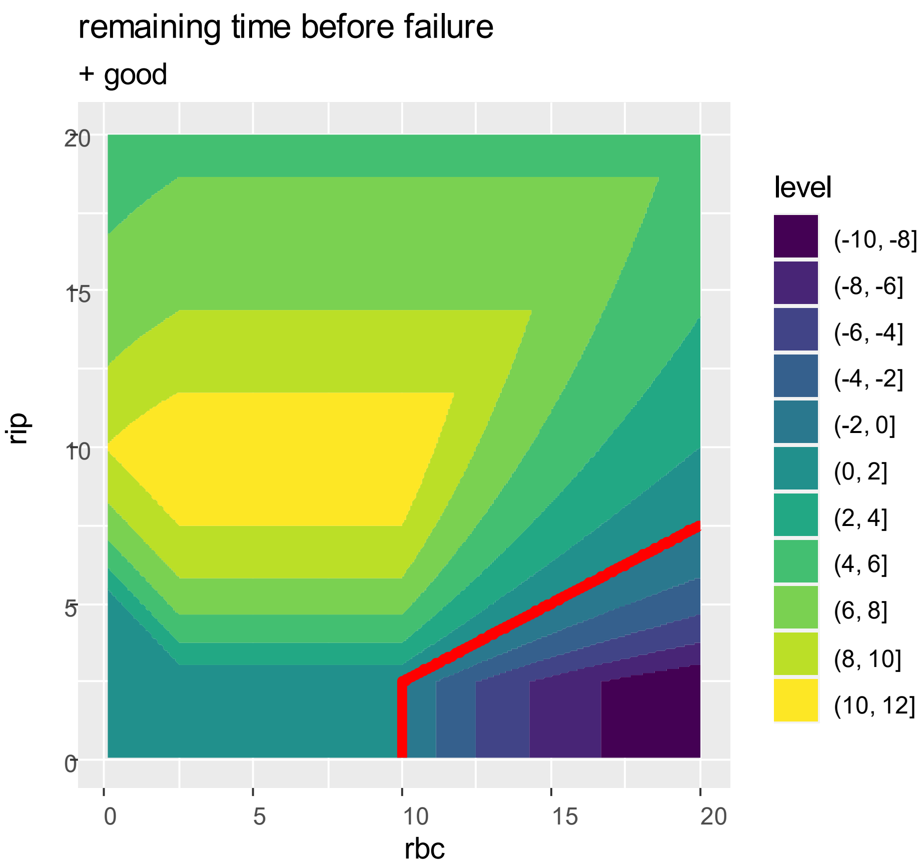

Figure 7 Figure showing where CRA produces systematic bottom leakage failures

The results of this plot are understandable, per the investigation into O_r / T_L previously discussed. When the corrosion rate is higher in the top than the bottom side, the CRA is conservative. This is because, when the top side corrosion rate is the driving factor, the CRA corrosion rate $StP_r + UP_r$ will be at least equal to or greater than the LCR rate $r^* = \max\left(r_{ip}, r_{bc}\right)$, as $StP_r = r_{ip}$ and $UP_r \leq r_{bc} < r_{ip}$. Since it is greater, this is an example when the summation of the two corrosion rates results in conservatism that overcomes the unconservative use of after-repair thickness in UP_r.

However, when bottom side corrosion is greater in the bottom than the top side, there is an issue. The CRA corrosion rate $StP_r + UP_r$ could be less than the LCR rate $r^* = \max\left(r_{ip}, r_{bc}\right)$. It depends on the inherent conservatism of top side corrosion rate's inclusion and the use of MRT.

Using CRA on both top and bottom side

Up to now we have assumed LCR on the topside but most inspectors use ACR on both sides meaning that the API corrosion rates are based on after repair thickness. Figure 8 shows what the unsafe region is. It is even larger in area that the previously worked out case. This shows that whenever corrosion rates exceed 10 mpy that failure of the tank bottom may occur.

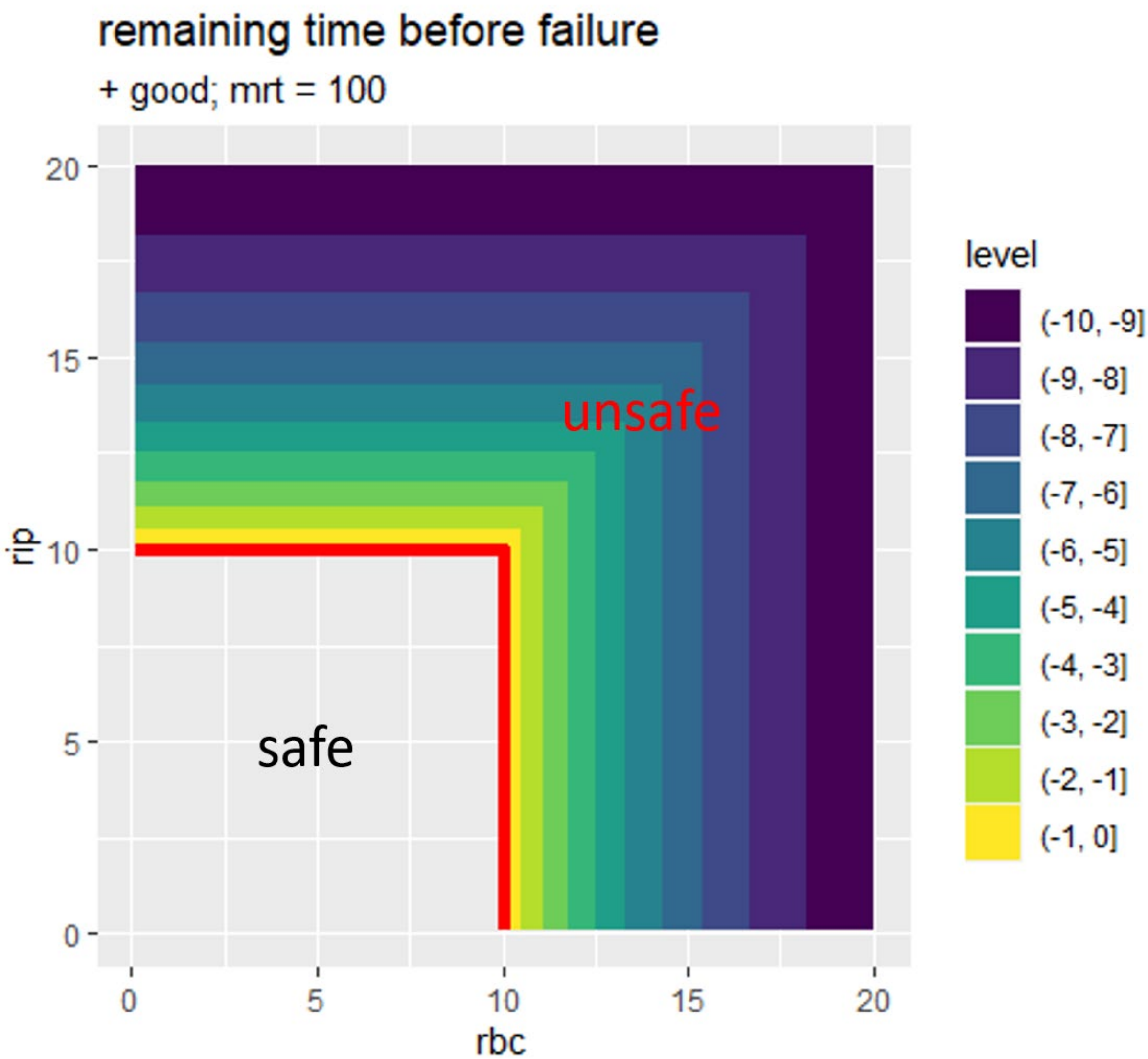

Figure 8 Using CRA on both top and bottomside

How to fix the problem

The fix is quite simple. The LCR should be independently applied to topside and to bottomside corrosion. Cleaning up the language and adding some example would assist inspectors make the right kinds of calculations.

The Pros and Cons of the change

The primary “con” for this proposed change might be the change to existing practices. Some retraining of inspectors may be required, but the change is quite simple and should be able to be addressed by both small and large inspection companies alike. A qualified inspector should be able to implement these changes without needing any special training. Certainly, the API certification program could ensure that these easy changes are executed by implementing them in the inspector certification program. Most importantly, it will make sense to any user and not provide an incomprehensible and confusing black box that takes analyses like those shown in this paper to understand.

The benefits, however, are profound:

- The CRA “black box” will be replaced by a transparent, defensible, and simple methodology that anyone can understand. In fact, the CRA has survived so long because it is not transparent and takes some effort to determine what it is really doing as demonstrated by this paper.
- Systematic tank bottom leaks caused by corrosion penetrations can be substantially reduced by removing the gap that exists in the current standard.
- Data collection on tank bottom corrosion rates can serve the needs of future industry data analysis, because it will represent actual corrosion rates whereas the CRA does not. The pool of data where inspectors have used this CRA method for decades is contaminated with incorrect bottomside corrosion rates which will haunt corrosion rate studies in the future.
- There will be a reduction in the number of leaks from tank bottoms in the new version compared to the old version of API 653.
- For API to continue to have a leadership position in worldwide standards this improvement is necessary for maintaining technical credibility.

Commentary and Recommendations

There are many corrosion rate models that may be superior to the standard LCR model. For example, a power law rate is more apt in many cases. Other models include an incubation time. However, corrosion research on these models has generally been applied to specific high alloys and corrosion environments. No public domain studies or research has been conducted on corrosion of tank steel bottoms. In the absence of these studies that could provide better models, the most appropriate model for tank bottoms remains the LCR model. It is recommended that future, properly designed data collection and analysis studies of tank bottom corrosion rates should be considered for improving the models for estimation of the tank bottom corrosion rate lives.

The examples and plots provided by this paper were based on an RT of 200 mils and an MRT of 100 mils. Other cases[5] will yield plots that vary somewhat from those shown here, however, they have the same features that were discussed and none of the principles are different that those already discussed. Keep in mind that none of this is necessary to correct API 653.

[5] PEMY Consulting, Inc. provides code to run other cases.

Appendix 1 API 653 CRA Language

4.4.5 Minimum Thickness for Tank Bottom Plate

Quantifying the minimum remaining thickness of tank bottoms based on the results of measurement can be done by the method outlined in 4.4.5.1. Other approaches such as the probabilistic method in 4.4.5.2 may be used.

4.4.5.1 An acceptable method for calculating the minimum acceptable bottom thickness for the entire bottom or portions thereof is as follows:

$$MRT = (\text{Minimum of } RT_{bc} \text{ or } RT_{ip}) - O_r\,(StP_r + UP_r)$$ 1

where

MRT is the minimum remaining thickness at the end of interval O_r. This value must meet the requirements of Table 4.4, 4.4.5.4, and 4.4.6;

O_r is the in-service interval of operation (years to next internal inspection) not to exceed that allowed by 6.4.2;

RT_{bc} is the minimum remaining thickness from bottom side corrosion after repairs;

RT_{ip} is the minimum remaining thickness from internal corrosion after repairs;

2

StP_r is the maximum rate of corrosion not repaired on the top side. StP_r = 0 for coated areas of the bottom. The expected life of the coating must equal or exceed O_r to use StP_r = 0;

UP_r is the maximum rate of corrosion on the bottom side. To calculate the corrosion rate, use the minimum remaining thickness after repairs. Assume a linear rate based on the age of the tanks. UP_r = 0 for areas that have effective cathodic protection. 3