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Action item Reference Number:

Title	Addition of Internal Liner to Thinning DF Calculation
Date:	July 27, 2020
Purpose:	Integrate the internal liner to the thinning DF calculation
Revision:	R3
Impact:	The internal liner will give credit to the thinning DF age. Merged inspection effectiveness tables to include internal liners with Thinning inspections. This will include the Baysian updating for internal liner inspections with the Thinning calculation.
Rationale:	The current edition separates the thinning DF from the internal liner DF. When the liner fails, the methodology uses the base material DF as if the internal liner never existed. This integration corrects that error.
Technical Reference(s):	None

Calculation Change	The component age will be adjusted based on the liner installation date and liner type (providing an estimated life) before applying the base material corrosion rate to calculate the Thinning DF. The internal liner module will be a part of thinning and the internal lining module section will be deleted. The inspection effectiveness tables in Annex 2.F (previously Annex 2.C) for Thinning and interner liners to include inspection credit in the Baysian updating equations.
Attachments	

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Proposed Changes and / or Wording (attach additional documentation after this point)

4 THINNING DF

4.1 Scope

The DF calculation for components subject to damage mechanisms that cause general or local thinning is covered in this section, including components with internal liners, strip lining or cladding/weld overlay. Thinning associated with external corrosion and CUI should be evaluated according to the procedures in Section 15.6.4 and Section 16.6.3, respectively.

4.2 Screening Criteria

All components should be checked for thinning.

4.3 Required Data

The basic component data required for analysis are given in Table 4.1. Component types and required geometry data are shown in Table 4.2 and Table 4.3, respectively. The data required for determination of the thinning DF are provided in Table 4.4.

4.4 Basic Assumptions

In the thinning DF calculation, it is assumed that the thinning corrosion rate is constant over time. This corrosion rate is updated based on the knowledge gained from subsequent inspections (see Section 4.5.3). An A_{rt} parameter is determined by calculating the ratio of total component wall loss (using the assigned corrosion rate during the in-service time period) to the wall thickness.

The DF is calculated using structural reliability theory[17,18,91]. A statistical distribution is applied to the thinning corrosion rate, accounting for the variability of the actual thinning corrosion rate, which can be greater than the rate assigned. The amount of uncertainty in the corrosion rate is determined by the number and effectiveness of inspections and the on-line monitoring that has been performed (see Section 4.4.2). Confidence that the assigned corrosion rate is the rate experienced in service increases with more thorough inspection, a greater number of inspections, and/or more relevant information gathered through the on-line monitoring. The DF is updated based on increased confidence in the measured corrosion rate provided by using Bayes Theorem (see Section 4.5.3 and Table 4.5) and the improved knowledge of the component condition (see Section 4.5.5, Section 4.5.6, and Table 4.6).

The composite wall may consist of three separate components that affect the Thinning DF calculation. Each component may have factors resulting in an impact on thickness and age. The three components are:

- Base Material
- Cladding Material
- Internal Lining

The base material represents the structural component of the total wall thickness and is typically carbon or low alloy steel. The cladding material represents explosion-bonded cladding or weld overlay which are typically provided to protect the base material from thinning. The internal lining represents any organic, metallic or non-metallic protection (e.g., refractory, alloy strip lining) - see Table 4.7 for more examples.

All ~~linings afford some~~internal liners provide a degree of protection from the operating environment. Many ~~linings~~liners will ~~last~~provide protection for an indefinite period of time, essentially being immune to damage mechanisms that may otherwise occur. Other ~~linings~~liners will slowly degrade with time and have a finite life. In ~~such~~ cases of liners with finite life, the age of the ~~lining~~liner (or the years since the last inspection) becomes important in ~~assigning a factor. Particularly in~~calculating the Thinning DF. In the case of organic linings, the assumption is made that the ~~lining~~liner is compatible with the environment, has operated within design temperature limits (including steam out), ~~and~~ was applied after proper surface preparation, and followed by curing of coatings and refractories or adequate heat treatment for an alloy liner. The thinning DF is calculated for a defined time period or plan period. The start of the plan period can be the component installation date with a furnished thickness, an inspection date with a reliable thickness measurement, or the date of a process service change with a reliable thickness measurement. In the DF calculation, it is assumed that thinning damage would eventually result in failure by plastic collapse or a small leak.

4.5 Determination of the DF

4.5.1 Overview

The following sections provide additional information and the calculation procedure to determine DF.

Uncertainty in the component condition is determined with consideration for the corrosion rate assigned (see Section 4.5.2 and Section 4.5.3) and an improved confidence in the assigned rate provided by subsequent inspection (Section 4.5.5).

4.5.2 Corrosion Rate

The corrosion rate can be obtained by several methods, as follows.

a) Calculated—Annex 2.B of this document provides conservative methods for determining a corrosion rate for various corrosion environments.

b) Measured—These are based on recorded thicknesses over time at condition monitoring location(s) (CMLs). See API 510[15] and API 570[16] for definition of CML.

c) Estimated—A corrosion specialist experienced with the process is usually the best source of providing realistic and appropriate estimated rates. See API 510[15] and API 570[16] for a definition of corrosion specialist.

As discussed in Section 4.4, the thinning corrosion rate is assumed to be constant over the plan period. For this reason, using long-term average corrosion rates is recommended for the DF calculation. Since the corrosion rate in practice may not be constant over time, use of short-term corrosion rates can lead to overly conservative and, in some cases, nonconservative results.

The measured corrosion rate should be used, if available. If a measured corrosion rate based on inspection history is not available, an estimated corrosion rate based on expert advice may be used to assign the expected corrosion rate, or a calculated corrosion rate may be determined for each potential thinning mechanism using Annex 2.B. If multiple thinning mechanisms are possible, the maximum corrosion rate should be used. If cladding/weld overlay is present, the cladding/weld overlay will corrode prior to corrosion ~~is applied to~~being applied to the base material. If an internal liner is present, the liner will provide corrosion protection for the liner remaining life before corrosion initiates on the base material.

4.5.3 Corrosion Rate Confidence Levels

The corrosion rate in process equipment is often not known with certainty. The ability to state the corrosion rate precisely is limited by equipment complexity, process and metallurgical variations, inaccessibility for inspection, and limitations of inspection and test methods. The best information comes from inspection results for the current equipment process operating conditions. Other sources of information include databases of plant experience or reliance on a knowledgeable corrosion specialist.

The uncertainty in the corrosion rate varies, depending on the source and quality of the corrosion rate data. For general thinning, the reliability of the information sources used to establish a corrosion rate can be put into the following three categories.

a) Low Confidence Information Sources for Corrosion Rates—Sources such as published data, corrosion rate tables, and expert opinion. Although they are often used for design decisions, the actual corrosion rate that will be observed in a given process situation may significantly differ from the design value.

b) Medium Confidence Information Sources for Corrosion Rates—Sources such as laboratory testing with simulated process conditions or limited in situ corrosion coupon testing. Corrosion rate data developed from sources that simulate the actual process conditions usually provide a higher level of confidence in the predicted corrosion rate.

c) High Confidence Information Sources for Corrosion Rates—Sources such as extensive field data from thorough inspections. Coupon data, reflecting five or more years of experience with the process equipment (assuming significant process changes have not occurred), provide a high level of confidence in the predicted corrosion rate. If enough data are available from actual process experience, the actual corrosion rate is very likely to be close to the expected value under normal operating conditions.

Thinning DF calculations are based on the probability of three damage states being present. The three damage states used in Section 4.5.7 are defined as follows.

a) Damage State 1—Damage is no worse than expected, or a factor of 1 applied to the expected corrosion rate.

b) Damage State 2—Damage is somewhat worse than expected, or a factor of 2 applied to the expected corrosion rate.

c) Damage State 3—Damage considerably worse than expected, or a factor of 4 applied to the expected corrosion rate.

General corrosion rates are rarely more than four times the expected rate, while localized corrosion can be more variable. The default values provided here are expected to apply to many plant processes. Note that the uncertainty in the corrosion rate varies, depending on the source and quality of the corrosion rate data. Table 4.5 provides suggested probabilities (prior probabilities) for the damage states based on the reliability of the information sources used with Bayes Theorem. However, the user may choose to customize the prior probabilities based on actual experience and confidence in the measured thickness values.

4.5.4 Thinning Type

Whether the thinning is expected to be localized wall loss or general and uniform in nature, this thinning type is used to define the inspection to be performed. Thinning type is assigned for each potential thinning mechanism. If the thinning type is not known, guidance provided in Annex 2.B should be used to help determine the local or general thinning type expected for various mechanisms. If multiple thinning mechanisms are possible and both general and localized thinning mechanisms are assigned, the localized thinning type should be used.

4.5.5 Thickness and Age

The thickness used for the DF calculation is either the furnished thickness (the thickness at the start of component in-service life) or the measured thickness (the thickness at any point of time in the component in-service life as a result of an inspection).

A furnished thickness may be replaced with a measured thickness as a result of a high-quality inspection (for thinning and external corrosion, as applicable) and high confidence in the measurement accuracy. Key reasons for replacing the furnished thickness with a measured thickness are as follows.

a) The component service start date when combined with a reasonably conservative corrosion rate predicts an unrealistically high wall loss when the measured wall loss based on quality inspection is much lower than predicted.

b) The process conditions differ significantly from historical service conditions that are the basis for historical measured corrosion rate.

c) The furnished thickness based on design is significantly different than the thickness measured by a baseline inspection or lack of reliable baseline data.

The start date for DF calculation should be consistent with the date of the installation in the case of a furnished thickness, or date of inspection in the case of a measured thickness. The inspection credit for the DF calculation should be only for those inspections performed during the time period assessed. Inspection performed prior to the start date is not typically included in the DF calculation.

The component corrosion rate is used to calculate DF and is assumed to be constant over time. Since this is not the case in reality, using long-term average rates for the current process conditions may be the preferred rate to use.

4.5.6 Inspection Effectiveness

Inspections are ranked according to their expected effectiveness at detecting thinning and correctly predicting the rate of thinning. Table 4.6 provides the conditional probabilities for each inspection effectiveness category in the thinning DF calculations. These probabilities are used with the three damage states and Bayes Theorem described in Section 4.5.3. The actual effectiveness of a given inspection technique depends on the characteristics of the thinning mechanism (i.e. whether it is general or localized).

Examples of inspection activities for specific applications are provided in Annex 2.~~C~~F for:

a) general and localized thinning that are either intrusive or nonintrusive in Table 2.~~C.8~~F.7.1 and Table 2.~~C.8~~F.7.2,

b) buried components in Table 2.~~C.7~~F.6.1,

~~c) general and localized thinning applied to AST shell courses and bottoms in Tables 2.C.5.1 through 2.C.5.3.~~

For localized thinning, selection of locations for examination must be based on a thorough understanding of the damage mechanism in the specific process.

The effectiveness of each inspection performed within the designated time period must be characterized in a manner similar to the examples provided in Annex 2.~~C~~F, as applicable. The number and effectiveness of each inspection is used to determine the DF. Inspections performed prior to the designated time period are typically not used to determine the DF.

~~Note that for AST bottoms, credit is given for only one inspection.~~

4.5.7 Calculation of Thinning Damage Factor

The following procedure may be used to determine the DF for thinning~~, see Figure 4.1.~~. Note that this procedure assumes that if cladding/weld overlay is present, it corrodes prior to any corrosion of the base material. If an internal liner is used, the procedure assumes that the liner prevents corrosion during the internal liner life.

a) STEP 1 – Determine the furnished thickness, t, age, ~~age, at the installation date and~~ age for the component. For components with cladding/weld overlay, determine thickness, ~~t_{cm}, if applicable~~ t_{cm} for the component from the installation date. If the component has an internal liner, determine the liner age, age_{liner} from the liner installation date.

b) STEP 2 – Determine the base material corrosion rate , $C_{r,bm}$, and the cladding/weld overlay corrosion rate, $C_{r,cm}$, as applicable, based on the material of construction and process environment, using guidance from Section 4.5.2 and examples in Annex 2.B for establishing corrosion rates.

c) STEP 3 – Determine the time in service ~~age~~, age_{tk} , since the last inspection and last known thickness ,~~t_{rdi} where t_{rdi}~~ t_{rdi} . The last know thickness is the furnished thickness, t, or measured thickness reading from a previous inspection, t_{rdi} (see Section 4.5.5).

   i. Determine the date of the last inspection with a measured thickness and calculate the service age since the inspection, age_{tk}, and the measured thickness, t_{rdi} . If no measured thickness is available, set $t_{rdi} = t$ and $age_{tk} = age$ from STEP 1.

   ii. For pressure vessels with cladding/weld overlay ~~pressure vessel components, calculated~~, calculate the remaining life of the cladding/weld overlay, age_{rc}, using the cladding/weld overlay thickness, t_{cm} and corrosion rate, $C_{r,cm}$, using Equation (2.11~~) and go to STEP 4.~~). If component does not contain cladding/weld overlay, set $age_{rc} = 0$ and go to next step.

$$age_{rc} = \max\left[\left(\frac{t_{cm}}{C_{r,cm}}\right), \quad 0.0\right] \tag{2.11}$$

   Note: t_{cm} is calculated by $t_{rdi} - t_{bm}$.

   iii. For pressure vessel components with internal liners, determine the ~~lining~~liner type and expected age using Table (4.7~~) and Table (4.8),~~), the condition of liner ~~at~~during the last inspection using Table 4.8, and remaining life of the internal liner, age_{rc} , using age_{liner} from STEP 1 and Equation (2.12). If the component does not contain an internal liner, set $age_{rc} = 0$ and go to STEP 4.

~~$age_{rc} = \frac{age_{liner}}{F_{LC}} \cdot F_{OM}$~~

$$age_{rc} = \frac{RL_{liner}^{exp} - age_{liner}}{F_{LC}} \cdot F_{liner,OM} \tag{2.12}$$

1) Adjustment for Lining Condition, F_{LC} – The adjustment factors are given in Table 4.8 based on a qualitative assessment of the lining condition.
2) Adjustment for On-Line Monitoring, ~~F_{OM}~~ $F_{liner,OM}$ – Some lined components have monitoring to allow early detection of a leak or other failure of the lining. The monitoring allows orderly shutdown of the component before failure occurs. If on-line monitoring is used, and it is known to be effective at detecting lining deterioration, $F_{OM} = 0.1$; otherwise $F_{OM} = 1.0$. Examples of monitoring systems include thermography or heat sensitive paint (refractory linings), weep holes with detection devices (loose alloy linings), and electrical resistance detection (glass linings).

d) STEP 4 – Determine $t_{\min}$ using one of the following methods:

1) For cylindrical, spherical or head components, determine the allowable stress, S, weld joint efficiency, E, and calculate the minimum required thickness, $t_{\min}$, using component type in Table 4.2, geometry type in Table 4.3 and per the original construction code or API 579-1/ASME FFS-1 [10].
2) In cases where components are constructed of uncommon shapes or where the component's minimum structural thickness, t_c, may govern, the user may use the t_c in lieu of $t_{\min}$.
3) A specific $t_{\min}$ calculated by another method and documented in the asset management program may be used at the owner-user's discretion.

e) STEP 5 - Determine the A_{rt} parameter using Equation (2.13), using $C_{r,bm}$ from STEP 2, and age_{tk}, t_{rdi} and age_{rc} from STEP 3.

$$A_{rt} = \max\left(\frac{C_{r,bm} \cdot (age_{tk} - age_{rc})}{t_{rdi}}, 0\right) \tag{2.13}$$

f) STEP 6 – Calculate the Flow Stress, FS^{Thin}, using E from STEP 5 and Equation (2.14).

$$FS^{Thin} = \frac{(YS + TS)}{2} \cdot E \cdot 1.1 \tag{2.14}$$

Note: Use Flow Stress (FS^{Thin}) at design temperature for conservative results, using the appropriate Equation (2.15) or Equation (2.16).

g) STEP 7 – Calculate the strength ratio parameter, SR_P^{Thin}, using the appropriate Equation (2.15) or Equation (2.16). Using Equation (2.15) with t_{rdi} from STEP 3, $t_{\min}$ or t_c from STEP 4, S, and E from STEP 5, and flow stress, FS^{Thin}, from STEP 6.

$$SR_P^{Thin} = \frac{S \cdot E}{FS^{Thin}} \cdot \frac{Max(t_{\min}, t_c)}{t_{rdi}} \tag{2.15}$$

Note: The $t_{\min}$ is based on a design calculation that includes evaluation for internal pressure hoop stress, external pressure and/or structural considerations, as appropriate. The minimum required thickness calculation is the design code $t_{\min}$. Consideration for internal pressure hoop stress alone may not be sufficient. t_c as defined in STEP 54 should be used when appropriate.

1. Using Equation (2.16) with t_{rdi} from STEP 3 and FS^{Thin} from STEP 6.

$$SR_P^{Thin} = \frac{P \cdot D}{\alpha \cdot FS^{Thin} \cdot t_{rdi}} \tag{2.16}$$

Where α is the shape factor for the component type

$\alpha = 2 \text{ for a cylinder}, 4 \text{ for a sphere}, 1.13 \text{ for a head}$

Note: This strength ratio parameter is based on internal pressure hoop stress only. It is not appropriate where external pressure and/or structural considerations dominate. When t_c dominates or if the $t_{\min}$ is calculated using another method, Equation (2.15) should be used.

h) STEP 8 – Determine the number of inspections for each of the corresponding inspection effectiveness, N_A^{Thin}, N_B^{Thin}, N_C^{Thin}, N_D^{Thin}, using Section 4.5.6 for past inspections performed during the in-service time.

i) STEP 9 – Calculate the inspection effectiveness factors, I_1^{Thin}, I_2^{Thin}, I_3^{Thin}, using Equation (2.17), Prior Probabilities, Pr_{p1}^{Thin}, Pr_{p2}^{Thin} and Pr_{p3}^{Thin}, from Table 4.5, the Conditional Probabilities (for each inspection effectiveness level), Co_{p1}^{Thin}, Co_{p2}^{Thin} and Co_{p3}^{Thin}, from Table 4.6, and the number of inspections, N_A^{Thin}, N_B^{Thin}, N_C^{Thin}, N_D^{Thin}, in each effectiveness level from STEP 8.

$$\begin{aligned}
I_1^{Thin} &= Pr_{p1}^{Thin}\left(Co_{p1}^{ThinA}\right)^{N_A^{Thin}}\left(Co_{p1}^{ThinB}\right)^{N_B^{Thin}}\left(Co_{p1}^{ThinC}\right)^{N_C^{Thin}}\left(Co_{p1}^{ThinD}\right)^{N_D^{Thin}} \\
I_2^{Thin} &= Pr_{p2}^{Thin}\left(Co_{p2}^{ThinA}\right)^{N_A^{Thin}}\left(Co_{p2}^{ThinB}\right)^{N_B^{Thin}}\left(Co_{p2}^{ThinC}\right)^{N_C^{Thin}}\left(Co_{p2}^{ThinD}\right)^{N_D^{Thin}} \\
I_3^{Thin} &= Pr_{p3}^{Thin}\left(Co_{p3}^{ThinA}\right)^{N_A^{Thin}}\left(Co_{p3}^{ThinB}\right)^{N_B^{Thin}}\left(Co_{p3}^{ThinC}\right)^{N_C^{Thin}}\left(Co_{p3}^{ThinD}\right)^{N_D^{Thin}}
\end{aligned} \tag{2.17}$$

See Section 4.5.3 for guidance on selection of the prior probabilities. Conservatively, the Low Confidence Data could be chosen from Table 4.5.

j) STEP 10 – Calculate the Posterior Probabilities, Po_{p1}^{Thin}, Po_{p2}^{Thin} and Po_{p3}^{Thin} using Equation (2.18) with I_1^{Thin}, I_2^{Thin} and I_3^{Thin} in Step 10.

$$\begin{aligned}
Po_{p1}^{Thin} &= \frac{I_1^{Thin}}{I_1^{Thin} + I_2^{Thin} + I_3^{Thin}} \\
Po_{p2}^{Thin} &= \frac{I_2^{Thin}}{I_1^{Thin} + I_2^{Thin} + I_3^{Thin}} \\
Po_{p3}^{Thin} &= \frac{I_3^{Thin}}{I_1^{Thin} + I_2^{Thin} + I_3^{Thin}}
\end{aligned} \tag{2.18}$$

k) STEP 11 – Calculate the parameters, β_1^{Thin}, β_2^{Thin}, β_3^{Thin} using Equation (2.19) and assigning $COV_{\Delta t} = 0.20$, $COV_{S_f} = 0.20$ and $COV_P = 0.05$.

$$\beta_1^{Thin} = \frac{1 - D_{S_1} \cdot A_{rt} - SR_p^{Thin}}{\sqrt{D_{S_1}{}^2 \cdot A_{rt}{}^2 \cdot COV_{\Delta t}{}^2 + \left(1 - D_{S_1} \cdot A_{rt}\right)^2 \cdot COV_{S_f}{}^2 + (SR_p^{Thin})^2 \cdot COV_P{}^2}},$$
$$\beta_2^{Thin} = \frac{1 - D_{S_2} \cdot A_{rt} - SR_p^{Thin}}{\sqrt{D_{S_2}{}^2 \cdot A_{rt}{}^2 \cdot COV_{\Delta t}{}^2 + \left(1 - D_{S_2} \cdot A_{rt}\right)^2 \cdot COV_{S_f}{}^2 + (SR_p^{Thin})^2 \cdot COV_P{}^2}}, \tag{2.19}$$
$$\beta_3^{Thin} = \frac{1 - D_{S_3} \cdot A_{rt} - SR_p^{Thin}}{\sqrt{D_{S_3}{}^2 \cdot A_{rt}{}^2 \cdot COV_{\Delta t}{}^2 + \left(1 - D_{S_3} \cdot A_{rt}\right)^2 \cdot COV_{S_f}{}^2 + (SR_p^{Thin})^2 \cdot COV_P{}^2}}.$$

Where $D_{S_1} = 1$, $D_{S_2} = 2$ and $D_{S_3} = 4$. These are the corrosion rate factors for damage states 1, 2 and 3 as discussed in Section 4.5.3 [35]. Note that the DF calculation is very sensitive to the value used for the coefficient of variance for thickness, $COV_{\Delta t}$. The $COV_{\Delta t}$ is in the range $0.10 \le COV_{\Delta t} \le 0.20$, with a recommended conservative value of $COV_{\Delta t} = 0.20$.

l) STEP ~~13~~12 – For all components, calculate the base damage factor, D_{fB}^{Thin}.

$$D_{fb}^{Thin} = \left[\frac{\left(Po_{p1}^{Thin} \Phi\left(-\beta_1^{Thin}\right)\right) + \left(Po_{p2}^{Thin} \Phi\left(-\beta_2^{Thin}\right)\right) + \left(Po_{p3}^{Thin} \Phi\left(-\beta_3^{Thin}\right)\right)}{1.56E-04} \right] \tag{2.20}$$

Where Φ is the standard normal cumulative distribution function (NORMSDIST in Excel).

m) STEP 14 – Determine the DF for thinning, D_f^{Thin}, using Equation (2.21).

$$D_f^{Thin} = \max\left[\left(\frac{D_{fB}^{Thin} \cdot F_{IP} \cdot F_{DL}}{F_{OM}}\right),\ 0.1\right] \tag{2.21}$$

The adjustment factors in are determined as described below.

1) Adjustment to DF for On-Line Monitoring, F_{OM} – In addition to inspection, on-line monitoring of corrosion (or key process variables affecting corrosion) is commonly used in many processes to prevent corrosion failures. The advantage of on-line monitoring is that changes in corrosion rates as a result of process changes can be detected long before they would be detected with normal periodic inspections. This earlier detection usually permits more timely action to be taken that should decrease the POF. Various methods are employed, ranging from corrosion probes, corrosion coupons, and monitoring of key process variables. If on-line monitoring is employed, then credit should be given to reflect higher confidence in the predicted thinning rate. However, these methods have a varying degree of success depending on the specific thinning mechanism. Using knowledge of the thinning mechanism and the type of on-line monitoring, determine the on-line monitoring factor from Table 4.9. If more than one monitoring method is used, only the highest monitoring factor should be used (i.e. the factors are not additive).

2) Adjustment for Injection/Mix Points, F_{IP} – An injection/mix point is defined as a point where a chemical (including water) is being added to the main flow stream. A corrosive mix point is defined as:

- mixing of vapor and liquid streams where vaporization of the liquid stream can occur;
- water is present in either or both streams; or
- temperature of the mixed streams is below the water dew point of the combined stream.

If a piping circuit contains an injection/mix point, then an adjustment factor equal to $F_{IP}=3$ should be used to account for the higher likelihood of thinning activity at this location. If an effective inspection program specifically for injection/mix point corrosion within the injection point circuit (according to API 570) is performed, the adjustment factor is ~~$F_{IP}=1$~~ $F_{IP}=1$.

3) Adjustment for Deadlegs, F_{DL} – A deadleg is defined as a section of piping or piping circuit that is used only during intermittent service such as start-ups, shutdowns, or regeneration cycles rather than continuous service. Deadlegs include components of piping that normally have no significant flow. If a piping circuit contains a deadleg, then an adjustment should be made to the thinning DF to account for the higher likelihood of thinning activity at this location. The adjustment factor is $F_{DL}=3$. If an effective inspection program is in place to address the potential of localized corrosion in the deadleg, the adjustment factor is ~~$F_{DL}=1$~~ $F_{DL}=1$.

4.6 Nomenclature

age	is the in-service time ~~since~~that the ~~last A or B effective lining inspection~~damage is applied, years
age_{liner}	is the in-service time that ~~the~~ damage is applied to the liner, years
age_{rc}	is the remaining life of the internal liner or cladding/weld overlay associated with the date of the starting thickness, years

age_{tk}	is the component in-service time since the last inspection thickness measurement or service start date, years
A_{rt}	is the component wall loss fraction since last inspection thickness measurement or service start date
$C_{r,bm}$	is the corrosion rate for the base material, mm/year (inch/year)
$C_{r,cm}$	is the corrosion rate for the cladding/weld overlay, mm/year (inch/year)
CA	is the corrosion allowance, mm (mpy)
Co_{p1}^{Thin}	is the conditional probability of inspection history inspection effectiveness for damage state 1
Co_{p2}^{Thin}	is the conditional probability of inspection history inspection effectiveness for damage state 2
Co_{p3}^{Thin}	is the conditional probability of inspection history inspection effectiveness for damage state 3
COV_P	is the pressure coefficient of variance
COV_{S_f}	is the flow stress coefficient of variance
$COV_{\Delta t}$	is the thinning coefficient of variance
D	is the component inside diameter, mm (mpy)
D_{S_1}	is the corrosion rate factor for damage state 1
D_{S_2}	is the corrosion rate factor for damage state 2
D_{S_3}	is the corrosion rate factor for damage state 3
D_f^{Thin}	is the DF for thinning
D_{fB}^{Thin}	is the base value of the DF for thinning
E	is the weld joint efficiency or quality code from the original construction code
F_{DL}	is the DF adjustment for deadlegs
F_{IP}	is the DF adjustment for injection points

F_{LC}	is the DF adjustment for lining condition
~~F_{OM}~~ $F_{liner,OM}$	is the DF adjustment for online monitoring
FS^{Thin}	is the flow stress, MPa (psi)
I_1^{Thin}	is the first order inspection effectiveness factor
I_2^{Thin}	is the second order inspection effectiveness factor
I_3^{Thin}	is the third order inspection effectiveness factor
N_A^{Thin}	is the number of A level inspections
N_B^{Thin}	is the number of B level inspections
N_C^{Thin}	is the number of C level inspections
N_D^{Thin}	is the number of D level inspections
P	is the pressure (operating, design, PRD overpressure, etc.), MPa (psi)
Po_{p1}^{Thin}	is the posterior probability for damage state 1
Po_{p2}^{Thin}	is the posterior probability for damage state 2
Po_{p3}^{Thin}	is the posterior probability for damage state 3
Pr_{p1}^{Thin}	is the prior probability of corrosion rate data confidence for damage state 1
Pr_{p2}^{Thin}	is the prior probability of corrosion rate data confidence for damage state 2
Pr_{p3}^{Thin}	is the prior probability of corrosion rate data confidence for damage state 3
~~S~~ RL_{liner}^{exp}	is the expected remaining life of the liner using Table 4.7, years
RL_{liner}^{exp}	is the allowable stress, MPa (psi)
SR_P^{Thin}	is the strength ratio parameter defined as the ratio of hoop stress to flow stress

t	is the furnished thickness of the component calculated as the sum of the base material and cladding/weld overlay thickness, as applicable, mm (inch)
t_{bm}	is the furnished or remaining base materials thickness of the component, mm (inch)
t_c	is the minimum structural thickness of the component base material, mm (inch)
t_{cm}	is the furnished or remaining cladding/weld overlay material thickness of the component, mm (inch)
t_{min}	is the minimum required thickness based on the applicable construction code, mm (inch)
t_{rdi}	the furnished thickness, t, or measured thickness reading from previous inspection, mm (inch)
TS	is the tensile strength at design temperature, MPa (psi)
YS	is the yield strength at design temperature, MPa (psi)
α	is the component geometry shape factor
β_1^{Thin}	is the β reliability indices for damage state 1
β_2^{Thin}	is the β reliability indices for damage state 2
β_3^{Thin}	is the β reliability indices for damage state 3
Φ	is the standard normal cumulative distribution function

4.7 Tables

Table 4.1—Basic Component Data Required for Analysis

Basic Data	Comments
Start date	The date the component was placed in service.
Thickness, mm (in.)	The thickness used for the DF calculation that is either the furnished thickness or the measured thickness (see Section 4.5.5). Consider base material thickness and cladding/weld overlay thickness, if applicable.
Corrosion allowance, mm (in.)	The corrosion allowance is the specified design or actual corrosion allowance upon being placed in the current service.
Design temperature, °C (°F)	The design temperature, shell side and tube side for a heat exchanger.
Design pressure, MPa (psi)	The design pressure, shell side and tube side for a heat exchanger.
Operating temperature, °C (°F)	The highest expected operating temperature expected during operation including normal and unusual operating conditions, shell side and tube side for a heat exchanger.
Operating pressure, MPa (psi)	The highest expected operating pressure expected during operation including normal and unusual operating conditions, shell side and tube side for a heat exchanger.
Design code	The design code of the component containing the component.
Equipment type	The type of equipment.
Component type	The type of component; see Table 4.2.
Component geometry data	Component geometry data depending on the type of component (see Table 4.3).
Material specification	The specification of the material of construction, the ASME SA or SB specification for pressure vessel components or of ASTM specification for piping and tankage components. Data entry is based on material specification, grade, year, UNS number, and class/condition/temper/size/thickness; these data are readily available in the ASME Code [12].
Yield strength, MPa (psi)	The design yield strength of the material based on material specification.
Tensile strength, MPa (psi)	The design tensile strength of the material based on material specification.
Weld joint efficiency	Weld joint efficiency per the Code of construction.
Heat tracing	Is the component heat traced? (Yes or No)

Table 4.2—Component and Geometry Types Based on the Equipment Type

Equipment Type	Component Type	Geometry Type
Compressor	COMPC, COMPR	CYL
Heat exchanger	HEXSS, HEXTS	CYL, ELB, SPH, HEM, ELL, TOR, CON, NOZ
Pipe	PIPE-1, PIPE-2, PIPE-4, PIPE-6, PIPE-8, PIPE-10, PIPE-12, PIPE-16, PIPEGT16	CYL, ELB
Pump	PUMP2S, PUMPR, PUMP1S	CYL
Tank620	TANKBOTEDGE	PLT
Tank620	TANKBOTTOM	PLT
Tank620	COURSE-1-10	CYL
Tank650	TANKBOTEDGE	PLT
Tank650	TANKBOTTOM	PLT
Tank650	COURSE-1-10	CYL
FinFan	FINFAN TUBE, FINFAN HEADER	CYL RECT, CYL, ELB, HEM, ELL, NOZ
Vessel	KODRUM, COLBTM, FINFAN, FILTER, DRUM, REACTOR, COLTOP, COLMID	CYL, ELB, SPH, HEM, ELL, TOR, CON, NOZ

NOTE 1 Tank620 Course components are the primary pressure boundary in the case of a double-walled tank. The secondary wall may be considered as having an effect on leak detection, isolation and mitigation.

NOTE 2 TANKBOTEDGE refers to the near shell region of the tank bottom and is considered to extend 24 to 30 inches inside the shell. This is consistent with most annular ring dimensions. This component type can be used for tanks with or without an annular ring. TANKBOTTOM refers to the entire bottom of the tank, or if a TANKBOTEDGE is modeled, it refers to the remaining part of the tank bottom that does not include the edge component.

Table 4.3—Required Geometry Data Based on the Geometry Type

Geometry Type	Geometry Description	Geometry Data
CYL	Cylindrical shell	— Diameter — Length — Volume
ELB	Elbow or pipe bend	— Diameter — Bend radius — Volume
SPH	Spherical shell	— Diameter — Volume
HEM	Hemispherical head	— Diameter — Volume
ELL	Elliptical head	— Diameter — Major-to-minor axis ratio — Volume
TOR	Torispherical head	— Diameter — Crown radius (IR) — Knuckle (IR) — Volume
CON	Conical shell	— Diameter — Length — Cone angle — Volume
RECTNOZ	Rectangular cross section	— Length — Width — Height — Volume
NOZ	Nozzle	— Diameter — Length — Volume

Table 4.4—Data Required for Determination of the Thinning DF

Basic Data	Comments
Thinning type (general or localized)	Determine whether the thinning is general or localized based on inspection results of effective inspections. General corrosion is defined as affecting more than 10 % of the surface area and the wall thickness variation is less than 1.27 mm (50 mils). Localized corrosion is defined as affecting less than 10 % of the surface area or a wall thickness variation greater than 1.27 mm (50 mils).

Table 4.4—Data Required for Determination of the Thinning DF

Basic Data	Comments
Corrosion rate (mmpy or mpy)	The current rate of thinning calculated from thickness data, if available. Corrosion rates calculated from thickness data typically vary from one inspection to another. These variations may be due to variations in the wall thickness, or they may indicate a change in the actual corrosion rate. If the short-term rate (calculated from the difference between the current thickness and the previous thickness) is significantly different from the long-term rate (calculated from the difference between the current thickness and the original thickness), then the component may be evaluated using the short-term rate, but the appropriate time and thickness must be used. Consider base material corrosion rate and cladding/weld overlay corrosion rate, if applicable.
Inspection effectiveness category	The effectiveness category of each inspection that has been performed on the component during the time period (specified above).
Number of inspections	The number of inspections in each effectiveness category that have been performed during the time period (specified above).
On-line monitoring	The types of proactive on-line monitoring methods or tools employed, such as corrosion probes, coupons, process variables (coupons, probes, process variables, or combinations, etc.).
Thinning mechanism	If credit is to be taken for on-line monitoring, the potential thinning mechanisms must be known. A knowledgeable materials/corrosion engineer should be consulted for this information; also see API 571 [13].
Presence of injection/mix point (Yes or No)	For piping, determine if there is an injection or mix point in the circuit.
Type of injection/mix point inspection	For piping circuits that contain an injection or mix point, determine whether not the inspection program is highly effective or not highly effective to detect local corrosion at these points.
Presence of a deadleg (Yes or No)	For piping, determine if there is a deadleg in the circuit.
Type of inspection for deadleg corrosion	For piping circuits that contain a deadleg, determine if the inspection program currently being used is highly effective or not highly effective to detect local corrosion in deadlegs has been performed.
Liner Type	The type of internal liner~~ or strip liner~~, if applicable Types are provided in Table 4.7.
Liner Installation Date	The date the internal liner or strip liner was installed, if applicable
Liner Inspection Date	The date of the last internal liner inspection, if applicable
Liner Condition	The condition of the liner, if applicable
Liner On-line Monitoring	The type of on-line monitoring for liner condition, if applicable

Table 4.5—Prior Probability for Thinning Corrosion Rate

Damage State	Low Confidence Data	Medium Confidence Data	High Confidence Data
Pr_{p1}^{Thin}	0.5	0.7	0.8
Pr_{p2}^{Thin}	0.3	0.2	0.15
Pr_{p3}^{Thin}	0.2	0.1	0.05

Table 4.6—Conditional Probability for Inspection Effectiveness

Conditional Probability of Inspection	E—None or Ineffective	D—Poorly Effective	C—Fairly Effective	B—Usually Effective	A—Highly Effective
Co_{p1}^{Thin}	0.33	0.4	0.5	0.7	0.9
Co_{p2}^{Thin}	0.33	0.33	0.3	0.2	0.09
Co_{p3}^{Thin}	0.33	0.27	0.2	0.1	0.01

Table 4.7 – Internal Liner Types

Liner Type	Lining Resistance	Expected Age
Cladding/Weld Overlay	Based on corrosion review and cladding/weld overlay corrosion rate assigned. Subject to failure by corrosion.	Calculated based on thickness and corrosion rate of cladding/weld overly
Alloy Strip Liner	Subject to failure at seams, particularly on flange faces in high pressure applications. Also subject to failure at areas where plug-welding was used to secure to pressure boundary.	5-15 years
Organic Coating - Low Quality Immersion Grade Coating (Spray Applied, to 40 mils)	Limited life	1-3 years
Organic Coating - Medium Quality Immersion Grade Coating (Filled, Trowel Applied, to 80 mils)	Limited life	3-5 years
Organic Coating - High Quality Immersion Grade Coating (Reinforced, Trowel Applied, ≥ 80 mils)	Limited life	5-10 years
Thermal Resistance Service: Castable Refractory Plastic Refractory Refractory Brick Ceramic Fiber Refractory Refractory/Alloy Combination	Subject to occasional spalling or collapse	1-5 years
Thermal Resistance Service: Castable Refractory Ceramic Tile	Limited life in highly abrasive service	1-5 years
Glass Liners	Complete protection, subject to failure due to thermal or mechanical shock	5-10 years
Acid Brick	Partial protection. The brick provides thermal protection~~,~~ but is not intended to keep the fluid away from the base material.	10-20 years

Table 4.8 – Lining Condition Adjustment

Qualitative Condition	Description	Adjustment Multiplier – F_{LC}
Poor	The lining has either had previous failures or exhibits conditions, such as distortions, thinning, cracks or seepage, that may lead to failure in the near future. Repairs to previous failures are not successful or are of poor quality.	10
Average	The lining is not showing signs of excessive attack by any damage mechanisms. Local repairs may have been performed, but they are of good quality and have successfully corrected the lining condition.	2
Good	The lining is in “like new” condition with no signs of attack by any damage mechanisms. There has been no need for any repairs to the lining.	1

Table 4.9—On-line Monitoring Adjustment Factors

Thinning Mechanism	**Adjustment Factors as a Function of On-line Monitoring, F_{OM}**		
	Key Process Variable	**Electrical Resistance Probes** [c]	**Corrosion Coupons** [c]
Hydrochloric acid (HCl) corrosion	10 (20 if in conjunction with probes)	10	2
High temperature sulfidic/naphthenic acid corrosion	10	10	2
High temperature H_2S/H_2 corrosion	1	10	1
Sulfuric acid (H_2S/H_2) corrosion Low velocity ≤3 ft/s for CS ≤5 ft/s for SS ≤7 ft/s for higher alloys	20	10	2
High velocity >3 ft/s for CS >5 ft/s for SS >7 ft/s for higher alloys	10 (20 if in conjunction with probes)	10	1
Hydrofluoric acid (HF) corrosion	10	1	1
Sour water corrosion Low velocity ≤20 ft/s	20	10	2
High velocity >20 ft/s	10	2	2
Amine Low velocity	20	10	2
High velocity	10	10	1
Other corrosion mechanism	1	1	1

[a] The adjustment factors shown above are estimates providing a measure of the relative effectiveness of various on-line monitoring methods. Factors based on the user’s experience can be used as a substitute for the values presented in this table.

[b] Factors shall not be added unless noted. This table assumes that an organized on-line monitoring plan is in place that recognizes the potential corrosion mechanism. Key process variables are, for example, oxygen, pH, water content, velocity, Fe content, temperature, pressure, H_2S content, CN levels, etc. The applicable variable(s) should be monitored at an appropriate interval, as determined by a knowledgeable specialist. For example, coupons may be monitored quarterly, while pH, chlorides, etc. may be monitored weekly.

[c] The effectivness of other on-line corrosion monitoring methods (e.g. hydrogen flux, FSM, LP probe) shall be evaluated by a corrosion engineer or other knowledgeable specialist.

PART 2, ANNEX F CONTENTS

Risk-Based Inspection Methodology
Part 2—Probability of Failure Methodology
Annex 2.F—Levels of Inspection Effectiveness

2.F.1 Overview

Inspection effectiveness directly impacts the calculation of the POF. Consequently, the POF provided in Part 2 is intended to be used to provide a risk ranking and inspection plan for a component subject to process and environmental conditions typically found in the refining and petrochemical industry. Inspection effectiveness is thus an integral part of a robust inspection planning methodology.

2.F.2 Inspection Effectiveness

2.F.2.1 The Value of Inspection

An estimate of the probability of failure for a component is dependent on how well the independent variables of the limit state are known [15]. In the models used for calculating the probability of failure, the flaw size (e.g. metal loss for thinning or crack size for environmental cracking) may have significant uncertainty especially when these parameters need to be projected into the future. An inspection program may be implemented to obtain a better estimate of the damage rate and associated flaw size.

An inspection program is the combination of NDE methods (i.e. visual, ultrasonic, radiographic, etc.), frequency of inspection, and the location and coverage of an inspection. These factors at a minimum define the “inspection effectiveness”. Inspection programs vary in their effectiveness for locating and sizing damage and thus for determining damage rates. Once the likely damage mechanisms have been identified, the inspection program should be evaluated to determine the effectiveness in finding the identified mechanisms. The effectiveness of an inspection program may be limited by:

a) lack of coverage of an area subject to damage;

b) inherent limitations of some inspection methods to detect and quantify certain types of damage;

c) selection of inappropriate inspection methods and tools;

d) application of methods and tools by inadequately trained inspection personnel;

e) inadequate inspection procedures;

f) the damage rate under some conditions (e.g. start-up, shutdown, or process upsets) may increase the likelihood or probability that failure may occur within a very short time; even if damage is not found during an inspection, failure may still occur as a result of a change or upset in conditions;

g) inaccurate analysis of results leading to inaccurate trending of individual components (problem with a statistical approach to trending); and

h) probability of detection of the applied NDE technique for a given component type, metallurgy, environment (including temperature), and geometry.

It is also important to evaluate the benefits of multiple inspections and to also recognize that the most recent inspection may best reflect the current state of the component under the current operating conditions. If the operating conditions have changed, damage rates based on inspection data from the previous operating conditions may not be valid.

Determination of inspection effectiveness should consider, but not be limited to, the following:

a) equipment or component type;

b) active and credible damage mechanism(s);

c) susceptibility to and rate of damage;

d) NDE methods, coverage and frequency; and

e) accessibility to expected damaged areas.

API 580, Section 5.5 states:

> *"A complete RBI program provides a consistent methodology for assessing the optimum combination of methods and frequencies of inspection. Each available inspection method can be analyzed and its relative effectiveness in reducing failure probability can be estimated. Given this information and the cost of each procedure, an optimization program can be developed. The key to developing such a procedure is the ability to assess the risk associated with each item of equipment and then to determine the most appropriate inspection techniques for that piece of equipment."*

2.F.2.2 Inspection Effectiveness Categories

Levels of inspection effectiveness (LoIE) examples for specific equipment types (heat exchangers, pressure-relief valves, tanks, and buried components) are provided in Sections 2.F.3 through 2.F.7. The associated inspection effectiveness examples (i.e. NDE technique and coverage) for each damage mechanism are provided in Section 2.F.8 through 2.F.11.

Inspection effectiveness is graded "A" through "E", with an "A" inspection providing the most effective inspection available (90 % effective) and an "E" inspection representing an ineffective or "no inspection" category. The inspection categories presented are intended as examples and to provide a guideline for assigning inspection effectiveness grades. The effectiveness grade of any inspection technique depends on many factors such as the skill, competency, and training of inspectors, as well as the level of expertise used in selecting inspection locations. Refer to Table 2.F.2.1 for a description of the inspection effectiveness categories.

IMPORTANT NOTE

The tables describing the levels of inspection effectiveness per damage mechanism included in this annex are examples only. It is the responsibility of the user to review these tables and do the following.

- Adapt and adopt similar tables for their specific use.
- Adapt user-specific knowledge and experience to add NDE techniques and areas of concern not currently in the tables.
- Implement these strategies as part of the user's RBI program as an aid for inspection planning.

It is not the intent of this document to specifically prescribe the exact NDE and/or areas of concern for the included damage factors. The user has the responsibility to utilize competent subject matter experts to review the tables and create similar items to be utilized in the user's inspection program.

Inspections are ranked according to their expected effectiveness at detecting damage and correctly predicting the rate of damage. The actual effectiveness of a given inspection technique depends on the characteristics of the damage mechanism, and total inspection credit can be approximated to an equivalent higher effectiveness inspection in accordance with the relationships in Part 2, Section 3.4.3. Furthermore, damage factors are determined as a function of inspection effectiveness.

2.F.2.3 Tables

Table 2.F.2.1—Inspection Effectiveness Categories

Inspection Effectiveness Category	Inspection Effectiveness Description	Description
A	Highly Effective	The inspection methods will correctly identify the true damage state in nearly every case (or 80 % to 100 % confidence)
B	Usually Effective	The inspection methods will correctly identify the true damage state most of the time (or 60 % to 80 % confidence)
C	Fairly Effective	The inspection methods will correctly identify the true damage state about half of the time (or 40 % to 60% confidence)
D	Poorly Effective	The inspection methods will provide little information to correctly identify the true damage state (or 20 % to 40 % confidence)
E	Ineffective	The inspection method will provide no or almost no information that will correctly identify the true damage state and are considered ineffective for detecting the specific damage mechanism (less than 20 % confidence)

NOTE On an inspection effectiveness Category E, the terminology of Ineffective may refer to one or more of the following cases.

1. No inspection was completed.
2. The inspection was completed at less than the requirements stated above.
3. An ineffective inspection technique and/or plan was utilized.
4. An unproven inspection technique was utilized.
5. Insufficient information was available to adequately assess the effectiveness of the inspection.

2.F.3 Pressure Relief Valves

Inspection programs vary in their effectiveness for determining failure rates. Examples of inspection effectiveness for PRDs are provided in Table 2.F.3.1. The inspection effectiveness is based on the ability of the inspection to adequately predict the failure (or pass) state of the PRD being inspected. Limitations in the ability of a program to improve confidence in the failure rate result from the inability of some test methods to detect and quantify damage.

Refer to the Part 1, Section 7.2.4 for further discussion on the inclusion of inspection effectiveness ranking into the determination of POF for PRDs.

2.F.3.1 Tables

Table 2.F.3.1—Inspection and Testing Effectiveness for Pressure-relief Devices

Inspection Effectiveness	Component Type	Description of Inspection
Highly Effective A	Pressure-relief device	A bench test has been performed on the PRD in the as-received condition from the unit, and the initial leak pressure, opening pressure, and reseat pressure have been documented on the test form. The inlet and outlet piping has been examined (e.g. visual or radiographic techniques) for signs of excessive plugging or fouling ^{2}.
	Rupture disk	No inspection methods are available to meet the requirements for an A level inspection.
Usually Effective B	Pressure-relief device	A bench test has been performed; however, the PRD was cleaned or steamed out prior to the bench test. Additionally, a visual inspection has been performed where detailed documentation of the condition of the PRD internal components was made. The inlet and outlet piping has been examined (e.g. visual or radiographic techniques) for signs of excessive plugging or fouling ^{2}. An in situ test has been performed using the actual process fluid to pressurize the system. The inlet and outlet piping has been examined (e.g. visual or radiographic techniques) for signs of excessive plugging or fouling ^{2}.
	Rupture disk	The rupture disk is removed and visually inspected for damage or deformations. The inlet and outlet piping has been examined (e.g. visual or radiographic techniques techniques) for signs of excessive plugging or fouling ^{2}.
Fairly Effective C	Pressure-relief device	A visual inspection has been performed without a pop test, where detailed documentation of the condition of the PRD internal components was made. The inlet and outlet piping has been examined (e.g. visual or radiographic techniques) for signs of excessive plugging or fouling ^{2}. An assist-lift test or in situ test has been performed where the actual process fluid was not used to pressurize the system.
	Rupture disk	No inspection methods are available to meet the requirements for a C level inspection.
Ineffective D	Pressure-relief device	Valve overhaul performed with no documentation of internal component conditions; No pop test conducted/documented. Any test (bench, assist-lift, in situ, or visual test) performed without examining the inlet and outlet piping for excessive plugging or fouling.
	Rupture disk	No details of the internal component were documented.

NOTE 1 This table does not prescribe specifically to the five effectiveness categories as discussed in this annex. However, given the methodology presented, it is in agreement with the division of those categories.

NOTE 2 This table assumes the PRD is in fouling service. If the PRD is in a documented, non-fouling service, the owner–user may decide to waive the inlet and outlet piping inspection requirement.

2.F.4 Heat Exchanger Tube Bundles

2.F.4.1 Inspection Planning with Inspection History

2.F.4.1.1 Effect of Inspection on Probability of Failure

The information gained from an inspection of the tube bundle can be used to assess the actual condition of the bundle and to make adjustments to the probability of failure rate curves as necessary.

An inspection provides the following two things.

a) Reduction in condition uncertainty due to the effectiveness of the inspection resulting in the use of a more accurate failure rate curve, e.g. moving from a 50 % AU curve (no inspection history) to a curve 20 % AU curve (Usually Effective Inspection); see Section 2.F.4.1.1 b) for a discussion of inspection effectiveness.

b) Knowledge of the true condition of the bundle. This can result in a shift of the failure rate curve to the right or to the left. The current condition of the bundle could either be quantified by remaining wall thickness data or by an estimate of the remaining life that comes directly from an actual inspection; see Part 1, Section 8.6.4 c).

2.F.4.1.2 Reduction in Uncertainty Due to Inspection Effectiveness

If the tube bundle has been inspected, the uncertainty is reduced and the probability of failure at any time changes. Table 2.F.4.1 provides the recommended default values for the uncertainty applied to the failure rate curve as a function of inspection effectiveness.

At this point the concept of inspection effectiveness is introduced, similar to the methodology used in other modules. Table 2.F.4.1 provides the recommended default values for the uncertainty applied to the failure rate curve as a function of inspection effectiveness.

As improved inspection techniques are used, the amount of uncertainty decreases and the Weibull plot shifts to the right. Using this concept will result in more rigorous inspection techniques being implemented as the bundle reaches end of life.

In the example bundle problem, the impact of more rigorous inspection techniques can be seen by evaluating the predicted duration as a function of inspection effectiveness in Table 2.F.4.1. The definitions for inspection effectiveness are provided in Table 2.F.2.1.

As explained in various sections of this recommended practice, it is the responsibility of the owner operator to interpret and define inspection strategies that satisfy the level of desired effectiveness to achieve the level of confidence in the condition of the tubes (susceptible population) in question. This may involve a defined logic to establish sample size and the use of one or multiple inspection techniques to find a single or multiple potential damage mechanisms at the desired level of effectiveness. Owner/operators may elect to create inspection effectiveness tables specific to that company or site's practices that satisfy the effectiveness criteria (A, B, C, D, and E) to help with consistency.

Typical examples of heat exchanger tube damage/degradation include and are not limited to, in relation to the tubes:

a) internal and/or external, localized or generalized corrosion;

b) preferential weld corrosion;

c) pitting (may be localized or generalized, ID and/or OD);

d) cracking (circumferential and/or longitudinal);

e) fretting;

f) tube end damage (cracking and/or corrosion);

g) seal weld cracking/failure;

h) erosion/erosion-corrosion, etc.

Examples of various typical NDE methods for tube inspection include and are not limited to:

a) visual inspection;

b) UT thickness readings where accessible;

c) eddy current testing;

d) remote field eddy current testing;

e) near field eddy current testing;

f) rotating/spinning UT probe examination;

g) laser scanning;

h) halide leak, hydrostatic, soap bubble, and other leak testing;

i) acoustic testing;

j) splitting of tubes for visual and other types of inspection like PT, pit depth gauging, caliper measurements, etc.

These lists of types of damage/degradation and typical NDE methods is provided as an example of items that the user should review when considering and/or creating inspection effectiveness tables. Understand that there are no specific LoIE tables developed as an example for tube bundle inspection. Rather Table 2.F.4.1 is provided as a basic guideline for the owner–user created LoIE table(s), which is based on their experience and confidence in the results.

2.F.4.1.3 Tables

Table 2.F.4.1—Inspection Effectiveness and Uncertainty

Inspection Effectiveness	Uncertainty (%)
A—Highly Effective	5
B—Usually Effective	10
C—Moderately Effective	20
D—Usually Not Effective	30
E—Ineffective	50

2.F.5 Atmospheric Storage Tank Components

2.F.5.1 Inspection Effectiveness for Atmospheric Storage Tanks

API 653 states that RBI may be utilized as an alternative to establishing the initial internal inspection date as well as the reassessment date. However, when an RBI assessment is performed, the maximum initial internal interval shall not apply to ASTs storing the following:

a) highly viscous substances that solidify at temperatures below 110 °F—some examples of these substances are asphalt, roofing flux, residuum, vacuum bottoms, and reduced crude, or

b) any substance or mixture that

  1) is not identified or regulated either as a hazardous chemical or material under the applicable laws of the jurisdiction, and

  2) the owner/operator has determined will not adversely impact surface or groundwater beyond the facility or affect human health or the environment.

In order for the owner/operator to establish the internal inspection interval using RBI, a methodology of assigning inspection effectiveness must be provided. API 581 provides for several areas of inspection that are accounted for within the risk assessment methodology. Overall, the results of the RBI assessment can be used to establish an AST inspection strategy that defines the most appropriate inspection methods, appropriate frequency for internal, external, and in-service inspections, and prevention and mitigation steps to reduce the likelihood and consequence of AST leakage or failure.

Furthermore, API 653 requires that when using RBI, the assessments shall:

a) follow all requirements listed in API 653;

b) consist of a systematic evaluation of both the likelihood of failure and the associated consequences of failure;

c) be thoroughly documented, clearly defining all factors contributing to both likelihood and consequence of AST leakage or failure;

d) be performed by a team including inspection and engineering expertise knowledgeable in the proper application of API 580 principles, AST design, construction, and types of damage.

LoIE Tables 2.F.5.1 through 2.F.5.3 outline inspection areas combined with examples of inspection effectiveness categories for AST components.

2.F.5.2 Tables

Table 2.F.5.1—LoIE Example for AST Shell Course Internal Corrosion

Inspection Category	Inspection Effectiveness Category	Inspection [1]
A	Highly Effective	Both inspections shall be done: — intrusive inspection—good visual inspection with pit depth gage measurements at suspect locations — UT scanning follow up on suspect location and as general confirmation of wall thickness
B	Usually Effective	Both inspections shall be done: — external spot UT scanning based on visual information from previous internal inspection of this AST or similar service ASTs — internal video survey with external UT follow-up
C	Fairly Effective	External spot UT scanning based at suspect locations without benefit of any internal inspection information on AST type or service
D	Poorly Effective	External spot UT based at suspect locations without benefit of any internal inspection information on AST type or service
E	Ineffective	Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.

Table 2.F.5.2—LoIE Example for AST Shell Course External Corrosion

Inspection Category	Inspection Effectiveness Category	Insulated Tank Inspection Example [1]	Non-Insulated Tank Inspection Example [1]
A	Highly Effective	— >95 % external visual inspection prior to removal of insulation — Remove >90 % of insulation at suspect locations **OR** >90 % pulse eddy current inspection — Visual inspection of the exposed surface area with follow-up by UT or pit gauge as required	>95 % visual inspection of the exposed surface area **AND** Follow-up by UT or pit gauge as required
B	Usually Effective	— >95 % external visual inspection prior to removal of insulation — Remove >50 % of insulation at suspect locations **OR** >50 % pulse eddy current inspection — Visual inspection of the exposed surface area with follow-up by UT or pit gauge as required	>50 % visual inspection of the exposed surface area **AND** Follow-up by UT or pit gauge as required
C	Fairly Effective	— >95 % external visual inspection prior to removal of insulation — Remove >30 % of insulation at suspect locations **OR** >30 % pulse eddy current inspection — Visual inspection of the exposed surface area with follow-up by UT or pit gauge as required	>25 % visual inspection of the exposed surface area **AND** Follow-up by UT or pit gauge as required
D	Poorly Effective	— >95 % external visual inspection prior to removal of insulation — Remove >10 % of insulation at suspect locations **OR** >10 % pulse eddy current inspection — Visual inspection of the exposed surface area with follow-up by UT or pit gauge as required	>10 % visual inspection of the exposed surface area **AND** Follow-up by UT or pit gauge as required
E	Ineffective	Ineffective inspection technique/plan was utilized	Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.

Table 2.F.5.3—LoIE Example for Tank Bottoms

Inspection Category	Inspection Effectiveness Category	Soil Side [1]	Product Side [1]
A	Highly Effective	Floor scan >90 % **AND** UT follow-up NOTE — *Include welds if warranted from the results on the plate scanning* — *Hand scan of the critical zone*	Bare plate: — Commercial blast — Effective supplementary light — Visual 100 % (API 653) — Pit depth gauge — 100 % vacuum box testing of suspect welded joints Coating or liner: — Sponge test 100 % — Adhesion test — Scrape test
B	Usually Effective	Floor scan >50 % **AND** UT follow-up **OR** Extreme value analysis (EVA) or other statistical method with floor scan follow-up (if warranted by the result)	Bare plate: — Brush blast — Effective supplementary light — Visual 100 % (API 653) — Pit depth gauge Coating or liner: — Sponge test >75 % — Adhesion test — Scrape test
C	Fairly Effective	Floor scan 5 to 10+% plates **AND** Supplement with scanning near shell **AND** UT follow-up **OR** Use a “Scan Circle-and-X” pattern (progressively increase if damage found during scanning) Other testing: — Helium/argon test — Hammer test — Cut coupons	Bare plate: — Broom swept — Effective supplementary light — Visual 100 % — Pit depth gauge Coating or liner: — Sponge test 50 % to 75 % — Adhesion test — Scrape test
D	Poorly Effective	Possible testing: — Spot UT — Flood test	Bare plate: — Broom swept — No effective supplementary lighting — Visual >50 % Coating or liner: — Sponge test <50 %
E	Ineffective	Ineffective inspection technique/plan was utilized	Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.

~~2.F.6 Non-Metallic Linings~~

~~2.F.6.1 Inspection Effectiveness for Non-Metallic Linings~~

~~Non-metallic lining assessment is important to any RBI analysis as an integral part of the ascribed equipment.~~

~~Although inspection effectiveness is not currently used in the calculation of the lining DF, LoIE Table 2.F.6.1 provides an example of inspection effectiveness categories for non-metallic linings.~~

~~2.F.6.2 Tables~~

~~Table 2.F.6.1—LoIE Example for Corrosion-resistant Non-Metallic Liners~~

~~Inspection Category~~	~~Inspection Effectiveness Category~~	~~Intrusive Inspection Example~~ [1,2]	~~Non-intrusive Inspection Example~~ [1,2]
~~A~~	~~Highly Effective~~	~~For the total surface area:~~ ~~100 % visual inspection~~ ~~**AND**~~ ~~100 % holiday test~~ ~~**AND**~~ ~~100 % UT or magnetic tester for disbonding for bonded liners~~	~~No inspection techniques are yet available to meet the requirements for an "A" level inspection~~
~~B~~	~~Usually Effective~~	~~For the total surface area:~~ ~~>65 % visual inspection~~ ~~**AND**~~ ~~>65 % holiday test~~ ~~**AND**~~ ~~>65 % UT or magnetic tester for disbonding for bonded liners~~	~~For the total surface area:~~ ~~100 % automated or manual ultrasonic scanning~~
~~C~~	~~Fairly Effective~~	~~For the total surface area:~~ ~~>35 % visual inspection~~ ~~**OR**~~ ~~>35 % holiday test~~ ~~**OR**~~ ~~>35 % UT or magnetic tester for disbonding for bonded liners~~	~~For the total surface area:~~ ~~>65 % automated or manual ultrasonic scanning~~
~~D~~	~~Poorly Effective~~	~~For the total surface area:~~ ~~>5 % visual inspection~~ ~~**OR**~~ ~~>5 % holiday test~~ ~~**OR**~~ ~~>5 % UT or magnetic tester for disbonding for bonded liners~~	~~For the total surface area:~~ ~~>35 % automated or manual ultrasonic scanning~~
~~E~~	~~Ineffective~~	~~Ineffective inspection technique/plan was utilized~~	~~Ineffective inspection technique/plan was utilized~~

~~NOTE 1 Inspection quality is high.~~

~~NOTE 2 Suspect area shall be considered the total surface area unless defined by knowledgeable individual (subject matter expert).~~

2.F.~~7~~6 Buried Components

2.F.6~~7~~.1 Inspection Effectiveness for Buried Components

Similar to other equipment, components that are buried may use RBI to assign inspection intervals. LoIE Table 2.F.6~~7~~.1 provides an example of inspection effectiveness categories for buried components.

2.F.6~~7~~.2 Tables

Table 2.F.6~~7~~.1—LoIE Example for Buried Components

Inspection Category	Inspection Effectiveness Category	Intrusive Inspection Example [1]	Non-intrusive Inspection Example [1]	
A	Highly Effective	100 % internal inspection via state-of-the-art pigging and in-line inspection technologies (UT, MFL, internal rotary UT, etc.)	100 % external inspection of equipment that is only partially buried using an NDE crawler with circumferential inspection technology (MFL, lamb-wave UT)	
			— Complete excavation, 100 % external visual inspection, and 100 % inspection with NDE technologies [2] — Sample soil and water resistivity and chemistry measurements along entire structure	— Cathodic protection (CP) system maintained and managed by NACE certified personnel and complying with NACE SP0169 [14] includes stray current surveys on a regular basis — Pipe-to-soil potentials should be measured at properly determined intervals
B	Usually Effective	Internal inspection via pigging and in-line inspection technologies (UT, MFL, internal rotary UT, etc.) of selected areas/sections, combined with statistical analysis or EVA	External inspection of equipment that is only partially buried using an NDE crawler with circumferential inspection technology (MFL, lamb-wave UT) on selected areas/sections, combined with statistical analysis or EVA	
			— Close interval survey used to assess the performance of the CP system locally and utilized to select the excavation sites (based on the findings) — Excavation at "selected" locations, 100 % external visual, and 100 % inspection with NDE technologies [2]	— CP system maintained and managed by NACE certified personnel and complying with NACE SP0169 [14] includes stray current surveys on a regular basis — Sample soil and water resistivity and chemistry measurements along entire structure — DC voltage gradient (DCVG) to determine coating damage
C	Fairly Effective	Partial inspection by internal smart pig or specialized crawler device, including a representative portion of the buried pipe (<25 %)	Partial excavation guided-wave UT global search inspection in each direction of pipe. Corrosion inspection and maintenance managed by NACE certified and CP specialist, or equivalent.	
D	Poorly Effective	Hydrostatic testing	Spot check with conventional NDE technologies [2] equipment of local areas exposed by excavation.	
E	Ineffective	Ineffective inspection technique/plan was utilized		

NOTE 1 Inspection quality is high.

NOTE 2 "NDE technologies" include, but are not limited to, UT thickness measurement such as handheld devices at close-interval grid locations, UT B-scan, automated ultrasonic scanning, guided-wave UT global search, crawler with circumferential inspection technology such as MFL or lamb-wave UT, and digital radiography in more than one direction.

2.F.7~~8~~ Inspection Effectiveness for Thinning

2.F.7~~8~~.1 Use of the Inspection Effectiveness Tables

LoIE Table 2.F.7~~8~~.1 and Table 2.F.7~~8~~.2 are examples for levels of inspection effectiveness for thinning damage mechanisms. The LoIE tables for Thinning damage include inspection examples for non-metallic liners, if applicable.

2.F.7~~8~~.2 Tables

Table 2.F.~~8~~7.1—LoIE Example for General Thinning

Inspection Category	Inspection Effectiveness Category	Intrusive Inspection Example ^{1,2,3,4}	Non-intrusive Inspection Example ^{1,2,3,4}
A	Highly Effective	**Components with and without Cladding/Weld Overlay** For the total surface area: >50 % visual examination (partial internals removed) **AND** >50 % of the spot ultrasonic thickness measurements **Components with Internal Liners** For the total surface area: 100 % visual inspection **AND** 100 % holiday test **AND** 100 % UT or magnetic tester for disbonding for bonded liners	**Components with and without Cladding/Weld Overlay** For the total surface area: 100 % UT/RT of CMLs **OR** For selected areas: 10 % UT scanning **OR** 10 % profile radiography **Components with Internal Liners** No inspection techniques are yet available to meet the requirements for an “A” level inspection
B	Usually Effective	**Components with and without Cladding/Weld Overlay** For the total surface area: >25 % visual examination **AND** >25 % of the spot ultrasonic thickness measurements **Components with Internal Liners** For the total surface area: >65 % visual inspection **AND** >65 % holiday test **AND** >65 % UT or magnetic tester for	**Components with and without Cladding/Weld Overlay** For the total surface area: >75 % spot UT **OR** >5 % UT scanning, automated or manual **OR** >5 % profile radiography of the selected area(s) **Components with Internal Liners** For the total surface area: 100 % automated or manual ultrasonic scanning

		disbonding for bonded liners	
C	Fairly Effective	**Components with and without Cladding/Weld Overlay** For the total surface area: >5 % visual examination **AND** >5 % of the spot ultrasonic thickness measurements **Components with Internal Liners** For the total surface area: >35 % visual inspection **OR** >35 % holiday test **OR** >35 % UT or magnetic tester for disbonding for bonded liners	**Components with and without Cladding/Weld Overlay** For the total surface area: >50 % spot UT or random UT scans (automated or manual) **OR** random profile radiography of the selected area(s) **Components with Internal Liners** For the total surface area: >65 % automated or manual ultrasonic scanning
D	Poorly Effective	**Components with and without Cladding/Weld Overlay** For the total surface area: <5 % visual examination without thickness measurements **Components with Internal Liners** For the total surface area: >5 % visual inspection **OR** >5 % holiday test **OR** >5 % UT or magnetic tester for disbonding for bonded liners	**Components with and without Cladding/Weld Overlay** For the total surface area: >25 % spot UT **Components with Internal Liners** For the total surface area: >35 % automated or manual ultrasonic scanning
E	Ineffective	**Components with and without Cladding/Weld Overlay** Ineffective inspection technique/plan was utilized **Components with Internal Liners** Ineffective inspection technique/plan was utilized	**Components with and without Cladding/Weld Overlay** Ineffective inspection technique/plan was utilized **Components with Internal Liners** Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.

NOTE 2 Inspection points (CMLs, scans, etc.) are set up by knowledgeable individuals.

NOTE 3 That the number of CMLs and area for scanning (UT or profile radiography) is one that will detect damage if occurring.

NOTE 4 Percentage refers to percent of established CMLs examined (e.g. for spot UT) or the percent surface area examined.

Table 2.F.~~8~~7.2—LoIE Example for Local Thinning

Inspection Category	**Inspection Effectiveness Category**	**Intrusive Inspection Example** [1,2,3,4]	**Non-intrusive Inspection Example** [1,2,3,4]
A	Highly Effective	**Components with and without Cladding/Weld Overlay** For the total surface area: 100 % visual examination (with removal of internal packing, trays, etc.) **AND** 100 % follow-up at locally thinned areas **Components with Internal Liners** For the total surface area: 100 % visual inspection **AND** 100 % holiday test **AND** 100 % UT or magnetic tester for disbonding for bonded liners	**Components with and without Cladding/Weld Overlay** For the total suspect area: 100 % coverage of the CMLs using ultrasonic scanning or profile radiography **Components with Internal Liners** No inspection techniques are yet available to meet the requirements for an “A” level inspection
B	Usually Effective	**Components with and without Cladding/Weld Overlay** For the total surface area: >75 % visual examination **AND** 100 % follow-up at locally thinned areas **Components with Internal Liners** For the total surface area: >65 % visual inspection **AND** >65 % holiday test **AND** >65 % UT or magnetic tester for disbonding for bonded liners	**Components with and without Cladding/Weld Overlay** For the total suspect area: >75 % coverage of the CMLs using ultrasonic scanning or profile radiography **Components with Internal Liners** For the total surface area: 100 % automated or manual ultrasonic scanning
C	Fairly Effective	**Components with and without Cladding/Weld Overlay** For the total surface area: >50 % visual examination **AND** 100 % follow-up at locally thinned areas **Components with Internal Liners** For the total surface area: >35 % visual inspection **OR** >35 % holiday test	**Components with and without Cladding/Weld Overlay** For the total suspect area: >50 % coverage of the CMLs using ultrasonic scanning or profile radiography **Components with Internal Liners** For the total surface area: >65 % automated or manual ultrasonic scanning

		OR >35 % UT or magnetic tester for disbonding for bonded liners	
D	Poorly Effective	**Components with and without Cladding/Weld Overlay** For the total surface area: >20 % visual examination **AND** 100 % follow-up at locally thinned areas **Components with Internal Liners** For the total surface area: >5 % visual inspection **OR** >5 % holiday test **OR** >5 % UT or magnetic tester for disbonding for bonded liners	**Components with and without Cladding/Weld Overlay** For the total suspect area: >20 % coverage of the CMLs using ultrasonic scanning or profile radiography **Components with Internal Liners** For the total surface area: >35 % automated or manual ultrasonic scanning
E	Ineffective	**Components with and without Cladding/Weld Overlay** Ineffective inspection technique/plan was utilized **Components with Internal Liners** Ineffective inspection technique/plan was utilized	**Components with and without Cladding/Weld Overlay** Ineffective inspection technique/plan was utilized **Components with Internal Liners** Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.
NOTE 2 Percentage coverage in non-intrusive inspection includes welds.
NOTE 3 Follow-up inspection can be UT, pit gauge, or suitable NDE techniques that can verify minimum wall thickness.
NOTE 4 Profile radiography technique is sufficient to detect wall loss at all planes.

2.F.~~9~~8 Inspection Effectiveness Tables for Stress Corrosion Cracking

2.F.~~9~~8.1 Use of the Inspection Effectiveness Tables

LoIE Tables 2.F.8~~9~~.1 through 2.F.8~~9~~.9 are examples for levels of inspection effectiveness for SCC damage mechanisms.

2.F.8~~9~~.2 Tables

Table 2.F.~~9~~8.1—LoIE Example for Amine Cracking

Inspection Category	Inspection Effectiveness Category	Intrusive Inspection Example [1,2]	Non-intrusive Inspection Example [1,2]
A	Highly Effective	For the total weld area: 100 % WFMT/ACFM with UT follow-up of relevant indications	For the total weld area: 100 % automated or manual ultrasonic scanning
B	Usually Effective	For selected welds/weld area: >75 % WFMT/ACFM with UT follow-up of all relevant indications	For selected welds/weld area: >75 % automated or manual ultrasonic scanning

			OR AE testing with 100 % follow-up of relevant indications
C	Fairly Effective	For selected welds/weld area: >35 % WFMT/ACFM with UT follow-up of all relevant indications	For selected welds/weld area: >35 % automated or manual ultrasonic scanning **OR** >35 % radiographic testing
D	Poorly Effective	For selected welds/weld area: >10 % WFMT/ACFM with UT follow-up of all relevant indications	For selected welds/weld area: >10 % automated or manual ultrasonic scanning **OR** >10 % radiographic testing
E	Ineffective	Ineffective inspection technique/plan was utilized	Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.

NOTE 2 Suspect area shall be considered the total surface area unless defined by knowledgeable individual (subject matter expert).

Table 2.F.8~~9~~.2—LoIE Example for ACSCC

Inspection Category	**Inspection Effectiveness Category**	**Intrusive Inspection Example [1,2]**	**Non-intrusive Inspection Example [1,2]**
A	Highly Effective	For the total weld area: 100 % WFMT/ACFM with UT follow-up of relevant indications	For the total weld area: 100 % automated or manual ultrasonic scanning
B	Usually Effective	For selected welds/weld area: >75 % WFMT/ACFM with UT follow-up of all relevant indications	For selected welds/weld area: >75 % automated or manual ultrasonic scanning **OR** AE testing with 100 % follow-up of relevant indications
C	Fairly Effective	For selected welds/weld area: >35 % WFMT/ACFM with UT follow-up of all relevant indications	For selected welds/weld area: >35 % automated or manual ultrasonic scanning **OR** >35 % radiographic testing
D	Poorly Effective	For selected welds/weld area: >10 % WFMT/ACFM with UT follow-up of all relevant indications	For selected welds/weld area: >10 % automated or manual ultrasonic scanning **OR** >10 % radiographic testing
E	Ineffective	Ineffective inspection technique/plan was utilized	Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.

NOTE 2 Suspect area shall be considered the total surface area unless defined by knowledgeable individual (subject matter expert).

Table 2.F.~~9~~8.3—LoIE Example for Caustic Cracking

Inspection Category	Inspection Effectiveness Category	Intrusive Inspection Example [1,2,3]	Non-intrusive Inspection Example [1,2,3]
A	Highly Effective	For the total weld area: 100 % WFMT/ACFM with UT follow-up of relevant indications	For the total weld area: 100 % automated or manual ultrasonic scanning
B	Usually Effective	For selected welds/weld area: >75 % WFMT/ACFM with UT follow-up of all relevant indications	For selected welds/weld area: >75 % automated or manual ultrasonic scanning **OR** AE testing with 100 % follow-up of relevant indications
C	Fairly Effective	For selected welds/weld area: >35 % WFMT/ACFM with UT follow-up of all relevant indications	For selected welds/weld area: >35 % automated or manual ultrasonic scanning **OR** >35 % radiographic testing
D	Poorly Effective	For selected welds/weld area: >10 % WFMT/ACFM with UT follow-up of all relevant indications	For selected welds/weld area: >10 % automated or manual ultrasonic scanning **OR** >10 % radiographic testing
E	Ineffective	Ineffective inspection technique/plan was utilized	Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.

NOTE 2 Suspect area shall be considered the total surface area unless defined by knowledgeable individual (subject matter expert).

NOTE 3 Cold bends may need inspection also for caustic cracking.

Table 2.F.~~9~~8.4—LoIE Example for CISCC

Inspection Category	Inspection Effectiveness Category	Intrusive Inspection Example [1,8,a]	Non-intrusive Inspection Example [1,8,a]
A	Highly Effective	For the total surface area: 100 % dye penetrant or eddy current test with UT follow-up of relevant indications	No inspection techniques are yet available to meet the requirements for an “A” level inspection
B	Usually Effective	For selected areas: >65 % dye penetrant or eddy current testing with UT follow-up of all relevant indications	For selected areas: 100 % automated or manual ultrasonic scanning **OR** AE testing with 100 % follow-up of relevant indications
C	Fairly Effective	For selected areas: >35 % dye penetrant or eddy current testing with UT follow-up of all relevant indications	For selected areas: >65 % automated or manual ultrasonic scanning **OR** >65 % radiographic testing
D	Poorly Effective	For selected areas: >10 % dye penetrant or eddy current testing with UT follow-up of all relevant indications	For selected areas: >35 % automated or manual ultrasonic scanning **OR** >35 % radiographic testing
E	Ineffective	Ineffective inspection technique/plan was utilized	Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.

NOTE 2 Suspect area shall be considered the total surface area unless defined by knowledgeable individual (subject matter expert).

NOTE 3 Internal stress corrosion cracking.

Table 2.F.~~9~~8.5—LoIE Example for PTA Cracking

Inspection Category	Inspection Effectiveness Category	Intrusive Inspection Example ^{1,2,3}	Non-intrusive Inspection Example ^{1,2,3}
A	Highly Effective	For the total surface area: 100 % dye penetrant or eddy current test with UT follow-up of relevant indications	No inspection techniques are yet available to meet the requirements for an “A” level inspection
B	Usually Effective	For selected areas: >65 % dye penetrant or eddy current testing with UT follow-up of all relevant indications	For selected areas: 100 % automated or manual ultrasonic scanning **OR** AE testing with 100 % follow-up of relevant indications
C	Fairly Effective	For selected areas: >35 % dye penetrant or eddy current testing with UT follow-up of all relevant indications	For selected areas: >65 % automated or manual ultrasonic scanning **OR** >65 % radiographic testing
D	Poorly Effective	For selected areas: >10 % dye penetrant or eddy current testing with UT follow-up of all relevant indications	For selected areas: >35 % automated or manual ultrasonic scanning **OR** >35 % radiographic testing.
E	Ineffective	Ineffective inspection technique/plan was utilized	Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.

NOTE 2 Suspect area shall be considered the total surface area unless defined by knowledgeable individual (subject matter expert).

NOTE 3 There is no highly effective inspection without a minimum of partial insulation removal and external VT and PT.

Table 2.F.8~~9~~.6—LoIE Example for SSC

Inspection Category	Inspection Effectiveness Category	Intrusive Inspection Example [1,2]	Non-intrusive Inspection Example [1,2]
A	Highly Effective	For the total weld area: 100 % WFMT/ACFM with UT follow-up of relevant indications	For the total weld area: 100 % automated or manual ultrasonic scanning
B	Usually Effective	For selected welds/weld area: >75 % WFMT/ACFM with UT follow-up of all relevant indications	For selected welds/weld area: >75 % automated or manual ultrasonic scanning **OR** AE testing with 100 % follow-up of relevant indications
C	Fairly Effective	For selected welds/weld area: >35 % WFMT/ACFM with UT follow-up of all relevant indications	For selected welds/weld area: >35 % automated or manual ultrasonic scanning **OR** >35 % radiographic testing
D	Poorly Effective	For selected welds/weld area: >10 % WFMT/ACFM with UT follow-up of all relevant indications	For selected welds/weld area: >10 % automated or manual ultrasonic scanning **OR** >10 % radiographic testing
E	Ineffective	Ineffective inspection technique/plan was utilized	Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.

NOTE 2 Suspect area shall be considered the total surface area unless defined by knowledgeable individual (subject matter expert).

Table 2.F.8~~9~~.7—LoIE Example for HIC/SOHIC-H_2S Cracking

Inspection Category	Inspection Effectiveness Category	Intrusive Inspection Example [1,2,3]	Non-intrusive Inspection Example [1,2,3]
A	Highly Effective	For the total surface area: — >95 % A or C scan with straight beam — Followed by TOFD/shear wave — 100 % visual	For the total surface area: — SOHIC: — >90 % C scan of the base metal using advanced UT — For the weld and HAZ—100 % shear wave and TOFD **AND** — HIC: Two 1-ft^2 areas, C scan of the base metal using advanced UT on each plate and the heads
B	Usually Effective	For the total surface area: — >75 % A or C scan with straight beam — Followed by TOFD/shear wave — 100 % visual	For the total surface area: — >65 % C scan of the base metal using advanced UT **AND** — HIC: Two 0.5-ft^2 areas, C scan of the base metal using advanced UT on each plate and the heads
C	Fairly Effective	For the total surface area: — >35 % A or C scan with straight beam — Followed by TOFD/shear wave — 100 % visual **OR** — >50 % WFMT/ACFM — UT follow-up of indications — 100 % visual of total surface area	For the total surface area: — >35 % C scan of the base metal using advanced UT **AND** — HIC: One 1-ft^2 area, C scan of the base metal using advanced UT on each plate and the heads
D	Poorly Effective	For the total surface area: — >10 % A or C scan with shear wave — 100 % visual **OR** — >25 % WFMT/ACFM — UT follow-up of indications — 100 % visual of total surface area	For the total surface area: — >5 % C scan of the base metal using advanced UT **AND** — HIC: One 0.5-ft^2 area, C scan of the base metal using advanced UT on each plate and the heads
E	Ineffective	Ineffective inspection technique/plan was utilized	Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.
NOTE 2 Suspect area shall be considered the total surface area unless defined by knowledgeable individual (subject matter expert).
NOTE 3 Inspection area: welds and plates that are susceptible to the damage mechanism.

Table 2.F.8~~9~~.8—LoIE Example for HSC-HF Cracking

Inspection Category	Inspection Effectiveness Category	Intrusive Inspection Example [1,2]	Non-intrusive Inspection Example [1,2]
A	Highly Effective	For the total weld area: 100 % WFMT/ACFM with UT follow-up of relevant indications	For the total weld area: 100 % automated or manual ultrasonic scanning
B	Usually Effective	For selected welds/weld area: >75 % WFMT/ACFM with UT follow-up of all relevant indications	For selected welds/weld area: >75 % automated or manual ultrasonic scanning **OR** AE testing with 100 % follow-up of relevant indications
C	Fairly Effective	For selected welds/weld area: >35 % WFMT/ACFM with UT follow-up of all relevant indications	For selected welds/weld area: >35 % automated or manual ultrasonic scanning **OR** >65 % radiographic testing
D	Poorly Effective	For selected welds/weld area: >10 % WFMT/ACFM with UT follow-up of all relevant indications	For selected welds/weld area: >10 % automated or manual ultrasonic scanning **OR** >35 % radiographic testing
E	Ineffective	Ineffective inspection technique/plan was utilized	Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.

NOTE 2 Suspect area shall be considered the total surface area unless defined by knowledgeable individual (subject matter expert).

Table 2.F.~~9~~8.9—LoIE Example for HIC/SOHIC-HF Cracking

Inspection Category	Inspection Effectiveness Category	Intrusive Inspection Example [1,2]	Non-intrusive Inspection Example [1,2]

A	Highly Effective	For the total surface area:
		— 100 % A or C scan with straight beam
		— Followed by TOFD/shear wave
		— 100 % visual
			For the total surface area:
			— SOHIC:
			  — >90 % C scan of the base metal using advanced UT
			  — For the weld and HAZ—100 % shear wave and TOFD
			AND
			— HIC: Two 1-ft^2 areas, C scan of the base metal using advanced UT on each plate and the heads

B	Usually Effective	For the total surface area: — >65 % A or C scan with straight beam — Followed by TOFD/shear wave — 100 % visual	For the total surface area: — >65 % C scan of the base metal using advanced UT **AND** — HIC: Two 0.5 ft^2 areas, C scan of the base metal using advanced UT on each plate and the heads.
C	Fairly Effective	For the total surface area: — >35 % A or C scan with straight beam — Followed by TOFD/shear wave — 100 % visual **OR** — >50 % WFMT/ACFM — UT follow-up of indications — 100 % visual of total surface area	For the total surface area: — >35 % C scan of the base metal using advanced UT **AND** — HIC: One 1-ft^2 area, C scan of the base metal using advanced UT on each plate and the heads
D	Poorly Effective	For the total surface area: — >10 % A or C scan with shear wave — >50 % visual **OR** — >25 % WFMT/ACFM — UT follow-up of indications — 100 % visual of total surface area	For the total surface area: — >5 % C scan of the base metal using advanced UT **AND** — HIC: One 0.5-ft^2 area, C scan of the base metal using advanced UT on each plate and the heads
E	Ineffective	Ineffective inspection technique/plan was utilized	Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.
NOTE 2 Inspection points (CMLs, scans, etc.) are set up by knowledgeable individuals.
NOTE 3 Inspection area: welds and plates that are susceptible to the damage mechanism.

2.F.9~~10~~ Inspection Effectiveness for External Damage

2.F.9~~10~~.1 Use of the Inspection Effectiveness Tables

LoIE Tables 2.F.10.1 through 2.F.10.4 are example for levels of inspection effectiveness for external damage mechanisms.

2.F.9~~10~~.2 Tables

Table 2.F.9~~10~~.1—LoIE Example for External Corrosion

Inspection Category	Inspection Effectiveness Category	Inspection [1]
A	Highly Effective	Visual inspection of >95 % of the exposed surface area with follow-up by UT, RT, or pit gauge as required
B	Usually Effective	Visual inspection of >60 % of the exposed surface area with follow-up by UT, RT, or pit gauge as required
C	Fairly Effective	Visual inspection of >30 % of the exposed surface area with follow-up by UT, RT, or pit gauge as required
D	Poorly Effective	Visual inspection of >5 % of the exposed surface area with follow-up by UT, RT, or pit gauge as required
E	Ineffective	Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.

Table 2.F.9~~10~~.2—LoIE Example for External ClSCC Cracking

Inspection Category	Inspection Effectiveness Category	Inspection [1,2]
A	Highly Effective	For the suspected surface area: 100 % dye penetrant or eddy current test with UT follow-up of relevant indications
B	Usually Effective	For the suspected surface area: >60 % dye penetrant or eddy current testing with UT follow-up of all relevant indications
C	Fairly Effective	For the suspected surface area: >30 % dye penetrant or eddy current testing with UT follow-up of all relevant indications
D	Poorly Effective	For the suspected surface area: >5 % dye penetrant or eddy current testing with UT follow-up of all relevant indications
E	Ineffective	Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.

NOTE 2 Suspect area shall be considered the total surface area unless defined by knowledgeable individual (subject matter expert).

NOTE 3 Inspection area: welds and plates that are susceptible to the damage mechanism.

Table 2.F.9~~10~~.3—LoIE Example for CUI

Inspection Category	**Inspection Effectiveness Category**	**Insulation Removed** [1,2,3,4]	**Insulation Not Removed** [1,2,3,4]
A	Highly Effective	For the total surface area: 100 % external visual inspection prior to removal of insulation **AND** Remove 100 % of the insulation for damaged or suspected areas **AND** 100 % visual inspection of the exposed surface area with UT, RT, or pit gauge follow-up of the selected corroded areas	For the total surface area: 100 % external visual inspection **AND** 100 % profile or real-time radiography of damaged or suspect area **AND** Follow-up of corroded areas with 100 % visual inspection of the exposed surface with UT, RT, or pit gauge
B	Usually Effective	For the total surface area: 100 % external visual inspection prior to removal of insulation **AND** Remove >50 % of suspect areas **AND** Follow-up of corroded areas with 100 % visual inspection of the exposed surface area with UT, RT, or pit gauge	For the total surface area: 100 % external visual inspection **AND** Follow-up with profile or real-time radiography of >65 % of suspect areas **AND** Follow-up of corroded areas with 100 % visual inspection of the exposed surface with UT, RT, or pit gauge
C	Fairly Effective	For the total surface area: 100 % external visual inspection prior to removal of insulation **AND** Remove >25 % of suspect areas **AND** Follow-up of corroded areas with 100 % visual inspection of the exposed surface area with UT, RT, or pit gauge	For the total surface area: 100 % external visual inspection **AND** Follow-up with profile or real-time radiography of >35 % of suspect areas **AND** Follow-up of corroded areas with 100 % visual inspection of the exposed surface with UT, RT, or pit gauge
D	Poorly Effective	For the total surface area: 100 % external visual inspection prior to removal of insulation **AND** Remove >5 % of total surface area of insulation including suspect areas **AND** Follow-up of corroded areas with 100 % visual inspection of the exposed surface area with UT, RT, or pit gauge	For the total surface area: 100 % external visual inspection **AND** Follow-up with profile or real-time radiography of >5 % of total surface area of insulation including suspect areas **AND** Follow-up of corroded areas with 100 % visual inspection of the exposed surface with UT, RT, or pit gauge
E	Ineffective	Ineffective inspection technique/plan was utilized	Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.
NOTE 2 Suspect area shall be considered the total surface area unless defined by knowledgeable individual (subject matter expert).
NOTE 3 Suspect areas include damaged insulation, penetrations, terminations, etc.
NOTE 4 Surface preparation is sufficient to detect minimum wall for the NDE technique used to measure thickness.

Table 2.F.9~~10~~.4—LoIE Example for CUI ClSCC

Inspection Category	Inspection Effectiveness Category	Insulation Removed [1]	Insulation Not Removed [1]
A	Highly Effective	For the suspected area: 100 % external visual inspection prior to removal of insulation **AND** >100 % dye penetrant or eddy current test with UT follow-up of relevant indications	No inspection techniques are yet available to meet the requirements for an “A” level inspection
B	Usually Effective	For the suspected area: 100 % external visual inspection prior to removal of insulation **AND** >60 % dye penetrant or eddy current testing with UT follow-up of all relevant indications	No inspection techniques are yet available to meet the requirements for a “B” level inspection
C	Fairly Effective	For the suspected area: 100 % external visual inspection prior to removal of insulation **AND** >30 % dye penetrant or eddy current testing with UT follow-up of all relevant indications	No inspection techniques are yet available to meet the requirements for a “C” level inspection
D	Poorly Effective	For the suspected area: 100 % external visual inspection prior to removal of insulation **AND** >5 % dye penetrant or eddy current testing with UT follow-up of all relevant indications	No inspection techniques are yet available to meet the requirements for a “D” level inspection
E	Ineffective	Ineffective inspection technique/plan was utilized	Ineffective inspection technique/plan was utilized

NOTE 1 Inspection quality is high.

2.F.10~~1~~ Inspection Effectiveness Tables for High Temperature Hydrogen Attack Damage

2.F.10~~1~~.1 Use of the Inspection Effectiveness Tables

Currently there is no LoIE for HTHA damage. Please refer to Part 2, Section 19, which has a discussion on HTHA as it pertains to this document. It is the owner–user's responsibility and accountability to develop an effective inspection program for assets potentially affected by HTHA and document their methodology, investigation, and results.

1. Calculate Thinning Damage Factor with Internal Lining

1.1 Data for Thinning DF Calculation with Internal Lining

The mechanical design basis of the drum is as follows:

Fabrication date	01/01/1981
Component Type	Drum
Total Generic Failure Frequency	3.06E−5 events/year
Design Pressure	1.138 MPa (165 psig)
Design Temperature	232 °C (450°F)
Operating Pressure	0.696 MPa (101 psig)
Operating Temperature	49°C (121°F)
Weld Joint Efficiency	0.85
Material of Construction - Base	ASTM 285 Gr. C 1968
Internal Lining	Organic, Medium Quality Immersion Grade Coating
Lining Condition	Average
Lining On-Line Monitoring	No

Yield Strength	206 MPa (30,000 psi)
Tensile Strength	413 MPa (55,000 psi)
Allowable Stress	102.04 MPa (14,800 psi)
Furnished thickness - Base	20.64 mm (0.8125 inch)
Corrosion Allowance	3.175 mm (0.125 inch)
Post Weld Heat Treatment (PWHT)	Yes
Diameter	2,479.675 mm (97.625 inch)
Length	9.144 m (30 ft)
Thinning Corrosion Rate – Base	0.254 mmpy (10 mpy)
Thinning Type	Localized
Inspection Date	4/4/2013 – 1B inspection
Measured Thickness	19.09 mm (0.75 inch)
Structural tmin	2.54 mm (0.100 inch)

Inspection Planning	
RBI Date	05/01/2017
Plan Date	05/01/2027

1.2 Thinning Damage Factor Calculation

a. Determine the furnished thickness, t, and age, age, for the component from the installation date.

$$t = 20.64\ mm\ (0.8175\ inch)$$

$$age@RBI\ Date = 4.07\ years$$
$$age@Plan\ Date = 14.07\ years$$

b. Determine the corrosion rate for the base material, $C_{r,bm}$, based on the material of construction and process environment.

$$C_{r,bm} = 0.254\ mmpy\ \left(10\ mpy\right)$$

c. Determine the time in service, age_{tk}, since the last inspection known thickness, t_{rdi}.

An inspection was performed on 04/04/2013 with a measured thickness of 19.05 mm (0.75 inch)

$$t_{rdi} = 19.05\ mm\ (0.75\ inch)$$
$$age_{tk}\ @\ RBIDate = 4.07$$
$$age_{tk}\ @\ PlanDate = 14.07$$

d. Calculate the liner age at the RBI Date, age_{liner} and determine the expected life of the internal liner using Table 4.7.

$$age_{liner} = \left(RBI\ Date - Liner\ Installation\ Date\right)$$
$$age_{liner} = \left(5/1/2017 - 4/4/2013\right)$$
$$age_{liner}\ @\ RBI\ Date = 4.07\ years$$

$$age_{liner}^{exp}\ for\ Organic\ Costing, Medium\ Quality = 7\ years$$

Calculate the liner remaining life of the liner at the RBI Date, age_{rc}

$$age_{rc} = \frac{age_{liner}^{exp} - age_{liner}}{F_{LC}} \cdot F_{liner,OM}$$
$$age_{rc} = \frac{7 - 4.07}{1} \cdot 1$$
$$age_{rc}\ @\ RBIDate = 2.93\ years$$

$$Where:$$
$$F_{liner,OM}\ is\ the\ online\ monitoring\ factor$$
$$F_{LC}\ is\ the\ lining\ condition\ factor$$

e. Determine the minimum required wall thickness, $t_{\min}$

$$t_{min}^{C} = \frac{PR}{SE - 0.6P}$$

$$t_{min} = \frac{165 \cdot \frac{97.625}{2}}{14{,}800 \cdot 0.85 - 0.6 \cdot 165} = 0.6453 \text{ inch}$$

f. Determine the A_{rt} parameter

$$A_{rt} = \max\left(\frac{C_{r,bm} \cdot \left(age_{tk} - age_{rc}\right)}{t_{rdi}}, 0\right)$$

$$A_{rt}\ @\ RBI\ \ Date = \max\left(\frac{C_{r,bm} \cdot \left(age_{tk} - age_{rc}\right)}{t_{rdi}}, 0\right)$$

$$A_{rt}\ @\ RBI\ \ Date = max\left(\frac{0.010 \cdot \left(4.07 - 2.93\right)}{0.75}, 0\right)$$

$$A_{rt}\ @\ RBI\ \ Date = max\left(0.0153, 0\right) = 0.0153$$

$$A_{rt}\ @\ Plan\ Date = max\left(\frac{C_{r,bm} \cdot \left(age_{tk} - age_{rc}\right)}{t_{rdi}}, 0\right)$$

$$A_{rt}\ @\ Plan\ Date = max\left(\frac{0.010 \cdot \left(14.07 - 2.93\right)}{0.75}, 0\right)$$

$$A_{rt}\ @\ Plan\ Date = max\left(0.1486, 0\right) = 0.1486$$

g. Calculate the Flow Stress, FS^{Thin}

$$FS^{Thin} = \frac{\left(YS + TS\right)}{2} \cdot E \cdot 1.1$$

$$FS^{Thin} = \frac{\left(30 + 55\right)}{2} \cdot 0.85 \cdot 1.1$$

$$FS^{Thin} = 39.7375$$

h. Calculate the Strength Ratio parameter, SR_{P}^{Thin}

$$SR_{P}^{Thin} = \frac{S \cdot E}{FS^{Thin}} \cdot \frac{Max(t_{\min}, t_{c})}{t_{rdi}}$$

$$SR_{P}^{Thin} = \frac{14.80 \cdot 0.85}{39.7375} \cdot \frac{Max(0.6453, 0.100)}{0.75}$$

$$SR_{P}^{Thin} = 0.2724\ in$$

i. Determine the number of inspections for each of the corresponding inspection effectiveness, $N_{A}^{Thin}, N_{B}^{Thin}, N_{C}^{Thin}, N_{D}^{Thin}$

Thinning Inspection History: 1B level inspection was performed on 04/04/2013

j. Calculate the inspection effectiveness factors, $I_{1}^{Thin}, I_{2}^{Thin}, I_{3}^{Thin}$

$$I_{1}^{Thin} = Pr_{p1}^{Thin} \left(Co_{p1}^{ThinA}\right)^{N_{A}^{Thin}} \left(Co_{p1}^{ThinB}\right)^{N_{B}^{Thin}} \left(Co_{p1}^{ThinC}\right)^{N_{C}^{Thin}} \left(Co_{p1}^{ThinD}\right)^{N_{D}^{Thin}}$$

$$I_{1}^{Thin} = 0.500\left(0.9\right)^{0} \left(0.7\right)^{1} \left(0.5\right)^{0} \left(0.4\right)^{0}$$

$$I_{1}^{Thin} = 0.35$$

$$I_{2}^{Thin} = Pr_{p2}^{Thin} \left(Co_{p2}^{ThinA}\right)^{{}_{A}^{Thin}} \left(Co_{p2}^{ThinB}\right)^{N_{B}^{Thin}} \left(Co_{p2}^{ThinC}\right)^{N_{C}^{Thin}} \left(Co_{p2}^{ThinD}\right)^{N_{D}^{Thin}}$$

$$I_{2}^{Thin} = 0.300\left(0.09\right)^{0} \left(0.2\right)^{1} \left(0.3\right)^{0} \left(0.33\right)^{0}$$

$$I_{2}^{Thin} = 0.06$$

$$I_{3}^{Thin} = Pr_{p3}^{Thin} \left(Co_{p3}^{ThinA}\right)^{N_{A}^{Thin}} \left(Co_{p3}^{ThinB}\right)^{N_{B}^{Thin}} \left(Co_{p3}^{ThinC}\right)^{N_{C}^{Thin}} \left(Co_{p3}^{ThinD}\right)^{N_{D}^{Thin}}$$

$$I_{3}^{Thin} = 0.200\left(0.01\right)^{0} \left(0.1\right)^{1} \left(0.20\right)^{0} \left(0.27\right)^{0}$$

$$I_{3}^{Thin} = 0.02$$

k. Calculate the Posterior Probabilities, $Po_{p1}^{Thin}, Po_{p2}^{Thin}, Po_{p3}^{Thin}$

$$Po_{p1}^{Thin} = \frac{I_{1}^{Thin}}{I_{1}^{Thin} + I_{2}^{Thin} + I_{3}^{Thin}}$$

$$Po_{p1}^{Thin} = \frac{0.35}{0.35 + 0.06 + 0.02}$$

$$Po_{p1}^{Thin} = 0.8140$$

$$Po_{p2}^{Thin} = \frac{I_{2}^{Thin}}{I_{1}^{Thin} + I_{2}^{Thin} + I_{3}^{Thin}}$$

$$Po_{p2}^{Thin} = \frac{0.06}{0.35 + 0.06 + 0.02}$$

$$Po_{p2}^{Thin} = 0.1395$$

$$Po_{p3}^{Thin} = \frac{I_{3}^{Thin}}{I_{1}^{Thin} + I_{2}^{Thin} + I_{3}^{Thin}}$$

$$Po_{p3}^{Thin} = \frac{0.02}{0.35 + 0.06 + 0.02}$$

$$Po_{p3}^{Thin} = 0.0465$$

I. Calculate the β parameters, $\beta_1^{Thin},\ \beta_2^{Thin},\ \beta_3^{Thin}$

$Where:$

$$COV_{\Delta t} = 0.20$$

$$COV_{S_f} = 0.20$$

$$COV_P = 0.05$$

$$\beta_1^{Thin}\ @\ RBI\ Date = \frac{1 - D_{S_1}\cdot A_{rt} - SR_p^{Thin}}{\sqrt{D_{S_1}{}^2\cdot A_{rt}{}^2\cdot COV_{\Delta t}{}^2 + \left(1 - D_{S_1}\cdot A_{rt}\right)^2\cdot COV_{S_f}{}^2 + (SR_p^{Thin})^2\cdot COV_P{}^2}}$$

$$\beta_1^{Thin}\ @\ RBI\ Date = \frac{1 - 1\cdot 0.0153 - 0.2724}{\sqrt{1^2\cdot 0.0153^2\cdot 0.20^2 + \left(1 - 1\cdot 0.0153\right)^2\cdot 0.20^2 + (0.2724)^2\cdot 0.05^2}}$$

$$\beta_1^{Thin}\ @\ RBI\ Date = 3.6079$$

$$\beta_2^{Thin}\ @\ RBI\ Date = \frac{1 - D_{S_2}\cdot A_{rt} - SR_p^{Thin}}{\sqrt{D_{S_2}{}^2\cdot A_{rt}{}^2\cdot COV_{\Delta t}{}^2 + \left(1 - D_{S_2}\cdot A_{rt}\right)^2\cdot COV_{S_f}{}^2 + (SR_p^{Thin})^2\cdot COV_P{}^2}}$$

$$\beta_2^{Thin}\ @\ RBI\ Date = \frac{1 - 2\cdot 0.0153 - 0.2724}{\sqrt{2^2\cdot 0.0153^2\cdot 0.20^2 + \left(1 - 2\cdot 0.0153\right)^2\cdot 0.20^2 + (0.2724)^2\cdot 0.05^2}}$$

$$\beta_2^{Thin}\ @\ RBI\ Date = 3.5845$$

$$\beta_3^{Thin}\ @\ RBI\ Date = \frac{1 - D_{S_3}\cdot A_{rt} - SR_p^{Thin}}{\sqrt{D_{S_3}{}^2\cdot A_{rt}{}^2\cdot COV_{\Delta t}{}^2 + \left(1 - D_{S_3}\cdot A_{rt}\right)^2\cdot COV_{S_f}{}^2 + (SR_p^{Thin})^2\cdot COV_P{}^2}}$$

$$\beta_3^{Thin}\ @\ RBI\ Date = \frac{1 - 4\cdot 0.0153 - 0.2724}{\sqrt{4^2\cdot 0.0153^2\cdot 0.20^2 + \left(1 - 4\cdot 0.0153\right)^2\cdot 0.20^2 + (0.2724)^2\cdot 0.05^2}}$$

$$\beta_3^{Thin}\ @\ RBI\ Date = 3.5325$$

$$\beta_1^{Thin}\ @\ Plan\ Date = \frac{1 - D_{S_1} \cdot A_{rt} - SR_p^{Thin}}{\sqrt{D_{S_1}{}^2 \cdot A_{rt}{}^2 \cdot COV_{\Delta t}{}^2 + \left(1 - D_{S_1} \cdot A_{rt}\right)^2 \cdot COV_{S_f}{}^2 + (SR_p^{Thin})^2 \cdot COV_P{}^2}}$$

$$\beta_1^{Thin}\ @\ Plan\ Date = \frac{1 - 1 \cdot 0.1486 - 0.2724}{\sqrt{1^2 \cdot 0.1486^2 \cdot 0.20^2 + \left(1 - 1 \cdot 0.1486\right)^2 \cdot 0.20^2 + (0.2724)^2 \cdot 0.05^2}}$$

$$\beta_1^{Thin}\ @\ Plan\ Date = 3.3393$$

$$\beta_2^{Thin}\ @\ Plan\ Date = \frac{1 - D_{S_2} \cdot A_{rt} - SR_p^{Thin}}{\sqrt{D_{S_2}{}^2 \cdot A_{rt}{}^2 \cdot COV_{\Delta t}{}^2 + \left(1 - D_{S_2} \cdot A_{rt}\right)^2 \cdot COV_{S_f}{}^2 + (SR_p^{Thin})^2 \cdot COV_P{}^2}}$$

$$\beta_2^{Thin}\ @\ Plan\ Date = \frac{1 - 2 \cdot 0.1486 - 0.2724}{\sqrt{2^2 \cdot 0.1486^2 \cdot 0.20^2 + \left(1 - 2 \cdot 0.1486\right)^2 \cdot 0.20^2 + (0.2724)^2 \cdot 0.05^2}}$$

$$\beta_2^{Thin}\ @\ Plan\ Date = 2.8090$$

$$\beta_3^{Thin}\ @\ Plan\ Date = \frac{1 - D_{S_3} \cdot A_{rt} - SR_p^{Thin}}{\sqrt{D_{S_3}{}^2 \cdot A_{rt}{}^2 \cdot COV_{\Delta t}{}^2 + \left(1 - D_{S_3} \cdot A_{rt}\right)^2 \cdot COV_{S_f}{}^2 + (SR_p^{Thin})^2 \cdot COV_P{}^2}}$$

$$\beta_3^{Thin}\ @\ Plan\ Date = \frac{1 - 4 \cdot 0.1486 - 0.2724}{\sqrt{4^2 \cdot 0.1486^2 \cdot 0.20^2 + \left(1 - 4 \cdot 0.1486\right)^2 \cdot 0.20^2 + (0.2724)^2 \cdot 0.05^2}}$$

$$\beta_3^{Thin}\ @\ Plan\ Date = 0.9209$$

m. Calculate the Base Thinning DF, D_{fb}^{Thin}, where Φ is the standard normal cumulative distribution function (NORMSDIST in Excel)

$$D_{fb}^{Thin}\ @\ RBI\ Date = \left[\frac{\left(Po_{p1}^{Thin} \cdot \Phi\left(-\beta_1^{Thin}\right)\right) + \left(Po_{p2}^{Thin} \cdot \Phi\left(-\beta_2^{Thin}\right)\right) + \left(Po_{p3}^{Thin} \cdot \Phi\left(-\beta_3^{Thin}\right)\right)}{1.56E-04}\right]$$

$$D_{fb}^{Thin}\ @\ RBI\ Date = \left[\frac{\begin{array}{l}\left(0.8140 \cdot NORMSDIST\left(-3.6079\right)\right) + \\ \left(0.1395 \cdot NORMSDIST\left(-3.5845\right)\right) + \\ \left(0.0465 \cdot NORMSDIST\left(-3.5325\right)\right)\end{array}}{1.56E-04}\right]$$

$$D_{fb}^{Thin}\ @\ RBI\ Date = 1.0179$$

$$D_{fb}^{Thin}\ @\ Plan\ Date = \left[\frac{\left(Po_{p1}^{Thin} \cdot \Phi\left(-\beta_1^{Thin}\right)\right) + \left(Po_{p2}^{Thin} \cdot \Phi\left(-\beta_2^{Thin}\right)\right) + \left(Po_{p3}^{Thin} \cdot \Phi\left(-\beta_3^{Thin}\right)\right)}{1.56E-04} \right]$$

$$D_{fb}^{Thin}\ @\ Plan\ Date = \left[\frac{\begin{array}{l}\left(0.8140 \cdot NORMSDIST\left(-3.3393\right)\right) + \\ \left(0.1395 \cdot NORMSDIST\left(-2.8090\right)\right) + \\ \left(0.0465 \cdot NORMSDIST\left(-0.9209\right)\right)\end{array}}{1.56E-04} \right]$$

$$D_{fb}^{Thin}\ @\ Plan\ Date = 57.6468$$

n. Determine the DF for thinning, D_f^{Thin}

$$D_f^{Thin} = \max\left[\left(\frac{D_{fB}^{Thin} \cdot F_{IP} \cdot F_{DL}}{F_{OM}}\right),\ 0.1\right]$$

o. Calculate the final thinning DF at the RBI Date and Plan Date

$$D_f^{Thin}\ @\ RBI\ Date = max\left[\left(\frac{D_{fb}^{Thin} \cdot F_{IP} \cdot F_{DL}}{F_{CM}}\right),1\right]$$

$$D_f^{Thin} = max\left[\left(\frac{1.0179 \cdot 1 \cdot 1}{1}\right),1\right]$$

$$D_{fb}^{Thin}\ @\ RBI\ Date = 1.0179$$

$$D_f^{Thin}\ @\ Plan\ Date = max\left[\left(\frac{D_{fb}^{Thin} \cdot F_{IP} \cdot F_{DL}}{F_{CM}}\right),1\right]$$

$$D_f^{Thin} = max\left[\left(\frac{57.6468 \cdot 1 \cdot 1}{1}\right),1\right]$$

$$D_{fb}^{Thin}\ @\ Plan\ Date = 57.6468$$

Table 4.5—Prior Probability for Thinning Corrosion Rate

Damage State	Low Confidence Data	Medium Confidence Data	High Confidence Data
Pr_{p1}^{Thin}	0.5	0.7	0.8
Pr_{p2}^{Thin}	0.3	0.2	0.15
Pr_{p3}^{Thin}	0.2	0.1	0.05

Table 4.6—Conditional Probability for Inspection Effectiveness

Conditional Probability of Inspection	E—None or Ineffective	D—Poorly Effective	C—Fairly Effective	B—Usually Effective	A—Highly Effective
Co_{p1}^{Thin}	0.33	0.4	0.5	0.7	0.9
Co_{p2}^{Thin}	0.33	0.33	0.3	0.2	0.09
Co_{p3}^{Thin}	0.33	0.27	0.2	0.1	0.01

Table 4.7 – Internal Liner Types

Liner Type	Lining Resistance	Expected Age
Cladding/Weld Overlay	Based on corrosion review and cladding/weld overlay corrosion rate assigned. Subject to failure by corrosion.	Calculated based on thickness and corrosion rate of cladding/weld overly
Alloy Strip Liner	Subject to failure at seams, particularly on flange faces in high pressure applications. Also subject to failure at areas where plug-welding was used to secure to pressure boundary.	5-15 years
Organic Coating - Low Quality Immersion Grade Coating (Spray Applied, to 40 mils)	Limited life	1-3 years
Organic Coating - Medium Quality Immersion Grade Coating (Filled, Trowel Applied, to 80 mils)	Limited life	3-5 years
Organic Coating - High Quality Immersion Grade Coating (Reinforced, Trowel Applied, ≥ 80 mils)	Limited life	5-10 years
Thermal Resistance Service: Castable Refractory Plastic Refractory Refractory Brick Ceramic Fiber Refractory Refractory/Alloy Combination	Subject to occasional spalling or collapse	1-5 years
Thermal Resistance Service: Castable Refractory Ceramic Tile	Limited life in highly abrasive service	1-5 years
Glass Liners	Complete protection, subject to failure due to thermal or mechanical shock	5-10 years
Acid Brick	Partial protection. The brick provides thermal protection but is not intended to keep the fluid away from the base material.	10-20 years

Table 4.8 – Lining Condition Adjustment

Qualitative Condition	Description	Adjustment Multiplier – F_{LC}
Poor	The lining has either had previous failures or exhibits conditions, such as distortions, thinning, cracks or seepage, that may lead to failure in the near future. Repairs to previous failures are not successful or are of poor quality.	10
Average	The lining is not showing signs of excessive attack by any damage mechanisms. Local repairs may have been performed, but they are of good quality and have successfully corrected the lining condition.	2
Good	The lining is in “like new” condition with no signs of attack by any damage mechanisms. There has been no need for any repairs to the lining.	1
Good	As installed condition	1