API RP 581 Risk-Based Inspection Methodology –

Documenting and Demonstrating the Thinning Probability of Failure Calculations, Third Edition (Revised)

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ABSTRACT

A Joint Industry Project for Risk-Based Inspection (API RBI JIP) for the refining and petrochemical industry was initiated by the American Petroleum Institute in 1993. The project was conducted in three phases:

1) Methodology development Sponsor Group resulting in the publication of the Base Resource Document on Risk-Based Inspection in October 1996.
2) Methodology improvements documentation and software development User Group resulting in the publication of API RP 581 Second Edition in September 2008.
3) API Software User Group split from methodology development through an API 581 task group in November 2008.

The work from the JIP resulted in two publications: *API 580 Risk-Based Inspection*, released in 2002 and *API 581 Base Resource Document – Risk-Based Inspection*, originally released in 1996. The concept behind these publications was for API 580 to introduce the principles and present minimum general guidelines for risk-based inspection (RBI) while API 581 was to provide quantitative RBI methods. The API RBI JIP has made improvements to the technology since the original publication of these documents and released API RP 581, Second Edition in September 2008. Since the release of the Second Edition, the API 581 task group has been improving the methodology and revising the document for a Third Edition release in 2015.

Like the Second Edition, the Third Edition will be a three volume set, *Part 1: Inspection Planning Methodology*, *Part 2: Probability of Failure Methodology*, and *Part 3: Consequence of Failure Methodology*.

Among the changes incorporated into the Third Edition of API RP 581 is a significant modification to the thinning Probability of Failure (POF) calculation. The methodology documented in the Third Edition forms the basis for the original A_{rt} table approach it will

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replace. This paper provides the background for the technology behind the thinning model as well as step-by-step worked examples demonstrating the methodology for thinning in this new edition of API RP 581. This paper is a revision to a previous publication: *API RP 581 Risk-Based Inspection Methodology – Basis for Thinning Probability of Failure Calculations* published in November 2013.

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1.0 INTRODUCTION

Initiated in May 1993 by an industry-sponsored group to develop practical methods for implementing RBI, the API RBI methodology focuses inspection efforts on process equipment with the highest risk. This sponsor group was organized and administered by API and included the following members at project initiation: Amoco, ARCO, Ashland, BP, Chevron, CITGO, Conoco, Dow Chemical, DNO Heather, DSM Services, Equistar Exxon, Fina, Koch, Marathon, Mobil, Petro-Canada, Phillips, Saudi Aramco, Shell, Sun, Texaco, and UNOCAL.

The stated objective of the project was to develop a Base Resource Document (BRD) with methods that were "aimed at inspectors and plant engineers experienced in the inspection and design of pressure-containing equipment." The BRD was specifically not intended to become "a comprehensive reference on the technology of Quantitative Risk Assessment (QRA)." For failure rate estimations, the project was to develop "methodologies to modify generic equipment item failure rates" via "modification factors." The approach that was developed involved specialized expertise from members of the API Committee on Refinery Equipment through working groups comprised of sponsor members. Safety, monetary loss, and environmental impact were included for consequence calculations using algorithms from the American Institute of Chemical Engineers (AIChE) Chemical Process Quantitative Risk Assessment (CPQRA) guidelines. The results of the API RBI JIP and subsequent development were simplified methods for estimating failure rates and consequences of pressure boundary failures. The methods were aimed at persons who are not expert in probability and statistical method for Probability of Failure (POF) calculations and detailed QRA analysis.

1.1 Perceived Problems with POF Calculation

The POF calculation is based on the parameter A_{rt} that estimates the percentage of wall loss and is used with inspection history to determine a Damage Factor (DF). The basis for the A_{rt} table (Table 1) was to use structural reliability for load and strength of the equipment to calculate a POF based on result in failure by plastic collapse.

A statistical distribution is applied to a thinning corrosion rate over time, 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. Confidence that the assigned corrosion rate is the rate that is 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 and the improved knowledge of the component condition.

The A_{rt} table contains DFs created by using a base case piece of equipment to modify the generic equipment item failure rates to calculate a final POF. The A_{rt} table has been used successfully since 1995 to generate DFs for plant equipment and POF for risk prioritization of inspection. The perceived problems that have been noted during almost 20 years of use are:

1) Use of three thinning damage states introduced non-uniform changes in DFs vs. A_{rt}, leading to confusion during inspection planning. Methods for smoothing of data to eliminate humps were undocumented.
2) Use of Mean Value First Order Reliability Method (MVFORM) affected POF accuracies over more accurate statistical methods such as First Order Reliability Method (FORM) or Weibull analysis.

3) Results for specific equipment studied could be significantly different from the base case equipment used due to different properties, specifically:
    a.) Component geometric shapes used a cylindrical shape equation (not applicable for a semi-hemispherical, spherical or other shapes).
    b.) Material of construction tensile strength, TS, and yield strength, YS, values may not be representative for all materials of construction used in service.
    c.) Design temperature and pressure values may not be representative for all design and operating conditions used in service.
    d.) The 25% corrosion allowance assumption of furnished thickness at the time of installation may not be representative for all equipment condition.
    e.) The A_{rt} approach does not reference back to a design minimum thickness, $t_{\min}$, value.
    f.) Statistical values for confidence and Coefficients of Variance (COV) are not representative of all equipment experience.
    g.) The uncertainty in corrosion rate is double counted by using three damage states as well as a thinning COV of 0.1.
4) The DFs in Table 1 are calculated with artificial limitations such as:
    a.) A POF limit of 0.5 for each damage state limits the maximum DF to 3,210.
    b.) Rounding DFs to integers limits the minimum DF to 1.
5) The A_{rt} approach does not apply to localized thinning.

1.2 Suggested Modified Approach

This paper will address these perceived problems and suggest a modified POF approach to address the stated limitations, as applicable. While some of the perceived problems in reality have little significance in the final calculated results, use of the model outlined in this publication addresses all of the above limitations (with the exception of smoothing) to eliminate the damage state step changes and the resulting humps. In addition, two worked examples are provided to:

1) Validate the step-by-step calculations representing the DFs values in a modified A_{rt}, Table 7.
2) Provide an example using results from Table 1 and the modified methodology. In this example, use of Table 1 results produces a non-conservative DF and POF.

The methodology and worked examples presented in this paper follow the step-by-step methods for calculation of the thinning DF as outlined in API RP 581, Third Edition planned for release in 2015. A major part of the POF calculation and increase over time is due to general or local thinning (both internal and external). The background for the original basis of the thinning DF determination and POF is also provided in this paper. Figure 1 shows the decision tree in determining the thinning DF.

2.0 ORIGINAL BASIS FOR THINNING DAMAGE FACTOR AND A_{rt} TABLE

2.1 Background of A_{rt} Table

The DF methodology, developed in the early 1990's as a part of the API RBI JIP development project, used probabilistic structural mechanics and inspection updating. Probabilistic analysis methods normally used for evaluating single equipment were simplified for use as a risk prioritization methodology. Table 1 was created as a part of the original API RBI JIP project to provide an easy look-up table for use in risk determination for multiple equipment items.

Table 1 (Table 5.11 in API RP 581 2nd Edition, Part 2) was developed using the flow stress approach outlined in Table 2 to evaluate the probability of failure due to thinning mechanisms such as corrosion, erosion, and corrosion under insulation (CUI). Flow stress is the minimum stress required to sustain plastic deformation of a pressure-containing envelope to failure and provides a conservative POF estimates. A_{rt} is a factor related to the fraction of wall loss at any point in time in the life of operating equipment. Table 1 was developed as a way to evaluate the impact of inspection on POF as equipment wall becomes thinner with time. The A_{rt} factor was developed using a structural reliability model integrated with a method based on Bayes' Theorem to allow credit for the number and type of inspections performed on the POF and risk. The model was outlined in the API RBI JIP project and documented in API RP 581 First Edition in sufficient detail for skilled and experienced structural reliability specialists to understand the basis for the factors in Table 1.

The two-dimensional Table 1 was generated using a base case equipment approach, as outlined in Section 2.2. This base case approach provided a limited number of variables available to determine the DF and limited the user's ability to enter actual values or change assumptions for different equipment design cases. Using the modified methodology outlined in Section 4.0 with actual data for physical dimensions, materials properties and operating conditions to calculate POF and DF will result in a more accurate POF and risk results and improve discrimination between equipment risk and risk ranking.

2.2 Base Case for A_{rt} Table Development

The fixed variables and assumptions used to develop Table 1 were:

Cylindrical shape
Corrosion rate used to determine POF at 1×, 2× and 4× the expected rate
Diameter of 60 inches
Thickness of 0.5 inches
Corrosion allowance of 0.125 inches (25% of thickness)
Design Pressure of 187.5 psig
Tensile strength of 60,000 psi
Yield strength of 35,000 psi
Allowable Stress of 15,000 psi
Weld Joint Efficiency of 1.0
Failure frequency adjustment factor of $1.56E^{-04}$
Maximum POF of 0.5 imposed for all each of the three damage states, limiting the maximum damage factor to 3,205 (or $\frac{0.5}{1.56E^{-05}} = 3,205$)
DF table values calculated up to $A_{rt} = 0.65$ and linearly extrapolated to $A_{rt} = 1.0$
COV for variables of pressure = 0.050, flow stress = 0.200, thinning = 0.100

Categories and values of prior probabilities using low confidence values from Table 3

Values for conditional probabilities using values from Table 4

Table 1 was based on the equipment dimensions and properties outlined above and applied to all general plant fixed equipment. It was considered sufficiently applicable for other equipment geometries, dimensions, and materials for the purposes of equipment inspection prioritization.

2.3 Methodology Used In Development of the Thinning Damage Factor

2.3.1 *State Changes In High Uncertainty Data Situations*

Three damage states were used to account for corrosion rates higher than expected or measured that could result in undesirable consequences to generate the A_{rt} in Table 1. The three damage states used in the methodology were:

1) Damage State 1 – Damage is no worse than expected or a factor of 1 is applied to the expected corrosion rate
2) Damage State 2 – Damage is no worse than expected or a factor of 2 is applied to the expected corrosion rate
3) Damage State 3 – Damage is no worse than expected or a factor of 4 is 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. The result of using the three discrete damage states creates a POF curve with humps for the low confidence (no inspection) case. As more inspections are performed, less uncertainty in the corrosion rate results and the POF curve is smoothed due to higher confidence in the equipment condition. The DFs in Table 1 were rounded and visually smoothed to eliminate these abrupt changes causing damage state changes.

The DFs shown in Table 5 were developed using the same flow stress approach used to create Table 1 but without rounding DF values or smoothing to remove humps in low confidence cases. Figure 2 uses the methodology to plot DFs for a 0E and 6A inspection case from Table 5 and base case data equipment (Section 2.2). The humps in the low confidence inspection curves are a function of combining three damage states with different rates of increase with time. As confidence in the current state of the equipment is improved through effective inspection, the influence of damage states 2 and 3 are reduced and the curve is smooth.

It is important to note that the humps only occur in inherently high uncertainty situations and are not noticeable in the practical application of the methodology for inspection planning. As thinning continues over time, the DF will increase until an inspection is performed. After inspection, the DF is recalculated based on the new inspection effectiveness case. While the DF is not increasing at a constant rate in the low confidence inspection curves, the changes in the rate are unnoticeable in the practical application. Changing the coefficient of variance for thickness, $COV_{\Delta t}$, value from 0.100 to 0.200 results in a smoother curve, as demonstrated in the examples in Sections 4 and shown in Figure 5. When using the modified methodology outlined in Section 4.0, the user may also redefine the three damage state definitions as well as the confidence probability values in Table 4 for specific situations.

2.3.2 *Corrosion Rate Uncertainty*

Since the future corrosion or damage rate in process equipment is not known with certainty, the methodology applies uncertainty when the assigned corrosion rate is a discrete random variable with three possible damage states (based on 1×, 2×, and 4× the corrosion rate). 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:

1) 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.
2) 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.
3) 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 is available from actual process experience, the actual corrosion rate is very likely to be close to the expected value under normal operating conditions.

Recommended confidence probabilities are provided in Table 4 and may be defined by the user for specific applications.

3.0 STATISTICAL AND RELIABILTY METHODS AND MODIFIED THINNING METHODOLOGY

3.1 Limitations of Simplified Statistical Methods

Use of continuous states involves development of a cumulative probability distribution function that best describes the underlying statistical distribution of corrosion rates (e.g., normal, lognormal, Weibull, etc.). All variables that affect that corrosion rate (material, temperature, velocity, etc.) for each piece of equipment should be considered. This approach is more accurate if the function uses the correct mean, variance and underlying distribution in each case. More detailed statistical methods were considered during development of the DF approach, but were believed to add unnecessary complexity for use in risk-based inspection prioritization. An MVFORM was adopted for use in the DF calculation and is known to be overly conservative, particularly at very low POF values ($< 3.00\text{E}^{-05}$).

MVFORM is known to be less accurate at estimating the POF at very small values (high reliability index, β), compared to other estimating methods (e.g. First Order Reliability Method (FORM), Second Order Reliability Method (SORM), etc.), for nonlinear limit state equations. MVFORM may be overly conservative if the input variable distributions are not normally distributed.

Figure 3 compares the reliability indices calculated by MVFORM with FORM for the linear thinning limit state equation. Three different distribution types were investigated: normal, Weibull, and lognormal over a wide range of mean and variance values. The three distribution type β values in Figure 3 were assumed inputs as all normal variables, all lognormal variables and all Weibull random variables. The results show that for reliability indices of $\beta < 4$ ($\text{POF} \geq 3.00\text{E}^{-05}$) are comparable for all three distribution types. The results diverge when $\beta > 4$ ($\text{POF} < 3.00\text{E}^{-05}$).

Since the primary goal of the POF calculation is to identify items at higher than generic failure rates, the divergence of β estimates at larger β values do not affect the practical application for risk prioritization and inspection planning practices.

3.2 Modified Vs Base Case Equipment Data Values

As outlined in Section 2.2, a base set of equipment data was initially used to generate the DF values in Table 1. If the modified methodology outlined in this paper is used in place of the base case data, equipment specific DF and POF will be calculated and none of the limitations discussed in Sections 3.2.1 through 3.2.6 will apply.

3.2.1 *Geometric Shapes*

Stress due to internal pressure varies with equipment geometry. The base case uses a cylindrical shape for the calculations. The modified approach in Section 4.0 allows for calculations for other geometric shapes. Non-circular equations can be substituted if additional geometries are desired (e.g., header boxes, pump and compressor casings, etc.). Testing indicated that component geometry did not significantly affect DFs since design typically accounts for the impact of geometry on applied stress.

3.2.2 *Material of Construction Properties*

The TS and YS values used in the base case apply to a large population of equipment in most applications. However these assumed values may be non-conservative or overly conservative depending on the actual materials of construction used. For improved accuracy, the modified approach in Section 4.0 allows for use of the TS and YS values for the materials of construction.

3.2.3 *Pressure*

The pressure, P, used in the base case is considered to be a high average condition for most applications but may be non-conservative or overly conservative depending on the actual service. The modified approach in Section 4.0 allows for use a pressure chosen by the user for more accuracy.

It is important to note that the DF is not a direct indication of predicted equipment thickness to t_{min}, particularly if operating pressure is used for the calculation. The user should consider the impact of P used in the calculation compared to the design condition basis for t_{min}. If DF and POF are required to provide a closer match to t_{min} values (i.e., inspection is recommended and higher DF and POF are required), the user should consider using design pressure or a pressure relief device (PRD) set pressure.

3.2.4 *Corrosion Allowance*

The most significant potential impact in the base case described in Section 2.2 used to generate the A_{rt} table is the assumption that the corrosion allowance, CA, is 25% of the furnished thickness. More importantly, this assumption is non-conservative in specific situations, i.e., when the actual $CA << 25\%$ (much less than 25%). Alternatively, the results are overly conservative when the when the $CA >> 25\%$.

The modified approach in Section 4.0 generates a DF and POF based on design and condition of the equipment without the need for the CA assumptions used in the base case. The result is an increased applicability and accuracy with direct application of the model.

3.2.5 *Minimum Thickness, t_{min}*

The A_{rt} factor equation does not use t_{min} directly to calculation the Thinning DF and POF. To address the desire to incorporate t_{min} in API RP 581, Second Edition, the A_{rt} factor equation was modified to incorporate t_{min} into the calculation. The equation modification eliminated an overly conservative DF result when $t >> t_{\min} + CA$ by assigning a DF of 0. However if equipment thickness, t is required to $= t_{\min} + CA$, there is no difference between the First and Second Edition equations.

Use of the above equation will reduce the non-conservative and overly conservative results when using the original A_{rt} table.

It was never the intent of the DF calculation using the A_{rt} approach to develop a methodology that was specifically tied to the equipment t_{min}. In fact, the intent was to develop a risk-based methodology that allowed for safe continued operation of very low consequence equipment at an equipment thickness below the t_{min}. In these very low consequence cases, a run to failure strategy might be acceptable and therefore, t_{min} is not relevant as an indication of fitness for service. The use of this methodology does not imply that t_{min} is not important for risk-based inspection planning. In fact, it is considered important to calculate the future predicted thickness and corrosion allowance compared to DF and risk with time to develop the most appropriate inspection planning strategies for each situation.

Thickness is represented in the methodology in part through the strength ratio parameter, SR_P^{Thin}, that is defined as the ratio of hoop stress to flow stress through two equations for strength ratio parameter, SR_P^{Thin}:

1) This strength ratio parameter uses $t_{\min}$ 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 $t_{\min}$. When consideration for internal pressure hoop stress alone is not sufficient, the minimum structural thickness, t_c, should be used when appropriate.

$$SR_{P_1}^{Thin} = \frac{S \cdot E}{FS^{Thin}} \cdot \frac{Max(t_{\min}, t_c)}{t_{rdi}}$$

2) 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 a method other than API 579-1/ASME FFS-1, the above equation should be used.

$$SR_{P_2}^{Thin} = \frac{P \cdot D}{\alpha \cdot FS^{Thin} \cdot t_{rdi}}$$

The final SR_P^{Thin} is the maximum of the two strength parameters, as shown below.

$$SR_P^{Thin} = Max(SR_{P_1}^{Thin}, SR_{P_2}^{Thin})$$

3.2.6 *Coefficient of Variances (COV)*

The Coefficient of Variances, COV, were assigned for three key measurements affecting POF, as follows:

1) Coefficient of Variance for thickness, $COV_{\Delta t}$ – 0.100; uncertainty in inspection measurement accuracy
2) Coefficient of Variance for pressure, COV_P – 0.050; uncertainty is accuracy of pressure measurements
3) Coefficient of Variance for flow stress, COV_{S_f} – 0.200; uncertainty of actual TS and YS properties of equipment materials of construction

The three possible damage states described in Section 2.3.1 are used by Bayes' theorem with inspection measurements, prior knowledge and inspection effectiveness. Uncertainty in equipment thickness due to inspection measurements is also accounted for when the probability of three damage states are combined using a normal distribution with a $COV_{\Delta t} = 0.10$. This approach has a cumulative effect on the calculated POF due to the combined uncertainty of expected damage rates in the future combined with inspection measurement inaccuracy. Development of Table 7 was based on using the most conservative values (Low Confidence) from Table 3. If the combined conservativeness is not applicable for the specific application, the user may modify the damage state confidence values or adjust the $COV_{\Delta t}$ to suit the situation using the Section 4.0 modified methodology.

As discussed in Section 2.3.1, the DF calculation is very sensitive to the value used for $COV_{\Delta t}$. The recommended range of values for $COV_{\Delta t}$ is $0.10 \le COV_{\Delta t} \le 0.20$. Note that the base case used a value of $COV_{\Delta t} = 0.10$, resulting in hump at transitions between damage states (Figure 2). Using a value of $COV_{\Delta t} = 0.20$, results in a more conservative DF but smoother transition between damage states, as shown in Figure 5.

Similarly, uncertainty is assigned to P measurements and FS^{Thin}, reflected by measurement of TS and YS for the equipment material of construction. The COVs in Section 4.0 modified methodology may be tailored by the user to suit the situation.

3.2.7 *Duplication of Corrosion Rate Uncertainty*

As discussed in Section 3.2.6, a $COV_{\Delta t}$ was assigned to reflect uncertainty in thickness measurements through inspection. The three damage states defined in Section 2.3.1 were assigned to reflect confidence in estimated or measured corrosion rates in reflecting a future equipment condition. If the combined conservativeness is not applicable for the specific application or considered too conservative, the user may modify the damage state confidence values or adjust the $COV_{\Delta t}$ to suit the situation using the Section 4.0 modified methodology.

3.3 Damage Factors Calculated With Artificial Limitations

3.3.1 *POF Extended to 1.0 for Three Damage States*

The damage factors in Table 1 were limited to 3,205 ($0.5/1.56\text{E}^{-05}=3,205$) by a POF maximum set at 0.5 for each of the three damage states. However since the maximum A_{rt} factor in Table 1 was originally set to 0.65, the impact of the limitation was not obvious unless the A_{rt} table is extended through 1.0, as shown in Table 5. The practical application of the methodology required setting $A_{rt} = 1.0$ to a DF of $5,000$ (expected through-wall) and interpolating DFs between $A_{rt} = 0.65$ and 1.0 in order to improve risk ranking discrimination between equipment nearing or at a failure thickness. The extrapolated values with values to 1.0 are shown in Table 6.

By removing the POF limit of 0.5, the maximum DF is increased to 6,410 ($1.0/1.56\text{E}^{-05}=6,410$) and the DFs calculated through an A_{rt} value of 1.0 rather than using interpolation, as shown in Table 7. The DF increase using this approach is most significant when $A_{rt} > 0.70$ as shown in Figure 4 and where the $DF > 2,500$ (Category 5 POF). The DFs from Table 7 are shown graphically in Figure 5 comparing DFs for the 0E (low confidence) and 1A (higher confidence) inspection cases.

An increase in thinning DF from 5,000 to 6,410 results in a maximum of 28% increase in DF. This increase is most significant at $A_{rt} > 0.70$ (Category 5 POF) when inspection is highly recommended regardless of consequence levels, unless a run to failure scenario is used.

3.3.2 *DF Lower Limit*

Table 1 rounded DFs to a minimum value 1 to prevent a $\text{POF} < G_{ff}$. Rounding in Table 7 has not been performed, allowing a final POF less than the base G_{ff} for equipment with very low or no in-service damage. A minimum DF of $D_f^{Thin} = \max\left[D_{fB}^{Thin},\ 0.1\right]$ is used to limit the final POF to an order of magnitude lower than G_{ff}. The user may specify a different minimum or no minimum DF for individual cases, if desired.

3.4 Localized Thinning

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 API RP 581 Part 2, Annex 2.B may 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.

Localized corrosion in API RP 581 methodology is defined as non-uniform thinning occurring over $\leq$ 10% of the equipment affected area such that spot thickness measurements would be highly unlikely to detect the localized behavior or even find the locally thinning areas. Localized thinning in this case is not intended to be a Fitness-For-Service (FFS) evaluation method for locally thin areas. For the localized thinning experienced, an area inspection method is required to achieve a high level of certainty in the inspection conducted.

4.0 EXAMPLES

4.1 Example 1 – Calculation of A_{rt} Using Base Case Equipment

4.1.1 *Base Case Thinning Damage Factor*

Using the Base Case example defined in Section 2.2, with modifications to the methodology behind the values in Table 1 recommended in Section 3.0, a step-by-step example is presented below. Equipment data from Section 2.2 that will be used in this example is as follows:

Design Pressure	187.5 psig
Design Temperature	650°F
Tensile Strength	60,000 psi
Yield Stress	35,000 psi
Allowable Stress	15,000 psi
Furnished Thickness	0.500 inch
Minimum Required Thickness	0.375 inch
Corrosion Allowance	0.125 inch
Weld Joint Efficiency	1.0
Diameter	60 inch
Corrosion Rate	0.005 ipy (5 mpy)
$COV_{\Delta t}$	0.200
COV_P	0.050
COV_{S_f}	0.200

4.1.2 *Calculation of Thinning Damage Factor using A_{rt} Approach*

The following example demonstrates the steps required for calculating the thinning damage factor using the A_{rt} approach:

1) Determine the thickness, t_{rdi} and corrosion allowance, CA.

   $t_{rdi} = 0.500\ inch$

   $CA = 0.125\ inch$

2) Determine the corrosion rate of the base material, $C_{r,bm}$.

   $C_{r,bm} = 5\ mpy$

3) Determine the time in-service, age, from the installation date or last inspection date.

   $age = 25.0$ years

4) Determine the minimum required wall thickness.

   $t_{\min} = 0.375$ inch

5) Determine the number of historical inspections and the inspection effectiveness category for each: Inspection History (1A).

6) Determine the A_{rt} parameter using Equation (2) based on t_{rdi} and CA from Step 1, $C_{r,bm}$ from Step 2, age from Step 3 and $t_{\min}$ from Step 4.

$$A_{rt} = \max\left[\left(1 - \frac{t_{rdi} - C_{r,bm} \cdot age}{t_{min} + CA}\right), \ \ 0.0\right]$$

$$A_{rt} = \max\left[\left(1 - \frac{0.500 - 0.005 \cdot 25.0}{0.375 + 0.125}\right), \ \ 0.0\right]$$

$$A_{rt} = \max\left[\left(1 - 0.75\right), \ \ 0.0\right] = 0.25 \tag{2}$$

7) Calculate thinning damage factor, D_{fB}^{thin}, using the inspection history from Step 5 and A_{rt} from Step 6.

   a) Based on values from Table 1:

   $$D_{fB}^{thin} @ A_{rt} \ of \ \ 0.25 \text{ and 0E inspection in Table } 1 = 520$$

   $$D_{fB}^{thin} @ A_{rt} \ of \ \ 0.25 \text{ and 1A inspection in Table } 1 = 20$$

   b) Based on values from Table 7:

   $$D_{fB}^{thin} @ A_{rt} \ of \ \ 0.25 \text{ and 0E inspection in Table } 7 = 1,272.90$$

   $$D_{fB}^{thin} @ A_{rt} \ of \ \ 0.25 \text{ and 1A inspection in Table } 7 = 29.73$$

   c) Based on values from Table 9:

   $$D_{fB}^{thin} @ A_{rt} \ of \ \ 0.25 \text{ and 0E inspection in Table } 9 = 1,145.23$$

   $$D_{fB}^{thin} @ A_{rt} \ of \ \ 0.25 \text{ and 1A inspection in Table } 9 = 10.64$$

4.1.3 *Probability of Failure Using Reliability Methodology Approach*

1) Calculate A_{rt} using the base material corrosion rate, $C_{r,bm}$, time in-service, age, last known thickness, t_{rdi}, from Section 4.1.1.

$$A_{rt} = \frac{C_{r,bm} \cdot age}{t_{rdi}}$$

$$A_{rt} = \frac{0.005 \cdot 25}{0.5}$$

$$A_{rt} = 0.25$$

2) Calculate flow stress, FS^{Thin}, using the Yield Stress, YS, Tensile Strength, TS, and weld joint efficiency, E

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

$$FS^{Thin} = \frac{(35 + 60)}{2} \cdot 1.0 \cdot 1.1$$

$$FS^{Thin} = 52.25$$

3) Calculate the strength ratio factor, SR_P^{Thin} using the greater of the following factors using the minimum required thickness, t_{min}:

$$SR_P^{Thin} = Max(SR_{P1}^{Thin}, SR_{P2}^{Thin})$$

a) Where SR_{P1}^{Thin} is calculated:

$$SR_{P_1}^{Thin} = \frac{S \cdot E}{FS^{Thin}} \cdot \frac{Min(t_{\min}, t_c)}{t_{rdi}}$$

$$SR_{P_1}^{Thin} = \frac{15 \cdot 1.0}{52.25} \cdot \frac{0.375}{0.5}$$

$$SR_{P_1}^{Thin} = 0.2153$$

Note: The minimum required thickness, $t_{\min}$, is based on a design calculation that includes evaluation for internal pressure hoop stress, external pressure and/or structural considerations, as appropriate. Consideration for internal pressure hoop stress alone is not sufficient.

b) Where SR_{P2}^{Thin} is calculated:

$$SR_{P_2}^{Thin} = \frac{P \cdot D}{\alpha \cdot FS^{Thin} \cdot t_{rdi}}$$

$$SR_{P_2}^{Thin} = \frac{187.5 \cdot 60}{2 \cdot 52.25 \cdot 0.5}$$

$$SR_{P_2}^{Thin} = 0.2153$$

Where α is the shape factor for the component type:

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

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.

The final Strength Ratio parameter, SR_P^{Thin}

$$SR_P^{Thin} = Max(SR_{P_1}^{Thin}, SR_{P_2}^{Thin})$$

$$SR_P^{Thin} = Max(0.2153, 0.2153)$$

$$SR_P^{Thin} = 0.2153$$

4) Determine the number of historical inspections for each of the corresponding inspection effectiveness, N_A^{Thin} , N_B^{Thin} , N_C^{Thin} , N_D^{Thin} :

$$N_A^{Thin} = 1$$

$$N_B^{Thin} = 0$$

$$N_C^{Thin} = 0$$

$$N_D^{Thin} = 0$$

5) Determine prior probabilities of predicted thinning states.

$$\textit{Low Probability Data from Table } 3:$$

$$Pr_{p1}^{Thin} = 0.5$$

$$Pr_{p2}^{Thin} = 0.3$$

$$Pr_{p3}^{Thin} = 0.2$$

6) Calculate the inspection effectiveness factors, I_1^{Thin} , I_2^{Thin} , I_3^{Thin} , using prior probabilities from Step 2 (Table 3), conditional probabilities from Table 4 and for no inspection history and the number of historical inspections from Step 4.

   a) For no inspection history:

$$I_1^{Thin} = Pr_{p1}^{Thin}\left(Co_{p1}^{ThinA}\right)^{N_A^{Thin}}\left(Co_{p1}^{ThinB}\right)^{N_B^{Thin}}\left(Co_{p1}^{ThinC}\right)^{N_C^{Thin}}\left(Co_{p1}^{ThinD}\right)^{N_D^{Thin}}$$

$$I_1^{Thin} = 0.50(0.9)^0(0.7)^0(0.5)^0(0.4)^0$$

$$I_1^{Thin} = 0.50$$

$$I_2^{Thin} = Pr_{p2}^{Thin}\left(Co_{p2}^{ThinA}\right)^{N_A^{Thin}}\left(Co_{p2}^{ThinB}\right)^{N_B^{Thin}}\left(Co_{p2}^{ThinC}\right)^{N_C^{Thin}}\left(Co_{p2}^{ThinD}\right)^{N_D^{Thin}}$$

$$I_2^{Thin} = 0.30(0.09)^0(0.2)^0(0.3)^0(0.33)^0$$

$$I_2^{Thin} = 0.30$$

$$I_3^{Thin} = Pr_{p3}^{Thin}\left(Co_{p3}^{ThinA}\right)^{N_A^{Thin}}\left(Co_{p3}^{ThinB}\right)^{N_B^{Thin}}\left(Co_{p3}^{ThinC}\right)^{N_C^{Thin}}\left(Co_{p3}^{ThinD}\right)^{N_D^{Thin}}$$

$$I_3^{Thin} = 0.20(0.01)^0(0.1)^0(0.2)^0(0.27)^0$$

$$I_3^{Thin} = 0.20$$

   b) For 1A inspection history:

$$I_1^{Thin} = Pr_{p1}^{Thin}\left(Co_{p1}^{ThinA}\right)^{N_A^{Thin}}\left(Co_{p1}^{ThinB}\right)^{N_B^{Thin}}\left(Co_{p1}^{ThinC}\right)^{N_C^{Thin}}\left(Co_{p1}^{ThinD}\right)^{N_D^{Thin}}$$

$$I_1^{Thin} = 0.50(0.9)^1(0.7)^0(0.5)^0(0.4)^0$$

$$I_1^{Thin} = 0.4500$$

$$I_2^{Thin} = Pr_{p2}^{Thin}\left(Co_{p2}^{ThinA}\right)^{N_A^{Thin}}\left(Co_{p2}^{ThinB}\right)^{N_B^{Thin}}\left(Co_{p2}^{ThinC}\right)^{N_C^{Thin}}\left(Co_{p2}^{ThinD}\right)^{N_D^{Thin}}$$

$$I_2^{Thin} = 0.30(0.09)^1(0.2)^0(0.3)^0(0.33)^0$$

$$I_2^{Thin} = 0.0270$$

$$I_3^{Thin} = Pr_{p3}^{Thin}\left(Co_{p3}^{ThinA}\right)^{N_A^{Thin}}\left(Co_{p3}^{ThinB}\right)^{N_B^{Thin}}\left(Co_{p3}^{ThinC}\right)^{N_C^{Thin}}\left(Co_{p3}^{ThinD}\right)^{N_D^{Thin}}$$

$$I_3^{Thin} = 0.20(0.01)^1(0.1)^0(0.2)^0(0.27)^0$$

$$I_3^{Thin} = 0.0020$$

7) Calculate the posterior probabilities using I_1^{Thin} , I_2^{Thin} and I_3^{Thin} from Step 7.

   a) For no inspection history:

$$Po_{p1}^{Thin} = \frac{I_1^{Thin}}{I_1^{Thin} + I_2^{Thin} + I_3^{Thin}}$$

$$Po_{p1}^{Thin} = \frac{0.50}{0.50 + 0.30 + 0.20}$$

$$Po_{p1}^{Thin} = 0.50$$

$$Po_{p2}^{Thin} = \frac{I_2^{Thin}}{I_1^{Thin} + I_2^{Thin} + I_3^{Thin}}$$

$$Po_{p2}^{Thin} = \frac{0.30}{0.50 + 0.30 + 0.20}$$

$$Po_{p2}^{Thin} = 0.30$$

$$Po_{p3}^{Thin} = \frac{I_3^{Thin}}{I_1^{Thin} + I_2^{Thin} + I_3^{Thin}}$$

$$Po_{p3}^{Thin} = \frac{0.20}{0.50 + 0.30 + 0.20}$$

$$Po_{p3}^{Thin} = 0.20$$

b) For 1A inspection history:

$$Po_{p1}^{Thin} = \frac{I_1^{Thin}}{I_1^{Thin} + I_2^{Thin} + I_3^{Thin}}$$

$$Po_{p1}^{Thin} = \frac{0.4500}{0.4500 + 0.0270 + 0.0020}$$

$$Po_{p1}^{Thin} = 0.9395$$

$$Po_{p2}^{Thin} = \frac{I_2^{Thin}}{I_1^{Thin} + I_2^{Thin} + I_3^{Thin}}$$

$$Po_{p2}^{Thin} = \frac{0.0270}{0.4500 + 0.0270 + 0.0020}$$

$$Po_{p2}^{Thin} = 0.0564$$

$$Po_{p3}^{Thin} = \frac{I_3^{Thin}}{I_1^{Thin} + I_2^{Thin} + I_3^{Thin}}$$

$$Po_{p3}^{Thin} = \frac{0.0020}{0.4500 + 0.0270 + 0.0020}$$

$$Po_{p3}^{Thin} = 0.0042$$

8) Calculate the parameters, β_1^{Thin}, β_2^{Thin}, β_3^{Thin} where $COV_{\Delta t} = 0.20$, $COV_{S_f} = 0.20$ and $COV_P = 0.05$.

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

$$\beta_1^{Thin} = \frac{(1 - 1 \cdot 0.25) - 0.2153}{\sqrt{1^2 \cdot 0.25^2 \cdot 0.2^2 + \left(1 - 1 \cdot 0.25\right)^2 \cdot 0.2^2 + (0.2153)^2 \cdot 0.05^2}}$$

$$\beta_1^{Thin} = 3.3739$$

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

$$\beta_2^{Thin} = \frac{(1 - 2 \cdot 0.25) - 0.2153}{\sqrt{2^2 \cdot 0.25^2 \cdot 0.2^2 + \left(1 - 2 \cdot 0.25\right)^2 \cdot 0.2^2 + (0.2153)^2 \cdot 0.05^2}}$$

$$\beta_2^{Thin} = 2.0072$$

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

$$\beta_3^{Thin} = \frac{(1 - 4 \cdot 0.25) - 0.2153}{\sqrt{4^2 \cdot 0.25^2 \cdot 0.2^2 + \left(1 - 4 \cdot 0.25\right)^2 \cdot 0.2^2 + (0.2153)^2 \cdot 0.05^2}}$$

$$\beta_3^{Thin} = -1.0750$$

Where D_{S_1}, D_{S_2} *and* D_{S_3} are the corrosion rate factors for Damage States 1, 2 and 3.

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 $COV_{\Delta t} = 0.20$.

9) Calculate the base damage factor, D_{fB}^{Thin}.

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

$$D_{fb}^{Thin} = \left[\frac{\left(0.50 \Phi\left(-3.3739\right)\right) + \left(0.30 \Phi\left(-2.0072\right)\right) + \left(0.20 \Phi\left(-(-1.0750)\right)\right)}{1.56E-04} \right]$$

$$D_{fb}^{Thin} = 1{,}145.23 \; for \; 0 \; Inspection$$

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

$$D_{fb}^{Thin} = \left[\frac{\left(0.9395 \Phi\left(-3.3739\right)\right) + \left(0.0564 \Phi\left(-2.0072\right)\right) + \left(0.0042 \Phi\left(-(-1.0750)\right)\right)}{1.56E-04} \right]$$

$$D_{fb}^{Thin} = 33.30 \; for \; 1A \; Inspection$$

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

10) Determine the DF for thinning, D_f^{Thin}

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

$$D_f^{Thin} = \max\left[\left(\frac{1,272.90 \cdot 1 \cdot 1}{1}\right),\ \ 0.1\right]$$

$$D_f^{Thin} = 1,272.90\ for\ 0\ Inspection$$

$$D_{fb}^{Thin} = 29.73\ for\ 1A\ Inspection$$

4.1.4 *Calculation of Probability of Failure*

The final POF calculation is performed using above Equation (1.1).

For 0E Inspection Case:

$$P_f(t) = 3.06E^{-05} \cdot 1,145.23 = 3.50\mathrm{E}^{-02}$$

For 1A Inspection Case:

$$P_f(t) = 3.06E^{-05} \cdot 33.30 = 1.09\mathrm{E}^{-03}$$

4.2 Example 2 – Calculation of Equipment Specific A_{rt} for Thin Wall, Low Corrosion Allowance Equipment

4.2.1 *Low CA Thinning Damage Factor*

Using the modifications to the methodology behind Table 7 and in Section 4.0, a step-by-step example is presented below for relatively thin equipment with very low corrosion allowance. An A_{rt} table for the data below is shown in Table 8. Figure 6 compares DFs from Table 1, Table 7, and Table 8 for the 1A inspection case. The example equipment data is as follows:

Design Pressure	109.5 psig
Design Temperature	650ºF
Tensile Strength	70,000 psi
Yield Stress	37,000 psi
Allowable Stress	17,000 psi
Furnished Thickness	0.188 inch
Minimum Thickness	0.188 inch
Corrosion Allowance	0.00 inch
Weld Joint Efficiency	1.00
Inside Diameter (ID)	60 inch
Corrosion Rate	0.0063 ipy (6.3 mpy)
$COV_{\Delta t}$	0.200
COV_P	0.050
COV_{S_f}	0.200

4.2.2 *Calculation of Thinning Damage Factor*

The following example demonstrates the steps required for calculating the thinning damage factor:

1)
2) Determine the thickness, t_{rdi} and corrosion allowance, CA.

   $t_{rdi} = 0.188\ inch$

   $CA = 0.0\ inch$

3) Determine the corrosion rate of the base material, $C_{r,bm}$.

   $C_{r,bm} = 6.3\ mpy$

4) Determine the time in-service, age, from the installation date or last inspection date.

   $age = 9.0$ years

5) Determine the minimum required wall thickness.

   $t_{\min} = 0.188$ inch

6) Determine the number of historical inspections and the inspection effectiveness category for each: Inspection History (3B).
7) Determine the A_{rt} parameter using Equation (2) based on t_{rdi} and CA from Step 1, $C_{r,bm}$ from Step 2, age from Step 3 and $t_{\min}$ from Step 4.

$$A_{rt} = \max\left[\left(1 - \frac{t_{rdi} - C_{r,bm} \cdot age}{t_{min} + CA}\right),\ 0.0\right]$$

$$A_{rt} = \max\left[\left(1 - \frac{0.188 - 0.0063 \cdot 9.0}{0.188 + 0.00}\right),\ 0.0\right] \qquad (2)$$

$$A_{rt} = \max\left[\left(1 - 0.6649\right),\ 0.0\right] = 0.3016$$

DF for 0E inspection is 700 and 3B inspection is 15.

8) Determine the thinning damage factor, D_{fB}^{thin}, using Table 1 and Table 6 based on the number of and highest effective inspection category from 1) and the A_{rt} from 6) in Section 4.2.2.

$$D_{fB}^{thin} @ A_{rt}\ of\ \text{0.3016 and 0E inspection in Table } 6 = 1,346$$

$$D_{fB}^{thin} @ A_{rt}\ of\ \text{0.3016 and 3B inspection in Table } 6 = 12.61$$

$$D_{fB}^{thin} @ A_{rt}\ of\ \text{0.3016 and 0E inspection in Table } 7 = 1,573$$

$$D_{fB}^{thin} @ A_{rt}\ of\ \text{0.3016 and 3B inspection in Table } 7 = 35.58$$

4.2.3 *Probability of Failure Using Reliability Methodology*

1) Calculate A_{rt} using the base material corrosion rate, in-service time, last known thickness, allowable stress, weld joint efficiency and minimum required thickness from Section 4.2.1.

$$A_{rt} = \frac{C_{r,bm} \cdot age}{t_{rdi}}$$

$$A_{rt} = \frac{0.0063 \cdot 9}{0.188}$$

$$A_{rt} = 0.3016$$

2) Calculate flow stress, FS^{Thin}

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

$$FS^{Thin} = \frac{(37 + 70)}{2} \cdot 1.0 \cdot 1.1$$

$$FS^{Thin} = 58.85$$

3) Calculate the strength ratio factor, SR_P^{Thin} using the greater of the following factors:

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

$$SR_P^{Thin} = \frac{17.5 \cdot 1.0}{58.85} \cdot \frac{0.188}{0.188}$$

$$SR_P^{Thin} = 0.2974$$

Note: The minimum required thickness, t_{min}, is based on a design calculation that includes evaluation for internal pressure hoop stress, external pressure and/or structural considerations, as appropriate. Consideration for internal pressure hoop stress alone is not sufficient.

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

$$SR_P^{Thin} = \frac{109.5 \cdot 60}{2 \cdot 58.85 \cdot 0.188}$$

$$SR_P^{Thin} = 0.2969$$

Where α is the shape factor for the component type:

$\alpha = 2 \; for \; a \; cylinder, 4 \; for \; a \; sphere, 1.13 \; for \; a \; head$

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.

The final Strength Ratio parameter, SR_P^{Thin}

$$SR_P^{Thin} = Max(SR_{P_1}^{Thin}, SR_{P_2}^{Thin})$$

$$SR_P^{Thin} = Max(0.2974, 0.2969)$$

$$SR_P^{Thin} = 0.2974$$

4) Determine the number of historical inspections for each of the corresponding inspection effectiveness, N_A^{Thin}, N_B^{Thin}, N_C^{Thin}, N_D^{Thin}:

$$N_A^{Thin} = 0$$

$$N_B^{Thin} = 3$$

$$N_C^{Thin} = 0$$

$$N_D^{Thin} = 0$$

5) Determine prior probabilities of predicted thinning states.

$Low \; Probability \; Data \; from \; Table \; 3:$

$$Pr_{p1}^{Thin} = 0.5$$

$$Pr_{p2}^{Thin} = 0.3$$

$$Pr_{p3}^{Thin} = 0.2$$

6) Calculate the inspection effectiveness factors, I_1^{Thin}, I_2^{Thin}, I_3^{Thin}, using prior probabilities from Step 2 (Table 3), conditional probabilities from Table 4 and the number of historical inspections from Step 4.

$$I_1^{Thin} = Pr_{p1}^{Thin} \left(Co_{p1}^{ThinA}\right)^{N_A^{Thin}} \left(Co_{p1}^{ThinB}\right)^{N_B^{Thin}} \left(Co_{p1}^{ThinC}\right)^{N_C^{Thin}} \left(Co_{p1}^{ThinD}\right)^{N_D^{Thin}}$$

$$I_1^{Thin} = 0.50(0.9)^0 (0.7)^3 (0.5)^0 (0.4)^0$$

$$I_1^{Thin} = 0.1715$$

$$I_2^{Thin} = Pr_{p2}^{Thin} \left(Co_{p2}^{ThinA}\right)^{N_A^{Thin}} \left(Co_{p2}^{ThinB}\right)^{N_B^{Thin}} \left(Co_{p2}^{ThinC}\right)^{N_C^{Thin}} \left(Co_{p2}^{ThinD}\right)^{N_D^{Thin}}$$

$$I_2^{Thin} = 0.30(0.09)^0 (0.2)^3 (0.3)^0 (0.33)^0$$

$$I_2^{Thin} = 0.0024$$

$$I_3^{Thin} = Pr_{p3}^{Thin} \left(Co_{p3}^{ThinA}\right)^{N_A^{Thin}} \left(Co_{p3}^{ThinB}\right)^{N_B^{Thin}} \left(Co_{p3}^{ThinC}\right)^{N_C^{Thin}} \left(Co_{p3}^{ThinD}\right)^{N_D^{Thin}}$$

$$I_3^{Thin} = 0.20(0.01)^0 (0.1)^3 (0.2)^0 (0.27)^0$$

$$I_3^{Thin} = 0.0002$$

7) Calculate the posterior probabilities using I_1^{Thin}, I_2^{Thin} and I_3^{Thin} from Step 7.

$$Po_{p1}^{Thin} = \frac{I_1^{Thin}}{I_1^{Thin} + I_2^{Thin} + I_3^{Thin}}$$

$$Po_{p1}^{Thin} = \frac{0.1715}{0.1715 + 0.0024 + 0.0002}$$

$$Po_{p1}^{Thin} = 0.9851$$

$$Po_{p2}^{Thin} = \frac{I_2^{Thin}}{I_1^{Thin} + I_2^{Thin} + I_3^{Thin}}$$

$$Po_{p2}^{Thin} = \frac{0.0024}{0.1715 + 0.0024 + 0.0002}$$

$$Po_{p2}^{Thin} = 0.0138$$

$$Po_{p3}^{Thin} = \frac{I_3^{Thin}}{I_1^{Thin} + I_2^{Thin} + I_3^{Thin}}$$

$$Po_{p3}^{Thin} = \frac{0.0002}{0.1715 + 0.0024 + 0.0002}$$

$$Po_{p3}^{Thin} = 0.0011$$

8) Calculate the parameters, β_1^{Thin}, β_2^{Thin}, β_3^{Thin} where $COV_{\Delta t} = 0.10$, $COV_{S_f} = 0.20$ and $COV_P = 0.05$.

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

$$\beta_1^{Thin} = \frac{(1 - 1 \cdot 0.3016) - 0.2974}{\sqrt{1^2 \cdot 0.3016^2 \cdot 0.2^2 + \left(1 - 1 \cdot 0.3016\right)^2 \cdot 0.2^2 + (0.2974)^2 \cdot 0.05^2}}$$

$$\beta_1^{Thin} = 2.6233$$

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

$$\beta_2^{Thin} = \frac{(1 - 2 \cdot 0.3016) - 0.2974}{\sqrt{2^2 \cdot 0.3016^2 \cdot 0.2^2 + \left(1 - 2 \cdot 0.3016\right)^2 \cdot 0.2^2 + (0.2974)^2 \cdot 0.05^2}}$$

$$\beta_2^{Thin} = 0.6850$$

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

$$\beta_3^{Thin} = \frac{(1 - 4 \cdot 0.3016) - 0.2974}{\sqrt{4^2 \cdot 0.3016^2 \cdot 0.2^2 + \left(1 - 4 \cdot 0.3016\right)^2 \cdot 0.2^2 + (0.2974)^2 \cdot 0.05^2}}$$

$$\beta_3^{Thin} = -2.0542$$

Where D_{S_1}, D_{S_2} *and* D_{S_3} are the corrosion rate factors for Damage States 1, 2 and 3.

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 $COV_{\Delta t} = 0.20$.

9) Calculate the base damage factor, D_{fB}^{Thin}.

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

$$D_{fb}^{Thin} = \left[\frac{\left(0.50\Phi\left(-2.6233\right)\right) + \left(0.30\Phi\left(-0.6850\right)\right) + \left(0.20\Phi\left(-(-2.0542)\right)\right)}{1.56E-04}\right]$$

$$D_{fb}^{Thin} = 1{,}744.74 \text{ } for \text{ } 0 \text{ } Inspection$$

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

$$D_{fb}^{Thin} = \left[\frac{\left(0.9851\Phi\left(-2.6233\right)\right) + \left(0.0138\Phi\left(-0.6850\right)\right) + \left(0.0011\Phi\left(-(-2.0542)\right)\right)}{1.56E-04}\right]$$

$$D_{fb}^{Thin} = 56.50 \text{ } for \text{ } 3\text{B} \text{ } Inspection$$

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

10) Determine the DF for thinning, D_f^{Thin}

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

$$D_f^{Thin} = \max\left[\left(\frac{1,744.74 \cdot 1 \cdot 1}{1}\right),\ \ 0.1\right]$$

$$D_f^{Thin} = 1,744.74\ for\ 0\ Inspection$$

$$D_{fb}^{Thin} = 56.50\ for\ 3\mathrm{B}\ Inspection$$

4.2.4 *Calculation of Probability of Failure*

The final probability of failure calculation is performed using above Equation (1.1).

For 0E Inspection Case:

$$P_f(t) = 3.06E^{-05} \cdot 1,744.74 = 5.34\mathrm{E}^{-02}$$

For 1A Inspection Case:

$$P_f(t) = 3.06E^{-05} \cdot 56.50 = 1.73\mathrm{E}^{-03}$$

5.0 SUMMARY AND CONCLUSIONS

The background and methodology for thinning DF and POF determinations and perceived problems with the original A_{rt} approach has been discussed. The basis for the original A_{rt} table is a structural reliability equation for load and strength of the equipment to calculate a POF using a base case of data. A suggested modified approach has been outlined to address the limitations of the table values using the base case. While some of the perceived problems or limitations have little impact on the accuracy of the final calculated results, use of the model addresses all of the potential limitations identified during 20 years of practical application (with the exception of smoothing to eliminate the damage state step changes and the resulting humps). Two worked examples have been provided: a validation of the step-by-step calculations compared to A_{rt} table values as well as an example that demonstrates more realistic results for non-conservative results (low corrosion allowance) in the original table.

Use of the modified methodology will provide the following results:

1) Three thinning damage states introduce non-uniform changes in DFs over time. The magnitude of the humps are reduced by using a $COV_{\Delta t}$ COV of 0.1. These humps occur in high uncertainty situations and are not noticeable in the practical application of the methodology for inspection planning. As thinning continues over time, the DF will increase until an inspection is performed. After inspection, the DF is recalculated based on the new inspection effectiveness case. In addition, the modified approach allows the user to tailor calculations to their actual experience by defining the damage states and corrosion rate confidence probabilities. Changing the coefficient of variance for thickness, $COV_{\Delta t}$, value from 0.100 to 0.200 results in a smoother curve. The user may define the three damage state definitions as well as the confidence probability values for the specific application.
2) MVFORM for calculation of POF is less accurate than other statistical methods if the variable is not normally distributed. This significantly affects reliability indices when β < 4 ($\text{POF} \geq 3.00\text{E}^{-05}$). The primary goal of the POF calculation is to identify items at higher than generic failure rates and provide a risk ranking priority. For this reason, loss of accuracy at very low POF values is sufficiently accurate for risk prioritization and inspection planning practices.
3) Uses specific equipment data rather than a base case. Equipment designed and operating differently than the base case data used for the A_{rt} table could generate less accurate results and affect risk prioritization:
    a.) The modified approach in allows the user to replace the calculations for other shapes and non-circular shapes (such as header boxes, pump and compressor casings, et al). While testing indicates that calculation of DF and POF is not very sensitive to component geometry, it is recommended that the user should tailor calculations to address varying geometric shapes.
    b.) While the material of construction tensile strength, TS, and yield strength, YS, are representative of a large population of in-service equipment, the base case values may be non-conservative or overly conservative depending on the actual materials of construction used. It is recommended that the user tailor calculations for actual TS and YS to improve accuracy for DF, POF, and risk prioritization determinations.
    c.) While the pressure, P, used in the base case is considered to be a high average condition for most applications, it may be non-conservative or overly conservative depending on the actual service. It is recommended that the user tailor

calculations for actual P to improve accuracy for DF, POF, and risk prioritization determinations.

It is important to note that the DF is not a direct indication of predicted between equipment thickness and t_{min}, particularly if operating pressure is used for the calculation. The user should consider the impact of the basis used for P in the calculation compared to the design condition basis for t_{min}. If DF and POF are required to provide a closer correlation to t_{min} (i.e., inspection is recommended and higher DF and POF are required), the user should consider using design pressure or a PRD set pressure.

d.) The most significant potential impact in the base case used to generate the A_{rt} table is the assumption that the corrosion allowance, CA, is 25% of the furnished thickness. This assumption is non-conservative when the actual $CA << 25\%$ and overly conservative when the when the $CA >> 25\%$. The modified methodology generates a POF based on design and measured thickness of the equipment without the need for CA assumptions. The result is an increased applicability and accuracy with direct application of the model.

e.) Corrosion rate uncertainty is introduced by using three damage states based on inspection measurements, prior knowledge and inspection effectiveness using Bayes' theorem. Uncertainty in measured equipment thickness accounted for when the probability of the damage states are combined using a normal distribution with a $COV_{\Delta t}$ = 0.100. This approach has a cumulative effect on the calculated POF due to the combined uncertainty of expected damage rates in the future combined with inspection measurement inaccuracy. It is recommended that the user tailor calculations for damage state confidence values or adjust the $COV_{\Delta t}$ to improve accuracy for DF, POF, and risk prioritization determinations.

f.) Uncertainty is applied to P measurements and flow stress, reflected by TS and YS measurements for material of construction. It is recommended that the COV_P and COV_{S_f} be tailored by the user for the actual application.

g.) A $COV_{\Delta t}$ was assigned to reflect uncertainty in thickness measurements through inspection. Uncertainty of corrosion rate in predicting the future equipment condition is assigned by using three possible damage states. It is recommended that the user tailor calculations for damage states and thinning COV to improve accuracy for DF, POF, and risk prioritization determinations.

4) Artificial constraints in Table 1 calculated DFs have been removed or modified, including the following:

a.) The original A_{rt} table included artificial constraints to DF and POF. The A_{rt} maximum was set to 0.65 and the POF for each damage state was limited to 0.5 (setting a maximum DF of 3,210). As a result, interpolation between 0.65 and 1.0 (with DF set to 5,000) was required for an $A_{rt} > 0.65$. Removing the POF limit of 0.5 allows calculation of a damage factor to $A_{rt} = 1.0$ at $DF = 6420$ (through wall failure) without the need for interpolation. An increased DF using the modified approach is most significant when $A_{rt} > 0.70$ and where the $DF > 2{,}500$ (Category 5 POF). The maximum DF increase of 5,000 to 6,410 reflects a possible 28% increase in DF and POF at the highest probabilities. This increase is most significant at $A_{rt} > 0.70$ (Category 5 POF) when inspection is highly recommended regardless of consequence levels, unless a run to failure scenario is used.

b.) The A_{rt} minimum DF values were originally set to 1, preventing a $POF < G_{ff}$. The modified approach allows a minimum DF of 0.1, allowing a final POF less than the G_{ff} with very low or no in-service damage potential. The user may specify a different minimum DF or minimum POF , if desired.

5) Definition for localized corrosion in API RP 581 methodology as non-uniform thinning occurring over ≤10% of the equipment affected area such that spot thickness measurements would be highly unlikely to detect the localized behavior or even find the locally thinning areas. Localized thinning in this case is not intended to be a FFS evaluation method for locally thin areas. For the localized thinning experienced, an area inspection method is required to achieve a high level of certainty in the inspection conducted. For the purposes of risk prioritization and inspection planning, the importance of localized corrosion is adequately addressed.

The modified DF and POF methodology discussed and examples presented provides a simplified approach for DF and POF calculations specifically developed for the purpose of equipment risk prioritization and inspection planning. While more quantitative methods are available to improve accuracy, the methodology presented avoids unnecessary statistical and probabilistic complexities that add little value for the purpose of fixed equipment inspection planning.

6.0 TABLES AND FIGURES

6.1 Figures

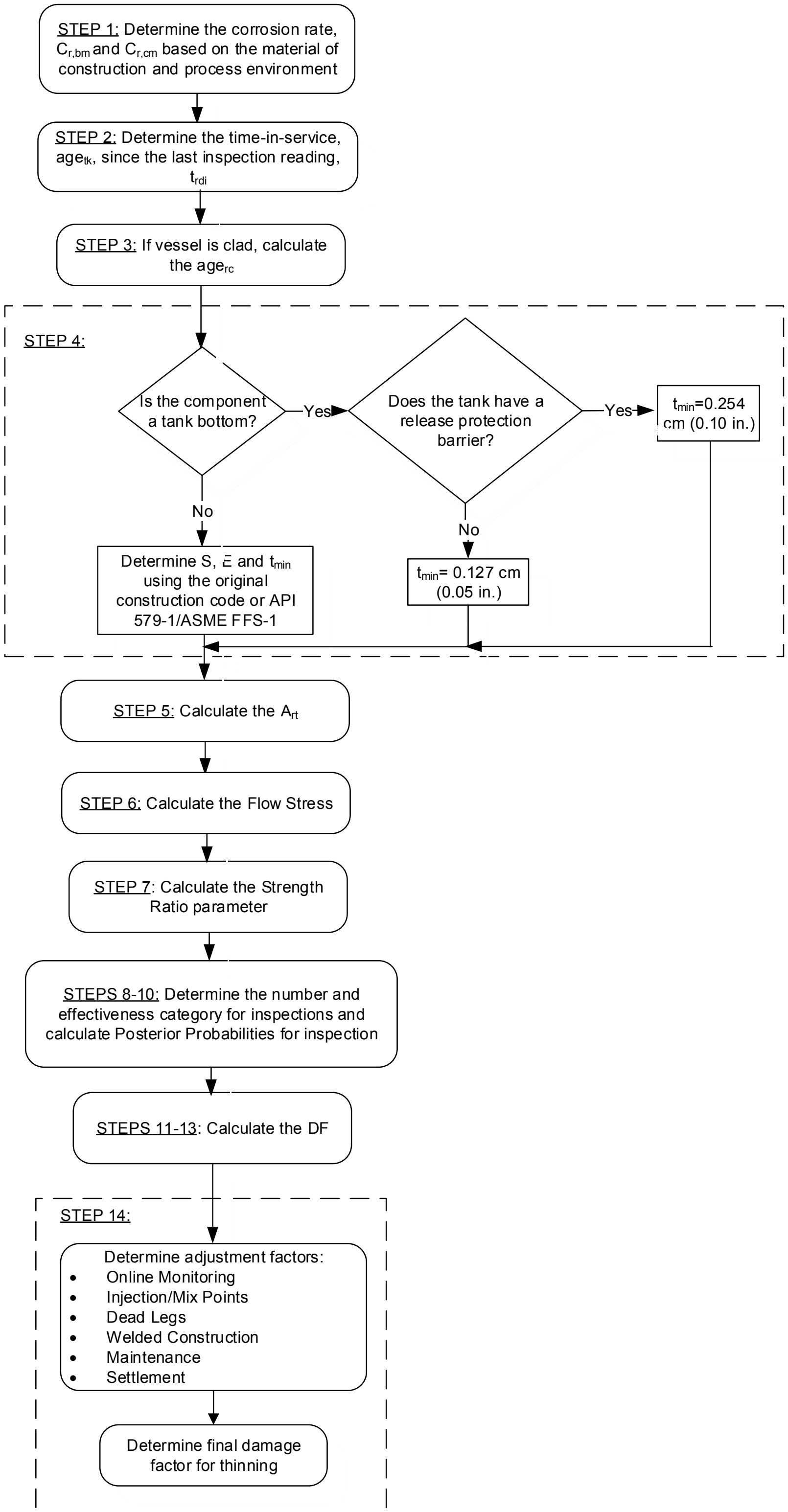

Figure 1 – Determination of the Thinning Damage Factor

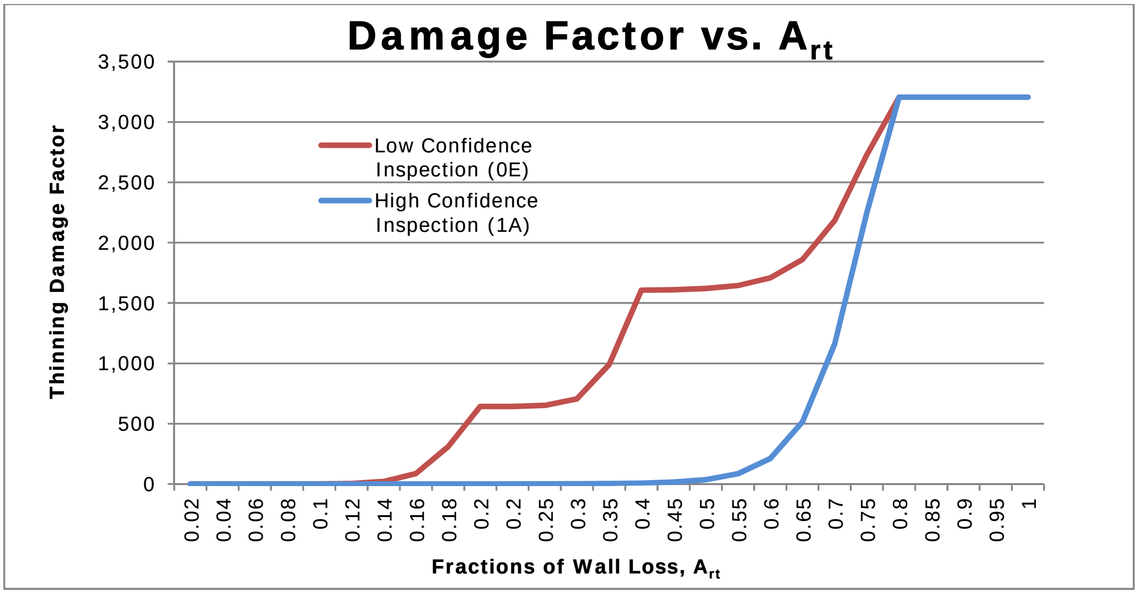

Figure 2 − Illustrates the DFs in Table 7 for a low confidence inspection case (0E) and high confidence inspection case (6A).

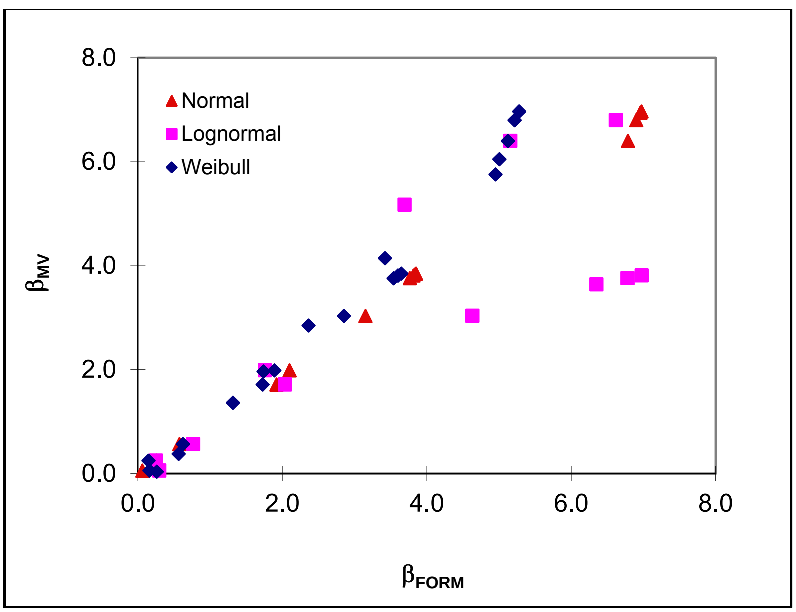

Figure 3 − Comparison of reliability indices calculated using FORM, β_{FORM} and MVFORM, β_{MV} [6].

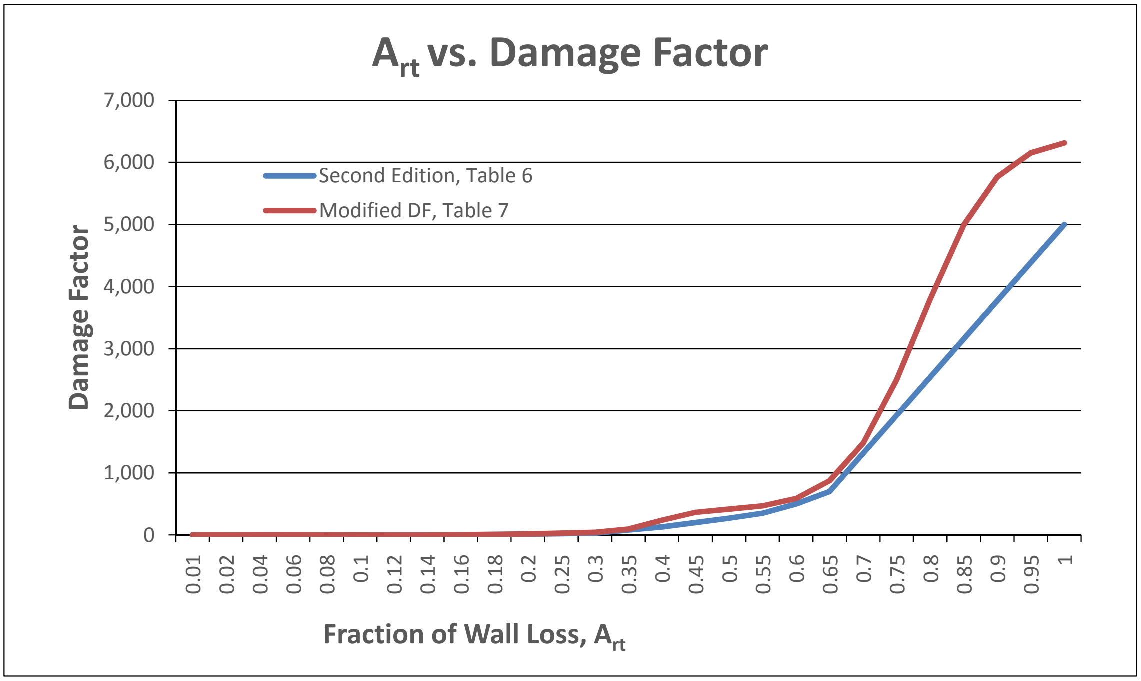

Figure 4 − Illustrates DFs for 1A inspection effectiveness comparisons from Table 6 and Table 7.

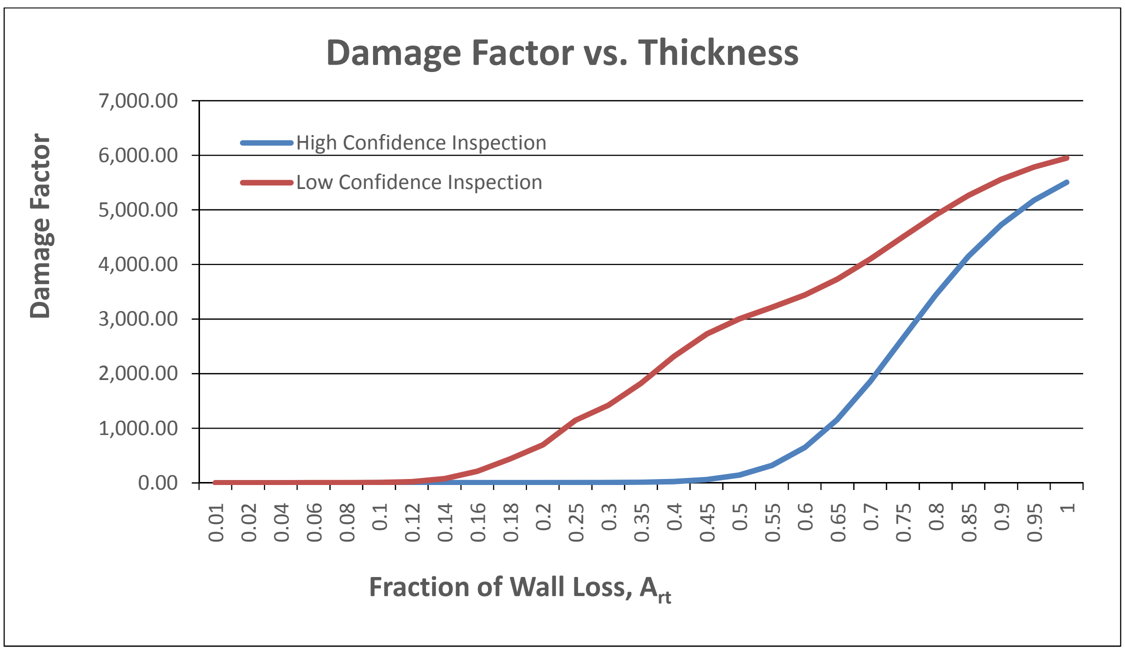

Figure 5 − Illustrates the DFs in Table 7 for a low confidence inspection case (0E) and high confidence inspection case (6A).

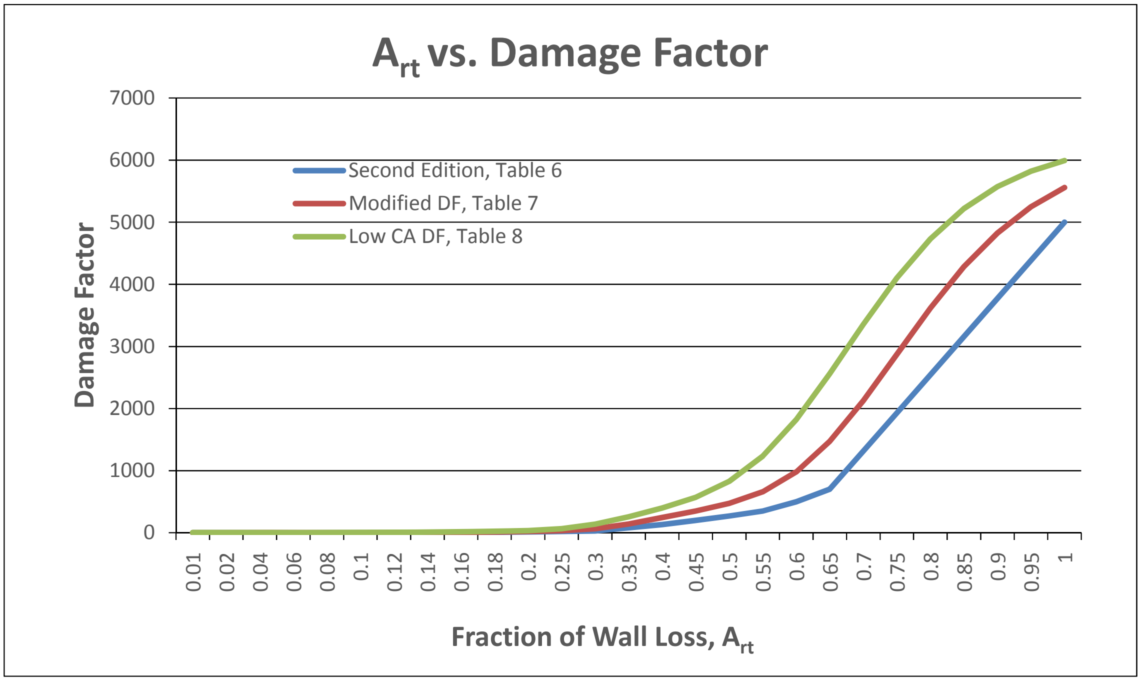

Figure 6 − Illustrates the comparison DFs from Table 6, Table 7, and Table 8 for the 1A inspection effectiveness case.

6.2 Tables

Table 1 – Table 5.11 From API RP 581 Second Edition Thinning Damage Factors

A_{rt}	Inspection Effectiveness												
	E	1 Inspection				2 Inspections				3 Inspections			
		D	C	B	A	D	C	B	A	D	C	B	A
0.02	1	1	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1	1	1
0.10	2	2	1	1	1	1	1	1	1	1	1	1	1
0.12	6	5	3	2	1	4	2	1	1	3	1	1	1
0.14	20	17	10	6	1	13	6	1	1	10	3	1	1
0.16	90	70	50	20	3	50	20	4	1	40	10	1	1
0.18	250	200	130	70	7	170	70	10	1	130	35	3	1
0.20	400	300	210	110	15	290	120	20	1	260	60	5	1
0.25	520	450	290	150	20	350	170	30	2	240	80	6	1
0.30	650	550	400	200	30	400	200	40	4	320	110	9	2
0.35	750	650	550	300	80	600	300	80	10	540	150	20	5
0.40	900	800	700	400	130	700	400	120	30	600	200	50	10
0.45	1050	900	810	500	200	800	500	160	40	700	270	60	20
0.50	1200	1100	970	600	270	1000	600	200	60	900	360	80	40
0.55	1350	1200	1130	700	350	1100	750	300	100	1000	500	130	90
0.60	1500	1400	1250	850	500	1300	900	400	230	1200	620	250	210
0.65	1900	1700	1400	1000	700	1600	1105	670	530	1300	880	550	500

A_{rt}	Inspection Effectiveness												
	E	4 Inspections				5 Inspections				6 Inspections			
		D	C	B	A	D	C	B	A	D	C	B	A
0.02	1	1	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1	1	1
0.10	2	1	1	1	1	1	1	1	1	1	1	1	1
0.12	6	2	1	1	1	2	1	1	1	1	1	1	1
0.14	20	7	2	1	1	5	1	1	1	4	1	1	1
0.16	90	30	5	1	1	20	2	1	1	14	1	1	1
0.18	250	100	15	1	1	70	7	1	1	50	3	1	1
0.20	400	180	20	2	1	120	10	1	1	100	6	1	1
0.25	520	200	30	2	1	150	15	2	1	120	7	1	1
0.30	650	240	50	4	2	180	25	3	2	150	10	2	2
0.35	750	440	90	10	4	350	70	6	4	280	40	5	4
0.40	900	500	140	20	8	400	110	10	8	350	90	9	8
0.45	1050	600	200	30	15	500	160	20	15	400	130	20	15
0.50	1200	800	270	50	40	700	210	40	40	600	180	40	40
0.55	1350	900	350	100	90	800	260	90	90	700	240	90	90
0.60	1500	1000	450	220	210	900	360	210	210	800	300	210	210
0.65	1900	1200	700	530	500	1100	640	500	500	1000	600	500	500

Notes: Determine the row based on the calculated A_{rt} parameter. Then determine the thinning damage factor based on the number and category of highest effective inspection. Interpolation may be used for intermediate values.

Table 2 – Impact of Thinning on POF [6]

Variable	Description	Variable	Description
FS^{Thin}	$FS^{Thin} = FS^{Thin} = \frac{(YS+TS)}{2} \cdot E \cdot 1.1$	P	Pressure (operating, design, PRD overpressure, etc.) used to calculate the limit state function for POF
D	Diameter	t	wall thickness (as furnished, measured from an inspection)
$Thin_n^{Thin}$	Thinning for Thinning Damage States ($Thin_1^{Thin}, Thin_2^{Thin}, Thin_3^{Thin}$)	n	1, 2 and 3 Thinning Damage States

Expression	Description
$g_n^{Thin} = \left(FS^{Thin} \cdot \left(1 - \frac{Thin_n^{Thin}}{t} \right) \right) - \left(\frac{PD}{2t} \right)$	Limit state function using $\frac{PD}{2t}$ and where pressure, P ksi, requiring that $D >>> t$ and when $g \le 0$ the vessel fails
$dFS_n^{Thin} = \left(1 - \frac{Thin_n^{Thin}}{t} \right)$	Derivative of limit state function with respect to flow stress
$dThin^{Thin} = \left(\frac{-FS^{Thin}}{t_{rdi}} \right)$	Derivative of limit state function with respect to thinning
$dP_{cyl}^{Thin} = \left(\frac{-D}{2 \cdot t_{rdi}} \right)$ Cylinder $dP_{sph}^{Thin} = \left(\frac{-D}{4 \cdot t_{rdi}} \right)$ Sphere/Spherical Head $dP_{head}^{Thin} = \left(\frac{-D}{1.13 \cdot t_{rdi}} \right)$ Semi-hemispherical Head	Derivative of limit state function with respect to internal pressure and component type
$\bar{g}_n^{Thin} = \left(\overline{FS}^{Thin} \cdot \left(1 - \frac{\overline{Thin_n}^{Thin}}{t} \right) \right) - \left(\frac{\bar{P}D}{2t} \right)$	First order approximation to the mean of the limit state function. The mean value of the limit state is calculated by evaluating g at the mean values of the flow stress, FS^{Thin} pressure, P and corrosion, $Thin_n^{Thin}$.
$StdDev\_g_n^{Thin} = \sqrt{((P_{SD}^{Thin} \cdot dP^{Thin} / 1000)^2 + (FS_{SD}^{Thin} \cdot dFS_1^{Thin})^2 + (Thin_{SD1}^{Thin} \cdot dThin_1^{Thin})^2))}$	First order approximation to the variance of the limit state function
$\beta_n^{Thin} = g_n^{Thin} / StdDev\_g_n^{Thin}$ $POF_n^{Thin} = \Phi(-\beta_n^{Thin}) = NormSDist(-\beta_n^{Thin})$	Reliability index and POF as the cumulative probability function of a normal random variable with a mean of 0 and standard deviation of 1

Table 3 – Prior Probability for Thinning Corrosion Rate

Damage State	Low Confidence Data	Medium Confidence Data	High Confidence Data
Pr_{p1}^{Thin} for Damage State 1, D_{S_1}	0.5	0.7	0.8
For Pr_{p2}^{Thin} for Damage State 2, D_{S_2}	0.3	0.2	0.15
Pr_{p3}^{Thin} for Damage State 3, D_{S_3}	0.2	0.1	0.05

Table 4 – 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} for Damage State 1, D_{S_1}	0.33	0.4	0.5	0.7	0.9
Co_{p2}^{Thin} for Damage State 2, D_{S_2}	0.33	0.33	0.3	0.2	0.09
Co_{p3}^{Thin} for Damage State 3, D_{S_3}	0.33	0.27	0.2	0.1	0.01

Table 5 – Calculated A_{rt} Damage Factors Without Rounding and Smoothing

A_{rt}	Inspection Effectiveness												
	E	1 Inspection				2 Inspections				3 Inspections			
		D	C	B	A	D	C	B	A	D	C	B	A
0.02	0.35	0.34	0.33	0.32	0.32	0.34	0.33	0.32	0.31	0.33	0.32	0.31	0.31
0.04	0.44	0.42	0.40	0.37	0.35	0.41	0.38	0.35	0.35	0.40	0.36	0.35	0.35
0.06	0.62	0.57	0.52	0.45	0.40	0.53	0.46	0.40	0.39	0.50	0.42	0.39	0.38
0.08	1.01	0.89	0.76	0.58	0.45	0.79	0.60	0.46	0.43	0.70	0.51	0.43	0.43
0.10	2.09	1.74	1.37	0.89	0.54	1.44	0.93	0.56	0.48	1.21	0.70	0.50	0.48
0.12	5.85	4.65	3.40	1.83	0.69	3.65	1.94	0.77	0.55	2.86	1.19	0.58	0.54
0.14	21.49	16.65	11.70	5.56	1.12	12.68	5.96	1.47	0.63	9.55	3.03	0.75	0.62
0.16	88.10	67.67	46.88	21.19	2.64	50.96	22.76	4.16	0.74	37.76	10.57	1.24	0.71
0.18	310.3	237.7	164.0	73.06	7.47	178.4	78.55	12.90	0.92	131.6	35.41	2.64	0.82
0.20	643.9	493.0	339.9	150.9	14.72	369.8	162.3	26.01	1.15	272.5	72.73	4.73	0.96
0.25	652.6	501.2	346.9	155.3	16.78	377.4	167.5	27.79	1.81	279.4	76.33	5.61	1.47
0.30	706.0	551.3	389.3	180.7	27.58	423.3	198.0	36.83	3.77	320.7	96.92	8.94	2.49
0.35	990.8	817.7	614.6	314.1	82.59	667.4	359.0	82.35	11.17	540.3	204.6	23.73	4.82
0.40	1,606	1,394	1,102	602.7	201.4	1,195	707.2	180.7	27.06	1,015	437.4	55.58	9.75
0.45	1,611	1,398	1,107	609.4	209.2	1,200	713.7	188.5	35.32	1,021	444.6	63.77	18.06
0.50	1,621	1,410	1,120	625.7	227.9	1,213	729.3	207.4	55.14	1,034	461.8	83.41	37.98
0.55	1,646	1,438	1,153	666.4	274.9	1,244	768.4	254.7	104.8	1,069	505.1	132.7	87.96
0.60	1,709	1,510	1,236	769.3	393.7	1,324	867.2	374.3	230.5	1,155	614.6	257.2	214.3
0.65	1,861	1,682	1,436	1,017	679.4	1,515	1,105	661.9	532.8	1,364	877.8	556.7	518.2
0.70	2,182	2,046	1,859	1,540	1,283	1,919	1,606	1,269	1,171	1,804	1,434	1,189	1,160
0.75	2,728	2,665	2,578	2,429	2,309	2,605	2,460	2,303	2,257	2,552	2,379	2,265	2,252
0.80	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205
0.85	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205
0.90	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205
0.95	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205
1.0	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205

A_{rt}	Inspection Effectiveness												
	E	4 Inspections				5 Inspections				6 Inspections			
		D	C	B	A	D	C	B	A	D	C	B	A
0.02	0.35	0.33	0.32	0.31	0.31	0.32	0.32	0.31	0.31	0.32	0.32	0.31	0.31
0.04	0.44	0.39	0.36	0.35	0.35	0.38	0.35	0.35	0.35	0.37	0.35	0.35	0.35
0.06	0.62	0.47	0.40	0.38	0.38	0.45	0.39	0.38	0.38	0.44	0.39	0.38	0.38
0.08	1.01	0.64	0.47	0.43	0.43	0.59	0.45	0.43	0.43	0.55	0.44	0.43	0.43
0.10	2.09	1.03	0.58	0.48	0.48	0.89	0.53	0.48	0.48	0.78	0.50	0.48	0.48
0.12	5.85	2.25	0.84	0.55	0.54	1.79	0.68	0.54	0.54	1.45	0.60	0.54	0.54
0.14	21.49	7.13	1.67	0.64	0.62	5.32	1.07	0.62	0.62	3.98	0.82	0.62	0.62
0.16	88.10	27.62	4.95	0.79	0.71	20.01	2.50	0.72	0.71	14.42	1.46	0.71	0.71
0.18	310.3	95.66	15.60	1.09	0.82	68.73	7.00	0.86	0.82	48.94	3.37	0.82	0.82
0.20	643.9	197.9	31.60	1.51	0.95	141.9	13.75	1.04	0.95	100.8	6.24	0.96	0.95
0.25	652.6	204.0	34.08	2.12	1.45	147.3	15.48	1.57	1.45	105.6	7.49	1.47	1.45
0.30	706.0	240.7	47.53	3.73	2.37	179.5	24.18	2.68	2.36	133.5	13.17	2.44	2.36
0.35	990.8	435.3	116.8	9.26	4.20	349.7	67.88	5.52	4.14	280.9	40.62	4.52	4.13
0.40	1,606	855.9	266.4	21.09	8.02	717.7	162.3	11.56	7.85	599.4	99.85	8.89	7.83
0.45	1,611	862.0	274.1	29.37	16.34	724.1	170.2	19.86	16.17	606.2	107.9	17.20	16.15
0.50	1,621	876.6	292.4	49.22	36.27	739.6	189.1	39.77	36.10	622.4	127.3	37.13	36.08
0.55	1,646	913.4	338.4	99.02	86.27	778.5	236.7	89.72	86.10	663.2	175.8	87.11	86.09
0.60	1,709	1,006	454.6	225.0	212.7	876.9	357.1	216.0	212.6	766.2	298.7	213.5	212.6
0.65	1,861	1,230	734.1	527.7	516.8	1,113	646.5	519.7	516.6	1,014	594.0	517.5	516.6
0.70	2,182	1,702	1,324	1,167	1,159	1,613	1,258	1,161	1,159	1,537	1,218	1,160	1,159
0.75	2,728	2,504	2,328	2,255	2,251	2,463	2,297	2,252	2,251	2,428	2,279	2,251	2,251
0.80	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205
0.85	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205
0.90	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205
0.95	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205
1.0	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205	3,205

Table 6 – Table 5.11 from API RP 581 Second Edition Thinning Damage Factors with Linear Extrapolation to A_{rt}=1.0

A_{rt}	Inspection Effectiveness												
	E	1 Inspection				2 Inspections				3 Inspections			
		D	C	B	A	D	C	B	A	D	C	B	A
0.02	1	1	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1	1	1
0.10	2	2	1	1	1	1	1	1	1	1	1	1	1
0.12	6	5	3	2	1	4	2	1	1	3	1	1	1
0.14	20	17	10	6	1	13	6	1	1	10	3	1	1
0.16	90	70	50	20	3	50	20	4	1	40	10	1	1
0.18	250	200	130	70	7	170	70	10	1	130	35	3	1
0.20	400	300	210	110	15	290	120	20	1	260	60	5	1
0.25	520	450	290	150	20	350	170	30	2	240	80	6	1
0.30	650	550	400	200	30	400	200	40	4	320	110	9	2
0.35	750	650	550	300	80	600	300	80	10	540	150	20	5
0.40	900	800	700	400	130	700	400	120	30	600	200	50	10
0.45	1,050	900	810	500	200	800	500	160	40	700	270	60	20
0.50	1,200	1,100	970	600	270	1,000	600	200	60	900	360	80	40
0.55	1,350	1,200	1,130	700	350	1,100	750	300	100	1,000	500	130	90
0.60	1,500	1,400	1,250	850	500	1,300	900	400	230	1,200	620	250	210
0.65	1,900	1,700	1,400	1,000	700	1,600	1,105	670	530	1,300	880	550	500
0.70	2,343	2,171	1,914	1,571	1,314	2,086	1,661	1,289	1,169	1,829	1,469	1,186	1,143
0.75	2,786	2,643	2,429	2,143	1,929	2,571	2,218	1,907	1,807	2,357	2,057	1,821	1,786
0.80	3,229	3,114	2,943	2,714	2,543	3,057	2,774	2,526	2,446	2,886	2,646	2,457	2,429
0.85	3,671	3,586	3,457	3,286	3,157	3,543	3,331	3,144	3,084	3,414	3,234	3,093	3,071
0.90	4,114	4,057	3,971	3,857	3,771	4,029	3,887	3,763	3,723	3,943	3,823	3,729	3,714
0.95	4,557	4,529	4,486	4,429	4,386	4,514	4,444	4,381	4,361	4,471	4,411	4,364	4,357
1.0	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000

A_{rt}	Inspection Effectiveness												
	E	4 Inspections				5 Inspections				6 Inspections			
		D	C	B	A	D	C	B	A	D	C	B	A
0.02	1	1	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1	1	1
0.10	2	1	1	1	1	1	1	1	1	1	1	1	1
0.12	6	2	1	1	1	2	1	1	1	1	1	1	1
0.14	20	7	2	1	1	5	1	1	1	4	1	1	1
0.16	90	30	5	1	1	20	2	1	1	14	1	1	1
0.18	250	100	15	1	1	70	7	1	1	50	3	1	1
0.20	400	180	20	2	1	120	10	1	1	100	6	1	1
0.25	520	200	30	2	1	150	15	2	1	120	7	1	1
0.30	650	240	50	4	2	180	25	3	2	150	10	2	2
0.35	750	440	90	10	4	350	70	6	4	280	40	5	4
0.40	900	500	140	20	8	400	110	10	8	350	90	9	8
0.45	1,050	600	200	30	15	500	160	20	15	400	130	20	15
0.50	1,200	800	270	50	40	700	210	40	40	600	180	40	40
0.55	1,350	900	350	100	90	800	260	90	90	700	240	90	90
0.60	1,500	1,000	450	220	210	900	360	210	210	800	300	210	210
0.65	1,900	1,200	700	530	500	1,100	640	500	500	1,000	600	500	500
0.70	2,343	1,743	1,314	1,169	1,143	1,657	1,263	1,143	1,143	1,571	1,229	1,143	1,143
0.75	2,786	2,286	1,929	1,807	1,786	2,214	1,886	1,786	1,786	2,143	1,857	1,786	1,786
0.80	3,229	2,829	2,543	2,446	2,429	2,771	2,509	2,429	2,429	2,714	2,486	2,429	2,429
0.85	3,671	3,371	3,157	3,084	3,071	3,329	3,131	3,071	3,071	3,286	3,114	3,071	3,071
0.90	4,114	3,914	3,771	3,723	3,714	3,886	3,754	3,714	3,714	3,857	3,743	3,714	3,714
0.95	4,557	4,457	4,386	4,361	4,357	4,443	4,377	4,357	4,357	4,429	4,371	4,357	4,357
1.0	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000

Table 7 – Calculated A_{rt} Damage Factors Without Rounding and Smoothing Using Base Case

A_{rt}	Inspection Effectiveness												
	E	1 Inspection				2 Inspections				3 Inspections			
		D	C	B	A	D	C	B	A	D	C	B	A
0.01	0.31	0.31	0.31	0.30	0.30	0.31	0.31	0.30	0.30	0.31	0.30	0.30	0.30
0.02	0.35	0.35	0.34	0.33	0.32	0.34	0.33	0.32	0.32	0.33	0.32	0.32	0.32
0.04	0.48	0.45	0.43	0.39	0.36	0.43	0.39	0.36	0.35	0.42	0.37	0.35	0.35
0.06	0.79	0.71	0.62	0.50	0.41	0.64	0.51	0.42	0.39	0.58	0.45	0.40	0.39
0.08	1.79	1.50	1.19	0.79	0.50	1.25	0.82	0.51	0.45	1.06	0.63	0.46	0.45
0.10	5.66	4.49	3.28	1.76	0.66	3.53	1.87	0.74	0.52	2.76	1.15	0.55	0.52
0.12	21.33	16.53	11.63	5.53	1.11	12.60	5.92	1.45	0.62	9.49	3.02	0.74	0.60
0.14	75.61	58.15	40.36	18.33	2.42	43.87	19.71	3.70	0.75	32.57	9.24	1.18	0.71
0.16	211.2	162.1	112.0	50.18	5.53	121.9	53.99	9.18	0.94	90.09	24.62	2.13	0.86
0.18	437.8	335.7	231.8	103.4	10.74	252.2	111.3	18.31	1.22	186.2	50.34	3.69	1.05
0.20	696.5	534.3	369.1	164.6	17.00	401.6	177.3	28.96	1.60	296.7	80.20	5.57	1.31
0.25	1,145	883.7	615.0	278.0	33.30	669.1	301.3	51.40	3.49	498.6	140.1	10.64	2.46
0.30	1,422	1,121	801.2	379.1	66.53	871.0	419.2	81.81	8.94	668.7	212.5	20.69	5.20
0.35	1,822	1,490	1,110	560.7	140.9	1,205	636.5	144.7	21.96	966.4	357.1	43.31	11.76
0.40	2,316	1,952	1,501	796.2	244.1	1,628	918.1	232.2	45.74	1,347	548.6	79.42	27.10
0.45	2,724	2,336	1,831	1,006	349.9	1,983	1,164	325.5	88.62	1,670	724.1	132.1	63.27
0.50	3,001	2,603	2,071	1,182	471.7	2,236	1,360	440.0	175.6	1,907	883.3	224.4	146.6
0.55	3,214	2,819	2,285	1,383	660.3	2,453	1,568	625.6	353.1	2,123	1,082	403.5	322.8
0.60	3,441	3,063	2,550	1,679	979.1	2,713	1,859	944.5	679.1	2,396	1,389	728.3	649.4
0.65	3,733	3,388	2,917	2,115	1,471	3,066	2,282	1,439	1,194	2,776	1,849	1,239	1,166
0.70	4,098	3,798	3,387	2,688	2,126	3,518	2,833	2,097	1,883	3,265	2,455	1,923	1,859
0.75	4,506	4,257	3,918	3,338	2,873	4,026	3,459	2,849	2,672	3,816	3,146	2,705	2,652
0.80	4,908	4,712	4,444	3,986	3,618	4,529	4,082	3,600	3,459	4,364	3,834	3,485	3,443
0.85	5,266	5,116	4,912	4,563	4,283	4,977	4,636	4,269	4,162	4,851	4,447	4,182	4,150
0.90	5,558	5,447	5,295	5,036	4,827	5,343	5,090	4,817	4,737	5,250	4,950	4,752	4,728
0.95	5,784	5,702	5,590	5,400	5,247	5,626	5,440	5,240	5,181	5,557	5,337	5,192	5,175
1.0	5,951	5,891	5,809	5,670	5,559	5,835	5,699	5,553	5,511	5,785	5,624	5,518	5,506
A_{rt}	Inspection Effectiveness												
	E	4 Inspections				5 Inspections				6 Inspections			
		D	C	B	A	D	C	B	A	D	C	B	A
0.01	0.31	0.31	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
0.02	0.35	0.32	0.32	0.32	0.32	0.33	0.32	0.32	0.32	0.32	0.32	0.32	0.32
0.04	0.48	0.36	0.36	0.35	0.35	0.39	0.36	0.35	0.35	0.38	0.35	0.35	0.35
0.06	0.79	0.47	0.42	0.39	0.39	0.50	0.41	0.39	0.39	0.48	0.40	0.39	0.39
0.08	1.79	0.79	0.53	0.45	0.45	0.79	0.49	0.45	0.45	0.70	0.47	0.45	0.45
0.10	5.66	2.01	0.80	0.52	0.52	1.72	0.65	0.52	0.52	1.39	0.58	0.52	0.52
0.12	21.33	6.87	1.66	0.62	0.60	5.29	1.06	0.61	0.60	3.96	0.80	0.60	0.60
0.14	75.61	23.58	4.40	0.78	0.71	17.37	2.28	0.72	0.71	12.57	1.38	0.71	0.71
0.16	211.2	65.27	11.08	1.05	0.86	47.37	5.18	0.89	0.86	33.91	2.67	0.86	0.86
0.18	437.8	135.0	22.26	1.45	1.04	97.56	10.00	1.11	1.04	69.62	4.80	1.05	1.04
0.20	696.5	215.3	35.37	1.96	1.30	155.6	15.76	1.40	1.29	111.0	7.41	1.31	1.29
0.25	1,145	365.4	64.24	3.85	2.38	267.5	30.09	2.67	2.38	193.8	14.96	2.44	2.38
0.30	1,422	506.0	108.3	8.38	4.85	386.2	57.16	5.69	4.82	292.5	31.99	5.05	4.82
0.35	1,822	763.6	201.7	19.04	10.76	614.1	117.1	12.90	10.66	489.1	70.83	11.27	10.65
0.40	2,316	1,091	328.8	39.70	25.25	910.6	201.4	29.10	25.07	747.0	128.0	26.19	25.05
0.45	2,724	1,355	453.5	80.10	60.75	1,169	292.3	65.95	60.50	974.8	197.4	62.02	60.48
0.50	3,001	1,514	585.3	165.7	143.7	1,372	405.8	149.6	143.4	1,163	299.1	145.1	143.3
0.55	3,214	1,599	776.6	342.7	319.7	1,583	591.6	325.9	319.4	1,370	481.2	321.2	319.4
0.60	3,441	1,642	1,092	668.9	646.5	1,875	911.9	652.5	646.2	1,669	804.3	647.9	646.1
0.65	3,733	1,665	1,575	1,184	1,164	2,297	1,409	1,169	1,163	2,107	1,310	1,165	1,163
0.70	4,098	1,677	2,217	1,875	1,857	2,847	2,071	1,861	1,856	2,681	1,984	1,858	1,856
0.75	4,506	1,684	2,948	2,665	2,650	3,471	2,828	2,654	2,650	3,334	2,756	2,651	2,650
0.80	4,908	1,689	3,678	3,454	3,442	4,091	3,583	3,445	3,442	3,982	3,526	3,443	3,442
0.85	5,266	1,692	4,328	4,158	4,148	4,643	4,256	4,151	4,148	4,560	4,212	4,149	4,148
0.90	5,558	1,694	4,861	4,734	4,727	5,095	4,807	4,729	4,727	5,034	4,775	4,728	4,727
0.95	5,784	1,695	5,272	5,179	5,174	5,444	5,233	5,175	5,174	5,399	5,209	5,174	5,174
1.0	5,951	1,696	5,577	5,509	5,505	5,702	5,548	5,506	5,505	5,669	5,531	5,505	5,505

Table 8 – Modified A_{rt} Damage Factors Using Example 2 Low CA

A_{rt}	Inspection Effectiveness												
	E	1 Inspection				2 Inspections				3 Inspections			
		D	C	B	A	D	C	B	A	D	C	B	A
0.01	1.65	1.63	1.61	1.59	1.56	1.62	1.59	1.56	1.56	1.61	1.58	1.56	1.56
0.02	1.87	1.83	1.78	1.72	1.67	1.79	1.73	1.67	1.65	1.76	1.69	1.66	1.65
0.04	2.53	2.40	2.26	2.06	1.90	2.29	2.08	1.91	1.87	2.20	1.98	1.87	1.86
0.06	3.79	3.45	3.08	2.58	2.20	3.17	2.63	2.22	2.12	2.93	2.39	2.14	2.11
0.08	6.66	5.76	4.80	3.53	2.60	5.01	3.66	2.64	2.42	4.40	3.04	2.46	2.41
0.10	14.43	11.86	9.17	5.72	3.18	9.74	6.00	3.34	2.79	8.03	4.33	2.88	2.77
0.12	38.82	30.74	22.40	11.88	4.23	24.09	12.64	4.77	3.24	18.80	7.59	3.47	3.20
0.14	118.6	92.0	64.9	31.10	6.60	70.3	33.33	8.49	3.81	53.10	17.20	4.50	3.73
0.16	342.0	263.5	183.4	84.0	12.23	199.2	90.3	17.97	4.54	148.3	43.07	6.50	4.37
0.18	749.2	575.7	399.0	180.2	22.10	433.8	193.8	34.86	5.49	321.6	89.82	9.76	5.16
0.20	1,120.6	861.1	596.6	268.8	31.89	648.8	289.4	50.88	6.69	480.9	133.5	13.12	6.15
0.25	1,354	1,050	735.1	338.0	48.99	799.0	366.8	69.43	11.42	599.5	176.3	20.19	9.92
0.30	1,588	1,269	921	450.2	98.3	1,000	501.1	111.2	22.67	780.8	267.8	37.34	17.12
0.35	2,237	1,876	1,436	759.4	231.2	1,557	872.3	222.6	48.40	1,283	519.1	79.7	31.44
0.40	2,961	2,556	2,015	1,112	389.7	2,183	1,293	357.5	88.9	1,849	808.0	138.5	59.3
0.45	3,228	2,811	2,240	1,268	487.0	2,422	1,471	447.3	149.1	2,071	945.7	204.5	115.7
0.50	3,318	2,907	2,343	1,380	605.5	2,523	1,582	565.5	269.1	2,176	1,061	324.2	235.8
0.55	3,448	3,054	2,513	1,589	845	2,686	1,782	807	522.4	2,353	1,282	575.2	490.3
0.60	3,702	3,341	2,847	2,001	1,322	3,005	2,178	1,286	1,026	2,700	1,721	1,075	997
0.65	4,144	3,843	3,429	2,722	2,153	3,561	2,870	2,124	1,906	3,306	2,487	1,946	1,881
0.70	4,772	4,553	4,254	3,743	3,331	4,350	3,850	3,310	3,153	4,165	3,573	3,182	3,135
0.75	5,442	5,313	5,136	4,834	4,591	5,193	4,898	4,579	4,486	5,084	4,734	4,503	4,475
0.80	5,957	5,897	5,814	5,672	5,558	5,840	5,702	5,553	5,509	5,789	5,625	5,517	5,504
0.85	6,239	6,216	6,185	6,132	6,089	6,195	6,143	6,087	6,070	6,176	6,114	6,073	6,068
0.90	6,355	6,347	6,337	6,320	6,306	6,341	6,324	6,305	6,300	6,334	6,314	6,301	6,300
0.95	6,393	6,391	6,388	6,383	6,379	6,389	6,384	6,378	6,377	6,387	6,381	6,377	6,377
1.0	6,405	6,404	6,403	6,402	6,400	6,404	6,402	6,400	6,400	6,403	6,401	6,400	6,400

A_{rt}	Inspection Effectiveness												
	E	4 Inspections				5 Inspections				6 Inspections			
		D	C	B	A	D	C	B	A	D	C	B	A
0.01	1.65	1.60	1.57	1.56	1.56	1.59	1.56	1.56	1.56	1.58	1.56	1.56	1.56
0.02	1.87	1.67	1.67	1.65	1.65	1.72	1.66	1.65	1.65	1.71	1.66	1.65	1.65
0.04	2.53	1.90	1.93	1.87	1.86	2.07	1.90	1.86	1.86	2.02	1.88	1.86	1.86
0.06	3.79	2.34	2.25	2.12	2.11	2.60	2.19	2.12	2.11	2.49	2.15	2.11	2.11
0.08	6.66	3.30	2.72	2.42	2.41	3.56	2.57	2.41	2.41	3.28	2.49	2.41	2.41
0.10	14.43	5.82	3.51	2.79	2.77	5.69	3.13	2.77	2.77	4.93	2.94	2.77	2.77
0.12	38.82	13.50	5.20	3.25	3.20	11.61	4.11	3.21	3.20	9.30	3.62	3.20	3.20
0.14	118.6	38.24	9.67	3.85	3.72	29.84	6.33	3.75	3.72	22.46	4.87	3.73	3.72
0.16	342.0	107.2	21.19	4.70	4.36	79.8	11.57	4.42	4.36	58.19	7.45	4.37	4.36
0.18	749.2	232.7	41.78	5.87	5.15	170.6	20.74	5.26	5.14	122.9	11.77	5.17	5.14
0.20	1,120.6	348.4	61.43	7.23	6.12	254.8	29.77	6.31	6.12	183.3	16.22	6.15	6.12
0.25	1,354	439.0	85.8	11.73	9.80	328.1	44.56	10.19	9.79	241.1	26.00	9.88	9.78
0.30	1,588	595.2	146.5	21.48	16.59	469.6	84.8	17.79	16.53	364.3	53.27	16.87	16.53
0.35	2,237	1,032	311.4	42.99	29.76	861.5	192.3	33.27	29.60	704.8	124.1	30.61	29.58
0.40	2,961	1,516	505.2	78.81	56.4	1,305	322.7	62.4	56.1	1,092	214.3	57.9	56.1
0.45	3,228	1,679	613.4	137.6	112.3	1,490	411.2	119.1	112.0	1,260	290.2	114.0	111.9
0.50	3,318	1,699	731.0	257.6	232.4	1,602	530.0	239.2	232.1	1,373	409.6	234.1	232.1
0.55	3,448	1,701	966	511.3	487.1	1,802	773	493.7	486.8	1,582	657	488.7	486.8
0.60	3,702	1,701	1,432	1,016	994	2,196	1,255	1,000	994	1,996	1,150	995	994
0.65	4,144	1,701	2,245	1,897	1,879	2,885	2,098	1,884	1,879	2,717	2,009	1,880	1,879
0.70	4,772	1,701	3,398	3,147	3,133	3,861	3,291	3,137	3,133	3,739	3,227	3,134	3,133
0.75	5,442	1,701	4,631	4,482	4,474	4,904	4,567	4,476	4,474	4,832	4,530	4,475	4,474
0.80	5,957	1,701	5,577	5,507	5,504	5,705	5,547	5,505	5,504	5,671	5,530	5,504	5,504
0.85	6,239	1,701	6,096	6,070	6,068	6,144	6,085	6,069	6,068	6,131	6,078	6,068	6,068
0.90	6,355	1,701	6,308	6,300	6,299	6,324	6,305	6,300	6,299	6,320	6,303	6,300	6,299
0.95	6,393	1,701	6,379	6,377	6,377	6,384	6,378	6,377	6,377	6,383	6,378	6,377	6,377
1.0	6,405	1,701	6,401	6,400	6,400	6,402	6,400	6,400	6,400	6,402	6,400	6,400	6,400

7.0 TERMINOLOGY

7.1 Nomenclature

age	In-service time that damage is applied
age_{rc}	Remaining life of the cladding associated with the date of starting thickness
age_{tk}	Component in-service time since the last inspection thickness measurement or service start date
A_{rt}	Expected material loss fraction since last inspection thickness measurement or service start date
α	Component geometry shape factor
β_1^{Thin}	Beta reliability indices for damage state 1
β_2^{Thin}	Beta reliability indices for damage state 2
β_1^{Thin}	Beta reliability indices for damage state 3
$C_{r,bm}$	Base material corrosion rate
$C_{r,cm}$	Cladding material corrosion rate
CA	Corrosion allowance
Co_{p1}^{Thin}	Conditional probability of inspection history inspection effectiveness for damage state 1
Co_{p2}^{Thin}	Conditional probability of inspection history inspection effectiveness for damage state 2
Co_{p3}^{Thin}	Conditional probability of inspection history inspection effectiveness for damage state 3
COV_P	Pressure variance
COV_{S_f}	Flow Stress variance
$COV_{\Delta t}$	Thinning variance
D	Component inside diameter, mm (in)
D_{S_1}	Corrosion rate factor for damage state 1
D_{S_2}	Corrosion rate factor for damage state 2
D_{S_3}	Corrosion rate factor for damage state 1
D_f^{Thin}	Final DF for thinning
D_{fB}^{Thin}	Base DF for thinning
E	Weld joint efficiency
FS^{Thin}	Flow Stress
I_1^{Thin}	First order inspection effectiveness factor
I_2^{Thin}	Second order inspection effectiveness factor
I_3^{Thin}	Third order inspection effectiveness factor
N_A^{Thin}	Number of A level inspections
N_B^{Thin}	Number of B level inspections
N_C^{Thin}	Number of C level inspections
N_D^{Thin}	Number of D level inspections
N_E^{Thin}	Number of E level inspections
P	Pressure (operating, design, PRD overpressure, etc.)
Φ	Standard normal cumulative distribution function
Po_{p1}^{Thin}	Posterior probability for damage state 1

Po_{p2}^{Thin}	Posterior probability for damage state 2
Po_{p3}^{Thin}	Posterior probability for damage state 1
Pr_{p1}^{Thin}	Prior probability of damage rate confidence for damage state 1
Pr_{p2}^{Thin}	Prior probability of damage rate confidence for damage state 2
Pr_{p3}^{Thin}	Prior probability of damage rate confidence for damage state 3
S	Allowable design stress
SR_{P}^{Thin}	Stress Ratio parameter
$SR_{P_1}^{Thin}$	Stress Ratio parameter 1
$SR_{P_2}^{Thin}$	Stress Ratio parameter 2
t	Furnished thickness of the component base material
t_{c}	Minimum structural thickness of the component base material
t_{min}	Minimum required wall thickness based on the applicable construction code
t_{rdi}	Furnished thickness, t, or measured thickness reading from previous inspection
TS	Tensile Strength at design temperature
YS	Yield Strength at design temperature

7.3 Acronyms

AIChE	American Institute of Chemical Engineers
AST	Aboveground Storage Tank
BRD	Base Resource Document
COV	Coefficients of Variance
CPQRA	Chemical Process Quantitative Risk Assessment
CUI	Corrosion Under Insulation
DF	Damage Factor
ID	Inside Diameter
FFS	Fitness-For-Service
FORM	First Order Reliability Method
MVFORM	Mean Value First Order Reliability Method
POF	Probability of Failure
PRD	Pressure Relief Device
QRA	Quantitative Risk Assessment
SORM	Second Order Reliability Method

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