API RP 581 RISK-BASED INSPECTION TECHNOLOGY – DEMONSTRATING THE TECHNOLOGY THROUGH A WORKED EXAMPLE PROBLEM

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1.0 ABSTRACT

The Joint Industry Project for Risk-Based Inspection (RBI JIP) was initiated and managed by API within the refining and petrochemical industry in 1992. 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 RBI while API 581 was to provide quantitative RBI methods. The API RBI JIP has made major advances in the technology since the original publication of these documents and released the second edition of API 581 - Recommended Practice for Risk-Based Inspection Technology in September 2008. The second edition is a three volume set, Part 1 – Inspection Planning Using API RBI Technology, Part 2 – Probability of Failure in API RBI, and Part 3 – Consequence Modeling in API RBI. This paper provides a step-by-step worked example that demonstrates the technology documented in API 581, Second Edition.

2.0 INTRODUCTION

The API Risk-Based Inspection (API RBI) methodology has been used in the Refining and Petrochemical industries to manage the overall risk of a plant since the mid-1990's as a methodology for focusing inspection efforts on the process equipment with the highest risk. API RBI provides the basis for making informed decisions on inspection frequency, the extent of inspection, and the most suitable type of NDE. In most processing plants, a large percent (80-90%) of the total unit risk will be concentrated in a relatively small percentage (10-20%) of the equipment. These potential high-risk components require greater attention, often through a more extensive inspection or by more advanced inspection methods. The cost of this increased inspection effort often is offset by reducing inspection efforts on the larger percentage of lower risk equipment.

API 581 provides quantitative RBI methods to establish an inspection program. The worked example presented in this paper follows the step-by-step procedure outlined in the document to demonstrate use of the technology developed by the API JIP. This will enable practitioners to better understand the methodology and facilitate effective peer review.

The second edition of API 581was published in September 2008 and presents the API RBI methodology in a three part volume:

- Part 1 – Inspection Planning Using API RBI Technology
- Part 2 – Determination of Probability of Failure in an API RBI Assessment
- Part 3 – Consequence Analysis in an API RBI Assessment

Calculation of risk in API RBI involves the determination of a probability of failure (POF) combined with the consequence of failure (COF). Failure in API RBI is defined as a loss of containment from the pressure boundary resulting in leakage to the atmosphere or rupture of a pressurized component. As damage accumulates in a pressurized component during in-service operation the risk increases. At some point, the risk tolerance or risk target is exceeded and an inspection of sufficient effectiveness to determine the damage state of the component is recommended. It is important to note that the inspection itself does not reduce risk; however, it reduces the uncertainty in the component condition by allowing better quantification of the damage present.

The following worked example follows API RBI's step-by-step procedure to calculate risk for a drum that is susceptible to internal corrosion and in-service stress corrosion cracking. . API RBI typically involves evaluating the risk associated with releases from four representative hole sizes. This example demonstrates the calculation of POF for each of these representative hole sizes. COF will be calculated using the Level 1 consequence model for one of the representative hole sizes; however consequence results for all four hole sizes will be used in the final consequence and risk calculations. Inspection planning will be demonstrated using a simplified approach to demonstrate the technology but without the iterative calculations typically required to plot risk over time and to determine the impact of inspection on risk.

All figure, table and equation numbers used in this paper correspond to the actual numbers in API 581 for an easy cross reference with the document.

3.0 WORKED EXAMPLE INTRODUCTION

The pressure vessel for the risk determination is V-07, a Debutanizer Overhead Accumulator in a Saturated Gas plant. The drum operates at a temperature of 49^{O}C (121^{O}F) and a pressure, P_s, of 0.696 MPa (101 psig) and contains a mixture of propane and butane with 0.11% H_2S. The drum operates with approximately a 50% liquid level.

The mechanical design basis of the drum is as follows:

Fabrication date	1972-01-01
Design Pressure	1.138 MPa (165 psig)
Design Temperature	232 ^{o}C (450^{o}F)
Weld Joint Efficiency	0.85
Material of Construction	ASTM 285 Gr. C 1968
Allowable Stress	94.8 MPa (13,750 psi)
Furnished thickness	20.637 mm (0.8125 inch)
Corrosion Allowance	3.175 mm (0.125 inch)
Post Weld Heat Treatment (PWHT)	Yes
Outside Diameter (OD)	2,520.95 mm (99.25 inch)
Inside Diameter (ID)	2,479.675 mm (97.625 inch)
Length	9.144 m (30 ft)

Operating conditions allow aqueous conditions to occur with a localized measured corrosion rate of 0.29 mmpy (11.4 mpy). In addition, stress corrosion cracking caused by wet H_2S is possible with a susceptibility of Low. Inspection history from 2003-04-04 (B effectiveness level) revealed some localized corrosion and a measured thickness of 19.05 mm (0.75 inch). No history of inspection for wet H_2S cracking has been conducted on this drum.

The process fluid in the drum has the following properties:

Vapor Density, ρ_V	13.8529 kg/m^3 (0.8652 lb/ft^3)
Liquid Density, ρ_l	538.4125 kg/m^3 (33.612 lb/ft^3)
NBP	-21.3056^{o}C (-6.3^{o}F)
Auto-Ignition Temperature; AIT	368.9^{o}C (696^{o}F)
Liquid Discharge Coefficient, C_{disch}	0.61
Gravitational constant, g_c	1 m/s^2 (32.2 ft/s^2)
Detection/Isolation factor $fact_{di}$	1.0
Mitigation Factor, $fact_{mit}$	1.0
Inventory Group Mass, lbs	181,528 kg (400,200 lbs)
Management Factor	1.0

The plant information for inspection planning is as follows:

Inspection Planning	
RBI Date	2008-05-01
Plan Date	2018-05-01
Financial Risk Target, €/yr	1,000
DF Target	3,000

4.0 PROBABILITY OF FAILURE

The probability of failure used in API RBI is computed from Equation (2.1).

$$P_f(t) = gff \cdot D_f(t) \cdot F_{MS}$$

In this equation, the probability of failure, $P_f(t)$, is determined as the product of a generic failure frequency , gff , a damage factor, $D_f(t)$, and a management systems factor, F_{MS} .

The gff for different component types was set at a value representative of the refining and petrochemical industry's failure data (Table 4.1) and is the rate of failure prior to damage occurring in-service due to the operating environment. The gff is provided for four discrete hole sizes by equipment type (i.e. vessels, drums, towers, piping tankage, etc.), covering the full range of consequence model release scenarios (i.e. small leak to rupture).

Adjustments are applied to the gff in order to account for damage mechanisms, operating environment and mechanical integrity management practices within a plant. The DF is based on the active damage mechanisms (local and general corrosion, cracking, creep, etc.), based on original design and the current condition of the component assessed during inspection. The DF modifies the industry gff to calculate the POF for the specific component being evaluated.

The management systems adjustment factor, F_{MS} , is based on the influence of the facility's management system on the mechanical integrity of the plant equipment. This factor accounts for the probability that accumulating damage which results in loss of containment will be discovered in time and is directly proportional to the quality of a facility's mechanical integrity program. The factor is the result of an audit of a facilities or operating unit's management systems that affect plant risk.

4.1 Calculation of Thinning Damage Factor

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

1) Determine the number of historical inspections and the inspection effectiveness category for each: A 1B level inspection was performed on 2003-04-04 with a measured thickness of 19.05 mm (0.75 inch)
2) Determine the time in-service, *age*, from the last inspection reading, t_{rd} to the RBI and Plan Dates.

   age @ RBI Date= 5.08 years

   age @ Plan Date= 15.08 years
3) Determine the corrosion rate of the base material, $C_{r,bm}$: 0.29 mmpy (11.4 mpy)

4) Determine the minimum required wall thickness, t_{min}, from API 579, Appendix A using the following Equation:

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

$$t_{min} \text{ at RBI Date} = \frac{1.138 \cdot 1,241.31}{94.8 \cdot 0.85 - 0.6 \cdot 1.138} = 17.6804 \text{ mm}$$

$$t_{min} \text{ at Plan Date} = \frac{1.138 \cdot 1,244.21}{94.8 \cdot 0.85 - 0.6 \cdot 1.138} = 17.7217 \text{ mm}$$

5) Determine the A_{rt} parameter using equation 2.13 based on *age* and t_{rd} from Step 1 and t_{min} from Step 4 using Equation (2.13).

$$A_{rt} = \max\left[\left(1 - \frac{t_{rd} - C_{r,bm} \cdot age}{t_{\min} + CA}\right), \ \ 0.0\right] \tag{2.13}$$

A_{rt} at RBI Date:

$$A_{rt} = 1 - \frac{19.05 - 0.29 \cdot 5.08}{17.6804 + 3.175} = 1 - 0.8428 = 0.1572$$

A_{rt} at Plan Date:

$$A_{rt} = 1 - \frac{19.05 - 029 \cdot 15.08}{17.5768 + 3.175} = 1 - 0.7024 = 0.2976$$

6) Determine the base damage factor for thinning, D_{fB}^{thin}, using Table 5.11 based on the number of and highest effective inspection category from Step 1 and the A_{rt} in Step 5.

D_{fB}^{thin} at RBI Date: 18

D_{fB}^{thin} at Plan Date: 198

4.2 Calculation of Stress Corrosion Cracking Damage Factor

The following example demonstrates the steps required for calculating the HIC/SOHIC-H_2S damage factor:

1) Determine the number of historical inspections and historical inspection effectiveness category: no appropriate inspection for cracking or blistering has been performed on this vessel (0E)
2) Determine time in-service, age, from the last A, B, C or D inspection performed to the RBI and Plan Dates. Since there has been no cracking inspection to date, the age for cracking is based on the installation date of 1972-01-01.

   age @ RBI Date = 36.33 years

   age @ Plan Date = 46.33 years

3) Determine the environmental severity for cracking based on the H_2S content of the water, PWHT and pH: Low
4) Based on susceptibility in Step 3, determine the severity index, SVI, from Table 10.5: SVI = 1
5) Determine the base damage factor for HIC/SOHIC-H_2S cracking, $D_{fB}^{HIC/SOHIC-H_2S}$ using Table 7.4 based on the number of and highest inspection effectiveness determined in Step 1, and the severity index, SVI, from Step 4:

   $D_{fB}^{HIC/SOHIC-H_2S} = 1$
6) Calculate the escalation in the damage factor at the RBI Date and Plan Date based on time in-service since the last inspection using the *age* from Step 2 using Equation (2.20).

$$D_f^{HIC/SOHIC-H_2S} = D_{fB}^{HIC/SOHIC-H_2S} \left(age\right)^{1.1} \qquad (2.20)$$

$$DF_f^{caustic} \text{ @ RBI Date } = 1\left(36.33\right)^{1.1} = 52$$

$$DF_f^{caustic} \text{ @ Plan Date } = 1\left(46.33\right)^{1.1} = 68$$

4.3 Calculation of Damage Factor Combination for Multiple Damage Mechanisms

If more than one damage mechanism is present, the total damage factor, $D_{f-total}$ is given by Equation (2.2).

$$D_{f-total} = \max\left[D_{f-gov}^{thin},\ D_{f-gov}^{extd}\right] + D_{f-gov}^{scc} + D_f^{htha} + D_{f-gov}^{brit} + D_f^{mfat} \qquad (2.2)$$

$$Total\ D_{f-total}\ at\ RBI\ Date = D_{f-gov}^{thin} + D_{f-gov}^{scc} = 18 + 52 = 70$$

$$Total\ D_{f-total}\ at\ Plan\ Date = D_{f-gov}^{thin} + D_{f-gov}^{scc} = 198 + 68 = 266$$

4.4 Calculation of Probability of Failure

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

$$P_f(t)\ at\ RBI\ \ Date = 3.06e^{-05} \cdot 70 \cdot 1 = 2.14E^{-03}$$

$$P_f(t)\ atPlan\ Date = \ 3.06e^{-05} \cdot 266 \cdot 1 = 8.14E^{-03}$$

Damage factors do not provide a definitive Fitness-For-Service assessment of the component. The basic function of the damage factor is to statistically evaluate the amount of damage that may be present as a function of time in service and the effectiveness of an inspection activity to quantify that damage.

5.0 CONSEQUENCE OF FAILURE

Loss of containment of hazardous fluids from pressurized processing equipment can result in damage to surrounding equipment, serious injury to personnel, production losses, and undesirable environmental impacts. In API RBI, the consequences of loss of containment are expressed as an affected impact area or in financial terms. Impact areas from such event outcomes as pool fires, flash fires, fireballs, jet fires and vapor cloud explosion (VCEs) are quantified based on the effects of thermal radiation and overpressure on surrounding equipment and personnel. Additionally, cloud dispersion analysis methods are used to quantify the magnitude of flammable releases and to determine the extent and duration of personnel exposure to toxic releases. Event trees are utilized to assess the probability of each of the various event outcomes and to provide a mechanism for probability-weighting the loss of containment consequences.

Methodologies for two levels of consequence analysis are provided in API RBI and outlined in Table 4.1. Level 1 consequence analysis provides a simplistic method to estimate the consequence area based on lookup tables for a limited number of generic or reference hazardous fluids. A Level 2 consequence analysis methodology is more rigorous in that it incorporates a detailed calculation procedure that can be applied to a wider range of hazardous fluids. The simpler Level 1 analysis will be used in this worked example to demonstrate the approach.

5.1 Calculation of Release Phase

1) Select a representative fluid group from Table 5.2M: C_3-C_4
2) Determine the stored fluid phase: Liquid (50%)
3) Determine stored fluid properties from Table 5.2M:
4) Liquid Density, ρ_l = 538.4125 kg/m^3 (33.612 lb/ft^3)
5) Vapor Density, ρ_V = 13.8529 kg/m^3 (0.8652 lb/ft^3)
6) Auto-Ignition Temperature, AIT = 368.9^{o}C (696^{o}F)
7) Normal Boiling Point, -21.3^{o}C (-6.3^{o}F)
8) Determine steady state phase of fluid after release to atmosphere: Gas

5.2 Determination of Release Hole Size Selection

A discrete set of release events or release hole sizes are used since it would be impractical to perform the consequence calculations for a continuous spectrum of release hole sizes. The four hole sizes calculated in Level 1 analysis are ¼ inch, 1 inch, 4 inch and rupture (to a maximum of 16 inch). For the purposes of this worked example, we will calculate the consequences of only one hole size to demonstrate the calculation procedure.

1) Determine the hole size for calculation: 101.6 mm (4 inch)
2) Determine the generic failure frequency, gff_n, for the 4 inch hole size: $2.00E^{-06}$

5.3 Calculation of Release Rate

1) Select the appropriate release rate calculation using the stored fluid phase determined.
2) Compute the release hole size area, A_n, using Equation (3.8)

$$A_{4,hole} = \frac{\pi}{4} \cdot d^2 = \frac{\pi}{4} \cdot 4^2 = 8{,}107.319\ mm \qquad (3.8)$$

3) Determine the viscosity correction factor, $K_{v,n}$: for non-viscous fluids, the viscosity correction factor is set equal to 1.
4) Calculate the release rate, W_n, for the release area A_n determined in Step 2 using Equation (3.3).

$$W_n = C_d \cdot K_{v,n} \cdot \rho_l \cdot \frac{A_n}{C_1} \sqrt{\frac{2 \cdot g_c \cdot (P_s - P_{atm})}{\rho_l}} \cdot (1 - fact_{di}) \qquad (3.3)$$

$$W_4 = 0.61 \cdot 1 \cdot 538.4125 \cdot \frac{8107.319}{1000} \sqrt{\frac{2 \cdot 1 \cdot (0.696 - 0)}{538.4125}} \cdot (1 - 0) = 135.3893 \text{ kg/s}$$

5.4 Estimate the Fluid Inventory Available for Release

In API RBI, the available mass for release is estimated as the lesser of two quantities:

- Inventory Group Mass – The component being evaluated is part of a larger group of components that can be expected to provide fluid inventory for the release. The inventory group mass is the sum of the inventory available for all components in the inventory group and is used as the upper limit mass of the fluid available for a release.
- Component Mass – An assumption is made that for large leaks, operator intervention will occur within 3 minutes, thereby limiting the amount of released fluid. Therefore the amount of additional mass, $mass_{add,n}$, is based on 3 minutes of leakage from the components inventory group for the hole size, limited to 203 mm (8 inch).

1) Calculate the inventory mass available: 181,528 kg (400,200 lbs)
2) Calculate the fluid mass, $mass_{comp}$, for the component.

Total Volume, and the Liquid and Vapor Volume

$$V_{cyl} = \pi R^2 \cdot L$$

$$= \pi \cdot \left(\frac{2479.675/2}{1000} \right)^2 \cdot 9.144$$

$$= 44.16\ m^3$$

$$Liquid\ Volume,\ V_l\ =\ 50\% \cdot 44.16\ m^3 = 22.0793\ m^3$$

$$Vapor\ Volume,\ V_v\ =\ (100\%\text{-}50\%) \cdot 44.16\ m^3 = 22.0793\ m^3$$

Component Mass, kg

$$Mass_{eqp} = (V_l \cdot \rho_l) + (V_v \cdot \rho_v)$$

$$= (22.0793\ \text{m}^3 \cdot 538.4125\ \text{kg/m}^3) + (22.0793\text{m}^3 \cdot 13.8529\ \text{kg/m}^3)\ = 12{,}194\ \text{kg}$$

3) Calculate the added fluid mass, $mass_{add,n}$, as a result of 3 minutes of flow from the inventory group using W_4 from Step 6 using Equation (3.10).

$$mass_{add,n} = 135.3893\ kg/s \cdot 180\ s = 24{,}370\ kg \quad (3.10)$$

5.5 Determine Release Type

Determine if the release type is instantaneous or continuous using the following criteria:

1) If the release hole size is 6.35 (1/4 inch) or less, release type is continuous
2) If the sum of the component mass and the release mass for 3 minutes is greater than 4,536 kg (10,000 lb), the release type is instantaneous; otherwise the release type is continuous using Equation (3.11).

$$Total\ mass = 12{,}194\ kg + 24{,}370\ kg = 36{,}564\ kg \quad (3.11)$$

$$mass_{avail,n} = \min\left[\left\{ mass_{comp} + mass_{add,n} \right\},\ mass_{inv} \right]$$

$$mass_{avail} = \min(36{,}564\ ,\ 181{,}528) = 36{,}564\ \text{kg}$$

Since the total $mass_{avail,n}$ 36,564 kg (53,778 lb) is greater than 4,536 kg (10,000 lb), the release is instantaneous.

5.6 Estimate Impact of Detection and Isolation Systems on Release Magnitude

Detection and isolation systems can have a significant impact on magnitude and duration of a hazardous fluid release. Guidance for assigning the effectiveness of detection and isolation systems is provided in Table 5.5.

1) Determine the detection and isolation system
2) Detection: C
3) Isolation: C
4) Mitigation: None
5) Determine release reduction factor, $fact_{di}$: 1
6) Determine mitigation factor, $fact_{mit}$: 1
7) Discharge coefficient Liquid, C_{disch}= 0.61
8) Gravitational constant, g_c=1 m/s^2

5.7 Determine Flammable and Explosive Consequence

Level 1 consequence analysis uses equations to compute flammable and explosive consequence areas presented in Table 5.1. The equations are estimated from a set of equation using release rate (for continuous releases) and mass (for instantaneous releases). The generic equation for calculation of instantaneous releases is shown in Equation (3.17).

$$CA_n^{INST} = a\left(mass_n\right)^b \tag{3.17}$$

1) Calculate the energy efficiency correction factor, $eneff_n$, using Equation (3.18).
   (Note that this is ONLY applied to Instantaneous releases.)

$$eneff_n = 4\cdot\log_{10}\left[mass_n\right]-15 \tag{3.18}$$

$$eneff_4 = 4\cdot\log_{10}\left[2.205\cdot 36564\right]-15 = 4.6258$$

2) Since the auto-ignition, AIT temperature is AIT of 368.9^{o}C (696^{o}F) is more than 80 above ambient conditions, auto-ignition upon release is unlikely.
3) Since the operating temperature of 49.44^{o}C (121^{O}F) is greater than the normal boiling point, NBP, of -21.3056^{o}C (-6.3^{o}F), model the released fluid as a gas.
4) Calculate the equipment damage consequence and personal injury areas for auto-ignition Not Likely, Instantaneous Release (AINL-INST), $CA_{inj,n}^{AINL-INST}$.
5) Determine the Flammable Equipment Damage Area constants *a* and *b* from Tables 5.8M and 5.9M for the release phase determined in Step 3 and using Equation (3.17).

$$CA_{equip,4} = 4.59\cdot\left(36,564 \text{ kg}\right)^{0.72} = 8,855 \text{ m}^2 \tag{3.17}$$

6) Determine the Flammable Personnel Damage Area constants *a* and *b* from Tables 5.8M and 5.9M for the release phase determined in Step 3.

$$\mathrm{CA}_{fatal,\,4} = 9.702 \cdot \left(36,564 \text{ kg}\right)^{0.75} = 25,564 \text{ m}^2$$

7) Compute the consequence areas for equipment and personnel areas using from Step 1 using Equation (3.61).

Adjusted Flammable Equipment Damage Area

$$CA^{flam}_{equip,4} = CA_{equip,4} \cdot \left(\frac{1 - fact_{mit}}{enerff_4} \right) \tag{3.61}$$

$$CA^{flam}_{equip,4} = 8,855 \cdot \left(\frac{1-0}{4.6258} \right) = 1,914 \text{ m}^2$$

Adjusted Flammable Personnel Injury Area:

$$CA^{flam}_{fatal,n} = CA_{fatal,n} \cdot \left(\frac{1 - fact_{mit}}{enerff_n} \right)$$

$$CA^{flam}_{fatal,n} = 25,654 \cdot \left(\frac{1-0}{4.6258} \right) = 5,546 \text{ m}^2$$

8) Determine the final probability weighted flammable consequence areas for equipment and personnel. An analysis (similar to the one for 101.6 mm (4 inch) hole size above) determines that the adjusted flammable consequence areas for each of the four hole size scenarios are as follows (Equation 3.71 and 3.72):

$CA^{flam}_{equip,1/4}$ = 27.40 m^2

$CA^{flam}_{fatal,1/4}$ = 72.01 m^2

$CA^{flam}_{equip,1}$ = 597.52 m^2

$CA^{flam}_{fatal,1}$ = 1,682.89 m^2

$CA^{flam}_{equip,4}$ = 1,914.44 m^2

$CA^{flam}_{fatal,4}$ = 5,546.59 m^2

$CA^{flam}_{equip,R}$ = 1,914.44 m^2

$CA^{flam}_{equip,R}$ = 5,546.59 m^2

$$CA^{flam} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot CA^{flam}_n}{gff_{total}} \right)$$

9) Final Weighted Flammable Consequence Area for Equipment Damage:

$$CA_{equip}^{flam} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot CA_{equip,n}^{flam}}{gff_{total}} \right) \tag{3.71}$$

$$= \frac{\left(8.00\text{E}^{-06} \cdot 27.40\right) + \left(2.00\text{E}^{-05} \cdot 597.52\right) + \left(2.00\text{E}^{-06} \cdot 1{,}914.44\right) + \left(6.00\text{E}^{-07} \cdot 1{,}914.44\right)}{3.060\text{E}^{-05}}$$

$$= 560.3627 \text{ m}^2$$

10) Final Weighted Flammable Consequence Area for Personnel Injury:

$$CA_{fatal}^{flam} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot CA_{fatal,n}^{flam}}{gff_{total}} \right) \tag{3.72}$$

$$= \frac{\left(8.00\text{E}^{-06} \cdot 72.01\right) + \left(2.00\text{E}^{-05} \cdot 1{,}682.89\right) + \left(2.00\text{E}^{-06} \cdot 5{,}546.59\right) + \left(6.00\text{E}^{-07} \cdot 5{,}546.59\right)}{3.060\text{E}^{-05}}$$

$$= 1{,}590.04 \text{ m}^2$$

The final consequence area for the equipment damage and personnel injury is the maximum of the areas calculated. For this worked example, the maximum damage area is the flammable consequence for personnel injury or 1,590 m^2.

A similar procedure is used for determining the consequences associated with releases of toxic chemicals such as H_2S, ammonia or chlorine. Toxic impact areas are based on probit equations and can be assessed whether the stream is pure or a percentage of a hydrocarbon stream. For simplicity, the toxic calculation is not included in this worked example.

A limitation of Level 1 consequence analysis is that it can only be performed for the cases where the component fluid is best represented by one of the reference fluids. The Level 1 consequence analysis has been used by the refining industry for over 10 years with success. However, as international interest has grown in API RBI in the refining and petrochemical industries, as well as in the chemical industries, the limited fluids available were insufficient and the cost to develop additional fluids was high. The Level 2 analysis was developed to address the limitations of Level 1 and to provide a wider industry audience with consequences a more rigorous approach.

5.8 Determining Financial Consequence

Failure (loss of containment) not only has safety consequences, represented by flammable and toxic consequence areas but there are costs associated the release of hazardous materials that does not result in damage to equipment or serious injury to personnel. Since the costs include more than business interruption, analysis for financial consequence is determined by the sum of the following individual costs, shown in Equation (3.97):

$$FC = FC_{cmd} + FC_{affa} + FC_{prod} + FC_{inj} + FC_{environ} \tag{3.97}$$

Where:

FC is the final financial consequence, €

FC_{affa} is the financial consequence of damage to surrounding equipment on the unit, €

$FC_{environ}$ is the financial consequence of environmental clean-up, €

FC_{cmd} is the financial consequence of component damage, €

FC_{inj} is the financial consequence as a result of serious injury to personnel, €

FC_{prod} is the financial consequence of lost production on the unit, €

And:

Population Density, personnel/m^2 = 0.0005

Production, €/day = 50,000

Injury Cost, €/fatality = $5,000,000

Environmental Cost, €/event = 0

Equipment Cost, €/m^2 = 12,000

5.9 Component Damage Cost, FC_{cmd}

The Damage cost uses a cost required for repair of the damaged component, independent of other damage caused by the event. The cost of repair, $holecost$, for different release hole sizes can be found in Table 5.15 and are provided below.

Damage Costs, $holecost$

¼" hole cost - €5,000

1" hole cost - €12,000

4" hole cost - €20,000

Rupture cost - €40,000

The values in Table 5.15 are based on carbon steel prices. For other materials a material cost factor, $matcost$, is used to adjust the cost of alloy materials. The drum in this worked example is constructed of carbon steel so a $matcost$ of 1 will be used.

Finally, the cost to repair or replace the component is a probability weighted average of the individual repair costs determined for each release hole size and calculated using Equation (3.98).

$$FC_{cmd} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot holecost_n}{gff_{total}} \right) \cdot matcost \qquad (3.98)$$

$$holecost_1 = 5,000 \cdot 8.00E^{-06} = 0.0400$$
$$holecost_2 = 12,000 \cdot 2.00E^{-05} = 0.2400$$
$$holecost_3 = 20,000 \cdot 2.00E^{-06} = 0.0400$$
$$holecost_4 = 40,000 \cdot 6.00E^{-07} = 0.0240$$
$$= 0.3440$$

$$FC_{cmd} = 0.3440 \cdot 1/3.06E^{-05} = €11,242$$

5.10 Damage Cost to Surrounding Equipment and Affected Area, FC_{affa}

The consequence cost to repair or replace surrounding components, $equipcost$, that are damaged in the affected area is probability weighted average of the affected areas costs determined for each release hole size and is calculated using Equation 3.99. The $equipcost$ is €12,000 for the worked example.

$$FC_{affa} = CA_{cmd} \cdot equipcost \qquad (3.99)$$

$$= 560.36\ m^2 \cdot 12,000\ €/m^2 = €\ 6,724,351$$

5.11 Business Interruption Costs, FC_{prod}

1) Outage Days, $Outage_{cmd}$ - The costs associated with business interruption is determined based on downtime (lost production) while repairs to the affected component and surrounding equipment are completed. For each release hole size, an estimated downtime, $Outage_n$, can be found in Table 5.17 but are presented below. An outage multiplier, $Outage_{mult}$, is used to adjust downtimes expected for extreme delivery situations. For this worked example, $Outage_{mult}$ is 1.

   Outage Days, $Outage_n$

   $$Outage_1 = 2.00$$
   $$Outage_2 = 3.00$$
   $$Outage_3 = 3.00$$
   $$Outage_4 = 7.00$$

Equation (3.100) is used to calculate $Outage_{cmd}$

$$Outage_{cmd} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot Outage_n}{gff_{total}} \right) \cdot Outage_{mult} \tag{3.100}$$

$$Outage_1 = 2.00 \cdot 8.00E^{-06} = 1.60E^{-05}$$
$$Outage_2 = 3.00 \cdot 2.00E^{-05} = 6.00E^{-05}$$
$$Outage_3 = 3.00 \cdot 2.00E^{-06} = 6.00E^{-06}$$
$$Outage_4 = 7.00 \cdot 6.00E^{-07} = 4.20E^{-06}$$
$$= 8.62E^{-05}$$

$$= 8.62E^{-05} \cdot 1/3.06E^{-05} = 2.817 \ days$$

2) Other Outage Days, $Outage_{affa}$ – If a component fails and that failure results in an affected area, the cost of downtime for replacement or repair of surrounding equipment in the area is considered using Equation (3.101).

$$Outage_{affa} = 10^{1.242 + 0.585 \cdot \log_{10}\left[FC_{affa} \cdot (10)^{-6}\right]} \tag{3.101}$$

$$= 10^{1.242 + 0.585 \cdot \log_{10}\left[6,724,351 \cdot (10)^{-6}\right]} = 53.23 \text{ days}$$

3) Business Interruption Cost, FC_{prod} – The cost of business interruption associated with repairing damaged equipment is equal to the cost associated with lost production due to shutdown of the unit/plant, shown in Equation (3.102). If the production outage per day costs is 50,000, FC_{prod} is calculated.

$$FC_{prod} = \left(Outage_{cmd} + Outage_{affa}\right)\left(prodcost\right) \tag{3.102}$$

$$= \left(2.817 \ + \ 53.23 \text{ days}\right) \cdot 50,000 \ \text{€} / \text{day}$$
$$= \ \text{€}2,802,466$$

5.12 Potential Injury Cost, FC_{inj}

When injuries as a result of an event are possible and costs of potential injuries are determined, appropriate resources can be managed and allocated to prevent injuries from occurring. A population density, $popdens$, is determined and reflects the proximity of personnel to the equipment location such as control rooms, walkways, roads, etc. In addition to the population density, the cost per individual, $injcost$, potentially affected by the failure is considered to reflect typical costs to businesses of an injury up to and including fatal injuries. When assigning this value, consideration should be given to the following:

1) Any existing company standards for such calculations,
2) Local medical/compensation costs associated with long-term disability,
3) Legal/settlement costs,
4) Indirect costs such as increased regulatory scrutiny, loss of reputation, etc.

The costs associated with personnel injury are computed using Equation (3.103). The $popdens$ is 0.0005/m^2 and $injcost$ €5,000,000/serious injury.

$$FC_{inj} = CA_{inj} \cdot popdens \cdot injcost \qquad (3.103)$$

$$= 5.00E^{-04} \cdot 5,000,000 \cdot 1,590 = €3,975,090$$

5.13 Environmental Cleanup Cost, $FC_{environ}$

Environmental consequences as a result of loss of containment can be a significant cost and considered along with other costs including fines and other financial penalties. The methods presented in API 581 are based on the amount of material spilled to the ground, the number of days to clean up the spill and the environmental hazards associated with the properties of the fluid released. The environmental cost for this worked example is €0.

$$FC_{environ} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot vol_n^{env}}{gff_{total}} \right) \cdot envcost \qquad (3.106)$$

$$= €0$$

5.14 Total Financial Consequence, FC

The financial consequence of a loss of containment and subsequent release of hazardous materials can be determined by adding up the individual costs determined above (Equation 3.97).

$$FC = FC_{cmd} + FC_{affa} + FC_{prod} + FC_{inj} + FC_{environ}$$

$$= €11,242 \ + \ €6,724,351 \ + \ €2,802,466 \ + \ €3,975,090 \ + \ €0$$
$$= €13,513,150$$

6.0 RISK ANALYSIS

6.1 Determination of Risk

The calculation of risk can be determined as a function of time by combining probability of failure and the consequence of failure, as shown in Equation (1.5).

$$R(t) = P_f(t) \cdot C(t) \tag{1.5}$$

Note that probability of failure, $P_f(t)$, is a function of time since damage factor increases as the damage in component due to thinning, cracking or other damage mechanisms accumulate with time. Consequence of failure, $C(t)$, is assumed to be invariant with time. Therefore, Equations (1.6) and (1.7) show the determination of risk, expressed in area or in financial terms.

$$R(t) = P_f(t) \cdot CA \qquad for\ Area - Based\ Risk \tag{1.6}$$

$$R(t) = P_f(t) \cdot FC \qquad for\ Financial - Based\ Risk \tag{1.7}$$

So for the area risk calculation for our worked example, the Risk at the RBI Date using the maximum area calculated in the consequence of failure section is:

$$R(t) = P_f(t) \cdot CA$$

$$\text{Risk}_{\text{fatal}} \text{ @ RBI Date } = 2.14E^{-03} \cdot 1{,}590.04 = 3.41E^{-00}$$
$$= 3.41 \text{ m}^2 / \text{yr}$$

$$\text{Risk}_{\text{fatal}} \text{ @ Plan Date } = 8.14E^{-03} \cdot 1{,}590.04 = 1.29E^{+01}$$
$$= 12.94 \text{m}^2 / \text{yr}$$

Similarly for Financial Risk,

$$R(t) = P_f(t) \cdot FC$$

$$\text{Risk}_{\text{finan}} \text{ @ RBI Date } = 2.14E^{-03} \cdot €13{,}513{,}150$$
$$= 28{,}918€ / \text{year}$$

$$\text{Risk}_{\text{finan}} \text{ @ Plan Date } = 8.14E^{-03} \cdot €13{,}513{,}150$$
$$= 109{,}988 \ € / \text{year}$$

In these equations, CA is the consequence impact area expressed in units of area and FC is the financial consequence expressed in economic terms. Note that Risk varies with time due to the influence of the changes probability.

7.0 INSPECTION PLANNING

The inspection planning module calculates risk over time until some point in time when the risk defined in Equations 10 and 11 will reach a specified risk target, as defined by the Owner-User. An inspection of the equipment is recommended on or before date that the risk target is reached. Inspection of equipment does not reduce the inherent risk associated with that piece of equipment but inspection provides knowledge of the damage state of the vessel and reduces uncertainty. As a result, the probability that loss of containment will occur is directly related to the amount and quality of the information available from past inspection and the ability of the inspection method to quantify the damage.

The reduction of uncertainty is a function of the effectiveness of the inspection method and coverage in identifying and quantifying the type and extent of the damage. The calculated risk is not only a function of time but it is also a function of the knowledge obtained on the condition or damage state of the component determined in an effective inspection program. When inspection effectiveness is introduced into risk, Equations (1.8) and (1.9) are the result:

$$R(t,I_E) = P_f(t,I_E)\cdot CA \qquad for\ Area-Based\ Risk \tag{1.8}$$

$$R(t,I_E) = P_f(t,I_E)\cdot FC \qquad for\ Financial-Based\ Risk \tag{1.9}$$

7.1 Inspection Planning Information

RBI Date: 2008-05-01

Plan Date: 2018-05-01

Financial Risk Target, €/yr: 1,000

DF Target: 3,000

1) Estimate Target Date

For our worked example, if the Target Area Risk is 3.716 m^2/yr (35 ft^2/yr), what inspection is required and what date should the inspection date occur (Target Date) in order to avoid exceeding the Area Risk Target by the Plan date?

At the RBI date of 2008-05-01, the calculated risk is 3.41 m^2/yr which is very close to the target risk of 3.716 m^2/yr. At the plan date of 2018-05-01, the calculated risk is 12.94 m^2/yr. If a linear risk vs. time curve is assumed (not necessarily correct), the target date will be reached approximately ½ year after the RBI date, or a Target Date on 2008-11-01.

2) Propose an Inspection Plan

Calculate the DF required at the Plan Date to achieve Target Risk

Risk @ Plan Date/Target Risk = 12.94/3.716 = 3.48

Based on the Risk ratio above, a Damage Factor reduction of 3.48 is required. Therefore, the target damage factor after inspection is 266/3.48 = 77. Thinning Damage factor at the plan date is 198 and the cracking damage factor at the plan date is 68 so it is likely that both a thinning and cracking inspection will be required by the target date. Let’s assume a 1B thinning and a 1C cracking inspection.

3) Calculate New Thinning Damage Factor

The previous 1B thinning inspection (2003-04-04) plus an additional 1B thinning inspection at the target date (2008-11-01) gives the inspection history is reflected by 1B + 1B = 2B = 1A, since 2B is approximately equal to 1A, inspection.

From Table 5.11 using the A_{rt} value at the plan date of 0.2976 the new Thinning Damage Factor is 28.

4) Calculate New Cracking Damage Factor:

The recommended Cracking Inspection is a 1C effectiveness. If the date of the cracking inspection is 2008-11-01 (note the inspection is performed 9 years and 6 months prior to Plan Date or 9.5 years), the cracking Damage Factor becomes:

$$Cracking\ Damage\ Factor = 1 \cdot (9.5)^{1.1} = 11.9$$

5) Determine Total Damage Factor at Plan Date

The new Total Damage Factor based on steps 3 and 4 above is 28 + 11.9 or 39.9

6) Calculate Future POF, COF and Risk at the Plan Date with recommended inspection, the POF at the Plan Date with the recommended inspection is:

$$POF_{Plan} = 3.06E^{-05} \times 39.9 \times 1 = 1.22E^{-03}\ failures/yr$$

The COF at the Plan Date with the recommended inspection is still 1,590 m^2, because COF is invariant with time. And the future Risk at the Plan Date with the recommended inspection is:

$$Risk_{plan} = 1.22\,\mathrm{E}^{-03}\ failures/yr \times 1,590\ m^2 = 1.94\ m^2/yr$$

Since the risk target is 1.94 m^2/yr, the Risk at the Plan Date with the recommended inspection is below our established Risk Target of 3.716 m^2/yr.

The following Table summarizes the results of the worked example demonstrated in this paper.

	RBI Date	Plan Date W/O Inspection	Plan Date With Inspection
COF Equipment, m^2	560.36	560.36	560.36
COF Personnel, m^2	1,590.04	1,590.04	1,590.04
Thinning Factor	18	198	28
Cracking Factor	52	68	11.9
Total Damage Factor	70	266	39.9
POF with inspection, failures/yr	2.14E-03	8.14E-03	1.22E-03
Risk, m^2/yr	3.41	12.94	1.94
Equipment Damage Hole Cost, €	11,242	11,242	11,242
Affected Area Cost, €	6,724,351	6,724,351	6,724,351
Outage Area Cost, €	2,802,466	2,802,466	2,802,466
Injury Area Cost, €	3,975,090	3,975,090	3,975,090
Flammable Financial Consequence, €	13,513,150	13,513,150	13,513,150
Flammable Financial Risk, €/yr	28,918	109,988	16,486
Cost of Inspection, €			28,000
Area Risk Reduction, m^2/yr			11
Financial Risk Reduction, €/yr			93,502

8.0 FUTURE DEVELOPMENT WORK

8.1 Overview

The technology embedded within API RBI is a continuous process of improvement. As the technology is improved, the methodology will be modified and revisions to API 581 will be issued. Highlights of the known technological improvements planned for the probability of failure, consequence analysis and inspection planning methods in API RBI are provided below.

1) An alternative methodology for calculating probability of failure is being developed based on fitness for service (FFS) damage models. Inputs to these structural reliability models will include statistical continuous distributions for material properties, physical dimensions, applied loadings, inspection effectiveness, and metal loss. The result of this approach will be a probabilistic calculation of the POF.
2) Release hole sizes used in a risk assessment should be strongly dependent on the active damage mechanisms and may more accurately represent the risk associated. Development work is planned for this area.
3) A detailed assessment of the industry failure data to re-evaluate the generic failure frequencies is planned. The current industry failure data is not truly generic since the data includes some effects of in-service damage. A true generic failure frequency should be independent of service life or damage mechanism. Recent plant failure rate data indicates that the current generic failure frequencies are very conservative, possibly due to the in-service damage influence.
4) Performing a consequence analysis utilizing a dense gas (heavier than air) cloud dispersion modeler to evaluate light gas releases, such as hydrogen and methane, is conservative. Future modifications to the Level 2 Consequence analysis in API RBI will incorporate the use of a neutrally buoyant cloud dispersion model.
5) Research has recently been conducted on ignition probabilities and correlations. This work will be reviewed in order to modify the event tree probability correlations currently used in API RBI. This research may also provide input to improve the methods for determining the probability that a delayed ignition will result in either a flash fire or VCE, tied to the NFPA reactivity value of the fluid.
6) Future work is being conducted to develop a consistent basis and guidelines for determining both area-based and financial-based risk targets.
7) An optimization methodology considering all damage mechanisms, inspection costs and inspection effectiveness is in development.

9.0 NOMENCLATURE

age	is the time since the last thickness reading
A_n	is the cross sectional hole area associated with the n^{th} release hole size
A_{rt}	is the metal loss parameter
C_a	is the corrosion allowance
C_r	is the corrosion rate
C_d	is the coefficient of discharge
$C(t)$	is the consequence of failure as a function of time
CA	is the consequence impact area
CA_{cmd}	is the final component damage consequence area
CA_{inj}	is the final personnel injury consequence area
$D_{f-total}$	is the total damage factor
D_f^{thin}	is the damage factor for thinning
D_f^{elin}	is the damage factor for component linings
D_f^{extd}	is the damage factor for external damage, i.e. corrosion under insulation
D_f^{scc}	is the damage factor for stress corrosion cracking
D_f^{htha}	is the damage factor for high temperature hydrogen attack
D_f^{mfat}	is the damage factor for mechanical fatigue
D_f^{brit}	is the damage factor for brittle fracture
$D_f(t)$	is the damage factor as a function of time, equal to $D_{f-total}$ evaluated at a specific time
F_{MS}	is the management systems factor
FC	is the financial consequence
g_c	is the gravitational constant
gff	is the generic failure frequency
k	is the release fluid ideal gas specific heat capacity ratio
K_v	is the viscosity correction factor
MW	is the release fluid molecular weight
P_a	is the atmospheric pressure
P_s	is the storage or normal operating pressure

$P_f(t)$	is the probability of failure as a function of time
$P_f(t, I_E)$	is the probability of failure as a function of time and inspection effectiveness
ρ_l	is the liquid density
R	is the universal gas constant
$R(t)$	is the risk as a function of time
$R(t, I_E)$	is the risk as a function of time and inspection effectiveness
t_{min}	is the minimum required thickness for the component established using the applicable construction code
t_{rd}	is the thickness reading
T_s	is the storage or normal operating temperature
W_n	is the release rate associated with the n^{th} release hole size

10.0 REFERENCES

1) API, API RP 581 *API RBI Technology*, Second Edition, September 2008, American Petroleum Institute, Washington, D.C.

11.0 TABLES

TABLE 4.1 – ANALYSIS STEPS IN AN API RBI CONSEQUENCE ANALYSIS

Step	Description	Paragraph in this Part	
		Level 1 Consequence Analysis	Level 2 Consequence Analysis
1	Determine the released fluid and its properties, including the release phase.	5.1	6.1
2	Select a set of release hole sizes to determine the possible range of consequences in the risk calculation.	5.2	
3	Calculate the theoretical release rate.	5.3	6.3
4	Estimate the total amount of fluid available for release.	5.4	
5	Determine the type of release, continuous or instantaneous, to determine the method used for modeling the dispersion and consequence.	5.5	
6	Estimate the impact of detection and isolation systems on release magnitude.	5.6	
7	Determine the Release Rate and Mass for the Consequence Analysis	5.7	6.7
8	Calculate Flammable/Explosive Consequences	5.8	6.8
9	Calculate Toxic Consequences	5.9	6.9
10	Calculate Non-flammable, non-toxic consequences	5.10	6.10
11	Determine the final probability weighted component damage and personnel injury consequence areas	5.11	
12	Calculate Financial Consequences	5.12	

Table 4.1 – Suggested Component Generic Failure Frequencies (gff)

Equipment Type	Component Type	gff as a Function of Hole Size (failures/yr)				gff_{total} (failures/yr)
		Small	Medium	Large	Rupture	
Compressor	COMPC	8.00E-06	2.00E-05	2.00E-06	0	3.00E-05
Compressor	COMPR	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Heat Exchanger	HEXSS	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Heat Exchanger	HEXTS	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Pipe	PIPE-1	2.80E-05	0	0	2.60E-06	3.06E-05
Pipe	PIPE-2	2.80E-05	0	0	2.60E-06	3.06E-05
Pipe	PIPE-4	8.00E-06	2.00E-05	0	2.60E-06	3.06E-05
Pipe	PIPE-6	8.00E-06	2.00E-05	0	2.60E-06	3.06E-05
Pipe	PIPE-8	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Pipe	PIPE-10	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Pipe	PIPE-12	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Pipe	PIPE-16	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Pipe	PIPEGT16	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Pump	PUMP1S	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Tank650	TANKBOTTOM	7.20E-04	0	0	2.00E-06	7.20E-04
Tank650	COURSE-1	7.00E-05	2.50E-05	5.00E-06	1.00E-07	1.00E-04
Tank650	COURSE-2	7.00E-05	2.50E-05	5.00E-06	1.00E-07	1.00E-04
Tank650	COURSE-3	7.00E-05	2.50E-05	5.00E-06	1.00E-07	1.00E-04
Tank650	COURSE-4	7.00E-05	2.50E-05	5.00E-06	1.00E-07	1.00E-04
Tank650	COURSE-5	7.00E-05	2.50E-05	5.00E-06	1.00E-07	1.00E-04
Tank650	COURSE-6	7.00E-05	2.50E-05	5.00E-06	1.00E-07	1.00E-04
Tank650	COURSE-7	7.00E-05	2.50E-05	5.00E-06	1.00E-07	1.00E-04
Tank650	COURSE-8	7.00E-05	2.50E-05	5.00E-06	1.00E-07	1.00E-04
Tank650	COURSE-9	7.00E-05	2.50E-05	5.00E-06	1.00E-07	1.00E-04
Tank650	COURSE-10	7.00E-05	2.50E-05	5.00E-06	1.00E-07	1.00E-04
Vessel/FinFan	KODRUM	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Vessel/FinFan	COLBTM	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Vessel/FinFan	FINFAN	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Vessel/FinFan	FILTER	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Vessel/FinFan	DRUM	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Vessel/FinFan	REACTOR	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Vessel/FinFan	COLTOP	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Vessel/FinFan	COLMID	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05

Note:
See references [1] through [8] for discussion of failure frequencies for equipment

TABLE 5.2M – PROPERTIES OF REPRESENTATIVE FLUIDS USED IN LEVEL 1 ANALYSIS

Fluid	MW	Liquid Density (kd/m^2)	NBP (°C)	Ambient State	Ideal Gas Specific Heat Eq.	C_p Ideal Gas Constant *A*	Ideal Gas Constant *B*	Ideal Gas Constant *C*	Ideal Gas Constant *D*	Ideal Gas Constant *E*	Auto Ignition Temp. (°C)
C1-C2	23	250.512	-125	Gas	Note 1	12.3	1.15E-01	-2.87E-05	-1.30E-09	N/A	558
C3-C4	51	538.379	-21	Gas	Note 1	2.632	0.3188	-1.35E+04	1.47E-08	N/A	369
C5	72	625.199	36	Liquid	Note 1	-3.626	0.4873	-2.60E-04	5.30E-08	N/A	284
C6-C8	100	684.018	99	Liquid	Note 1	-5.146	6.76E-01	-3.65E-04	7.66E-08	N/A	223
C9-C12	149	734.012	184	Liquid	Note 1	-8.5	1.01E+00	-5.56E-04	1.18E-07	N/A	208
C13-C16	205	764.527	261	Liquid	Note 1	-11.7	1.39E+00	-7.72E-04	1.67E-07	N/A	202
C17-C25	280	775.019	344	Liquid	Note 1	-22.4	1.94E+00	-1.12E-03	-2.53E-07	N/A	202
C25+	422	900.026	527	Liquid	Note 1	-22.4	1.94E+00	-1.12E-03	-2.53E-07	N/A	202
Water	18	997.947	100	Liquid	Note 3	2.76E+05	-2.09E+03	8.125	-1.41E-02	9.37E-06	N/A
Steam	18	997.947	100	Gas	Note 3	3.34E+04	2.68E+04	2.61E+03	8.90E+03	1.17E+03	N/A
Acid	18	997.947	100	Liquid	Note 3	2.76E+05	-2.09E+03	8.125	-1.41E-02	9.37E-06	N/A
H_2	2	71.010	-253	Gas	Note 1	27.1	9.27E-03	-1.38E-05	7.65E-09	N/A	400
H_2S	34	993.029	-59	Gas	Note 1	31.9	1.44E-03	2.43E-05	-1.18E-08	N/A	260
HF	20	967.031	20	Gas	Note 1	29.1	6.61E-04	-2.03E-06	2.50E-09	N/A	17760
CO	28	800.920	-191	Gas	Note 2	2.91E+04	8.77E+03	3.09E+03	8.46E+03	1.54E+03	609
DEE	74	720.828	35	Liquid	Note 2	8.62E+04	2.55E+05	1.54E+03	1.44E+05	-6.89E+02	160
HCL	36	1185.362	-85	Gas	---	---	---	---	---	---	N/A
Nitric Acid	63	1521.749	121	Liquid	---	---	---	---	---	---	N/A
ALCL3	133.5	2434.798	194	Powder	Note 1	4.34E+04	3.97E+04	4.17E+02	2.40E+04	N/A	558
NO_2	90	929.068	135	Liquid	---	---	---	---	---	---	N/A
Phosgene	99	1377.583	83	Liquid	---	---	---	---	---	---	N/A
TDI	174	1217.399	251	Liquid	---	---	---	---	---	---	620
Methanol	32	800.920	65	Liquid	Note 2	3.93E+04	8.79E+04	1.92E+03	5.37E+04	8.97E+02	464

TABLE 5.8M – COMPONENT DAMAGE FLAMMABLE CONSEQUENCE EQUATION CONSTANTS

Fluid	Continuous Releases Constants								Instantaneous Releases Constants							
	Auto-Ignition Not Likely (CAINL)				Auto-Ignition Likely (CAIL)				Auto-Ignition Not Likely (IAINL)				Auto-Ignition Likely (IAIL)			
	Gas		Liquid		Gas		Liquid		Gas		Liquid		Gas		Liquid	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
C_1-C_2	8.669	0.98			55.13	0.95			6.469	0.67			163.7	0.62		
C_3-C_4	10.13	1.00			64.23	1.00			4.590	0.72			79.94	0.63		
C_5	5.115	0.99	100.6	0.89	62.41	1.00			2.214	0.73	0.271	0.85	41.38	0.61		
C_6-C_8	5.846	0.98	34.17	0.89	63.98	1.00	103.4	0.95	2.188	0.66	0.749	0.78	41.49	0.61	8.180	0.55
C_9-C_{12}	2.419	0.98	24.60	0.90	76.98	0.95	110.3	0.95	1.111	0.66	0.559	0.76	42.28	0.61	0.848	0.53
C_{13}-C_{16}			12.11	0.90			196.7	0.92			0.086	0.88			1.714	0.88
C_{17}-C_{25}			3.785	0.90			165.5	0.92			0.021	0.91			1.068	0.91
C_{25} +			2.098	0.91			103.0	0.90			0.006	0.99			0.284	0.99
H_2	13.13	0.992			86.02	1.00			9.605	0.657			216.5	0.618		
H_2S	6.554	1.00			38.11	0.89			22.63	0.63			53.72	0.61		
HF																
Aromatics	3.952	1.097	21.10	1.00	80.11	1.055			1.804	0.667	14.36	1.00	83.68	0.713	143.6	1.00
Styrene	3.952	1.097	21.10	1.00	80.11	1.055			1.804	0.667	14.36	1.00	83.68	0.713	143.6	1.00
CO	0.040	1.752							10.97	0.667						
DEE	9.072	1.134	164.2	1.106	67.42	1.033	976.0	0.649	24.51	0.667	0.981	0.919			1.090	0.919
Methanol	0.005	0.909	340.4	0.934					4.425	0.667	0.363	0.900				
PO	3.277	1.114	257.0	0.960					10.32	0.667	0.629	0.869				
EEA	0	1.035	23.96	1.00					1.261	0.667	14.13	1.00				
EE	2.595	1.005	35.45	1.00					6.119	0.667	14.79	1.00				
EG	1.548	0.973	22.12	1.00					1.027	0.667	14.13	1.00				
EO	6.712	1.069							21.46	0.667						
Pyrophoric	2.419	0.98	24.60	0.90	76.98	0.95	110.3	0.95	1.111	0.66	0.559	0.76	42.28	0.61	0.848	0.53

Table 5.9M – Personnel Injury Flammable Consequence Equation Constants

Fluid	Continuous Releases Constants								Instantaneous Releases Constants							
	Auto-Ignition Not Likely (CAINL)				Auto-Ignition Likely (CAIL)				Auto-Ignition Not Likely (IAINL)				Auto-Ignition Likely (IAIL)			
	Gas		Liquid		Gas		Liquid		Gas		Liquid		Gas		Liquid	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
C_1-C_2	21.83	0.96			143.2	0.92			12.46	0.67			473.9	0.63		
C_3-C_4	25.64	1.00			171.4	1.00			9.702	0.75			270.4	0.63		
C_5	12.71	1.00	290.1	0.89	166.1	1.00			4.820	0.76	0.790	0.85	146.7	0.63		
C_6-C_8	13.49	0.96	96.88	0.89	169.7	1.00	252.8	0.92	4.216	0.67	2.186	0.78	147.2	0.63	31.89	0.54
C_9-C_{12}	5.755	0.96	70.03	0.89	188.6	0.92	269.4	0.92	2.035	0.66	1.609	0.76	151.0	0.63	2.847	0.54
C_{13}-C_{16}			34.36	0.89			539.4	0.90			0.242	0.88			4.843	0.88
C_{17}-C_{25}			10.70	0.89			458.0	0.90			0.061	0.91			3.052	0.91
C_{25} +			6.196	0.89			303.6	0.90			0.016	0.99			0.833	0.99
H_2	32.05	0.933			228.8	1.00			18.43	0.652			636.5	0.621		
H_2S	10.65	1.00			73.25	0.94			41.43	0.63			191.5	0.63		
HF																
Aromatics	12.76	0.963	66.01	0.883	261.9	0.937	56.00	0.268	2.889	0.686	0.027	0.935	83.68	0.713	0.273	0.935
Styrene	12.76	0.963	66.01	0.883	261.9	0.937	56.00	0.268	2.889	0.686	0.027	0.935	83.68	0.713	0.273	0.935
CO	5.491	0.991							16.91	0.692						
DEE	26.76	1.025	236.7	1.219	241.5	0.997	488.9	0.864	31.71	0.682	8.333	0.814	128.3	0.657	9.258	0.814
Methanol	0	1.008	849.9	0.902					6.035	0.688	1.157	0.871				
PO	8.239	1.047	352.8	0.840					13.33	0.682	2.732	0.834				
EEA	0	0.946	79.66	0.835					1.825	0.687	0.030	0.924				
EE	7.107	0.969	8.142	0.800					25.36	0.660	0.029	0.927				
EG	5.042	0.947	59.96	0.869					1.435	0.687	0.027	0.922				
EO	11.00	1.105							34.70	0.665						
Pyrophoric	5.755	0.96	70.03	0.89	188.6	0.92	269.4	0.92	2.035	0.66	1.609	0.76	151.0	0.63	2.847	0.54

Table 5.11 – 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 10.5 – Determination of Severity Index – HIC/SOHIC-H_2S Cracking

Susceptibility	Severity Index – S_{VI}
High	100
Medium	10
Low	1
None	1

Table 7.4 – SCC Damage Factors – All SCC Mechanisms

S_{VI}	Inspection Effectiveness												
	E	1 Inspection				2 Inspections				3 Inspections			
		D	C	B	A	D	C	B	A	D	C	B	A
1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	10	8	3	1	1	6	2	1	1	4	1	1	1
50	50	40	17	5	3	30	10	2	1	20	5	1	1
100	100	80	33	10	5	60	20	4	1	40	10	2	1
500	500	400	170	50	25	300	100	20	5	200	50	8	1
1000	1000	800	330	100	50	600	200	40	10	400	100	16	2
5000	5000	4000	1670	500	250	3000	1000	250	50	2000	500	80	10
S_{VI}	Inspection Effectiveness												
	E	4 Inspections				5 Inspections				6 Inspections			
		D	C	B	A	D	C	B	A	D	C	B	A
1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	10	2	1	1	1	1	1	1	1	1	1	1	1
50	50	10	2	1	1	5	1	1	1	1	1	1	1
100	100	20	5	1	1	10	2	1	1	5	1	1	1
500	500	100	25	2	1	50	10	1	1	25	5	1	1
1000	1000	200	50	5	1	100	25	2	1	50	10	1	1
5000	5000	1000	250	25	2	500	125	5	1	250	50	2	1

Notes: S_I is the Maximum Severity Index determined for each specific SCC Cracking Mechanism