Ballot ID: API Staff to Insert

Action item Reference Number:

Title:	Tank Module Revision
Date:	3/2019
Purpose:	Revised Tank Module to clarify, modify and add API 620 tanks to methodology
Revision:	
Impact:	
Rationale:	
Technical Reference(s):	Include technical reference (published reference)

Calculation Change

Guidance for the calculations in current version of API RP 581 are difficult to follow and are missing the application to API 620 tanks. This revision adds 620 tanks as well as additional components. In addition, the revision pulls all of the tank discussions from Parts 1, 2 and 3 into one section and splits the course and bottom methodology for a cleaner flow.

Summary of the modifications:

- Reorganized all tank calculations and discussion into one section.
- Split course and bottom calculations for clarity.
- Removed tank bottom calculations from Part 2 Thinning Section 4.5.7
- Added 620 tank components and notes to Part 2, Table 3.1
- Added Component and Geometry types and notes to Part 2, Table 4.2
- Addressed ballot 2599, 2600 and 2012-038 comments and elements.

Additional Future Needs:

- Add internal lining methodology
- Add guidance for release rate calculations from a shell course hole.
- Add discussion and calculation steps for pressure (static head) to be used in equations in Sections4.3.2 and 4.3.3.
- Add discussion for adding fluid choices and properties.

API RP 581 Risk-Based Inspection Methodology

Ballot ID: API Staff to Insert

Action item Reference Number:

Attachments	Ballot_Part 5, Atmospheric Storage Tanks_2019_Tanks_r2 .pdf Part 2 Tank Modification Changes.pdf

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Tracking Status					
Submitted to Task Group		Submitted to SCI		Submitted to Master Editor	
Date	Resolution	Date	Resolution	Date	Resolution

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

Include redline document section(s), Tables and Figures with revisions shown.

Notes to 620 Ballot:

1. A separate ballot looks to divide the TANKBOTTOM (both API 650 and API 620) into two components.
2. Other than API 620 Tmin calculation differences, no additional changes are recommended to tables or calculations for Inspection Effectiveness, Damage Factors, etc. to add flat bottom API 620 tanks. Existing API 650 requirements will apply.

Editorial Note: References throughout API 581 to “atmospheric” storage tanks should be revised to “atmospheric and flat bottom, low-pressure” storage tanks.

More Rationale for Addition of API 620 Tanks

In the current edition of API 581, Tank650 is the only equipment type considered for AST’s. One proposed revision to API 581 is the addition of an equipment type Tank620, which would include only API 620 flat-bottom, cylindrical tank geometries. For double-walled tanks (tank-in-tank systems), it is proposed that only the primary liquid container be evaluated, with the secondary container considered leak isolation. Tank components to be considered for Tank620 would include shell courses, the tank bottom (as modified in the next section of this bulletin) and fixed roofs. Table 4.1 and Table 5.2 of API 581 Part 2, which list gff values for various components, and geometry considerations for various equipment and components, respectively, require modifications. In the absence of any additional data, it is recommended that there be no differentiation between gff for Tank620 components and the corresponding Tank650 components.

In determining POF, the tmin calculation for API 620 tanks differs from API 650 in that the internal pressure component is included in the hoop stress calculation. With the addition of API 620 Appendix Q and Appendix R tanks, the annular ring requirements for API 620 and API 650 tanks are also different.

With the addition of API 620 tanks and other recommended changes, such as the addition of fluid and safety risk to the API 581 AST methodology, the need to evaluate stainless steel and aluminum tanks will likely increase. Stainless tanks can be considered with the API 581 AST methodology with little additional changes. The addition of aluminum tanks will require the consideration of additional damage mechanisms.

Notes to Edge Ballot:

1. It is proposed that the near shell region be considered to extend 24 to 30 inches inside the shell. This is consistent with most annular rings.
2. A separate ballot looks to add API 620 flat bottom tanks. This split of tank bottoms would also apply to API 620 AST.
3. Other than near shell tmin calculation differences, no additional changes are recommended to tables or calculations for Inspection Effectiveness, Damage Factors, etc. to split the tank bottom components. Changes to certain tables with financial impact of tank bottoms are identified in additional ballots.

More Rationale for Addition/Revision of Bottoms Component

In the current edition of API 581, a single bottom component, *TANKBOTTOM*, is considered in the evaluation of ASTs. While not all tanks are constructed with annular rings, the plates on the soil-side of the under-shell (edge) and the remainder of the tank bottom may have very different environments and foundation conditions. The product side, corrosion in the area of the perimeter of the tank may be different than the remainder of the tank due to such things as the bottom’s as-built or settled profile, and the existence of edge sump(s), mixers or other appurtenances.

3.7 Tables

Table 3.1 – Suggested Component Generic Failure Frequencies

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. HEXTS,	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Pipe	PIPE-1, PIPE-2	2.80E-05	0	0	2.60E-06	3.06E-05
Pipe	PIPE-4, PIPE-6	8.00E-06	2.00E-05	0	2.60E-06	3.06E-05
Pipe	PIPE-8, PIPE-10, PIPE-12, PIPE-16, PIPEGT16	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Pump	PUMP2S, PUMPR, PUMP1S	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Tank620	TANKBOTTOM	7.20E-04	0	0	2.00E-06	7.22E-04
Tank620	COURSE-1-10	7.00E-05	2.50E-05	5.00E-06	1.00E-07	1.00E-04
Tank650	TANKBOTTOM	7.20E-04	0	0	2.00E-06	7.22E-04
Tank650	TANKBOTEDGE	7.20E-04	0	0	2.00E-06	7.22E-04
Tank650	COURSE-1-10	7.00E-05	2.50E-05	5.00E-06	1.00E-07	1.00E-04
Vessel/FinFan	KODRUM, COLBTM, FINFAN, FILTER, DRUM, REACTOR, COLTOP, COLMID	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05

Table 3.1 – Suggested Component Generic Failure Frequencies

Equipment Type	Component Type	gff as a Function of Hole Size (failures/yr)				gff_{total} (failures/yr)
		Small	Medium	Large	Rupture	

Notes:

1. See references [1] through [8] for discussion of failure frequencies for equipment
2. TANKBOTEDGE refers to the near shell region of the tank bottom and is considered to extend 24 to 30 inches inside the shell. This is consistent with most annular ring dimensions. This component type can be used for tanks with or without an annular ring. TANKBOTREM refers to the remaining part of the tank bottom that does not include the edge component.
3. Tank620 Course components are the primary pressure boundary in the case of a double-walled tank. The secondary wall may be considered as having an effect on leak detection, isolation and mitigation.

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

Equipment Type	Component Type	Geometry Type
Compressor	COMPC, COMPR	CYL
Heat Exchanger	HEXSS, HEXTS	CYL, ELB, SPH, HEM, ELL, TOR, CON, NOZ
Pipe	PIPE-1, PIPE-2, PIPE-4, PIPE-6, PIPE-8, PIPE-10, PIPE-12, PIPE-16, PIPEGT16	CYL, ELB
Pump	PUMP2S, PUMPR, PUMP1S	CYL
Tank620	TANKBOTTOM	PLT
Tank620	TANKBOTEDGE	PLT
Tank620	COURSE-1-10	CYL
Tank650	TANKBOTTOM	PLT
Tank650	COURSE-1-10	CYL

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

Equipment Type	Component Type	Geometry Type
Vessel/FinFan	KODRUM COLBTM, FINFAN, FILTER, DRUM, REACTOR, COLTOP, COLMID	CYL, ELB, SPH, HEM, ELL, TOR, CON, NOZ

Notes:

1. Tank620 Course components are the primary pressure boundary in the case of a double-walled tank. The secondary wall may be considered as having an effect on leak detection, isolation and mitigation.
2. TANKBOTEDGE refers to the near shell region of the tank bottom and is considered to extend 24 to 30 inches inside the shell. This is consistent with most annular ring dimensions. This component type can be used for tanks with or without an annular ring. TANKBOTREM refers to the remaining part of the tank bottom that does not include the edge component.

Part 2, Section 4.5.7

4.5.7 Calculation of Thinning Damage Factor

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

a) STEP 1 – Determine the furnished thickness, t, and age, age, and cladding/weld overlay thickness, t_{cm}, if applicable for the component from the installation date.

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

c) STEP 3 – Determine the time in service, age_{tk}, since the last inspection known thickness , t_{rdi} . The t_{rdi} is the starting thickness with respect to wall loss associated with internal corrosion (see Section 4.5.5). If no measured thickness is available, set $t_{rdi} = t$ and $age_{tk} = age$.

d) STEP 4 – For cladding/weld overlay pressure vessel components, calculate the age from the date of the starting thickness from STEP 3 required to corrode away the cladding/weld overlay material, age_{rc}, using Equation (2.11).

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

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

e) STEP 5 – Determine $t_{\min}$ using one of the following methods:

1) For cylindrical, spherical or head components, determine the allowable stress, S, weld joint efficiency, E, and calculate the minimum required thickness, $t_{\min}$, using component type in Table 4.2, geometry type in Table 4.3 and per the original construction code or API 579-1/ASME FFS-1 [10].

2) In cases where components are constructed of uncommon shapes or where the component's minimum structural thickness, t_c, may govern, the user may use the t_c in lieu of $t_{\min}$.

~~3) If the component is a tank bottom, use $t_{\min} = 0.1\ in$ if the AST does not have a release prevention barrier or $t_{\min} = 0.05\ in$ if the AST has a release prevention barrier, in accordance with API STD 653 [11].~~

~~4)~~3) A specific $t_{\min}$ calculated by another method and documented in the asset management program may be used at the owner-user's discretion.

f) STEP 6 - Determine the A_{rt} parameter using Equations (2.12), (2.13), (2.14) or (2.15), as appropriate, based on t from STEP 1, $C_{r,bm}$ and $C_{r,cm}$ from STEP 2, age_{tk} and t_{rdi} from STEP 3, and the age required to corrode away the cladding/weld overlay, age_{rc}, if applicable, from STEP 4. Note that the age parameter in these equations is equal to age_{tk} from STEP 3.

~~1) For tank bottom components, calculate the A_{rt} parameter using Equation (2.12) and skip to STEP 13.~~

~~$A_{rt} = \max\left[\left(1 - \frac{t_{rdi} - (C_{r,bm} \cdot age_{tk})}{t_{\min} + CA}\right), \; 0.0\right]$ (2.12)~~

~~2)~~ For components with or without cladding/weld overlay use **Equation (2.13)**.

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

g) STEP 7 – Calculate the Flow Stress, FS^{Thin}, using E from STEP 5 and Equation (2.14).

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

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

h) STEP 8 – Calculate the strength ratio parameter, SR_P^{Thin}, using the appropriate Equation (2.15) or Equation (2.16). Using Equation (2.15) with t_{rdi} from STEP 3, $t_{\min}$ or t_c from STEP 5, S, and E from STEP 5, and flow stress, FS^{Thin}, from STEP 7.

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

Note: The $t_{\min}$ is based on a design calculation that includes evaluation for internal pressure hoop stress, external pressure and/or structural considerations, as appropriate. The minimum required thickness calculation is the design code $t_{\min}$. Consideration for internal pressure hoop stress alone may not be sufficient. t_c as defined in STEP 5 should be used when appropriate.

1. Using Equation (2.16) with t_{rdi} from STEP 3 and FS^{Thin} from STEP 7.

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

Where α is the shape factor for the component type

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

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. When t_c dominates or if the $t_{\min}$ is calculated using another method, Equation (2.15) should be used.

i) STEP 9 – Determine the number of inspections for each of the corresponding inspection effectiveness, N_A^{Thin}, N_B^{Thin}, N_C^{Thin}, N_D^{Thin}, using Section 4.5.6 for past inspections performed during the in-service time.

j) STEP 10 – Calculate the inspection effectiveness factors, $I_1^{Thin}, I_2^{Thin}, I_3^{Thin}$, using Equation (2.17) $Pr_{p1}^{Thin}, Pr_{p2}^{Thin}$ and Pr_{p3}^{Thin}, from Table 4.5, the Conditional Probabilities (for each inspection effectiveness level), $Co_{p1}^{Thin}, Co_{p2}^{Thin}$ and Co_{p3}^{Thin}, from Table 4.6, and the number of inspections, N_A^{Thin}, N_B^{Thin}, N_C^{Thin}, N_D^{Thin}, in each effectiveness level from STEP 9.

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

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

k) STEP 11 – Calculate the Posterior Probabilities, Po_{p1}^{Thin}, Po_{p2}^{Thin} and Po_{p3}^{Thin} using Equation (2.18) with I_1^{Thin}, I_2^{Thin} and I_3^{Thin} in Step 10.

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

l) STEP 12 – Calculate the parameters, β_1^{Thin}, β_2^{Thin}, β_3^{Thin} using Equation (2.19) and assigning $COV_{\Delta t} = 0.20$, $COV_{S_f} = 0.20$ and $COV_P = 0.05$.

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

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

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

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

~~m) STEP 13 – For tank bottom components, determine the base damage factor for thinning, D_{fB}^{thin}, using Table 4.8 and based on the A_{rt} parameter from STEP 6 and Skip to STEP 15.~~

~~n)~~m) STEP 14 – For all components (excluding tank bottoms covered in STEP 13), calculate the base damage factor, D_{fB}^{Thin}.

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

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

~~o)~~n) STEP 15 – Determine the DF for thinning, D_f^{Thin}, using Equation (2.21).

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

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

The adjustment factors in are determined as described below.

1) Adjustment to DF for On-Line Monitoring, F_{OM} – In addition to inspection, on-line monitoring of corrosion (or key process variables affecting corrosion) is commonly used in many processes to prevent corrosion failures. The advantage of on-line monitoring is that changes in corrosion rates as a result of process changes can be detected long before they would be detected with normal periodic inspections.

This earlier detection usually permits more timely action to be taken that should decrease the POF. Various methods are employed, ranging from corrosion probes, corrosion coupons, and monitoring of key process variables. If on-line monitoring is employed, then credit should be given to reflect higher confidence in the predicted thinning rate. However, these methods have a varying degree of success depending on the specific thinning mechanism. Using knowledge of the thinning mechanism and the type of on-line monitoring, determine the on-line monitoring factor from Table 4.9. If more than one monitoring method is used, only the highest monitoring factor should be used (i.e. the factors are not additive).

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

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

2. If a piping circuit contains an injection/mix point, then an adjustment factor equal to $F_{IP} = 3$ should be used to account for the higher likelihood of thinning activity at this location. If a highly effective inspection specifically for injection/mix point corrosion within the injection point circuit (according to API 570) is performed, then an adjustment is not necessary, or $F_{IP} = 1$.

3) Adjustment For Dead Legs, F_{DL} – A deadleg is defined as a section of piping or piping circuit that is used only during intermittent service such as start-ups, shutdowns, or regeneration cycles rather than continuous service. Deadlegs include components of piping that normally have no significant flow. If a piping circuit contains a deadleg, then an adjustment should be made to the thinning DF to account for the higher likelihood of thinning activity at this location. The adjustment factor is $F_{DL} = 3$. If a highly effective inspection method is used to address the potential of localized corrosion in the deadleg, then an adjustment is not necessary, or $F_{DL} = 1$.

~~4) Adjustment for Welded Construction, F_{WD} – Applicable only to ASTs. If the component is welded (i.e. not riveted), then $F_{WD} = 1$; otherwise, $F_{WD} = 10$.~~

~~5) Adjustment for Maintenance in Accordance with API STD 653, F_{AM} – Applicable only to AST. If the AST is maintained in accordance with API STD 653, then $F_{AM} = 1$; otherwise, $F_{AM} = 5$.~~

~~6) Adjustment for Settlement, F_{SM} – Applicable only to AST bottoms. It is determined based on the following criteria:~~

- ~~Recorded settlement exceeds API STD 653 criteria – $F_{SM} = 2$~~
- ~~Recorded settlement meets API STD 653 criteria – $F_{SM} = 1$~~
- ~~Settlement never evaluated – $F_{SM} = 1.5$~~
- ~~Concrete foundation, no settlement – $F_{SM} = 1$~~

The stresses in the under-shell region of the bottom are also very different than those in the remainder of the bottom. In fact, API 653 defines the first three inches of bottom inside the shell to be the critical zone (CZ) and t_{min} requirements for the CZ are different than the values given in Table 6-1 of API 653 for the remainder of the bottom. For API 650 tanks, t_{min} for the CZ is calculated per API 653 as:

$$t_{min}^{CZ} = min\left(0.5 \cdot t_{btm,orig}, 0.5 \cdot t_{min,course-1}, 0.1\right) \; inch$$

For API 650 tanks, t_{min} for the annular ring is calculated per API 653 Table 4-4 based on the hydrostatic stress in the lowest course and lowest course thickness. Table Q-4 and Table R-6 provide t_{min} values for *Tank620* annular ring plates.

Given the difference between the under-shell and remainder of the bottom, it is proposed that the tank bottom be considered two components, the portion immediately under the shell (*TANKBOTEDGE*) and the remainder of bottom (*TANKBOTREM*). In this case, it is proposed to consider the 24 inches inside shell as the edge component. This is consistent with typical annular ring dimensions and similar in magnitude to the width of the shell foundation material (i.e., width of ringwall). It is greater than the defined CZ of 3 inches in API 653, but it is proposed that the t_{min} used for the *TANKBOTEDGE* (24 inch wide area) be either the CZ requirement for tanks without annular rings, or the API 653 (or API 620) annular ring requirement for tanks with annular rings, whichever is applicable.

API RP 581 PART 5

RISK-BASED INSPECTION METHODOLOGY FOR SPECIAL EQUIPMENT

PART 5 CONTENTS

1. References

1.1. Normative

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

1. API Standard 653 – Tank Inspection, Repair, Alteration, and Reconstruction, American Petroleum Institute, Washington, D.C, 20005.
2. API Standard 620 – Design and Construction of Large, Welded, Low-Pressure Storage Tanks, American Petroleum Institute, Washington, D.C, 20005.
3. API RP 581 Part 1 – *Inspection Planning Methodology*, American Petroleum Institute, Washington, D.C, 20005.
4. API RP 581 Part 2 – *Probability of Failure Methodology*, American Petroleum Institute, Washington, D.C, 20005.
5. API RP 581 Part 3 – *Consequence of Failure Methodology*, American Petroleum Institute, Washington, D.C, 20005.

1.2. Informative

2. ~~Atmospheric~~ Storage Tanks

The calculation of the consequence of a leak or rupture of a API 620 low pressure and API 650 atmospheric storage tanks ~~(AST)~~ bottom, edge and course components are covered in this section. The DF and POF calculation uses a methodology similar to the approach outlined in Part 2. The methodology for consequence analysis specialized for ~~ASTs~~ storage tanks are provided for the COF calculation.

2.1. Probability of Failure

POF calculation procedures for ~~AST~~storage tank shell courses and bottom plates are provided in this section. The POF as a function of time and inspection effectiveness is determined using a generic failure frequency, a management systems factor, and DFs for the applicable active damage mechanisms. The DFs for thinning DF calculation is provided in this section for storage tank~~AST~~ components. DFs for other active damage mechanisms are calculated using Part 2, Sections 5 through Section 24.

2.2. Determination of the Damage Factor

2.1.1.1 Determination of the Thinning Damage Factor

a) STEP 1.1 – Determine the furnished thickness, t, and age, age, for the tank component from the installation date.

b) STEP 1.2 – Determine the corrosion rate for the base material, $C_{r,bm}$, based on the material of construction and process environment, using guidance from Section 4.5.2 and examples in Annex 2.B for establishing corrosion rates.

c) STEP 1.3 – Determine the time in service, age_{tk}, since the last inspection known thickness, t_{rdi}. The t_{rdi} is the starting thickness with respect to wall loss associated with internal corrosion (see Section 4.5.5). If no measured thickness is available, set $t_{rdi} = t$ and $age_{tk} = age$.

d) STEP 1.4 – Determine $t_{\min}$ using one of the following methods:

1) For the API STD 620 and API STD 653 tank courses, determine the allowable stress, S, weld joint efficiency, E, and calculate the minimum required thickness, $t_{\min}$, using component type in Table 4.2, geometry type in Table 4.3 and per the original construction code or API 579-1/ASME FFS-1 [10] or API STD 620, as applicable.

2) API STD 650 Tank bottoms can be modeled with two components. If the component type is TANKBOTTOM~~For a tank bottom~~, use $t_{\min} = 0.1\ in$ if the storage tank~~AST~~ does not have a release prevention barrier or $t_{\min} = 0.05\ in$ if the storage tank~~AST~~ has a release prevention barrier, in accordance with API STD 653 [11]. If the component is a TANKEDGE, use the minimum thickness for an annular ring or the critical zone (for tanks without annular rings), whichever is applicable, in accordance with API STD 653.

3) API STD 620 Tank bottoms are determined by using $t_{\min} = min(0.75, t_{rdi} - CA)$, in accordance with API STD 620.

~~3)~~4) A specific $t_{\min}$ calculated by another method and documented in the asset management program may be used at the owner-user's discretion.

e) STEP 1.5 - Determine the A_{rt} parameter using Equations (2.12), (2.13), (2.14) or (2.15), as appropriate, based on t from STEP 1, $C_{r,bm}$ from STEP 1.2, age_{tk} and t_{rdi} from STEP 1.3. Note that the age parameter in these equations is equal to age_{tk} from STEP 1.3.

   1) For tank courses, go to STEPs 7 through 15 in Part 2, Section 4.5.7 and skip to STEP 1.7.
   2) For tank bottom components, calculate the A_{rt} parameter using Equation (2.12).

$$A_{rt} = \max\left[\left(1 - \frac{t_{rdi} - (C_{r,bm} \cdot age_{tk})}{t_{\min} + CA}\right),\ 0.0\right] \tag{2.12}$$

f) STEP 1.6 – For tank bottom components, determine the base damage factor for thinning, D_{fB}^{thin}, using Table 4.8 and based on the A_{rt} parameter.

g) STEP 1.7 – Determine the DF for thinning, $D_f^{AST,Thin}$, using Equation (2.21).

$$D_f^{AST,Thin} = \max\left[\left(D_{fB}^{Thin} \cdot F_{WD} \cdot F_{AM} \cdot F_{SM}\right),\ 0.1\right] \tag{2.21}$$

The adjustment factors in are determined as described below.

1) Adjustment for Welded Construction, F_{WD} – Applicable only to storage tank~~AST~~s. If the component is welded (i.e. not riveted), then $F_{WD} = 1$; otherwise, $F_{WD} = 10$.

2) Adjustment for Maintenance in Accordance with API STD 653, F_{AM} – Applicable only to storage tank~~AST~~. If the storage tank~~AST~~ is maintained in accordance with API STD 653, then $F_{AM} = 1$; otherwise, $F_{AM} = 5$.

3) Adjustment for Settlement, F_{SM} – Applicable only to storage tank~~AST~~ bottoms. It is determined based on the following criteria:

   - Recorded settlement exceeds API STD 653 criteria – $F_{SM} = 2$
   - Recorded settlement meets API STD 653 criteria – $F_{SM} = 1$
   - Settlement never evaluated – $F_{SM} = 1.5$
   - Concrete foundation, no settlement – $F_{SM} = 1$

2.1.1.2 Determination of the SCC Damage Factors

Follow calculating procedures outlined in Part 2, Section 5 through Section 14 for SCC of storage tank~~AST~~ shell courses.

2.1.1.3 Determination of the External Damage Factors

Follow calculating procedures outlined in Part 2, Section 15 through Section 18 for external damage of storage tank~~AST~~ shell courses.

2.1.1.4 Determination of the Brittle Fracture Damage Factors

Follow calculating procedures outlined in Part 2, Section 21 for brittle fracture of storage tank~~AST~~ shell courses.

2.1.1.5 Damage Factor Combination for Multiple Damage Mechanisms

Follow calculating procedures outlined in Part 2, Section 3.4.2 for combining DFs or multiple damage mechanisms of storage tank~~AST~~ shell courses.

2.3. Consequence of Failure

The COF is calculated in terms of affected area or in financial consequence. Consequences from flammable and explosive events, toxic releases, and nonflammable/nontoxic events are considered in both methods based on the process fluid and operating conditions. Financial consequences from component damage, product loss, financial impact, and environmental penalties are considered.

2.3.1. Overview

The COF methodology is performed to aid in establishing a ranking of equipment items on the basis of risk. The consequence measures are intended to be used for establishing priorities for inspection programs. Methodologies for two levels of analysis are provided. A special COF methodology is provided for low pressure and atmospheric storage tanks ~~(AST)~~ and is covered in this section.

2.4. Consequence of Failure Methodology for Atmospheric Storage Tank Courses

The COF associated with storage tank~~AST~~s is concerned primarily with the financial losses due to leakage and/or rupture of an storage tank~~AST~~ course. Safety/area based consequences are addressed for the courses following the Level 1 or Level 2 consequence analysis methods provided in Part 3, Section 4.0 or Section 5.0. Detailed procedures for calculating the financial COF for both bottom plates and courses are provided in this section.

2.5. Representative Fluid and Associated Properties

The procedure for determining COF of storage tank~~AST~~ course components consists of calculations for area and financial-based methods.

2.6. Required Properties at Storage Conditions

Fluid properties should be determined for calculation of a safety area using Level 1 or 2 Consequence of Failure methodology. See Part 3, Section 5.1.2 for detailed description of required properties at storage conditions.

The representative fluid should be chosen from the closest matching fluid from Table 6.1 for financial COF for the storage tank~~AST~~ course.

2.6.1. Required Properties at Flashed Conditions

Fluid properties are determined for a safety based COF for use in the Level 1 or 2 Consequence of Failure methodology. See Part 3, Section 5.1.3 for detailed description of required properties at flashed conditions.

2.7. Release Hole Size Selection

2.7.1. Overview

A discrete set of release events or release hole sizes are used for consequence analysis.

2.7.2. Calculation of Release Hole Sizes

The following procedure may be used to determine the release hole size and the associated generic failure frequencies.

a) STEP 2.1 – Determine the release hole size, d_n, from Table 6.3 for storage tank~~AST~~ courses.

b) STEP 2.2 – Determine the generic failure frequency, gff_n, for the d_n release hole size and the total generic failure frequency from Part 2, Table 3.1 or from Equation (3.208).

$$gff_{tot} = \sum_{n=1}^{4} gff_n \tag{3.208}$$

2.8. Release Rate Calculation

2.8.1. Overview

Release rate calculations are provided for a leak in a storage tank~~AST~~ course. The liquid head of the product is assumed to be constant over time, and the leak is to atmospheric pressure for a course leak.

2.8.2. Atmospheric Storage Tank Course

The discharge of a liquid through a sharp-edged orifice in an storage tank~~AST~~ course with a liquid height above the orifices may be calculated using Equation (3.209).

$$W_n = C_{32} \cdot C_d \cdot A_n \sqrt{2 \cdot g \cdot LHT_{above,i}} \tag{3.209}$$

In Equation (3.209), the discharge coefficient, C_d, for fully turbulent liquid flow from sharp-edged orifices is in the range of $0.60 \le C_d \le 0.65$. A value of $C_d = 0.61$ is recommended.

2.8.3. Calculation of Atmospheric Storage Tank Course Release Rate

a) STEP 3.1 – For each release hole size, Determine the height of the liquid, h_{liq}, above the release hole size, d_n for each hole size.

b) STEP 3.2 – Determine the hole area, A_n, for each hole size using Equation (3.213).

$$A_n = \frac{\pi d_n^2}{4} \tag{3.213}$$

c) STEP 3.3 - Determine the liquid height above the i^{th} course where h_{liq} is the maximum fill height in the tank and CHT is the height of each course.

$$LHT_{above,i} = \left[h_{liq} - (i-1) \cdot CHT\right] \tag{3.214}$$

d) STEP 3.3 – Determine the flow rate, W_n, for each hole size using Equation (3.209) based on h_{liq} from STEP 3.1 and A_n from STEP 3.2.

2.9. Estimate the Inventory Volume and Mass Available for Release

2.9.1. Overview

The inventory in the storage tank~~AST~~ available for release depends on the component being evaluated. The available inventory for courses is a function of the location of the release hole and is calculated as the volume of fluid above the release hole.

2.9.2. Calculation of Atmospheric Storage Tank Course Inventory Mass

The amount of fluid inventory used in the course consequence analysis is the amount of fluid that is above the lower elevation of the course under evaluation.

a) STEP 4.1 – Determine the liquid height above the i^{th} course where h_{liq} is the maximum fill height in the tank and CHT is the height of each course.

$$LHT_{above,i} = \left[h_{liq} - (i-1) \cdot CHT\right] \tag{3.215}$$

b) STEP 4.2 – Determine the volume above the course being evaluated.

$$Lvol_{above,i} = \left(\frac{\pi D_{tank}^2}{4}\right) \cdot LHT_{above,i} \tag{3.216}$$

c) STEP 4.3 – Determine the location of the hole on the storage tank~~AST~~ course for each hole size. Based on this location, determine the available volume of the release. Note that the release hole should be assumed to be at the bottom of the course.

$$Lvol_{avail,n} = Lvol_{above,i} \tag{3.217}$$

d) STEP 4.4 – Calculate the storage tank~~AST~~ volume in barrels using Equation (3.216).

$$Bbl_{avail,n} = Lvol_{avail,n} \cdot C_{13} \tag{3.218}$$

e) STEP 4.5 – Calculate the storage tank~~AST~~ mass using ρ_l from Table 6.1 and using Equation (3.219).

$$mass_{avail,n} = Lvol_{avail,n} \cdot \rho_l \tag{3.219}$$

2.10. Determine the Type of Release

The type of release for the storage tank~~AST~~ is assumed to be continuous.

2.11. Estimate the Impact of Detection and Isolation Systems on Release Magnitude

Detection and isolation systems are not accounted for in the storage tank~~AST~~ course consequence analysis.

2.12. Determine the Release Rate and Volume for the Consequence of Failure Analysis

2.12.1. Overview

The storage tank~~AST~~ course release is assumed to be continuous and the release rate is calculated from Equation (3.223) where W_n is determined in Section 1.2.6.

$$rate_n = W_n \tag{3.223}$$

2.12.2. Calculation for Atmospheric Storage Tank Course Release Volume

A step-by-step methodology for determining the release rate and volume is in accordance with the modeling in Section 4 for Level 1 COF and Section 5 for Level 2 COF with the following differences:

- The pool fire area should not exceed the area of the dike.
- The release volume should be calculated with the following steps.

a) STEP 5.1 – Determine the release rate, $rate_n$, for each hole size in bbls/day using Equation (3.223) where the release rate, W_n, is from STEP 3.3.

b) STEP 5.2 – Determine the leak detection time, t_{ld}, as follows:

$$t_{ld} = 7\ days\ \ for\ d_n \le 3.17 mm\ [0.125\ in]$$, or

$$t_{ld} = 1\ days\ \ for\ d_n > 3.17 mm\ [0.125\ in]$$

c) STEP 5.3 – Calculate the leak duration, ld_n, of the release for each hole size using Equation (3.224) based on the release rate, $rate_n$, from STEP 5.1, the leak detection time, t_{ld}, from STEP 5.2, and the storage tank~~AST~~ volume, $Bbl_{avail,n}$, from STEP 4.4.

$$ld_n = \min\left[\left\{\frac{Bbl_{avail,n}}{rate_n}\right\},\ 7\ days\right] \qquad for\ d_n \le 3.17 mm\ [0.125\ in] \tag{3.224}$$

d) STEP 5.4 – Calculate the release volume from leakage, Bbl_n^{leak}, for each hole size using Equation (3.225) based on the release rate, $rate_n$, from STEP 5.1, the leak duration, ld_n, from STEP 5.3, available volume, $Bbl_{avail,n}$, from STEP 4.4.

$$Bbl_n^{leak} = \min\left[\left\{rate_n \cdot ld_n\right\},\ \ Bbl_{avail,n}\right] \tag{3.225}$$

e) STEP 5.5 – Calculate the release mass from leakage, $mass_n^{leak}$, for each hole size using Equation (3.236) based on the available volume, Bbl_n^{leak}, from STEP 5.4.

$$mass_n^{leak} = Bbl_n^{leak} \tag{3.226}$$

f) STEP 5.6 – Calculate the release volume from a rupture, $Bbl_n^{rupture}$, for each hole size using Equation (3.227) based on the available volume, $Bbl_{avail,n}$, from STEP 4.4.

$$Bbl_n^{rupture} = Bbl_{avail,n} \tag{3.227}$$

g) STEP 5.7 – Calculate the mass from a rupture, $mass_n^{rupture}$, for each hole size using Equation (3.228) based on the available volume, $Bbl_n^{rupture}$, from STEP 5.6.

$$mass_n^{rupture} = Bbl_n^{rupture} \tag{3.228}$$

2.13. Determine Flammable and Explosive Consequences for Storage Tank~~AST~~ Shell Courses

2.13.1. General

Flammable and explosive consequences for storage tank~~AST~~s shell courses are determined using a similar approach as implemented for Level 1 and 2 consequence analysis.

2.13.2. Calculation of Flammable and Explosive Consequences

The step-by-step procedure for determining the flammable and explosive consequences are in accordance with the level of consequence analysis, see Part 3, Section 4.8 and Part 3, Section 5.8.9.

2.14. Determine Toxic Consequences for Storage Tank~~AST~~ Shell Courses

2.14.1. General

Toxic consequences for storage tank~~AST~~ shell courses are determined using a similar approach as implemented for Level 1 and 2 consequence analysis.

2.14.2. Calculation of Toxic Consequences for Storage Tank~~AST~~ Shell Courses

The step-by-step methodology for determining the toxic consequences are in accordance with the Level 1 and 2 consequence analysis; see Part 3, Section 4.9 and Part 3, Section 5.9.8.

2.15. Determine Non-Flammable, Non-Toxic Consequences

2.15.1. General

Non-flammable, non-toxic consequences are not determined for storage tank~~AST~~s.

2.16. Determine Component Damage and Personnel Injury Consequences for Storage Tank~~AST~~ Shell Courses

2.16.1. General

Flammable and explosive consequences for storage tank~~AST~~ shell courses are determined using a similar approach as implemented for Level 1 and 2 consequence analysis.

2.16.2. Calculation for Component Damage and Personnel Injury Consequences

The step-by-step procedure for determining the flammable and explosive consequences are in accordance with the Level 1 COF Part 3, Section 4.8 and Level 2 COF in Part 3, Section 5.11.5.

2.17. Determine the Financial Consequences

2.17.1. Overview

The financial consequence is determined in accordance with the Level 1 COF in Part 3, Section 4.12.

2.17.2. Calculation of Atmospheric Storage Tank Shell Course Financial Consequence

The step-by-step procedure for estimating the financial consequence is in accordance with Section 4.12.7, except when calculating the environmental financial consequence. The storage tank~~AST~~ shell course financial consequence can be calculated with the steps provided below.

- Component Damage Cost in accordance to Section 4.12.2
- Damage cost to surrounding equipment in accordance with Section 4.12.3
- Business interruption costs in accordance to Section 4.12.4
- Potential Injury costs in accordance to Section 4.12.5

The storage tank~~AST~~ Environmental financial consequence can be calculated following the steps provided below.

a) STEP 6.1 – Determine the following parameters.
   1) P_{lvdike} – percentage of fluid leaving the dike
   2) P_{onsite} – percentage of fluid that leaves the dike area but remains on-site
   3) $P_{offsite}$ – percentage of fluid that leaves the dike area but does not enter nearby water

b) STEP 6.2 – Determine the environmental sensitivity used to establish C_{indike}, $C_{ss-onsite}$, $C_{ss-offsite}$, and C_{water} from Table 6.6.

c) STEP 6.3 – Determine the probability weighted total barrels of fluid released by leakage, $Bbl_{released}$.

$$Bbl_{release}^{leak} = \frac{\sum_{n=1}^{3}\left(Bbl_n^{leak} \cdot gff_n\right)}{gff_{tot}} \tag{3.232}$$

d) STEP 6.4 – Calculate the total barrels of fluid within the dike from leakage, Bbl^{leak}_{indike}, the total barrels of fluid in the on-site surface soil, $Bbl^{leak}_{ss-onsite}$, the total barrels of fluid in the off-site surface soil, $Bbl^{leak}_{ss-offsite}$, and the total barrels of fluid in that reach water, Bbl^{leak}_{water}, using Equation (3.233) through Equation (3.236), respectively.

$$Bbl^{leak}_{indike} = Bbl^{leak}_{release}\left(1-\frac{P_{lvdike}}{100}\right) \tag{3.233}$$

$$Bbl^{leak}_{ss-onsite} = \frac{P_{onsite}}{100}\left(Bbl^{leak}_{release} - Bbl^{leak}_{indike}\right) \tag{3.234}$$

$$Bbl^{leak}_{ss-offsite} = \frac{P_{offsite}}{100}\left(Bbl^{leak}_{release} - Bbl^{leak}_{indike} - Bbl^{leak}_{ss-onsite}\right) \tag{3.235}$$

$$Bbl^{leak}_{water} = Bbl^{leak}_{release} - \left(Bbl^{leak}_{indike} + Bbl^{leak}_{ss-onsite} + Bbl^{leak}_{ss-offsite}\right) \tag{3.236}$$

e) STEP 6.5 – Calculate the financial environmental cost from leakage, $FC^{leakage}_{environ}$.

$$FC^{leak}_{environ} = Bbl^{leak}_{indike}\cdot C_{indike} + Bbl^{leak}_{ss-onsite}\cdot C_{ss-onite} + Bbl^{leak}_{ss-offsite}\cdot C_{ss-offite} + Bbl^{leak}_{water}\cdot C_{water} \tag{3.237}$$

f) STEP 6.6 – Determine the total barrels of fluid released by a shell course rupture, $Bbl^{rupture}_{release}$.

$$Bbl^{rupture}_{release} = \frac{Bbl^{rupture}_{n}\cdot gff_4}{gff_{tot}} \tag{3.238}$$

g) STEP 6.7 – Calculate the total barrels of fluid within the dike from a rupture, $Bbl^{rupture}_{indike}$, the total barrels of fluid in the on-site surface soil that, $Bbl^{rupture}_{ss-onsite}$, the total barrels of fluid in the off-site surface soil that, $Bbl^{rupture}_{ss-offsite}$, and the total barrels of fluid that reach water, Bbl^{leak}_{water}, using Equation (3.239) through Equation (3.242), respectively.

$$Bbl^{rupture}_{indike} = Bbl^{rupture}_{release}\left(1-\frac{P_{lvdike}}{100}\right) \tag{3.239}$$

$$Bbl^{rupture}_{ss-onsite} = \frac{P_{onsite}}{100}\left(Bbl^{rupture}_{release} - Bbl^{rupture}_{indike}\right) \tag{3.240}$$

$$Bbl^{rupture}_{ss-offsite} = \frac{P_{offsite}}{100}\left(Bbl^{rupture}_{release} - Bbl^{rupture}_{indike} - Bbl^{rupture}_{ss-onsite}\right) \tag{3.241}$$

$$Bbl^{rupture}_{water} = Bbl^{rupture}_{release} - \left(Bbl^{rupture}_{indike} + Bbl^{rupture}_{ss-onsite} + Bbl^{rupture}_{ss-offsite}\right) \tag{3.242}$$

h) STEP 6.8 – Calculate the financial environmental cost for a shell course rupture, $FC^{rupture}_{environ}$.

$$FC^{rupture}_{environ} = Bbl^{rupture}_{indike}\cdot C_{indike} + Bbl^{rupture}_{ss-onsite}\cdot C_{ss-onite} + Bbl^{rupture}_{ss-offsite}\cdot C_{ss-offite} + Bbl^{rupture}_{water}\cdot C_{water} \tag{3.243}$$

i) STEP 6.9 – Calculate the total financial environmental cost from a leak and a rupture, $FC_{environ}$, where $FC_{environ}^{leak}$ is from STEP 12.5 and $FC_{environ}^{rupture}$ is from STEP 12.8.

$$FC_{environ} = FC_{environ}^{leak} + FC_{environ}^{rupture} \tag{3.244}$$

2.18. Consequence of Failure Methodology for Atmospheric Storage Tank Bottoms

The COF associated with storage tank~~AST~~s is concerned primarily with the financial losses due to loss of containment and leakage through the storage tank~~AST~~ bottom. Safety/area based consequences are not calculated for storage tank~~AST~~ bottoms Detailed procedures for calculating the financial COF for bottom plates are provided in this section.

2.19. Determine the Representative Fluid and Associated Properties

The procedure for determining the COF for storage tank~~AST~~ bottom components consists of calculations for financial COF based on environmental consequences, component damage cost and business interruption cost. storage tank~~AST~~ consequence analysis for flammable and/or explosive or toxic are not calculated for storage tank~~AST~~ bottoms.

2.19.1. Required Properties at Storage Conditions

For the financial COF for the storage tank~~AST~~ bottom, the representative fluid will be picked from a close matching fluid from Table 6.1.

2.19.2. Hydraulic Conductivity for Storage Tank~~AST~~ Bottom

The amount of and rate of leakage from storage tank~~AST~~ bottoms is dependent on the type of soil and its properties as well as whether or not the storage tank~~AST~~ bottom has a release prevention barrier (RBP). A list of soil types and properties used in the storage tank~~AST~~ consequence analysis routine is shown in Table 6.2

The fundamental soil property required in the analysis is the soil hydraulic conductivity, k_h. The hydraulic conductivity as a function of soil type is provided in Table 6.2 based on water. The hydraulic conductivity for other fluids can be estimated based on the hydraulic conductivity, density, and dynamic viscosity of water, denoted as $k_{h,water}$, ρ_w, and μ_w, respectively, and the density and dynamic viscosity of the actual fluid using Equation (3.205).

$$k_{h,prod} = k_{h,water}\left(\frac{\rho_l}{\rho_w}\right)\left(\frac{\mu_w}{\mu_l}\right) \tag{3.205}$$

2.19.3. Fluid Seepage Velocity for Storage Tank~~AST~~ Bottom

The seepage velocity of the fluid in the storage tank~~AST~~ bottom or product through the soil is given by Equation (3.206) where k_h is the soil hydraulic conductivity and p_s is the soil porosity.

$$vel_{s,prod} = \frac{k_{h,prod}}{p_s} \tag{3.206}$$

2.19.4. Calculation of Fluid Seepage Velocity for Storage Tank~~AST~~ Bottom

a) STEP 7.1 – If a Level 1 analysis is being performed, select a representative fluid from Table 6.1 to be used in the analysis.

b) STEP 7.2 – Determine properties including density, ρ_l, and dynamic viscosity, μ_l, of the stored fluid. If a representative fluid is being used, these properties can be obtained in Table 6.1.

h) STEP 7.3 – Calculate the hydraulic conductivity for water by averaging the upper and lower bound hydraulic conductivities provided in Table 6.2 for the soil type selected using Equation (3.207).

$$k_{h,water} = C_{31} \frac{\left(k_{h,water-lb} + k_{h,water-ub}\right)}{2} \tag{3.207}$$

i) STEP 7.4 – Calculate the fluid hydraulic conductivity, $k_{h,prod}$, for the fluid stored in the storage tank~~AST~~ using Equation (3.205) based on the density, ρ_l, and dynamic viscosity, μ_l, from STEP 1.2 and the hydraulic conductivity for water, $k_{h,water}$, from STEP 1.3.

j) STEP 7.5 – Calculate the product seepage velocity, $vel_{s,prod}$, for the fluid stored in the storage tank~~AST~~ using Equation (3.206) based on fluid hydraulic conductivity, $k_{h,prod}$, from STEP 1.4 and the soil porosity provided in Table 6.2.

2.20. Release Hole Size Selection

2.20.1. Overview

A discrete set of release events or release hole sizes similar to the approach outlined in the Level 1 consequence analysis are used.

2.20.2. Calculation of Release Hole Sizes

The following procedure may be used to determine the release hole size and the associated generic failure frequencies.

a) STEP 8.1 – Determine the release hole size, d_n, from Table 6.4 for storage tank~~AST~~ bottoms.

b) STEP 8.2 – Determine the generic failure frequency, gff_n, for the d_n release hole size and the total generic failure frequency from Part 2, Table 3.1 or from Equation (3.208).

$$gff_{tot} = \sum_{n=1}^{4} gff_n \tag{3.208}$$

2.21. Release Rate Calculation

2.21.1. Overview

Release rate calculations are provided for a leak in a storage tank~~AST~~ bottom plate. The liquid head is assumed to be constant in time, and the leak is into the ground that is modeled as a continuous porous media approximated by soil properties typically used for storage tank~~AST~~ foundations.

2.21.2. Atmospheric Storage Tank Bottom Release Rate

The product leakage flow rate through a small hole in the storage tank~~AST~~ bottom is a function of the soil and fluid properties as well as the liquid head (fill height) above the bottom. The flow rate equations can be found in Rowe [34]. The flow rate through a storage tank~~AST~~ bottom into a porous media is calculated using the Bernoulli equation, Equation (3.210), or the Giroud equation, Equation (3.211), based on the hydraulic conductivity, $k_{h,prod}$, and release hole size, d_n.

$$W_n = C_{33} \cdot \pi \cdot d_n^2 \sqrt{2 \cdot g \cdot h_{liq}} \cdot n_{rh,n} \qquad for\ k_{h,prod} > C_{34} \cdot d_n^2 \tag{3.210}$$

$$W_n = C_{35} \cdot C_{qo} \cdot d_n^{0.2} \cdot h_{liq}^{0.9} \cdot k_{h,prod}^{0.74} \cdot n_{rh,n} \qquad for\ k_{h,prod} \le C_{37} \cdot \left[\frac{d_n^{1.8}}{C_{qo} \cdot h_{liq}^{0.4}} \right]^{\frac{1}{0.74}} \tag{3.211}$$

$$W_n = C_{38} \cdot 10^{2 \cdot \log(d_n) + 0.5 \cdot \log(h_{liq}) - 0.74 \cdot \left(\frac{C_{39} + 2 \cdot \log(d_n) - \log(k_{h,prod})}{m} \right)^m} \qquad for\ all\ other\ cases \tag{3.212}$$

$$Where\ m = C_{40} - 0.4324 \cdot \log(d_n) + 0.5405 \cdot \log(h_{liq})$$

In Equation (3.211), the parameter C_{qo} is an adjustment factor for degree of contact with soil and ranges from $C_{qo} = 0.21$ for good contact to $C_{qo} = 1.15$ for poor contact. A value of $C_{qo} = 0.21$ is recommended in the consequence analysis.

If the storage tank~~AST~~ bottom has a release prevention barrier (RBP), then the liquid height, h_{liq}, to be used in the flow rate calculations is set to .0762 m (0.25 ft). If the storage tank~~AST~~ does not have a release prevention barrier, the liquid height, h_{liq}, to be used in the flow rate calculations is the actual height of the stored product.

The number of release holes, $n_{rh,n}$, for each release hole size is a function of the storage tank~~AST~~ diameter and is shown in Table 6.5.

2.21.3. Calculation for Atmospheric Storage Tank Bottom Release Hole Size

a) STEP 9.1 – For each release hole size, determine the number of release holes, $n_{rh,n}$, from Table 6.5.

b) STEP 9.2 – Determine the hydraulic conductivity of the stored liquid, $k_{h,prod}$, from STEP 1.4.

c) STEP 9.3 – For each release hole size, determine the flow rate, W_n, using Equation (3.210) or Equation (3.211), as applicable. The liquid height, h_{liq}, to use in this calculation is determined as follows:

d) The storage tank~~AST~~ has an RPB: $h_{liq} = 0.0762\ m\ [0.25\ ft]$

e) The storage tank~~AST~~ does not have an RPB: $h_{liq} = Actual\ Product\ Height$

2.22. Inventory Volume and Mass Available for Release

2.22.1. Overview

The amount of inventory in the storage tank~~AST~~ available for release depends on the component being evaluated. The available inventory is the entire contents of the storage tank~~AST~~ for bottom components.

2.22.2. Calculation of Atmospheric Storage Tank Bottom Inventory Mass

The amount of fluid available for release through storage tank~~AST~~ bottoms is the fluid level up to the storage tank~~AST~~ design fill height or the operating fill height.

a) STEP 10.1 – Calculate liquid volume in the storage tank~~AST~~ in m^3 (ft^3) using Equation (3.220).

$$Lvol_{total} = \left(\frac{\pi D_{tank}^2}{4}\right) \cdot h_{liq} \tag{3.220}$$

b) STEP 10.2 – Calculate the total storage tank~~AST~~ volume in barrels using Equation (3.221).

$$Bbl_{total} = Lvol_{total} \cdot C_{13} \tag{3.221}$$

c) STEP 10.3 – Calculate the storage tank~~AST~~ mass using Equation (3.222).

$$mass_{total} = Lvol_{total} \cdot \rho_l \tag{3.222}$$

2.23. Type of Release

The type of release for the storage tank~~AST~~ bottom is assumed to be continuous.

2.24. Impact of Detection and Isolation Systems on Release Magnitude

Detection and isolation systems are not accounted for in the storage tank~~AST~~ consequence analysis.

2.25. Release Rate and Volume for the Consequence of Failure Analysis

2.25.1. Overview

The release for the storage tank~~AST~~ is assumed to be continuous, and the release rate is calculated from Equation (3.223) where W_n is determined in Section 1.2.5.

$$rate_n = W_n \tag{3.223}$$

2.25.2. ~~Atmospheric~~ Storage Tank Bottom Release Volume

A step-by-step procedure for determining the release rate and volume is as follows:

a) STEP 11.1 – Determine the release rate, $rate_n$, for each release hole size using Equation (3.223) where the release rate, W_n, is from STEP 3.5.

b) STEP 11.2 – Determine the leak detection time, t_{ld}, as follows:

c) $t_{ld} = 7\ days$ for a storage tank~~AST~~ on a concrete or asphalt foundation, or

d) $t_{ld} = 30\ days$ for a storage tank~~AST~~ with a RPB, or

e) $t_{ld} = 360\ days$ for a storage tank~~AST~~ without a RPB.

f) STEP 11.3 – Calculate the leak duration, ld_n, for each release hole size using Equation (3.229) based on the release rate, $rate_n$, from STEP 11.1, the leak detection time, t_{ld}, from STEP 1.2, and the total volume, Bbl_{total}, from STEP 4.2

$$ld_n = \min\left[\left\{\frac{Bbl_{total}}{rate_n}\right\},\ t_{ld}\right] \tag{3.229}$$

g) STEP 11.4 – Calculate the release volume from leakage, Bbl_n^{leak}, for each release hole size using Equation (3.230) based on the release rate, $rate_n$, from STEP 11.1, the leak duration, ld_n, from STEP 11.3, and the total volume, Bbl_{total}, from STEP 4.2.

$$Bbl_n^{leak} = \min\left[\left\{rate_n \cdot ld_n\right\},\ Bbl_{total}\right] \tag{3.230}$$

h) STEP 11.5 – Calculate the release volume from a rupture, $Bbl_n^{rupture}$, for each release hole size using Equation (3.231) based on the total volume, Bbl_{total}, from STEP 4.2.

$$Bbl_n^{rupture} = Bbl_{total} \tag{3.231}$$

2.26. Determine the Financial Consequences

2.26.1. Calculation of ~~Atmospheric~~ Storage Tank Bottom Financial Consequence

The step-by-step procedure for estimating the financial consequence is in accordance with Section 4.12.7. The financial consequences for the storage tank~~AST~~ bottom are calculated with the steps provided below:

- Damage cost to surrounding equipment in accordance with Section 4.12.3 is not applicable for storage tank~~AST~~ bottom component
- Business interruption costs in accordance to Section 4.12.4
- Potential Injury costs in accordance to Section 4.12.5 is not applicable for storage tank~~AST~~ bottom component

a) STEP 12.1 – Determine the following parameters:

1) P_{lvdike} – percentage of fluid leaving the dike
2) $P_{lvdike-onsite}$ – percentage of fluid that leaves the dike area but remains on-site
3) $P_{lvdike-offsite}$ – percentage of fluid that leaves the site area, but does not enter nearby water

b) STEP 12.2 – Determine the environmental sensitivity to establish C_{indike}, $C_{ss-onsite}$, $C_{ss-offsite}$, C_{water}, $C_{subsoil}$, and $C_{groundwater}$ from Table 6.6.

c) STEP 12.3 – Determine the seepage velocity of the product, vel_{s-prod}, using Equation (3.206).

d) STEP 12.4 – Determine the total distance to the ground water underneath the storage tank~~AST~~, s_{gw}, and the time to initiate leakage to the ground water, t_{gl}.

$$t_{gl} = \frac{s_{gw}}{vel_{s,prod}} \tag{3.245}$$

e) STEP 12.5 – Determine the volume of the product for each hole size in the subsoil and ground water where the leak detection time, t_{ld}, is determined in STEP 11.2.

$$Bbl^{leak}_{groundwater,n} = Bbl^{leak}_{n}\left(\frac{t_{ld} - t_{gl}}{t_{ld}}\right) \qquad for\ t_{gl} < t_{ld} \tag{3.246}$$

$$Bbl^{leak}_{groundwater,n} = 0 \qquad for\ t_{gl} \geq t_{ld} \tag{3.247}$$

$$Bbl^{leak}_{subsoil,n} = Bbl^{leak}_{n} - Bbl^{leak}_{groundwater,n} \tag{3.248}$$

f) STEP 12.6 – Determine the environmental financial consequence of a leak, $FC^{leak}_{environ}$, for each hole size.

$$FC^{leak}_{environ} = \frac{\sum_{n=1}^{3}\left(Bbl^{leak}_{groundwater,n} \cdot C_{groundwater} + Bbl^{leak}_{subsoil,n} \cdot C_{subsoil}\right) gff_{n}}{gff_{tot}} \tag{3.249}$$

g) STEP 12.7 – Determine the total barrels of fluid released by a storage tank~~AST~~ bottom rupture, $Bbl^{rupture}_{release}$.

$$Bbl^{rupture}_{release} = \frac{Bbl_{total} \cdot gff_{4}}{gff_{tot}} \tag{3.250}$$

h) STEP 12.8 – Calculate the total barrels of fluid within the dike from a rupture, $Bbl^{rupture}_{indike}$, the total barrels of fluid in the on-site surface soil, $Bbl^{rupture}_{ss-onsite}$, the total barrels of fluid in the off-site surface soil, $Bbl^{rupture}_{ss-offsite}$, and the total barrels of fluid that reach water, Bbl^{leak}_{water}, using Equation (3.239) through Equation (3.242), respectively.

i) STEP 12.9 – Calculate the financial environmental cost for a storage tank~~AST~~ bottom rupture, $FC^{rupture}_{environ}$, using Equation (3.243) where $Bbl^{rupture}_{indike}$, $Bbl^{rupture}_{ss-onsite}$, $Bbl^{rupture}_{ss-offsite}$, and Bbl^{leak}_{water} are from STEP 12.8.

j) STEP 12.10 – Calculate the total financial environmental cost from a leak and a rupture, $FC_{environ}$, using Equation (3.243) where $FC^{leak}_{environ}$ is from STEP 12.6 and $FC^{rupture}_{environ}$ is from STEP 12.8.

k) STEP 12.11 – Calculate the component damage cost, FC_{cmd}, using Equation (3.251) with the release hole size damage costs from Table 4.15 and generic failure frequencies for the release hole sizes from STEP 2.3. The material cost factor, $matcost$, is obtained from Table 4.16.

$$FC_{cmd} = \left(\frac{\sum_{n=1}^{3} gff_n \cdot holecost_n + gff_4 \cdot holecost_4 \cdot \left(\frac{D_{tank}}{C_{36}} \right)^2}{gff_{total}} \right) \cdot matcost \qquad (3.251)$$

The parameter, $\left(\frac{D_{tank}}{C_{36}} \right)^2$, is a cost adjustment factor for a storage tank~~AST~~ bottom replacement. The cost factor included in Table 4.15 is normalized for an storage tank~~AST~~ with a diameter of 30.5 m (100 ft), and this factor corrects the cost for other storage tank~~AST~~ diameters.

2.27. Nomenclature

The following lists the nomenclature used in Section 6.0. The coefficients C_1 through C_{36} which provide the metric and U.S conversion factors for the equations are provided in Annex 3.B.

A_n	is the hole area associated with the n^{th} release hole size, mm^2 (inch^2)
Bbl_{total}	is the product volume in the storage tank~~AST~~, barrels
$Bbl_{avail,n}$	is the available product volume for the n^{th} release hole size due to a leak, barrels
$Bbl_{groundwater,n}^{leak}$	is the product volume for the n^{th} release hole size due to a leak in the groundwater, barrels
$Bbl_{subsoil,n}^{leak}$	is the product volume for the n^{th} release hole size due to a leak in the subsoil, barrels
Bbl_{n}^{leak}	is the product volume for the n^{th} release hole size due to a leak, barrels
$Bbl_{groundwater}^{leak}$	is the total product volume in the groundwater due to a leak, barrels
Bbl_{indike}^{leak}	is the total product volume in the dike due to a leak, barrels
$Bbl_{release}^{leak}$	is the total product volume released due to a leak, barrels
$Bbl_{ssoffsite}^{leak}$	is the total product volume released on the surface located on-site due to a leak, barrels
$Bbl_{ssonsite}^{leak}$	is the total product volume released on the surface located off-site due to a leak, barrels
$Bbl_{subsoil}^{leak}$	is the total product volume in the subsoil due to a leak, barrels
Bbl_{water}^{leak}	is the total product volume in the water due to a leak, barrels
$Bbl_{n}^{rupture}$	is the product volume for the n^{th} release hole size due to a rupture, barrels
$Bbl_{indike}^{rupture}$	is the product volume in the dike due to a rupture, barrels
$Bbl_{release}^{rupture}$	is the product volume in released due to a rupture, barrels
$Bbl_{ssonsite}^{rupture}$	is the product volume on the surface located on-site due to a rupture, barrels
$Bbl_{ssoffsite}^{rupture}$	is the product volume on the surface located off-site due to a rupture, barrels
$Bbl_{water}^{rupture}$	is the total product volume in the water due to a rupture, barrels
CHT	is the course height of the storage tank~~AST~~, m (ft)
C_d	is the discharge coefficient
C_{indike}	is the environmental cost for product in the dike area, \$/bbl
$C_{ss-onsite}$	is the environmental cost for product on the surface located on-site, \$/bbl
$C_{ss-offsite}$	is the environmental cost for product on the surface located off-site, \$/bbl
C_{water}	is the environmental cost for product in water, \$/bbl
$C_{subsoil}$	is the environmental cost for product in the subsoil, \$/bbl
$C_{groundwater}$	is the environmental cost for product in the groundwater, \$/bbl
C_{qo}	is the adjustment factor for degree of contact with soil
d_n	is the diameter of the n^{th} release hole, mm (inch)
D_{tank}	is the storage tank~~AST~~ diameter, m (ft)

$FC_{environ}$	is the financial consequence of environmental clean-up, $
FC_{cmd}	is the financial consequence of component damage, $
FC_{prod}	is the financial consequence of lost production on the unit, $
FC_{total}	is the total financial consequence, $
$FC_{environ}^{leak}$	is the financial consequence of environmental cleanup for leakage, $
$FC_{environ}^{rupture}$	is the financial consequence of environmental cleanup for leakage, $
g	is the acceleration due to gravity on earth at sea level = 9.81 m/s^2 (32.2 ft/s^2)
gff_n	are the generic failure frequencies for each of the n release hole sizes selected for the type of equipment being evaluated
gff_{total}	is the sum of the individual release hole size generic frequencies
h_{liq}	is the maximum fill height in the storage tank~~AST~~, m (ft)
k_h	is the soil hydraulic conductivity, m/day (ft/day)
$k_{h,prod}$	is the soil hydraulic conductivity based on the storage tank~~AST~~ product, m/day (ft/day)
$k_{h,water}$	is the soil hydraulic conductivity based on water, m/day (ft/day)
$k_{h,water-lb}$	is the lower bound soil hydraulic conductivity based on water, cm/s (in/s)
$k_{h,water-ub}$	is the upper bound soil hydraulic conductivity based on water, cm/s (in/s)
ld_n	is the actual leak duration of the release based on the available mass and the calculated release rate, associated with the n^{th} release hole size, day
$Lvol_{above,n}$	is the total liquid volume for the n^{th} release hole size, m^3 (ft^3)
$Lvol_{avail,n}$	is the available liquid volume for the n^{th} release hole size, m^3 (ft^3)
$Lvol_{above,i}$	is the total liquid volume above the i^{th} storage tank~~AST~~ shell course, m^3 (ft^3)
$Lvol_{total}$	is the total liquid volume in the storage tank~~AST~~, m^3 (ft^3)
$LHT_{above,i}$	is the liquid height above the i^{th} storage tank~~AST~~ shell course, m (ft)
$matcost$	is the material cost factor
$mass_{total}$	is the available mass for release
N_c	is the total number of storage tank~~AST~~ shell courses
n^{th}	is the representative holes sizes
$n_{rh,n}$	is the number of release holes for each release hole size as a function of the storage tank~~AST~~ diameter
μ_l	is the dynamic viscosity, (N-s)/m^2 ((lb$_f$-s)/ft^2)
μ_w	is the dynamic viscosity of water at storage or normal operating, (N-s)/m^2 ((lb$_f$-s)/ft^2)
$Outage_{affa}$	is the numbers of days of downtime required to repair damage to the surrounding equipment, days
$Outage_n$	is the number of downtime days to repair damage associated with the n^{th} release hole size, days
p_s	is the soil porosity

P_{lvdike}	is the percentage of fluid leaving the dike
P_{onsite}	is the percentage of fluid that leaves the dike area but remains on-site
$P_{offsite}$	is the percentage of fluid that leaves the dike area, remains off-site and remains out of nearby water
ρ_l	is the liquid density at storage or normal operating conditions, kg/m^3 (lb/ft^3)
ρ_w	is the density of water at storage or normal operating conditions, kg/m^3 (lb/ft^3)
$rate_n$	is the adjusted or mitigated discharge rate used in the consequence calculation associated with the n^{th} release hole size, bbl/day
s_{gw}	is the distance to the groundwater underneath the storage tank~~AST~~, m (ft)
t_{gl}	is the time required for the product to reach the groundwater through a leak in the storage tank~~AST~~ bottom, day
t_{ld}	is the leak detection time, day
$vel_{s,prod}$	is the seepage velocity, m/day (ft/day)
W_n	is the discharge rate of the storage tank~~AST~~ product through a hole in the shell course, bbl/day

2.28. Tables

Table 6.1 – Fluids and Fluid Properties for Storage Tank~~AST~~ Consequence Analysis

Fluid	Level 1 Consequence Analysis Representative Fluid	Molecular Weight	Liquid Density (lb/ft^3)	Liquid Dynamic Viscosity (lb_f-s/ft^2)
Gasoline	C_6-C_8	100	42.702	8.383E-05
Light Diesel Oil	C_9-C_{12}	149	45.823	2.169E-05
Heavy Diesel Oil	C_{13}-C_{16}	205	47.728	5.129E-05
Fuel Oil	C_{17}-C_{25}	280	48.383	7.706E-04
Crude Oil	C_{17}-C_{25}	280	48.383	7.706E-04
Heavy Fuel Oil	C_{25+}	422	56.187	9.600E-04
Heavy Crude Oil	C_{25+}	422	56.187	9.600E-04

Table 6.1M – Fluids and Fluid Properties for Storage Tank~~AST~~ Consequence Analysis

Fluid	Level 1 Consequence Analysis Representative Fluid	Molecular Weight	Liquid Density (kg/m^3)	Liquid Dynamic Viscosity (N-s/m^2)
Gasoline	C_6-C_8	100	684.018	4.01E-03
Light Diesel Oil	C_9-C_{12}	149	734.011	1.04E-03
Heavy Diesel Oil	C_{13}-C_{16}	205	764.527	2.46E-03
Fuel Oil	C_{17}-C_{25}	280	775.019	3.69E-02
Crude Oil	C_{17}-C_{25}	280	775.019	3.69E-02
Heavy Fuel Oil	C_{25+}	422	900.026	4.60E-02
Heavy Crude Oil	C_{25+}	422	900.026	4.60E-02

Table 6.2 – Soil Types and Properties for Storage Tank~~AST~~ Consequence Analysis

Soil Type	Hydraulic Conductivity for Water Lower Bound (in/s)	Hydraulic Conductivity for Water Upper Bound (in/s)	Soil Porosity
Coarse Sand	3.94E-02	3.94E-03	0.33
Fine Sand	3.94E-03	3.94E-04	0.33
Very Fine Sand	3.94E-04	3.94E-06	0.33
Silt	3.94E-06	3.94E-07	0.41
Sandy Clay	3.94E-07	3.94E-08	0.45
Clay	3.94E-08	3.94E-09	0.50
Concrete-Asphalt	3.94E-11	3.94E-12	0.3
Gravel	3.94E-01	3.94	0.40

Table 6.2M – Soil Types and Properties for Storage Tank~~AST~~ Consequence Analysis

Soil Type	Hydraulic Conductivity for Water Lower Bound (cm/s)	Hydraulic Conductivity for Water Upper Bound (cm/s)	Soil Porosity
Coarse Sand	1E-01	1E-02	0.33
Fine Sand	1E-02	1E-03	0.33
Very Fine Sand	1E-03	1E-05	0.33
Silt	1E-05	1E-06	0.41
Sandy Clay	1E-06	1E-07	0.45
Clay	1E-07	1E-08	0.50
Concrete-Asphalt	1E-10	1E-11	0.3
Gravel	1E00	1E01	0.40

Table 6.3 – Release Hole Sizes and Areas – Storage Tank~~AST~~ Shell Courses

Release Hole Number	Release Hole Size	Range of Hole Diameters (inch)	Release Hole Diameter (inch)
1	Small	0 – 1/8	$d_1 = 0.125$
2	Medium	> 1/8 – ¼	$d_2 = 0.25$
3	Large	> ¼ – 2	$d_3 = 2$
4	Rupture	> 2	$d_4 = 12\left(\frac{D_{tank}}{4}\right)$

Table 6.3M – Release Hole Sizes and Areas – Storage Tank~~AST~~ Shell Courses

Release Hole Number	Release Hole Size	Range of Hole Diameters (mm)	Release Hole Diameter (mm)
1	Small	0 – 3.175	$d_1 = 3.175$
2	Medium	> 3.175 – 6.35	$d_2 = 6.35$
3	Large	> 6.35 – 50.8	$d_3 = 50.8$
4	Rupture	> 50.8	$d_4 = 1000\left(\frac{D_{tank}}{4}\right)$

Table 6.4 – Release Hole Sizes and Areas – Storage Tank~~AST~~ Bottoms

Release Hole Number	Release Hole Size	Release Prevention Barrier?	Range of Hole Diameters (inch)	Release Hole Diameter (inch)
1	Small	Yes	0 – 1/8	$d_1 = 0.125$
		No	0 – ½	$d_1 = 0.50$
2	Medium	NA	0	$d_2 = 0$
		NA	0	
3	Large	NA	0	$d_3 = 0$
		NA	0	
4	Rupture	Yes	> 1/8	$d_4 = 12\left(\frac{D_{tank}}{4}\right)$
		No	> 1/2	

Table 6.4M – Release Hole Sizes and Areas – Storage Tank~~AST~~ Bottoms

Release Hole Number	Release Hole Size	Release Prevention Barrier?	Range of Hole Diameters (mm)	Release Hole Diameter (mm)
1	Small	Yes	0 – 3.175	$d_1 = 3.175$
		No	0 – 12.7	$d_1 = 12.7$
2	Medium	NA	0	$d_2 = 0$
		NA	0	
3	Large	NA	0	$d_3 = 0$
		NA	0	
4	Rupture	Yes	> 3.175	$d_4 = 1000\left(\frac{D_{tank}}{4}\right)$

Table 6.5 – Number of Release Holes as a Function of Storage Tank~~AST~~ Diameter

Storage Tank~~AST~~ Diameter (m (ft))	Number of Release Holes With or Without a Release Prevention Barrier		
	Small	Medium	Large
30.5 (100)	1	0	0
61.0 (200)	4	0	0
91.4 (300)	9	0	0

Note: For intermediate AST diameters, the number of small release holes may be calculated using the following equation where the function nint() is defined as the nearest integer. For example, nint(3.2)=3, nint(3.5)=4, and nint(3.7)=4.

$$n_{rh,1} = \max\left[\operatorname{nint}\left[\left(\frac{D}{C_{36}}\right)^2\right],\ 1\right]$$

Table 6.6 – Cost Parameters Based on Environmental Sensitivity

Location (1)	Description	Environmental Sensitivity		
		Low (US$/bbl)	Medium (US$/bbl)	High (US$/bbl)
1	C_{indike} – Environmental cost for product located in the dike area	10	10	10
2	$C_{ss-onsite}$ – Environmental cost for product located in surface soil located on-site	50	50	50
3	$C_{ss-offsite}$ – Environmental cost for product located in surface soil located off-site	100	250	500
4	$C_{subsoil}$ – Environmental cost for product located in subsoil	500	1500	3000
5	$C_{groundwater}$ – Environmental cost for product located in groundwater	1,000	5,000	10,000
6	C_{water} – Environmental cost for product in surface water	500	1,500	5,000

Notes:

1. See Figure 6.1
2. The values shown above are estimates. The end user should decide if these values are appropriate for the specific application.

2.29. Figures

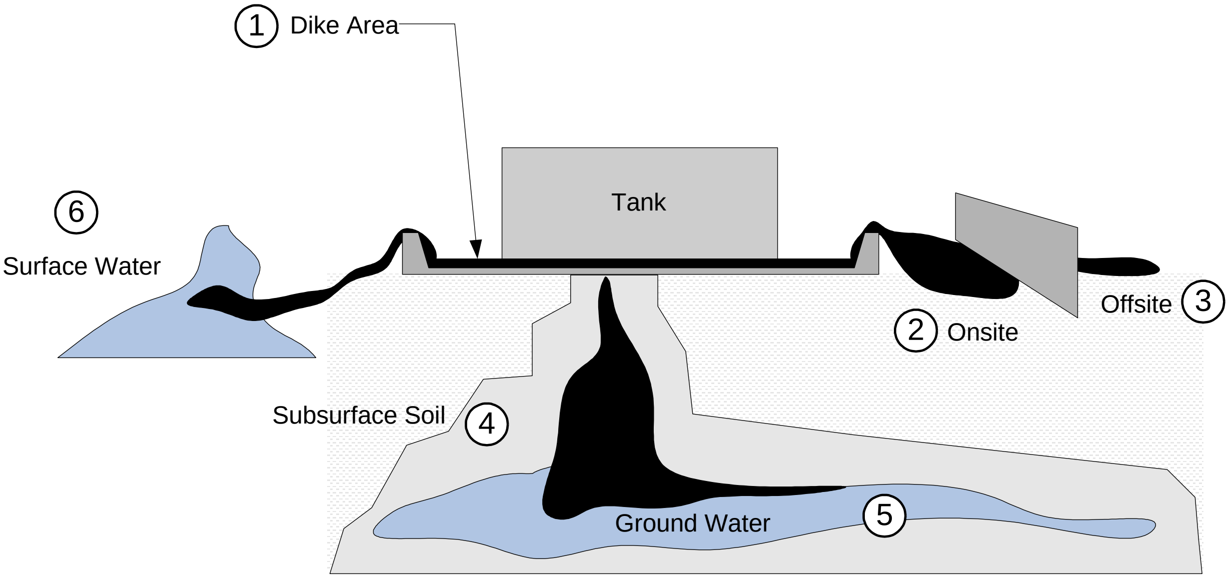

Figure 6.1 – Storage Tank~~AST~~ Consequence