Life Estimation of High Level Waste Tank Steel for H-Tank Farm Closure Performance Assessment

By Brenda L. García-Díaz, Bruce Wiersma, and Steve Harris

H-Tank Farm Design and Construction

High level radioactive waste (HLW) is stored in underground storage tanks at the Savannah River Site (SRS). SRS is proceeding with closure of tanks located in H-Area. This performance assessment is being developed by Savannah River Remediation in support of closure of the H-Tank Farm. Closure consists of removing the bulk of the waste, chemical cleaning, heel removal, and filling the tank with tailored grout formulations and severing/sealing external penetrations. The corrosion assessment began with the expected initial condition of each of the tanks at closure, and considered general and pitting corrosion once grouted.

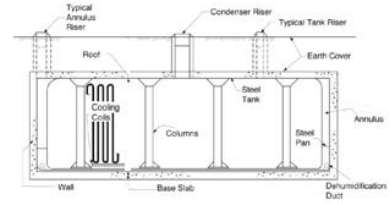
The H-Tank Farm includes of Type I and Type II tanks numbered 9 through 16. Tanks 9 through 12 are Type I tanks with a primary steel containment and partial secondary containment encased in a concrete vault. Tanks 13 through 16 are Type II tanks with a primary steel containment and with partial secondary containment encased in a concrete vault. The Type I and Type II waste tanks were made of ASTM Type A285-50T, Grade B Carbon Steel. The thinnest dimension of the tank steel is used in the deterministic and stochastic life estimations to calculate the failure time.

Non-iron Composition of ASTM A285-50T Grade B Carbon Steel [1]

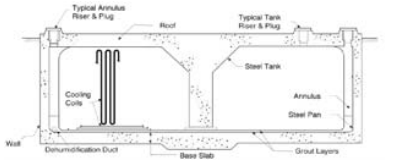
For plates ≤ 0.75" thick	Composition %			
	Carbon (C) max	Manganese (Mn) max	Phosphorous (P) max	Sulfur (S) max
	0.2*	0.8	0.035	0.04

* C = 0.22% for plate thicknesses between 0.75" and 2"

Type I Tank



Type II Tank



Description	Type I Tanks	Type II Tanks
Capacity (gal)	750,000	1,030,000
Diameter (ft)	75	85
Height (ft)	24.5	27
Minimum wall thickness (in)	0.5	0.5
Minimum concrete wall thickness of the vault (in)	22	33

Crack Opening Area

The most direct way for waste to leak through the steel tank liner would be through existing cracks in the tanks.

Axial COA

$$A = \frac{\sigma_y}{E} 2\pi Rt\left(\lambda^2 + 0.625\lambda^4\right), \quad \lambda = \frac{a}{\sqrt{Rt}}$$

Circumferential COA

$$A = \frac{4\sigma_y \pi (2t)^2}{E}\left(1 - \sqrt{\sqrt{1+\alpha^4} - \alpha^2}\right), \quad \alpha = \frac{a}{2t}$$

A = Crack opening area (in²)
E = Young's modulus (psi)
σ_y = Yield stress (psi)
R = Radius of the inner surface (in)
t = Thickness (in)
a = Crack length (in)

Parameter	Value	
a	6	in.
E	30,000,000	psi
σ_y (ASTM A285)	27000	psi
R (Type I)	450	in.
R (Type II)	510	in.
t (Type I)	0.5	in.
t (Type II)	0.625	in.

Results for the COA on an individual crack

Tank Type	Wall Thickness (in)	Axial COA (in²)	Circumferential COA (in²)
Type I	0.5	0.022	0.01
Type II	0.625	0.025	0.015

The total crack area could be obtained by multiplying the number of cracks in a tank by the circumferential COA since most cracks from stress corrosion cracking are perpendicular to the axial welds.

Tank Number	Tank Type	Number of Leaksites	Circumferential COA (in²)
9	I	4*	0.04
10	I	1*	0.01
11	I	2*	0.02
12	I	5*	0.05
13	II	2	0.03
14	II	50	0.75
15	II	20	0.3
16	II	350	5.25

* Results of a 25% visual inspection (real number may be higher)

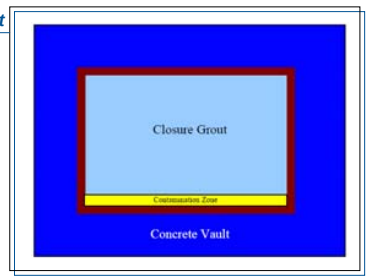
The total crack opening area (COA) for the tanks is negligible compared to the total area of the waste tank. Therefore, the COA for the tanks is not considered in the analysis.

Tank Life Estimation Approach

Tank in Closed Condition Used for Life Assessment

The exposure of the tank for purposes of life estimation was simplified to a concrete liner in a concrete vault grouted on the interior. The primary corrosion mechanisms considered were due to (1) exposure of the interior of the tank bottom to the contamination zone, and (2) exposure of the exterior of the walls, and the interior to corrosion mechanisms typical within concrete, i.e. chloride attack and carbonation.

General corrosion and pitting were the primary corrosion mechanisms considered in the tank steel life estimation. General corrosion and pitting were considered with exposures to the grouted conditions and soils when the grout is not present. In addition, credit was taken only for the primary wall liner, and not for the secondary tank.



Type I Tank Exposure Conditions in Closure Configuration

Tank Wall Location	Exposure
Primary Bottom - Internal	Contamination Zone
Primary Bottom - External	Initial Grout Pad
Primary Wall - Internal	Closure Grout
Primary Wall - External	Closure Grout
Secondary Bottom - Internal	Grout Pad
Secondary Bottom - External	Concrete Vault (Base Slab)
Secondary Wall - Internal	Closure Grout
Secondary Wall - External	Concrete Vault
Top - Internal	Closure Grout
Top - External	Concrete Vault

Type II Tank Exposure Conditions in Closure Configuration

Tank Wall Location	Exposure
Primary Bottom - Internal	Contamination Zone
Primary Bottom - External	Initial Grout Pad
Primary Wall - Internal	Closure Grout
Primary Wall - External	Closure Grout
Secondary Bottom - Internal	Initial Grout Pad
Secondary Bottom - External	Concrete Vault (Base Slab)
Secondary Wall - Internal	Closure Grout
Secondary Wall - External	Concrete Vault
Top - Internal	Closure Grout
Top - External	Concrete Vault

Corrosion in Contamination Zone

Corrosion of the steel exposed to the contamination zone is a function of the chemistry of the undissolved solids in the residual on the tank bottom. During corrosion in nitrate solutions, carbon steel reacts anodically by:

$$3Fe + 8OH^- \leftrightarrow Fe_3O_4 + 4H_2O + 8e^-$$

and the cathodic reaction is:

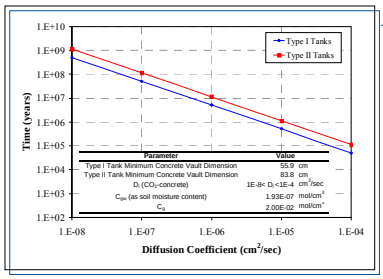
$$NO_3^- + H_2O + 2e^- \leftrightarrow NO_2^- + 2OH^-$$

The ratio of the concentration of inhibitor species (nitrite and hydroxide) to aggressive species (nitrate + chloride), referred to as the R-value, was utilized to assess the potential for corrosion by exposure to the contamination zone. High R-values indicate that the potential for corrosion is minimal, while low R-values indicate a high potential for corrosion due to insufficient inhibitor concentrations

Tank	R-Value
9	3.68
10	0.10
11	24.40
12	3.32
13	5.97
14	1.89
15	1.10
16	Tank has been cleaned and has no liquid.

The general corrosion rate in these conditions is estimated at 0.04 mils/year (mpy) [2].

Corrosion Mechanism in Concrete/Grout



Carbonation

Carbonation is the process through which pore water pH reduces dramatically due to the conversion of the calcium hydroxide to calcium carbonate through reaction with carbon dioxide.

$$Ca(OH)_2 + H_2O + CO_2 \leftrightarrow CaCO_3 + 2H_2O$$

$$X = \left(2D_i t \frac{C_{gw}}{C_g}\right)^{\frac{1}{2}}$$

X = Carbonation depth (cm)
D_i = Diffusion coefficient for CO_2 in concrete (cm²/s)
C_{gw} = Total inorganic carbon in groundwater (mol/cm³)
C_g = $Ca(OH)_2$ bulk concentration in concrete (mol/cm³)
t = Time (s)

For conservative estimation of the vault life, a diffusion coefficient of 1 x 10^{-4} cm²/s was used. Assuming that the diffusion coefficient remains constant, carbonation is not expected to be an issue in the Type I and Type II tanks within 50,000 years if the diffusion coefficient remains below 1 x 10^{-4} cm²/s.

Chloride Attack

Chloride induced corrosion is due to the breakdown of the passive film, thereby indicating that chloride diffusion is the rate controlling step for corrosion initiation.

$$t_{initiation} = \frac{129 \cdot t_c^{1.22}}{WCR \cdot [Cl^-]^{0.42}}$$

$t_{initiation}$ = Time required for initiation (years)
t_c = Thickness of concrete cover (in)
WCR = Water to cement ratio
$[Cl^-]$ = Concentration of chloride in the groundwater (ppm)

Values of 10 ppm chloride in groundwater were used as a conservative estimate that was more than 2 times measured values [3].

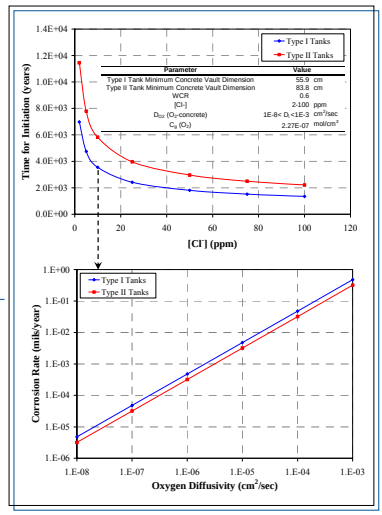
Once initiation has occurred, the oxygen diffusion to the steel surface will control the corrosion propagation. The corrosion rate of propagation can be calculated by relating oxygen diffusion through the concrete to the corrosion reaction.

$$Fe + \frac{3}{2}H_2O + \frac{3}{4}O_2 \leftrightarrow Fe(OH)_3$$

$$R_{corrosion} = \frac{4}{3} N_{O_2} \frac{M_{Fe}}{\rho_{Fe}}$$

$$N_{O_2} = D_{O_2} \frac{C_{O_2}}{\Delta X}$$

$R_{corrosion}$ = Corrosion Rate (cm/s)
N_{O2} = Flux of O_2 through the concrete (mol/s/cm²)
M_{Fe} = Molecular Weight of Iron (56 g/mol)
ρ_{Fe} = Density of Iron (7.86 g/cm³)
D_{O2} = Diffusion Coefficient for O_2 in concrete (cm²/s)
C_{O2} = Dissolved Oxygen in Groundwater (mol/cm³)
ΔX = Concrete thickness (cm)



SRNL is managed and operated for the U.S. Department of Energy by Savannah River Nuclear Solutions, LLC

We Put Science To Work™

Print

Close

Life Estimation of High Level Waste Tank Steel for H-Tank Farm Closure Performance Assessment

By Brenda L. García-Díaz, Bruce Wiersma, and Steve Harris

Corrosion of Steel Exposed to Soil or Groundwater

The corrosion of tank steel exposed to soil or groundwater was also estimated under the most conservative scenario in which the concrete vault has completely degraded. Corrosion of steels in soil is influenced by a variety of factors with large dependence on: (1) resistivity of soil and salt concentration in groundwater, (2) aeration and permeability of the soil, and (3) soil acidity.

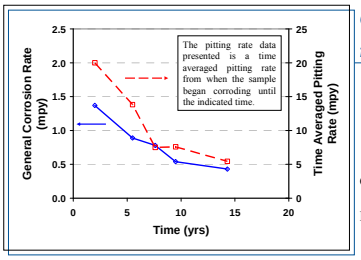
The database of metallic corrosion compiled by the National Bureau of Standards (NBS) was used to determine the corrosion rates to be used for the calculation [4]. The cecil clay loam soil data at the Atlanta test site is used for life assessments of the tanks. Corrosion rates in this soil type are assumed to be conservative estimates of corrosion rates at SRS because the soil is more aggressive than SRS soil.

The pitting corrosion model assumes formation of a hemispherical pit and estimates the fraction of tank area breached based upon the maximum pit depth, the corrosion allowance, and the number of penetrating pits per container:

$$A_b = N_p \pi \left(h^2 - d^2\right) \qquad h = kt^n \left(\frac{A}{372}\right)^a$$

A_b = Fraction of area pitted
N_p = Penetrating pits per container (pits/m^2) (Assumed – 5,000 [5])
h = Maximum pit depth (m)
d = Corrosion allowance (m)
k = Empirical pitting parameter (m/yr^n)
t = Corrosion time (yr)
n = Empirical pitting exponent
A = Representative surface area (cm^2)
a = Experimental coefficient

Exposure of sections of steels to groundwater can increase corrosion susceptibility and variation of groundwater exposure levels can further increase corrosion due to the variation in soil aeration. To quantify corrosion rates of steels in groundwater the soil type with the highest moisture content and having a pH similar to SRS soil was used. Muck from New Orleans, LA was selected to quantify corrosion rates of steels in groundwater.



Corrosion Rate and Penetration Rate for Steel in Cecil Clay Loam

Soil Property	Value
Location	Atlanta, GA
Type of Soil	Cecil Clay Loam
Annual Precipation	48.3 in.
Resistivity	17,790 Ω-cm
pH	4.6
Temperature	61.2 °F
Moisture Equivalent	33.7 %

General corrosion rate used: 0.43 mpy

Pitting rate (mpy):

$$h = 56.56t^{0.3205}$$

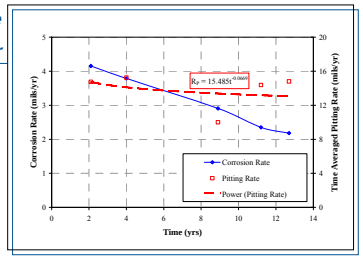
Corrosion Rate and Penetration Rate for Steel in Groundwater

Soil Property	Value
Location	New Orleans, LA
Type of Soil	Muck
Annual Precipation	57.4 in.
Resistivity	712 Ω-cm
pH	4.8
Temperature	69.3 °F
Moisture Equivalent	57.8 %

General corrosion rate used: 2.18 mpy

Pitting rate (mpy):

$$h = 15.49t^{0.9331}$$



Tank Steel Life Estimation Results

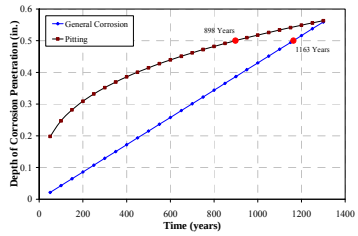
The life of the tank steel was estimated for exposures to grouted conditions and also exposures to soils conditions as the conservative case-study if the concrete vault fails.

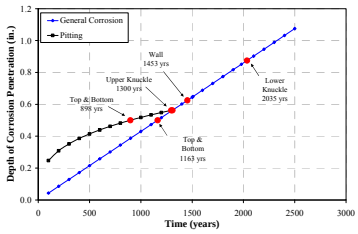
The life of the tank steel under grouted conditions was estimated following a sequence of corrosion mechanisms. Initially, general corrosion proceeds at 0.04 mpy for the tank steel exposed to the concrete/grout. Next, chloride attack initiates as chloride ions in the groundwater diffuse through the concrete. It is conservatively assumed that the attack is initiated on the both internal and external surfaces of the tank once chloride has penetrated through the thinnest section of concrete.

The life of the tank steel under soil conditions was estimated using corrosion rates for cecil clay loam soil. The cecil clay loam soil is similar to areas of the H-Tank Farm with no significant groundwater. When general corrosion depth equals the thickness of a specific portion of the tank, that section of the tank is considered to be 100% breached. For pitting corrosion it is assumed that a steel structure fails when 25% of the area is breached. The percent breached lines stays nearly linear because the value of the term (h^2-d^2) in the pitting equation remains very small throughout the entire range.

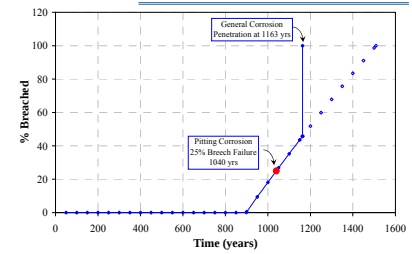
The life of the tank steel under groundwater conditions was estimated using corrosion rates for Muck soil. The Muck soil is somewhat similar to areas of the H-Tank Farm with significant groundwater, but the Muck soil has a lower resistivity. The corrosion rates for the Muck soil should provide a very conservative estimate of the tank lifetime exposed to soil conditions with groundwater.

Soil

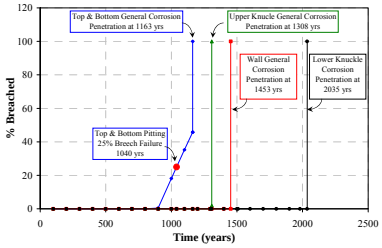




Type I Tank

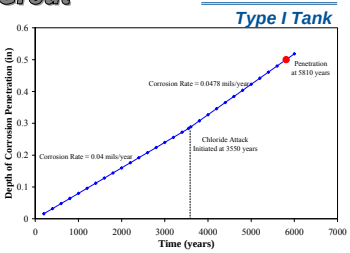


Type II Tank

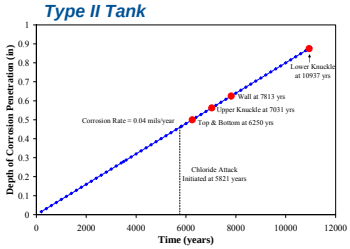


Grout

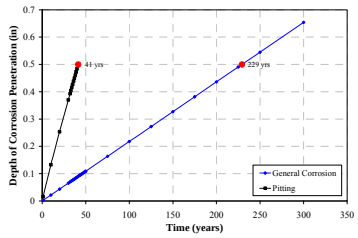
Type I Tank

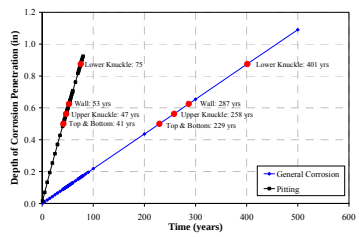


Type II Tank

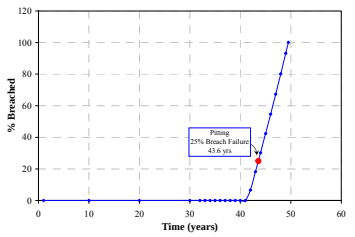


Groundwater

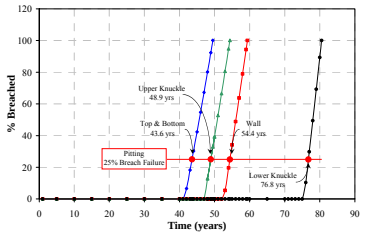




Type I Tank



Type II Tank



Print

Close

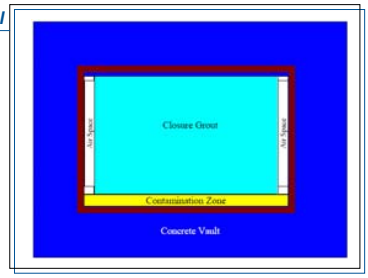
Life Estimation of High Level Waste Tank Steel for H-Tank Farm Closure Performance Assessment

By Brenda L. García-Díaz, Bruce Wiersma, and Steve Harris

Corrosion of Steel Exposed to Humid Air Pipe Conditions

Humid Air Space Between Grout and Tank Steel

The life of the tank steel was also estimated for the condition in which a pipe of humid air may form between the grout/vault and the tank steel. This configuration could form due to shrinkage of the grout or corrosion of the transfer line that penetrates through the sidewall of the tanks. Humid air corrosion in the tanks can be modeled as analogous to damp atmospheric corrosion that occurs due to the formation of thin electrolyte layers on a metal surface leading to corrosion with any contaminants, e.g. NaCl, Na_2SO_4, leading to increased corrosion rates. It is assumed that the critical humidity is always maintained for these calculations and that there are no contaminants of consequence in any humid air exposed to the tank surface. The corrosion of the tank steel under thin films proceeds with the anodic reaction being the dissolution of the metal and the cathodic reaction being the oxygen reduction reaction. It is important to recognize that oxygen is always available for thin films and diffusion through the thin films is relatively fast.



Data that has been developed for the Yucca Mountain Project (YMP) may be used for this analysis. The corrosion testing in support of the YMP included exposing A516 Gr. 55 coupons to the vapor space above simulated dilute water (SDW) and simulated concentrated well water (SCW) for a year of exposure at 60 and 90°C [6]. The SCW composition consisted of 1,000 times the expected contaminant levels in the typical SDW. The data for the vapor space corrosion of the coupons indicated a higher corrosion rate than that of the aqueous exposure potentially due to the carbon dioxide evolution from the carbonate in the solution.

Corrosion Rates of Vapor Space Coupons in Yucca Mountain Study

Solution	Temperature	Corrosion Rate 6 month test (μm/yr)	6 month test (mpy)	12 month test (μm/yr)	12 month test (mpy)
SDW	60°C	46	1.8	27	1.06
SDW	90°C	77	3.03	56	2.2
SCW	60°C	210	8.27	194	7.64
SCW	90°C	240	9.45	227	8.94

The corrosion rates were averaged for each of the types of exposure leading to the following corrosion rates used for the calculation of the tank consumption due to general corrosion in humid air:

SDW: Average Corrosion Rate = 51.5 μm/yr (2.03 mpy)

SCW: Average Corrosion Rate = 217.72 μm/yr (8.57 mpy)

The time to consumption of the tank are estimated as shown below:

Time to Consumption of Tank Steel Due to Humid Air Corrosion

Tank Type	Location	Steel Thickness (in.)	SDW Consumption Time (yrs)	SCW Consumption Time (yrs)
I	all sides	0.5	246	58
II	op & botton	0.5	246	58
II	pper knuckl	0.563	277	66
II	walls	0.625	308	73
II	ower knuckl	0.875	431	102

The lifetime estimates due to humid air corrosion are significantly shorter than the grouted or soil conditions as expected. However, the likelihood and/or impact of the humid air corrosion is expected to be very low due to the locations where these are likely to occur. The estimation scheme also does not account for the length of time necessary for such a pipe to form or the likelihood of the occurrence. Therefore, the use of the humid air corrosion estimates is simply an extremely conservative case study to indicate that highly unlikely events were considered for the life estimation methodology.

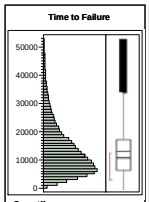
Stochastic Approach to Tank Life Estimation

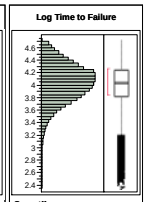
A comprehensive stochastic methodology (CSM) was utilized to estimate the life of the tank steel liner. The comprehensive methodology developed distributions for the corrosion rate as well as the diffusion coefficients for carbon dioxide related to the potential carbonation and the oxygen related to the chloride induced depassivation of the steel. The stochastic approach was implemented to account for potential uncertainty in the time-frames proposed for regulatory compliance.

The soil conditions within H-area vary between locations. The Type II tanks in H-area are in an area without a significant amount of groundwater. However, the Type I tanks in the H-Tank Farm are in an area with significant groundwater. This section summarizes the time to failure for the Type II tanks in soils without groundwater and Type I tanks and Type II tanks exposed to soils with significant amounts of groundwater. The groundwater can increase the general corrosion rate due to higher electrolyte mobility and higher conductivity that can increase corrosion. Differences in oxygen concentration at the interface where soil with groundwater meets soil without groundwater can cause galvanic cells that increase the corrosion rate. The Type I tanks in the H-area tank farm can be submerged more than 50% in groundwater. Type II tanks in the H-tank farm have some exposure of the vault bottom to soil with groundwater.

The results are presented as quantiles and log-time to failure. The results can be interpreted in several ways. The quantiles may be used as input for modeling the outflow of contaminants from the tanks by (1) using the median value as a best estimate for failure times under the assumption of complete consumption or (2) using the entire distribution in any stochastic modeling.

Time to Failure for Type II Tanks in Soils with No Groundwater





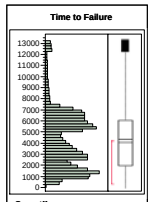
Quantiles		
100.00%	maximum	52889
99.50%		47478
97.50%		38962
90.00%		26664
75.00%	quartile	17763
50.00%	median	11274
25.00%	quartile	6818
10.00%		4256
2.50%		2189
0.50%		1035
0.00%	minimum	229

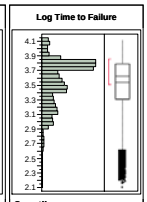
Moments	
Mean	1.36E+04
Std Dev	9340.2602
Std Er Mean	1.10E+01
upper 95% Mean	1.37E+04
lower 95% Mean	1.36E+04
N	715920

Quantiles		
100.00%	maximum	4.7234
99.50%		4.6765
97.50%		4.5906
90.00%		4.4259
75.00%	quartile	4.2495
50.00%	median	4.0573
25.00%	quartile	3.8337
10.00%		3.629
2.50%		3.3403
0.50%		3.015
0.00%	minimum	2.3604

Moments	
Mean	4.03E+00
Std Dev	0.3163845
Std Er Mean	3.74E-04
upper 95% Mean	4.03E+00
lower 95% Mean	4.03E+00
N	715920

Time to Failure for Type I Tanks in Soils with Groundwater





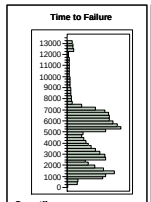
Quantiles		
100.00%	maximum	13250
99.50%		13015
97.50%		12083
90.00%		7209
75.00%	quartile	6153
50.00%	median	4163
25.00%	quartile	2097
10.00%		1152
2.50%		649
0.50%		362
0.00%	minimum	132

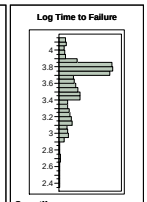
Moments	
Mean	4.42E+03
Std Dev	2733.5739
Std Er Mean	3.19E+00
upper 95% Mean	4.42E+03
lower 95% Mean	4.41E+03
N	732506

Quantiles		
100.00%	maximum	4.1222
99.50%		4.1144
97.50%		4.0822
90.00%		3.8579
75.00%	quartile	3.7891
50.00%	median	3.6215
25.00%	quartile	3.3216
10.00%		3.0613
2.50%		2.8121
0.50%		2.5592
0.00%	minimum	2.1214

Moments	
Mean	3.54E+00
Std Dev	0.3273375
Std Er Mean	3.83E-04
upper 95% Mean	3.54E+00
lower 95% Mean	3.54E+00
N	732506

Time to Failure for Type II Tanks in Soils with Groundwater





Quantiles		
100.00%	maximum	13250
99.50%		13028
97.50%		12271
90.00%		7283
75.00%	quartile	6283
50.00%	median	4890
25.00%	quartile	2461
10.00%		1258
2.50%		824
0.50%		419
0.00%	minimum	245

Moments	
Mean	4.63E+03
Std Dev	2723.1382
Std Er Mean	3.18E+00
upper 95% Mean	4.64E+03
lower 95% Mean	4.63E+03
N	732506

Quantiles		
100.00%	maximum	4.1222
99.50%		4.1149
97.50%		4.0889
90.00%		3.8623
75.00%	quartile	3.7982
50.00%	median	3.6893
25.00%	quartile	3.391
10.00%		3.0996
2.50%		2.9161
0.50%		2.6224
0.00%	minimum	2.3896

Moments	
Mean	3.57E+00
Std Dev	0.3159151
Std Er Mean	3.69E-04
upper 95% Mean	3.57E+00
lower 95% Mean	3.57E+00
N	732506

Summary

A tank life estimation was performed in support of closure of the H-Tank Farm. The estimation considered general and localized corrosion mechanisms of the tank steel exposed to the contamination zone, grouted, and soil conditions. The life estimation was done deterministically as well as stochastically. The lifetime estimation accounted for the amount of groundwater in the soils surrounding the tank. For the Type I tanks it was assumed that the soil surrounding the tank contained a significant amount of groundwater. For Type II tanks it was assumed that the soil around the tank did not contain significant amounts of groundwater.

Consumption of the tank steel encased in grouted conditions was determined to occur either due to carbonation of the concrete leading to low pH conditions, or the chloride-induced de-passivation of the steel leading to accelerated corrosion. The life of the tank steel under soil conditions was estimated using corrosion rates for cecil clay loam soil. The cecil clay loam soil is similar to areas of the H-Tank Farm with no significant groundwater. The life of the tank steel under groundwater conditions was estimated using corrosion rates for Muck soil. The Muck soil is somewhat similar to areas of the H-Tank Farm with significant groundwater.

When general corrosion depth equals the thickness of a specific portion of the tank, that section of the tank is considered to be 100% breached. For pitting corrosion it is assumed that a steel structure fails when 25% of the area is breached. A summary of the tank life estimation is shown below for grouted and soil conditions.

Summary of Tank Steel Life Estimation Results in Grouted Conditions

Tank Type	Condition	Thickness / Location	Mechanism	Time
Type I	Grouted	1/2" Top & Bottom 1/2" Walls	Chloride Attack Initiation Tank Consumption	3550 years 5810 years
Type II	Grouted	1/2" Top & Bottom	Chloride Attack Initiation Tank Consumption (GC)	5821 years 6250 years
Type II	Grouted	9/16" Upper Knuckle	Chloride Attack Initiation Tank Consumption (GC)	5821 years 7031 years
Type II	Grouted	5/8" Walls	Chloride Attack Initiation Tank Consumption	5821 years 7813 years
Type II	Grouted	7/8" Lower Knuckle	Chloride Attack Initiation Tank Consumption	5821 years 10937 years

Summary of Tank Steel Life Estimation Results in Soil Conditions with and without Groundwater

Tank Type	Condition	Thickness / Location	Mechanism	Time
Type I	Soil with Groundwater	1/2" Top & Bottom 1/2" Walls	Chloride Attack Initiation Tank Consumption (GC)	41 years 229 years
Type II	Soil without Groundwater	1/2" Top & Bottom	Chloride Attack Initiation 25% Pitting Breach	872 years 1040 years
Type II	Soil without Groundwater	9/16" Upper Knuckle	Chloride Attack Initiation Tank Consumption (GC)	872 years 1308 years
Type II	Soil without Groundwater	5/8" Walls	Chloride Attack Initiation Tank Consumption (GC)	872 years 1453 years
Type II	Soil without Groundwater	7/8" Lower Knuckle	Chloride Attack Initiation Tank Consumption (GC)	872 years 2035 years
Type II	Soil with Groundwater	1/2" Top & Bottom	Chloride Attack Initiation Tank Consumption (GC)	41 years 229 years
Type II	Soil with Groundwater	9/16" Upper Knuckle	Chloride Attack Initiation Tank Consumption (GC)	47 years 258 years
Type II	Soil with Groundwater	5/8" Walls	Chloride Attack Initiation Tank Consumption (GC)	53 years 287 years
Type II	Soil with Groundwater	7/8" Lower Knuckle	Chloride Attack Initiation Tank Consumption (GC)	75 years 401 years

References

1. ASTM Standard A285, "Standard Specification for Pressure Vessel Plates, Carbon Steel, Low- and Intermediate Tensile Strength", American Society for Testing of Materials, 2006.
2. B. J. Wiersma, *Coupon Immersion Testing in Simulated Hazardous Low-Level Waste*, WSRC-TR-91-493, 1991.
3. M. R. Millings, J. V. Noonkester, M. E. Denham, and B. P. Jackson, *Natural Strontium, Iodine, Cesium, and Cobalt in Savannah River Site Groundwater: Data Report*, WSRC-TR-2002-00479, 2003.
4. M. Romanoff, *Underground Corrosion*. National Bureau of Standards Circular 579. 1957, Washington, DC: National Bureau of Standards.
5. T. M. Sullivan, *Assessment of Release Rates for Radionuclides in Activated Concrete*, BNL-71537-2003, 2003.
6. R. D. McCright, *Engineered Materials Characterization Report Vol 3, Corrosion Data and Modeling Update for Viability Assessment*, UCRL-ID-119564, Vol. 3, Rev. 1, 1998.

Acknowledgements

- Heather Burns
- Kristine Zeigler
- Karthik Subramanian
- Thomas Robinson
- Kent Rosenberger

Print

Close