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

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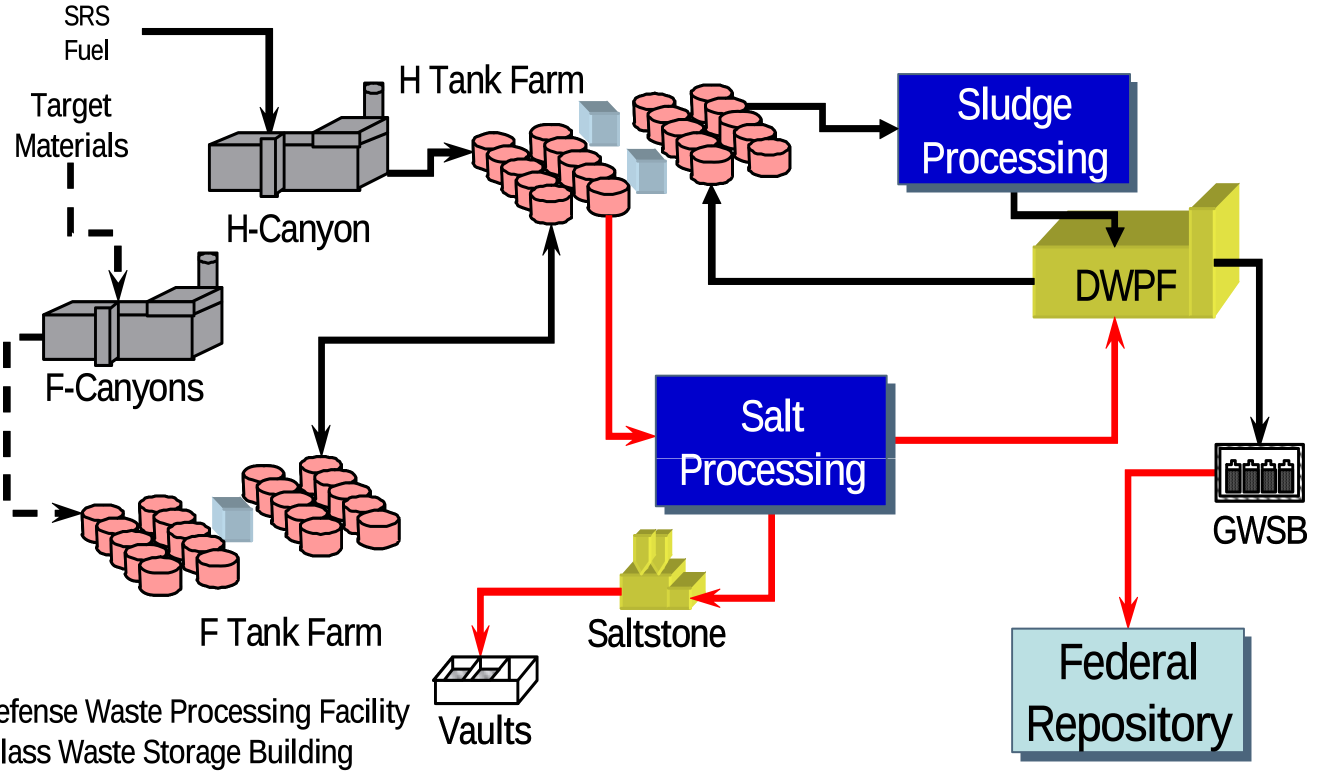
# Outline

- Savannah River Site liquid waste operations
- Performance assessment for tank closure
- Tank life estimation technical approach
- Results
- Recommendations

# Savannah River Site Liquid Waste System




DWPF - Defense Waste Processing Facility
GWSB - Glass Waste Storage Building

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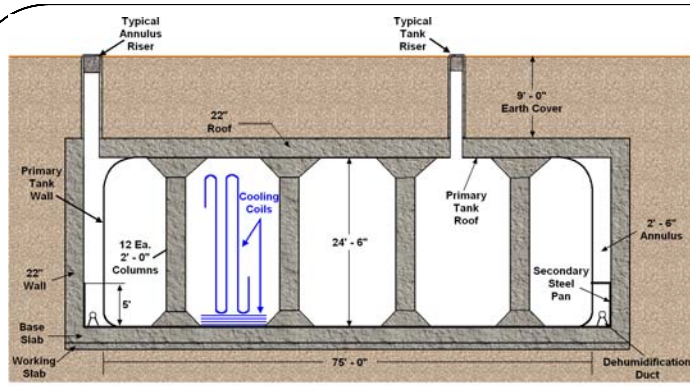
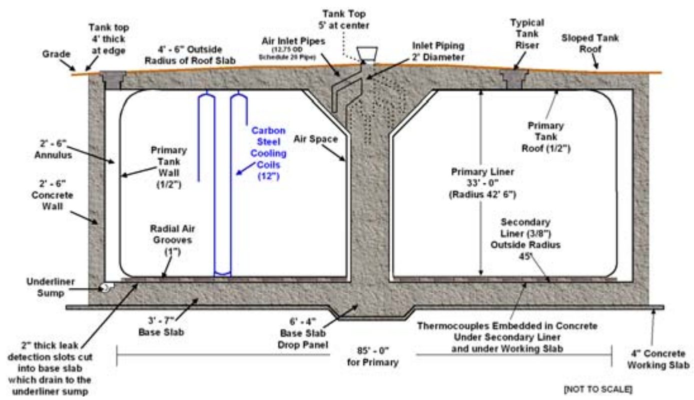
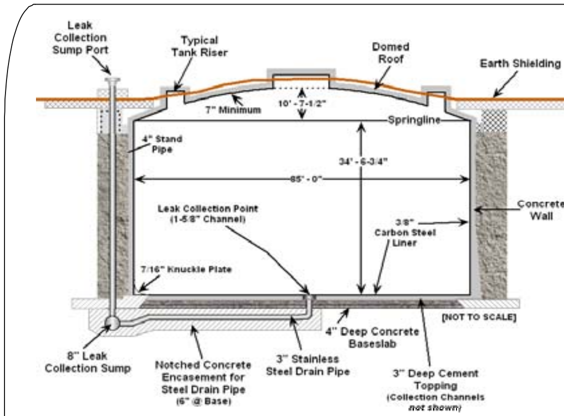
# F-Tank Farm Liquid Waste Tanks




- Type I Tanks
- Vintage 1950s
- Built of ASTM A285, Grade B
- Non-stress relieved
- Partial secondary containment
- 0.5-in plate construction




- Type III/IIIA Tanks
- Vintage 1970s-1980s
- Built of ASTM A537-Cl.1, A516-70
- Stress relieved
- Full secondary containment
- Tapered design from 0.5-in to 0.875-in thickness




- Type IV Tanks
- Steel-lined prestressed concrete tank
- ASTM A285 Grade B Steel
- 0.375-in thick walls
- 0.4375-in thick bottom
- Vintage 1950s

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# Waste Tank Closure

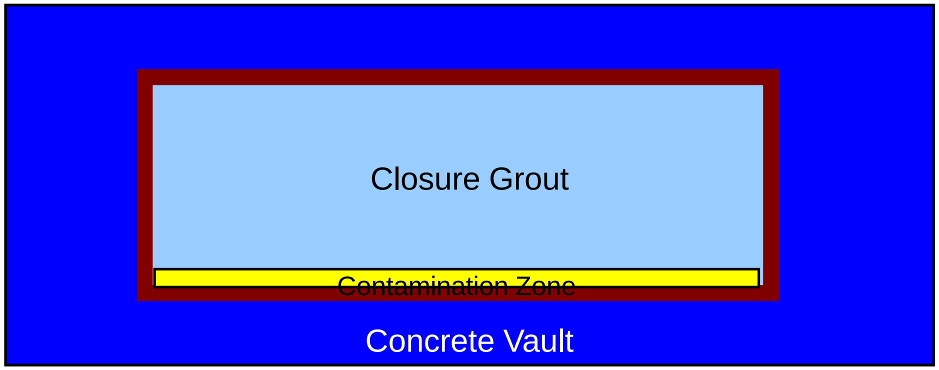
- Closed through bulk waste removal, chemical cleaning, heel removal, stabilizing remaining residuals with tailored grout formulations, and severing/sealing external penetrations
- Performance assessment supporting closure of F-Tank Farm

- Carbon steel of high level waste tank initially provide a barrier contaminant escape
- Corrosion mechanisms will degrade liner over time
- Liner will no longer provide a barrier

- Estimate the time to failure of the tank liner due to corrosion processes

# Life Estimation Methodology

- Goal: Determine time period that steel liners can act as a barrier to contaminant escape
  - Penetrations of tank steel
  - Size of penetrations
- Active corrosion mechanisms on the steel under closure conditions



# Contamination Zone

- Function of the undissolved solids in the residual on tank bottom
- R-value: Ratio of inhibitor species (nitrite and hydroxide) to aggressive species (nitrate + chloride)
  - High R-values: Minimal Corrosion
  - Low R-values High corrosion due to insufficient inhibitors
- Results indicate no accelerated corrosion from contamination zone

| Tank | R-Value |
|---|---|
| 1 | 5.47 |
| 2 | 4.36 |
| 3 | 3.94 |
| 4 | 9.67 |
| 5 | 5.31 |
| 6 | 12.39 |
| 7 | 3.44 |
| 8 | 3.87 |
| 17 | 3.18 |
| 18 | 4.51 |
| 19 | 0.24 |
| 20 | 3.18 |
| 25 | 3.19 |
| 26 | 3.19 |
| 27 | 3.19 |
| 28 | 3.19 |
| 33 | 4.53 |
| 34 | 12.40 |
| 44 | 4.45 |
| 45 | 3.19 |
| 46 | 3.19 |
| 47 | 3.19 |

# Corrosion in Concrete/Grout

- Corrosion of steel exposed to concrete/grout occurs by a complex mechanism that occurs through metal dissolution at the concrete/metal interface.
- Concrete generally prevents corrosion of the steel
  - Forms passive oxide on the steel surface
  - Maintains a high pH environment
  - Provides a matrix resistant to diffusion of aggressive species
- Passivity can be lost through carbonation or through chloride induced film breakdown
  - Pore water characteristics change with the introduction of chlorides or carbon dioxide, the passive film on the steel may break down

# Stochastic Technical Approach

- Proposed to account for potential uncertainty in the time-frames proposed for regulatory compliance
- Initially Considered
  - First order reliability methods (FORM)
    - Statistical information is sparse
    - Marginal probability distributions
  - Direct uncertainty analysis
    - Separation of the probability calculations from the evaluation of the performance measure
    - Discretization of the probability intervals
- Ultimately, USED Monte Carlo Simulation
  - Inherently represent the uncertainties in the deterministic approach
  - Large number of simulations
  - Exploits the in-depth knowledge of SRS subsurface environments and HLW tanks as input distributions for the simulations

# Stochastic Technical Approach

- Life of the tank liners was assumed to be a function of the time to corrosion initiation plus the time for corrosion to propagate through the liner
- Grouted Conditions
- Corrosion in grouted conditions
- Chloride induced depassivation, followed by general corrosion
- Carbonation induced loss of protective capacity of the concrete

$$t_{failure} = t_{initiation} + \frac{Thickness(mils)}{CorrosionRate(mils / year)}$$

| | | |
|---|---|---|
| $t_{failure}$ | = | time to penetration of the tank wall by corrosion |
| $t_{initiation}$ | = | time to chloride induced depassivation or carbonation front |
| Thickness | = | initial thickness of liner (mils) |
| Corrosion rate | = | Dependent upon condition, i.e. chloride or carbonation |

## Case 1: IF $t_{initiation}$ [$Cl^-$] ≥ $t_{initiation}$ [Carbonation]

$$t_{failure} = t_{initiation[carbonation]} + \frac{Thickness(mils)}{CorrosionRate(mils/year)}$$

| | | |
|---|---|---|
| $T_0$ | = | Initial Thickness (mils) |
| Thickness | = | $T_0$ – RNDCR*$t_{init[carbonation]}$ [mils] |
| RNDCR | = | Corrosion Rate per Distribution |
| Corrosion Rate (Rcarb) | = | 10 mils/year |

$$t_{failure} = t_{initiation[carbonation]} + \frac{T_o - \left( RNDCR(\frac{mils}{yr}) \cdot t_{initiation[carbonation]} \right)}{10(\frac{mils}{yr})}$$

## Case 2: IF $t_{initiation}$ [Cl-] < $t_{initiation}$ [Carbonation]

$$t_{failure} = t_{initiation[chloride]} + \frac{Thickness(mils)}{CorrosionRate(mils/year)}$$

| | | |
|---|---|---|
| $T_0$ | = | Initial Thickness (mils) |
| Thickness | = | $T_0$ – RNDCR*$t_{init[chloride]}$ [mils] |
| Corrosion Rate ($R_{Cl-}$) | = | Calculated |

# Embedded Case 3:
# IF $t_{failure}$ [$Cl^-$] ≥ $t_{initiation}$ [Carbonation]

$$t_{failure} = t_{initiation[chloride]} + \frac{Thickness(mils)}{CorrosionRate(mils/year)}$$

$T_0$ (mils) = Initial Thickness

Thickness = $T_0$ – RNDCR*$t_{init[carbonation]}$] [mils]

Corrosion Rate (R) = Dependent upon Reaction

$$T_o - \left[\left(t_{initiation[carbonation]} - t_{initiation[Cl]}\right) \cdot R_{Cl} + \left(t_{initiation[Cl]} \cdot RNDCR\right)\right]$$

$$t_{failure} = t_{initiation[carbonation]} + \frac{T_o - \left[\left(t_{initiation[carbonation]} - t_{initiation[Cl]}\right) \cdot R_{Cl} + \left(t_{initiation[Cl]} \cdot 0.04\right)\right](mils)}{10(mils/year)}$$

# Chloride Induced Corrosion: Initiation

- Due to the breakdown of the passive film, thereby indicating that chloride diffusion is the rate controlling step for corrosion initiation

- Followed by oxygen diffusion for corrosion reactions to occur

- Simple Empirical Model:

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

$t_{initiation}$ = time required for initiation (years)
$t_c$ = thickness of the concrete cover (in.)
WCR = water-to-cement ratio
[Cl-] = chloride concentration in the groundwater (ppm)

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# Chloride Induced Corrosion: Reaction

- Oxygen diffusion to breakdown of passivity: corrosion reaction

$$Fe + \frac{3}{2} H_2O + \frac{3}{4} O_2 = Fe\left(OH\right)_2$$

- Corrosion rate

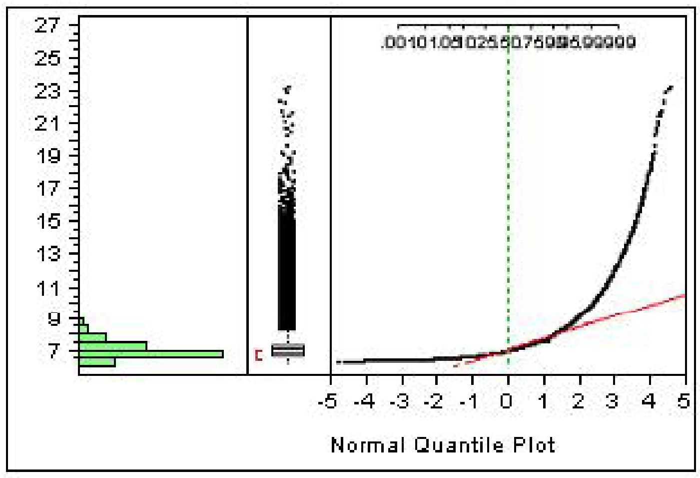
$$R_{corrosion} = \frac{4}{3} N_{O_2} \frac{M_{Fe}}{\rho_{Fe}}$$

$M_{Fe}$ = molecular weight of iron (56 g/mol)
$\rho_{Fe}$ = density of iron (7.86 g/cm3)

$$N_{O_2} = D_i \frac{C_{gw}}{\Delta X}$$

$N_{O2}$ = Flux of oxygen through concrete (mol/s/cm$^2$)
$D_i$ = Oxygen diffusion coefficient in concrete (cm$^2$/sec)
$C_{gw}$ = Concentration of oxygen in groundwater (mol/cm$^3$)
$\Delta X$ = Depth of concrete (cm)

# Chloride Distribution




| | | |
|---|---|---|
| 100.0% | maximum | 26.893 |
| 99.5% | | 10.365 |
| 97.5% | | 8.875 |
| 90.0% | | 7.846 |
| 75.0% | quartile | 7.269 |
| 50.0% | median | 6.866 |
| 25.0% | quartile | 6.619 |
| 10.0% | | 6.480 |
| 2.5% | | 6.382 |
| 0.5% | | 6.327 |
| 0.0% | minimum | 6.249 |

# Carbonation

- Pore water pH reduces dramatically due to the conversion of the calcium hydroxide to calcium carbonate through reaction with carbon dioxide
- Complex function of the permeability of the concrete, relative humidity, and the carbon dioxide availability

$$t_{initiation[carbonation]} = \frac{X^2 C_g}{D_{i(CO_2)} C_{gw(carbon)}}$$

| | | |
|---|---|---|
| $X$ | = | carbonation depth (cm) |
| $D_i$ | = | diffusion coefficient of $CO_2$ in concrete ($cm^2/s$) |
| $C_{gw\ (carbon)}$ | = | total inorganic carbon ($mol/cm^3$) |
| $C_g$ | = | $Ca(OH)_2$ bulk concentration ($mole/cm^3$) |
| $T$ | = | time (years) |

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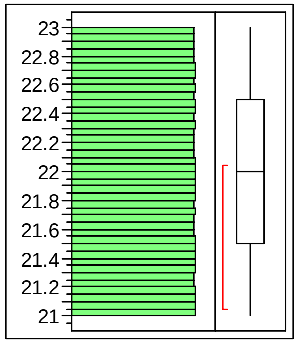
# Concrete Thickness Input

## Distribution of Type I Tank Concrete Thickness (in.)



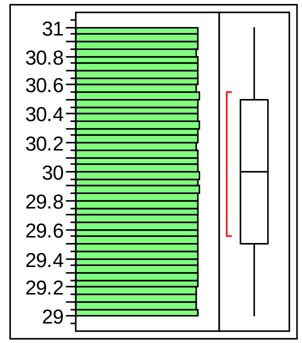

### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 23.000 |
| 99.5% | | 22.990 |
| 97.5% | | 22.950 |
| 90.0% | | 22.799 |
| 75.0% | quartile | 22.499 |
| 50.0% | median | 21.998 |
| 25.0% | quartile | 21.499 |
| 10.0% | | 21.199 |
| 2.5% | | 21.050 |
| 0.5% | | 21.010 |
| 0.0% | minimum | 21.000 |

### Moments

| | |
|---|---|
| Mean | 21.999208 |
| Std Dev | 0.577186 |
| Std Err Mean | 0.0005772 |
| upper 95% Mean | 22.00034 |
| lower 95% Mean | 21.998077 |
| N | 1000000 |

## Distribution of Type III Tank Concrete Thickness (in.)



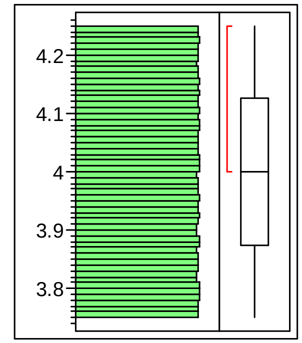

### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 31.000 |
| 99.5% | | 30.990 |
| 97.5% | | 30.950 |
| 90.0% | | 30.800 |
| 75.0% | quartile | 30.500 |
| 50.0% | median | 30.000 |
| 25.0% | quartile | 29.502 |
| 10.0% | | 29.201 |
| 2.5% | | 29.050 |
| 0.5% | | 29.010 |
| 0.0% | minimum | 29.000 |

### Moments

| | |
|---|---|
| Mean | 30.000481 |
| Std Dev | 0.5769515 |
| Std Err Mean | 0.000577 |
| upper 95% Mean | 30.001612 |
| lower 95% Mean | 29.99935 |
| N | 1000000 |

## Distribution of Type IV Tank Concrete Thickness (in.)




### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 4.2500 |
| 99.5% | | 4.2475 |
| 97.5% | | 4.2375 |
| 90.0% | | 4.2001 |
| 75.0% | quartile | 4.1251 |
| 50.0% | median | 4.0005 |
| 25.0% | quartile | 3.8751 |
| 10.0% | | 3.7998 |
| 2.5% | | 3.7625 |
| 0.5% | | 3.7525 |
| 0.0% | minimum | 3.7500 |

### Moments

| | |
|---|---|
| Mean | 4.0001247 |
| Std Dev | 0.1443445 |
| Std Err Mean | 0.0001443 |
| upper 95% Mean | 4.0004076 |
| lower 95% Mean | 3.9998418 |
| N | 1000000 |

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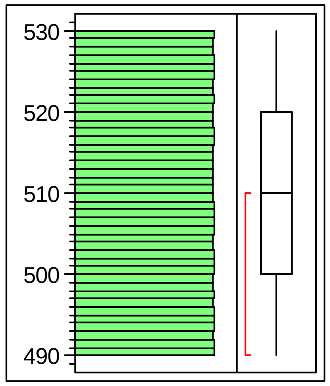
# Tank Steel Thickness Input

## Distribution of Type I Tank Steel Thickness (mils)



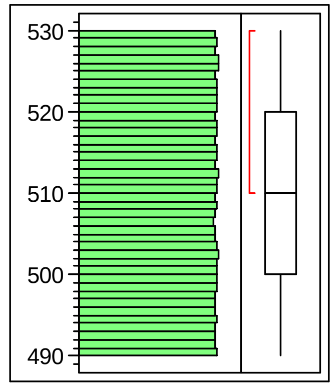

### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 530.00 |
| 99.5% | | 529.80 |
| 97.5% | | 529.00 |
| 90.0% | | 526.00 |
| 75.0% | quartile | 520.01 |
| 50.0% | median | 509.98 |
| 25.0% | quartile | 500.00 |
| 10.0% | | 494.00 |
| 2.5% | | 491.00 |
| 0.5% | | 490.20 |
| 0.0% | minimum | 490.00 |

### Moments

| | |
|---|---|
| Mean | 509.99614 |
| Std Dev | 11.550194 |
| Std Err Mean | 0.0115502 |
| upper 95% Mean | 510.01878 |
| lower 95% Mean | 509.97351 |
| N | 1000000 |

## Distribution of Type III Tank Steel Thickness (mils)



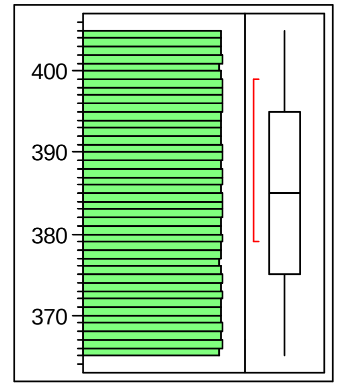

### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 530.00 |
| 99.5% | | 529.80 |
| 97.5% | | 529.00 |
| 90.0% | | 526.01 |
| 75.0% | quartile | 520.04 |
| 50.0% | median | 510.05 |
| 25.0% | quartile | 500.03 |
| 10.0% | | 494.02 |
| 2.5% | | 491.00 |
| 0.5% | | 490.20 |
| 0.0% | minimum | 490.00 |

### Moments

| | |
|---|---|
| Mean | 510.02181 |
| Std Dev | 11.54662 |
| Std Err Mean | 0.0115466 |
| upper 95% Mean | 510.04444 |
| lower 95% Mean | 509.99918 |
| N | 1000000 |

## Distribution of Type IV Tank Steel Thickness (mils)



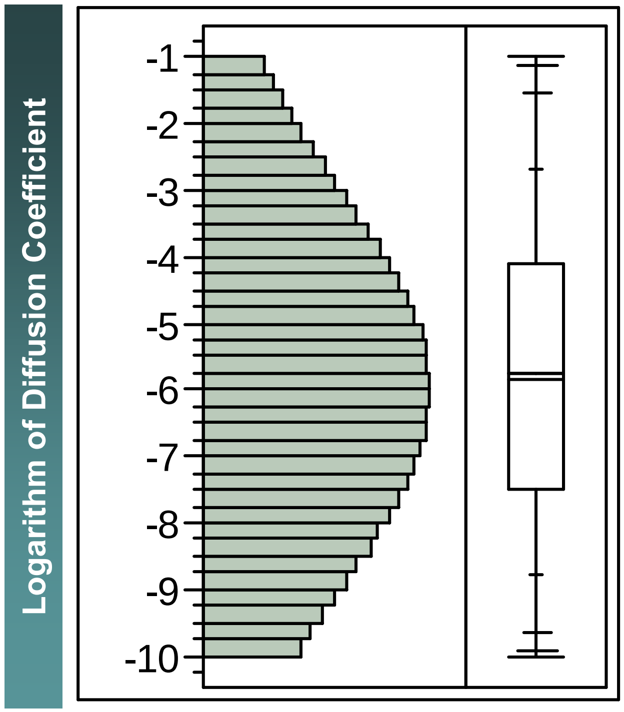

### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 405.00 |
| 99.5% | | 404.80 |
| 97.5% | | 404.00 |
| 90.0% | | 401.00 |
| 75.0% | quartile | 395.00 |
| 50.0% | median | 385.01 |
| 25.0% | quartile | 374.99 |
| 10.0% | | 369.00 |
| 2.5% | | 366.02 |
| 0.5% | | 365.21 |
| 0.0% | minimum | 365.00 |

### Moments

| | |
|---|---|
| Mean | 385.00467 |
| Std Dev | 11.542438 |
| Std Err Mean | 0.0115424 |
| upper 95% Mean | 385.02729 |
| lower 95% Mean | 384.98205 |
| N | 1000000 |

# Diffusion Coefficient Input




| quantiles | | |
|---|---|---|
| 100.0% | max | 0.10000 |
| 99.5% | | 0.07509 |
| 97.5% | | 0.02822 |
| 90.0% | | 0.00215 |
| 75.0% | quartile | 0.00008 |
| 50.0% | median | 1.47e-6 |
| 25.0% | quartile | 3.06e-8 |
| 10.0% | | 1.68e-9 |
| 2.5% | | 2.3e-10 |
| 0.5% | | 1.2e-10 |
| 0.0% | min | 1e-10 |

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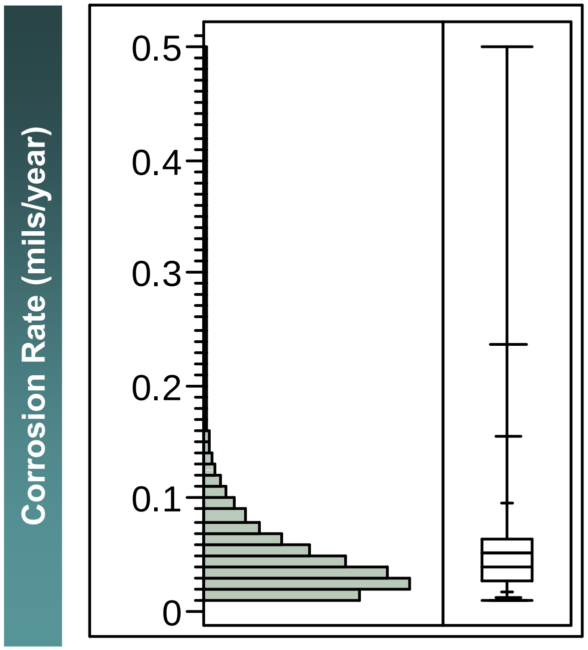
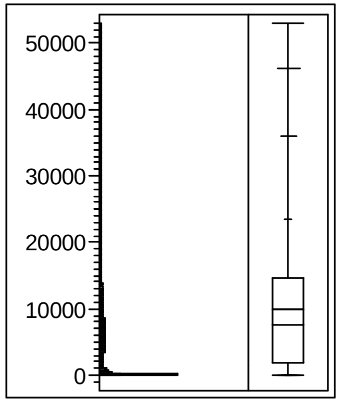
# Corrosion Rate Distribution




| % | | mils/yr | $I_{corr}$ ($\mu A/cm^2$) |
|---|---|---|---|
| 100.0% | Max | 0.44978 | 0.9830 |
| 99.5% | | 0.23641 | 0.5167 |
| 97.5% | | .15527 | 0.3393 |
| 90.0% | | 0.09727 | 0.2126 |
| 75.0% | Quartile | 0.06418 | 0.1402 |
| 50.0% | Median | 0.04058 | 0.0886 |
| 25.0% | Quartile | 0.02590 | 0.0566 |
| 10.0% | | 0.01769 | 0.0386 |
| 2.5% | | 0.01253 | 0.0273 |
| 0.5% | | 0.01059 | 0.0231 |
| 0.0% | Min | 0.01 | 0.0218 |

# Type I Monte Carlo Simulation

## Time to Failure



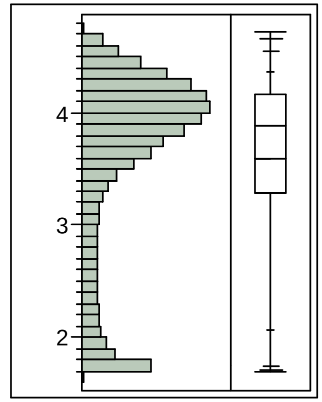

### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 52887 |
| 99.5% | | 46227 |
| 97.5% | | 36154 |
| 90.0% | | 23481 |
| 75.0% | quartile | 14679 |
| 50.0% | median | 7630 |
| 25.0% | quartile | 1925 |
| 10.0% | | 115 |
| 2.5% | | 55 |
| 0.5% | | 51 |
| 0.0% | minimum | 49 |

### Moments

| | |
|---|---|
| Mean | 9982.4153 |
| Std Dev | 9791.9605 |
| Std Err Mean | 8.8182837 |
| upper 95% Mean | 9999.6988 |
| lower 95% Mean | 9965.1317 |
| N | 1233023 |

## Log Time to Failure:



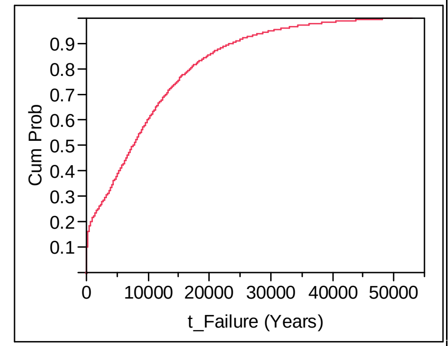

### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 4.7234 |
| 99.5% | | 4.6649 |
| 97.5% | | 4.5582 |
| 90.0% | | 4.3707 |
| 75.0% | quartile | 4.1667 |
| 50.0% | median | 3.8825 |
| 25.0% | quartile | 3.2844 |
| 10.0% | | 2.0619 |
| 2.5% | | 1.7402 |
| 0.5% | | 1.7115 |
| 0.0% | minimum | 1.6918 |

### Moments

| | |
|---|---|
| Mean | 3.5948208 |
| Std Dev | 0.8144007 |
| Std Err Mean | 0.0007334 |
| upper 95% Mean | 3.5962583 |
| lower 95% Mean | 3.5933834 |
| N | 1233023 |

## CDF Plot

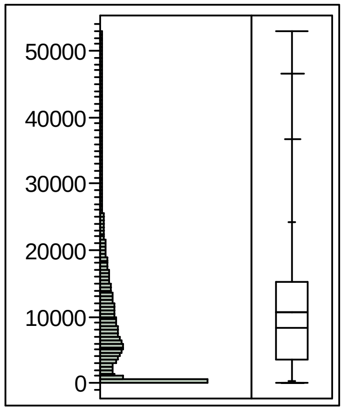



## Failure Mode Frequency

| Level | Count | Prob |
|---|---|---|
| 0 | 440223 | 0.35703 |
| 1 | 792800 | 0.64297 |
| Total | 1233023 | 1.00000 |

# Type III/IIIA Monte Carlo Simulation

## Time to Failure



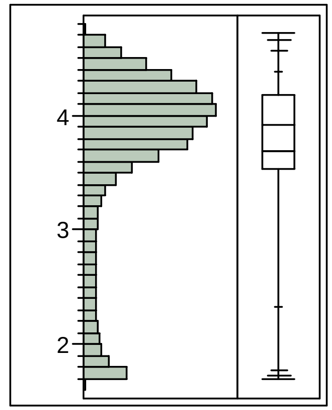

### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 52937 |
| 99.5% | | 46494 |
| 97.5% | | 36754 |
| 90.0% | | 24123 |
| 75.0% | quartile | 15289 |
| 50.0% | median | 8272 |
| 25.0% | quartile | 3397 |
| 10.0% | | 213 |
| 2.5% | | 59 |
| 0.5% | | 53 |
| 0.0% | minimum | 49 |

### Moments

| | |
|---|---|
| Mean | 10650.171 |
| Std Dev | 9763.8428 |
| Std Err Mean | 8.7929618 |
| upper 95% Mean | 10667.405 |
| lower 95% Mean | 10632.937 |
| N | 1233023 |

## Log Time to Failure:



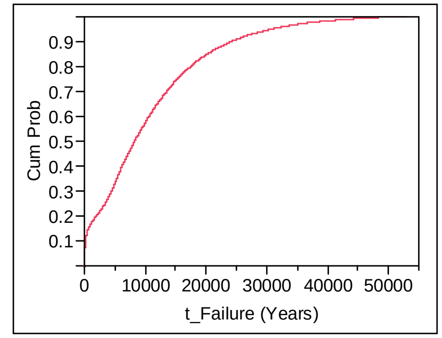

### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 4.7238 |
| 99.5% | | 4.6674 |
| 97.5% | | 4.5653 |
| 90.0% | | 4.3824 |
| 75.0% | quartile | 4.1844 |
| 50.0% | median | 3.9176 |
| 25.0% | quartile | 3.5311 |
| 10.0% | | 2.3274 |
| 2.5% | | 1.7731 |
| 0.5% | | 1.7210 |
| 0.0% | minimum | 1.6921 |

### Moments

| | |
|---|---|
| Mean | 3.6912643 |
| Std Dev | 0.7431468 |
| Std Err Mean | 0.0006693 |
| upper 95% Mean | 3.692576 |
| lower 95% Mean | 3.6899256 |
| N | 1233023 |

## CDF Plot




## Failure Mode Frequency

| Level | Count | Prob |
|---|---|---|
| 0 | 365139 | 0.29613 |
| 1 | 867884 | 0.70387 |
| Total | 1233023 | 1.00000 |

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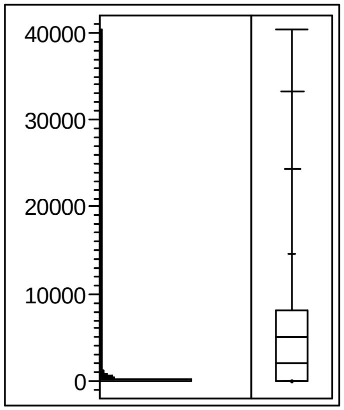
# Type IV Monte Carlo Simulation

## Time to Failure



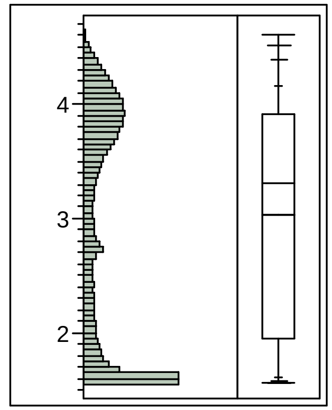

### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 40391 |
| 99.5% | | 33244 |
| 97.5% | | 24287 |
| 90.0% | | 14610 |
| 75.0% | quartile | 8104 |
| 50.0% | median | 2010 |
| 25.0% | quartile | 90 |
| 10.0% | | 41 |
| 2.5% | | 38 |
| 0.5% | | 37 |
| 0.0% | minimum | 37 |

### Moments

| | |
|---|---|
| Mean | 5161.4916 |
| Std Dev | 6847.8707 |
| Std Err Mean | 6.1669434 |
| upper 95% Mean | 5173.5786 |
| lower 95% Mean | 5149.4046 |
| N | 1233023 |

## Log Time to Failure:



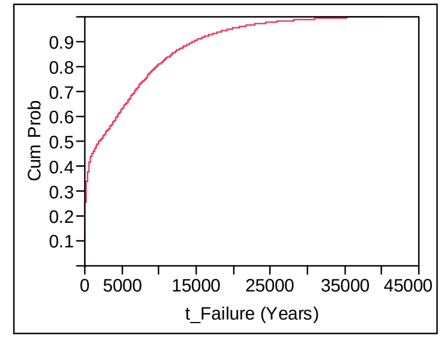

### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 4.6063 |
| 99.5% | | 4.5217 |
| 97.5% | | 4.3854 |
| 90.0% | | 4.1647 |
| 75.0% | quartile | 3.9087 |
| 50.0% | median | 3.3031 |
| 25.0% | quartile | 1.9521 |
| 10.0% | | 1.6091 |
| 2.5% | | 1.5801 |
| 0.5% | | 1.5684 |
| 0.0% | minimum | 1.5624 |

### Moments

| | |
|---|---|
| Mean | 3.0267292 |
| Std Dev | 0.9836818 |
| Std Err Mean | 0.0008859 |
| upper 95% Mean | 3.0284655 |
| lower 95% Mean | 3.0249929 |
| N | 1233023 |

## CDF Plot




## Failure Mode Frequency

| Level | Count | Prob |
|---|---|---|
| 0 | 709530 | 0.57544 |
| 1 | 523493 | 0.42456 |
| Total | 1233023 | 1.00000 |

# Recommendations

- The distributions of failure may be used as input for modeling the migration of contaminants via various mechanisms

- Median value as a best estimate for failure times under the assumption of complete consumption
- Figure of merit for percentage breached for a “patch” type models which will progressively fail the tank and assume that past a critical percentage breached, the tank no longer acts as a barrier to contaminant escape
- Entire distribution in any stochastic modeling

# Concluding Remarks

- Unique condition of modeling vintage materials and infrastructural components as compared to design and build
- Utilize best engineering judgment to quantify assumptions

- Questions???