# Current Knowledge and Understanding of Tank Bottom Corrosion

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# Efficient Risk Management of Components that Age

- Risk management Involves balancing the risk of component failure against cost of preventive maintenance.
- Risk of failure is the combining the consequences of leakage and the probability of failure into a meaningful measure.
- Probability of failure of members of a class of components that degrade with age, such as tank bottoms, is represented by a *survival function*.
- Constructing a survival function requires a *theory* of how the components degrade and an *experience poo*l to fine-tune the theory and identify factors, such as soil resistivity, that impact survival.

# Outline of this presentation

- NBS/NIST 1910-1945 buried-pipe experiments.
- What (little) we know about factors that influence corrosion rate in the field.
- Theory of diffusion-limited corrosion (we are talking about pitting)
- Survival functions for buried steel pipe.
- Survival functions for above-ground atmospheric storage tanks.
- More and better data is needed.
  - A protocol for tank-bottom inspections and measurements
  - Standardized definitions of corrosion measures (pit depth, remaining thickness, …)
  - A standardized suite of soil measurements (resistivity, pH, … )
  - Cathodic protection record (percent time in operation, …)

# NBS/NIST 1922 – 1952 Buried Metal Experiments

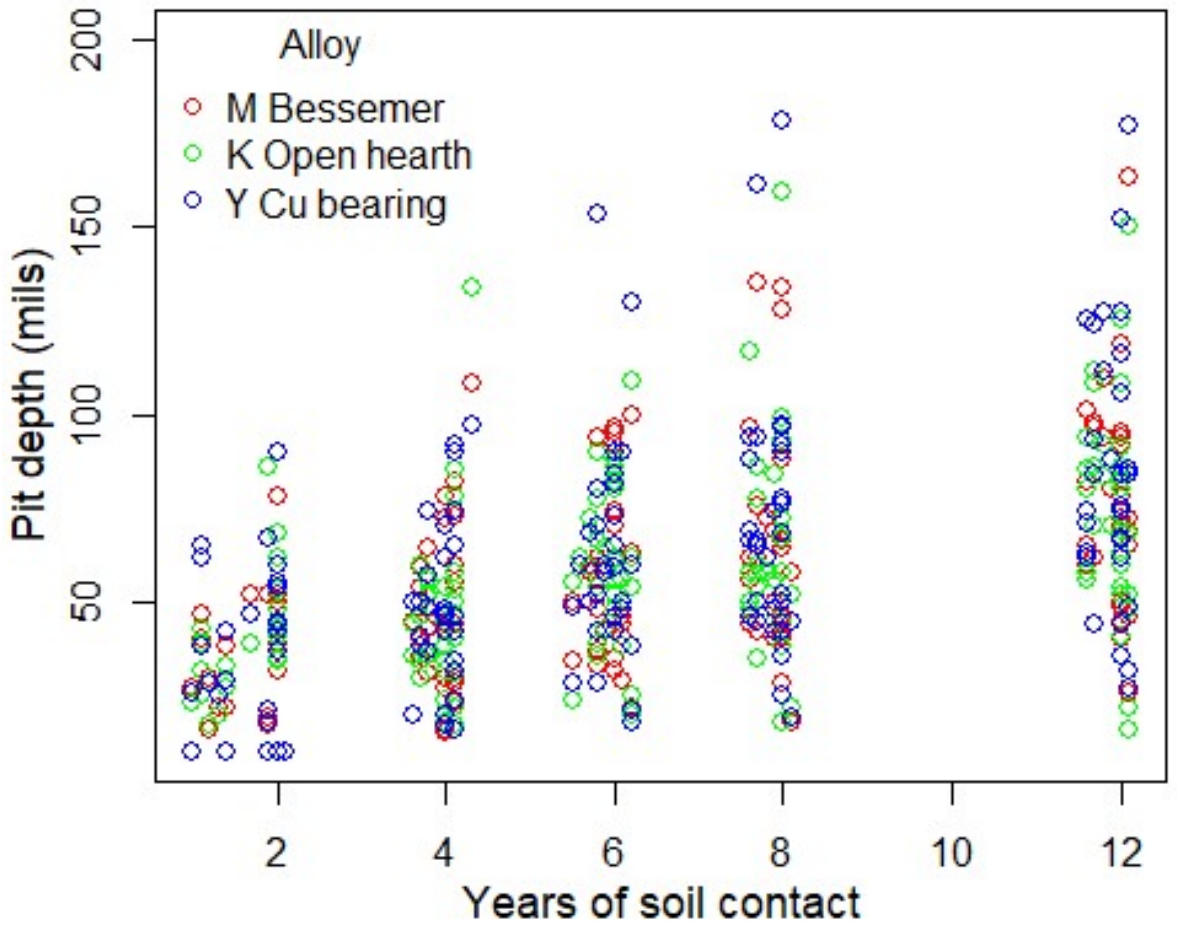
- Between the years 1922 and 1939 the National Bureau of Standards buried metallic specimens in six trenches at 47 sites throughout the United States. Specimens in one trench were exhumed about every 2 years for periods as long as 17 years, Romanoff [1]
- We analyzed sites with complete data for 2, 4, 6, 8 and 12 years [2]
- We analyzed 3” wrought steel pipes made of low carbon steel [3]

| Alloy | Description | C % | Mn % | Cu % |
|---|---|---|---|---|
| K | Open hearth steel | 0.12% | 0.41 | |
| M | Bessemer steel | 0.08% | 0.40 | |
| Y | Copper bearing steel | 0.07% | 0.24 | 0.22 |

# NBS (NIST) Sample Burial Sites

Source: Ricker [3]

# The Data are Very Noisy

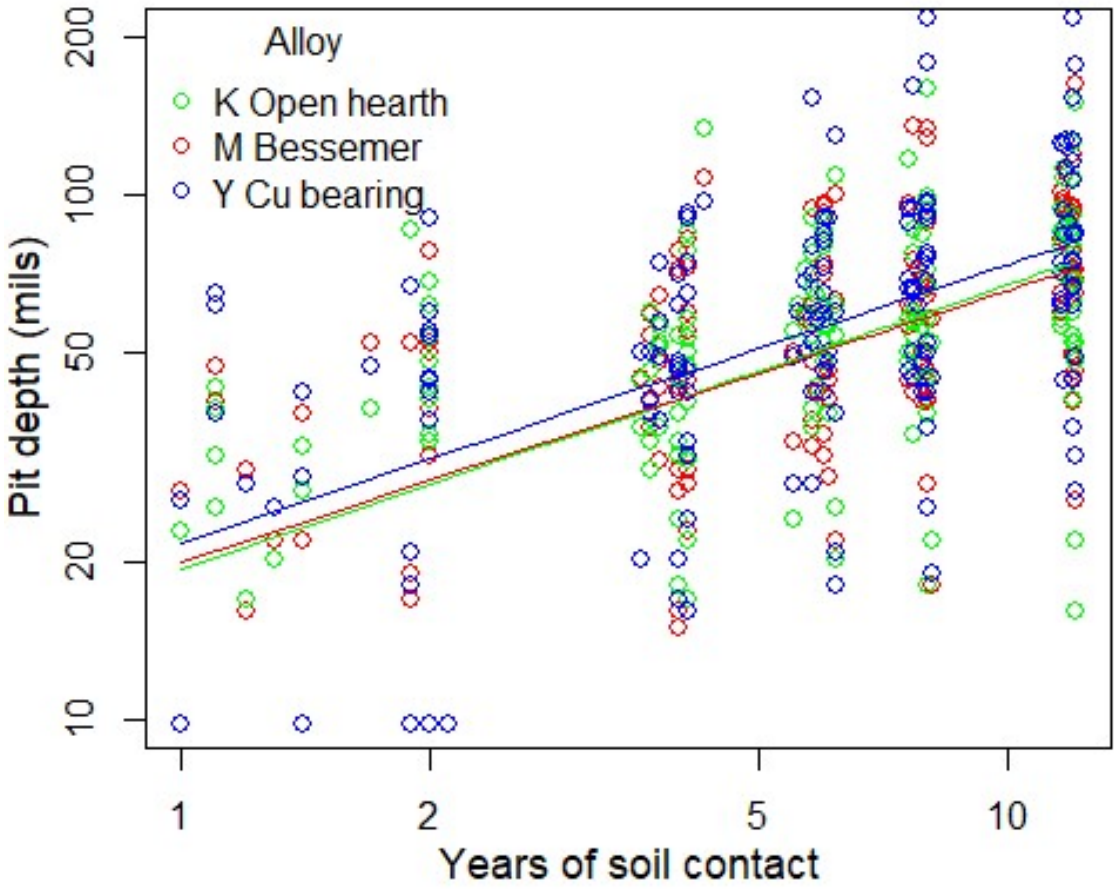


# Pit depth is log-log linear [4]

$$\ln(pit) = a + b \cdot ln(yr)$$

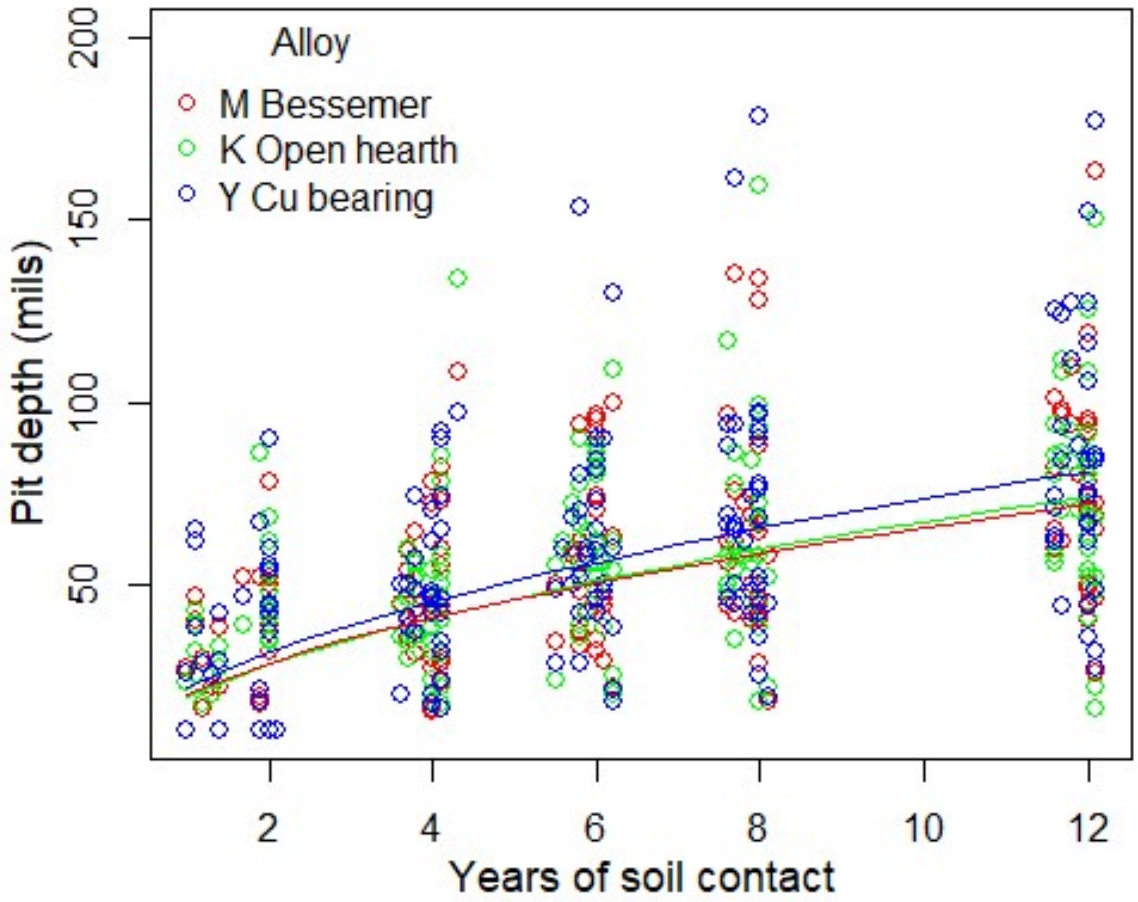
$$pit = A \cdot yr^{b}$$

| Alloy | Rate A=exp(a) | Slope b |
|---|---|---|
| M | 19.26 | 0.54 |
| K | 19.96 | 0.52 |
| Y | 21.76*** | 0.53 |



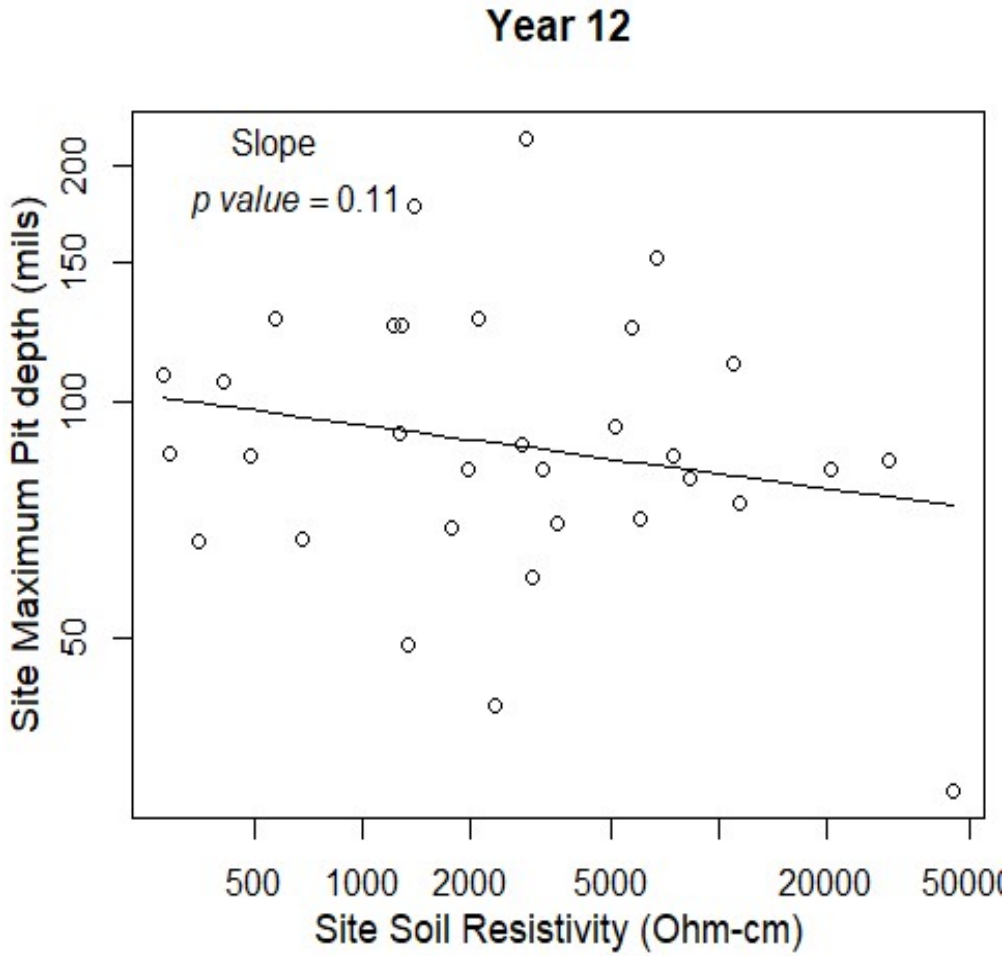
# Alloy Matters

- Copper bearing alloy Y corrodes at a significantly faster rate ($p < .001$).
- Open hearth alloy K and Bessemer alloy M have identical corrosion rates.



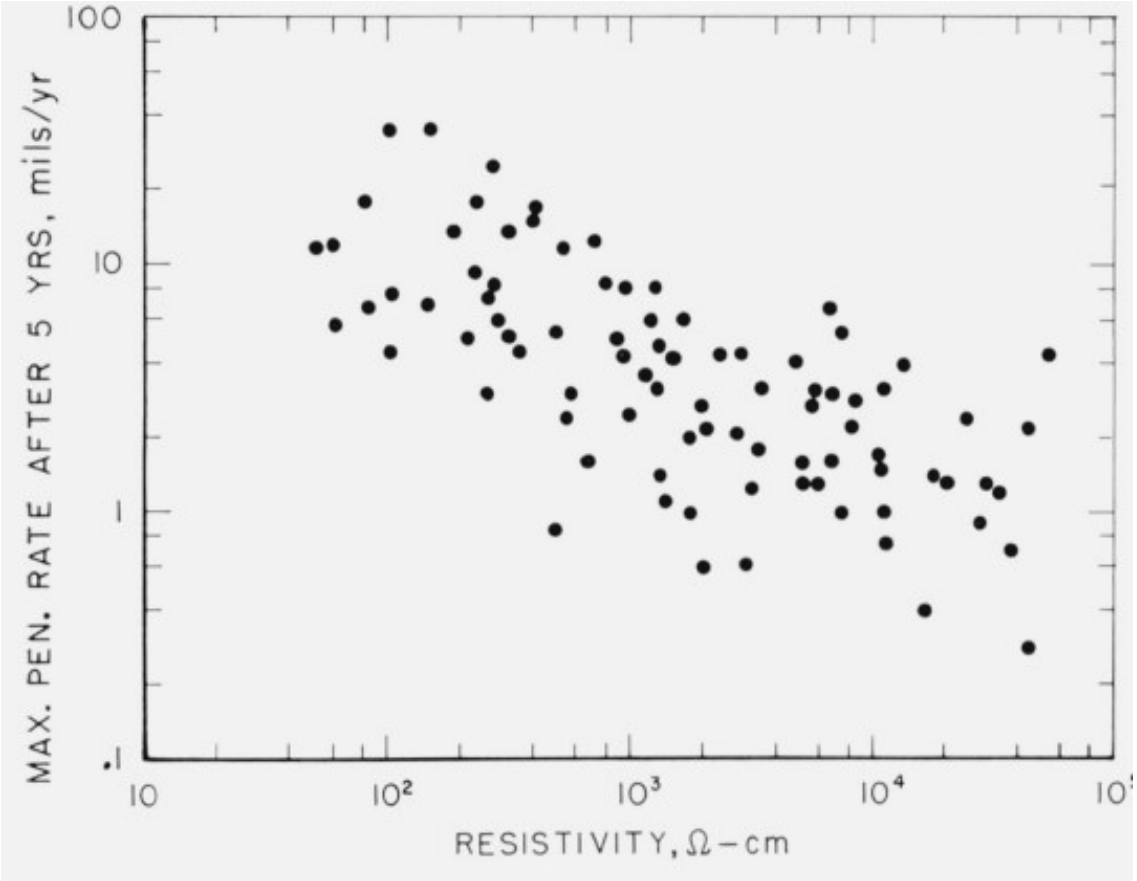
# Soil Chemistry Matters

Each point corresponds to the 12-year-exposure trench at a given site; it is the maximum pit depth of specimens of alloys M, K, and Y.



## Schwerdtfeger [5] analyzed all ferrous alloys at 86 sites.

Each point is the maximum penetration rate (pit depth/years exposed) at a given site over all ferrous alloy specimens with 6 to 17 years of exposure; each point is the maximum of at least 24 specimens (6 alloys x 4 trenches).

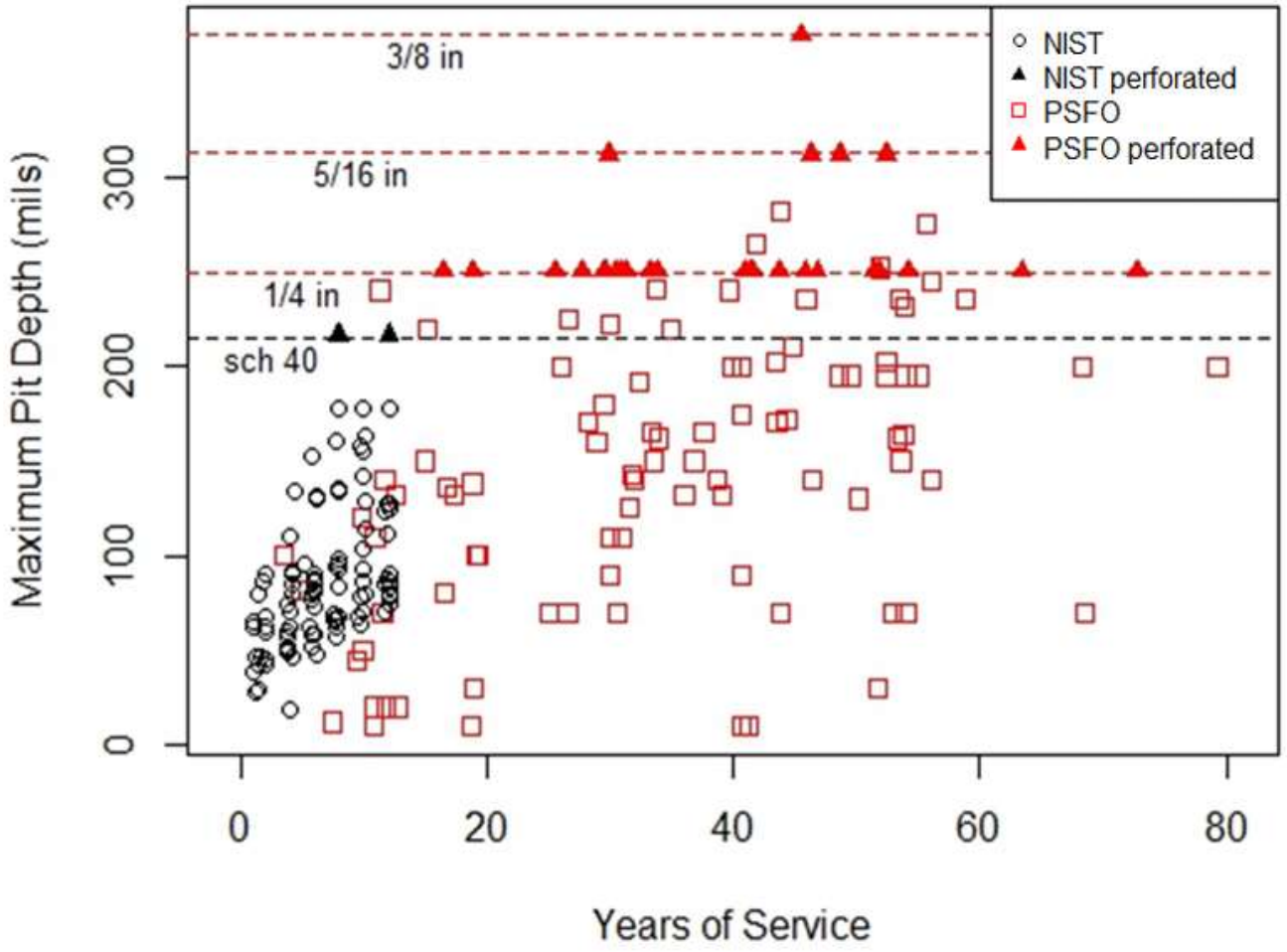


# Application to Atmospheric Storage Tanks

- We have access to data from out of service tank bottom inspections at several storage facilities provided by Petroleum Storage Facility Operators (PSFO's).
- The data are sparse:
  - One maximum pit depth value per inspected tank
  - At 10 to 80 years in service
  - No soil chemistry data.
  - No cathodic protection data.

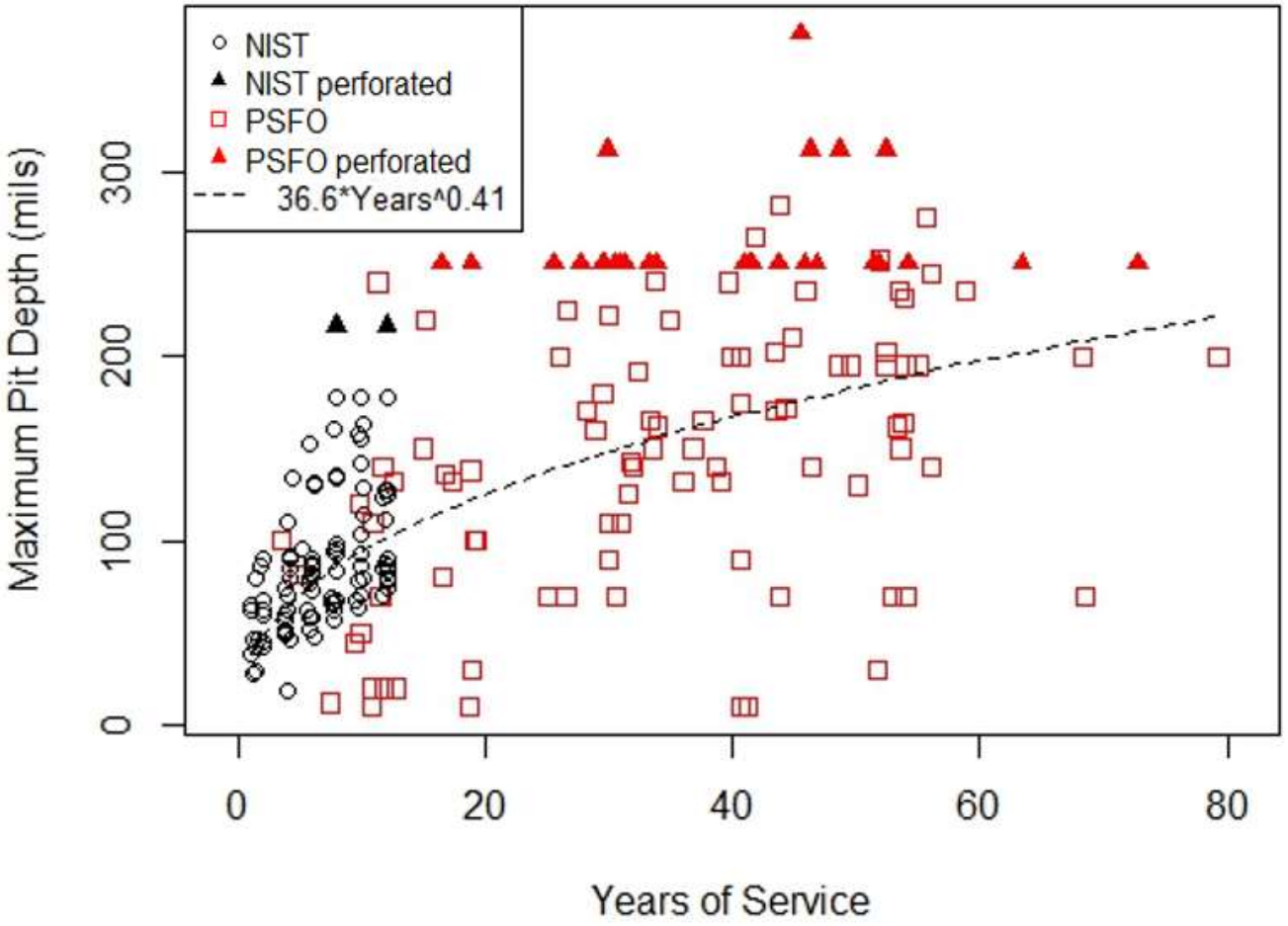
# Combined NIST and PSFO Data

Thickness of tank bottom plates and of schedule 40 pipe walls are shown. Perforated-pit depths are lower bounds on potential penetration. Such "censored" observations require special handling in statistical analyses [6].



# Power Law

- Oxygen diffusion is increasingly limited by accumulating corrosion product.
- So on average, pit depth increases at a decreasing rate, typically as a fractional power of time.
- $Depth = A \cdot time^{b}$
- Tank-to-tank variation is large.



# Forecasting Component Failure

- Actuarial methods are fine when there is a massive amount of data on component lifetimes.
- When data are sparse and expensive we need a good statistical model of component lifetimes.
- The gamma diffusion process is a productive way to model diffusion limited corrosion [7]

# Gamma Process Pit-depth Depth Model

*Mean depth at year t (mils)*:

$$\mu(t) = t_{ref} \cdot A\left(t/t_{ref}\right)^{b}$$

*Reference time:* $t_{ref}$ *(years)*

*Corrosion rate at* $t_{ref}$ *(mils/yr):*

$$A = \mu\left(t_{ref}\right)/t_{ref}$$

*Power parameter: b (unitless)*

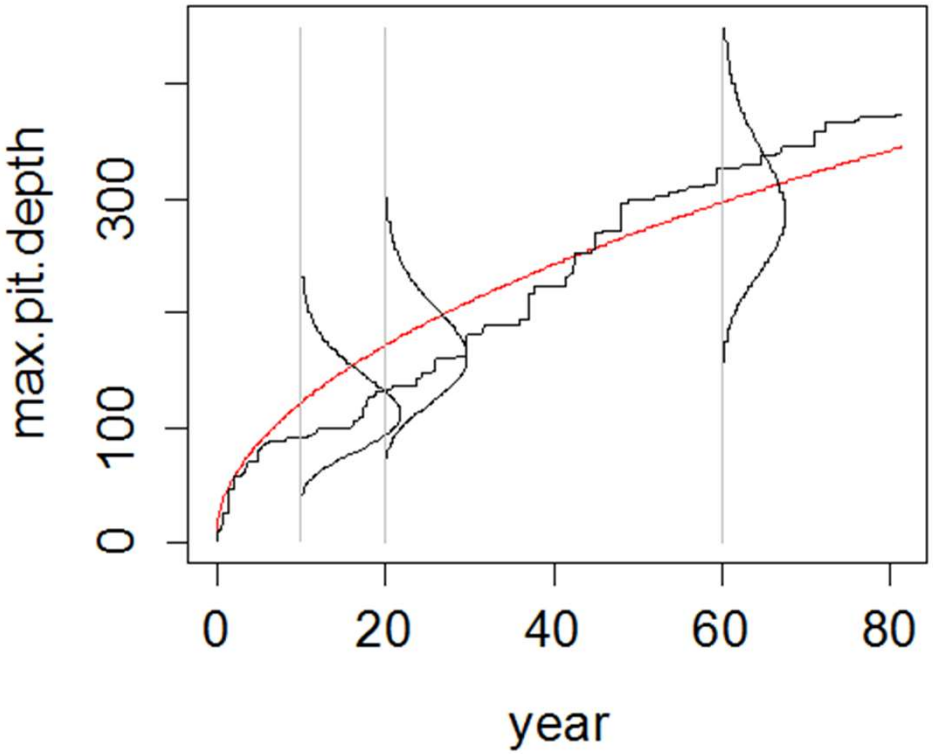
*Noise intensity:* $s$ *(mils/yr)*

*Standard deviation:* $\sqrt{\mu(t) \cdot s}$

*Distribution: gamma with*

$$shape = \mu(t)/s$$

$$scale = s$$



# Growth Increments are Independent gamma RV's

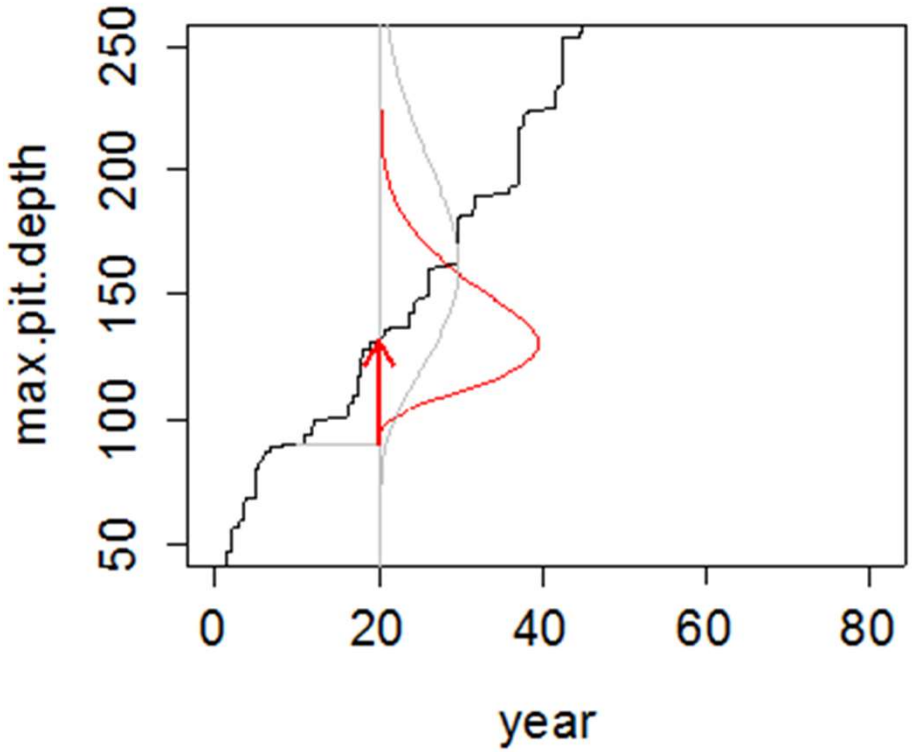
Growth ↑ from year 10 to 20 has a gamma distribution with

$$mean = \mu(20) - \mu(10)$$

$$scale = s$$

$$shape = mean/s$$

Cumulative growth is the sum of independent increments.



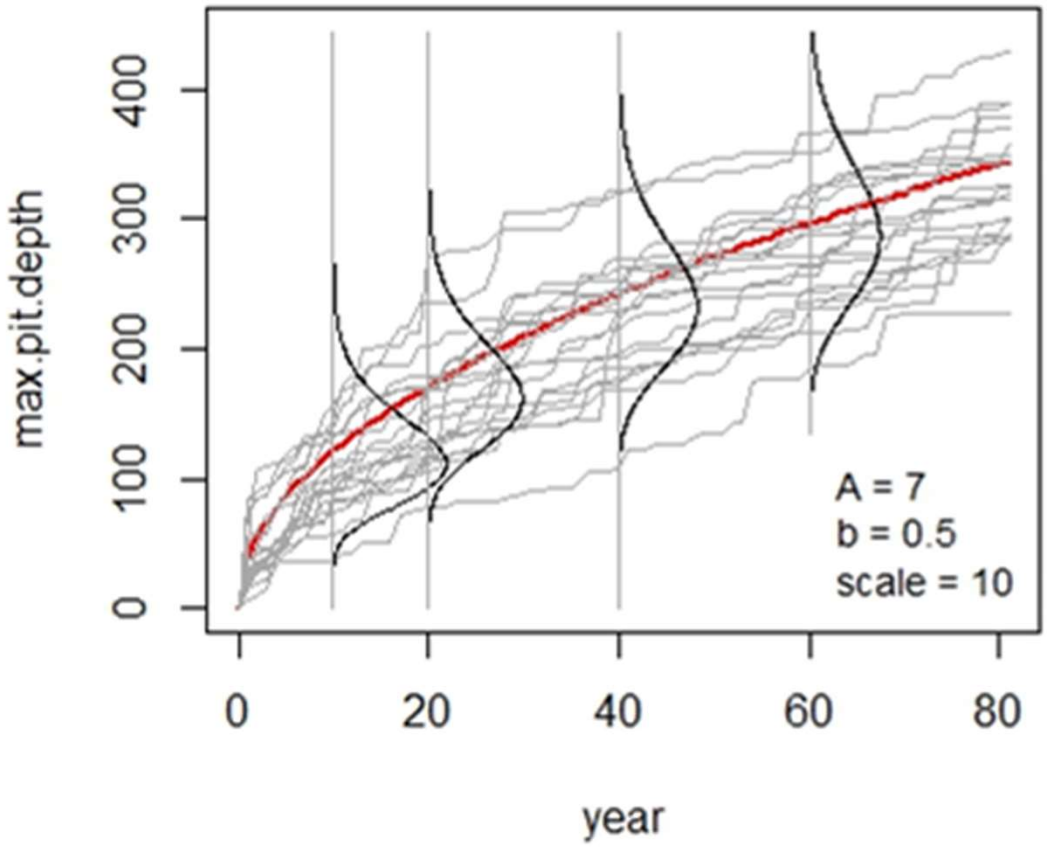
# Making it Easy to Simulate Fine-Grained Corrosion Histories

In this example,

$t_{ref} = 20\ yrs,$

so mean pit depth at 20 yrs is,

$A \cdot 20 = 140\ mils$



# Survival Function Given estimates of A, b, and s

- S(t) is the proportion of  still not perforated at time t
- S(t) can be estimated by simulation or integration

EITHER

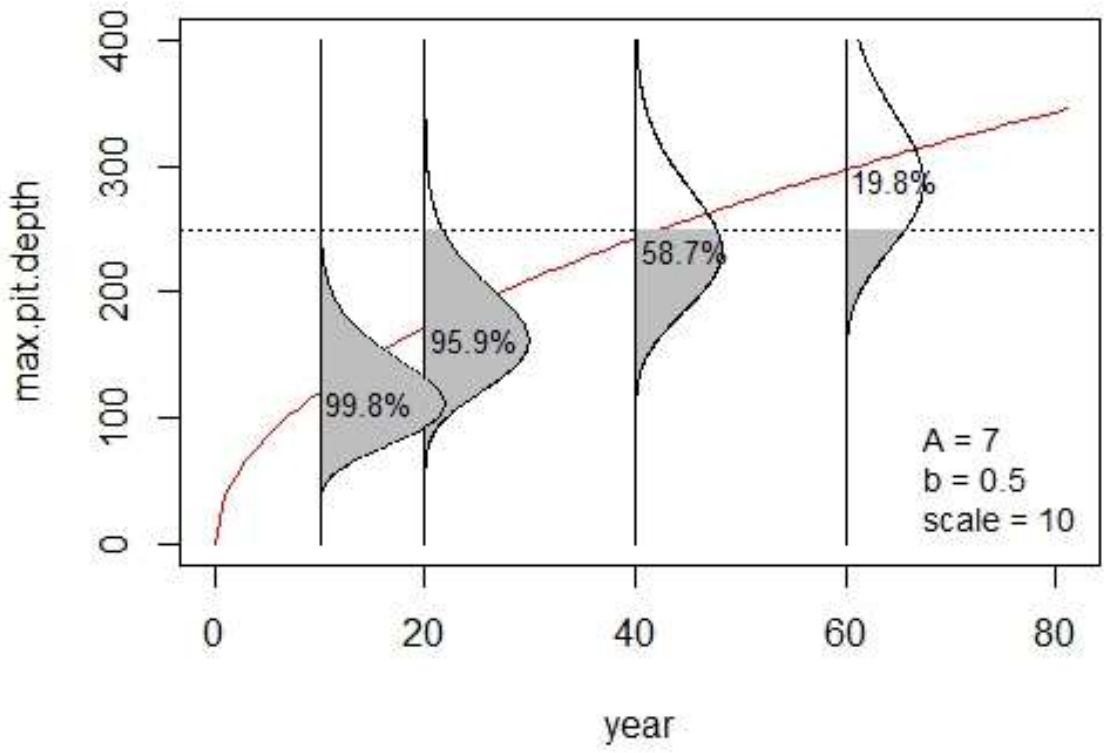
- Count the proportion of simulated histories that are under 250 mils at 10 years, 20 years, etc.

OR

- Use the gamma cumulative distribution function (pgamma function in R) to compute the exact proportion of survivors at t years.

$$S(t) = pgamma\left(250, shape = 30 \cdot A \cdot (t/30)^b / s\,, scale = s\right)$$

# Noise distribution around the mean determines % surviving (gray area) at a age.

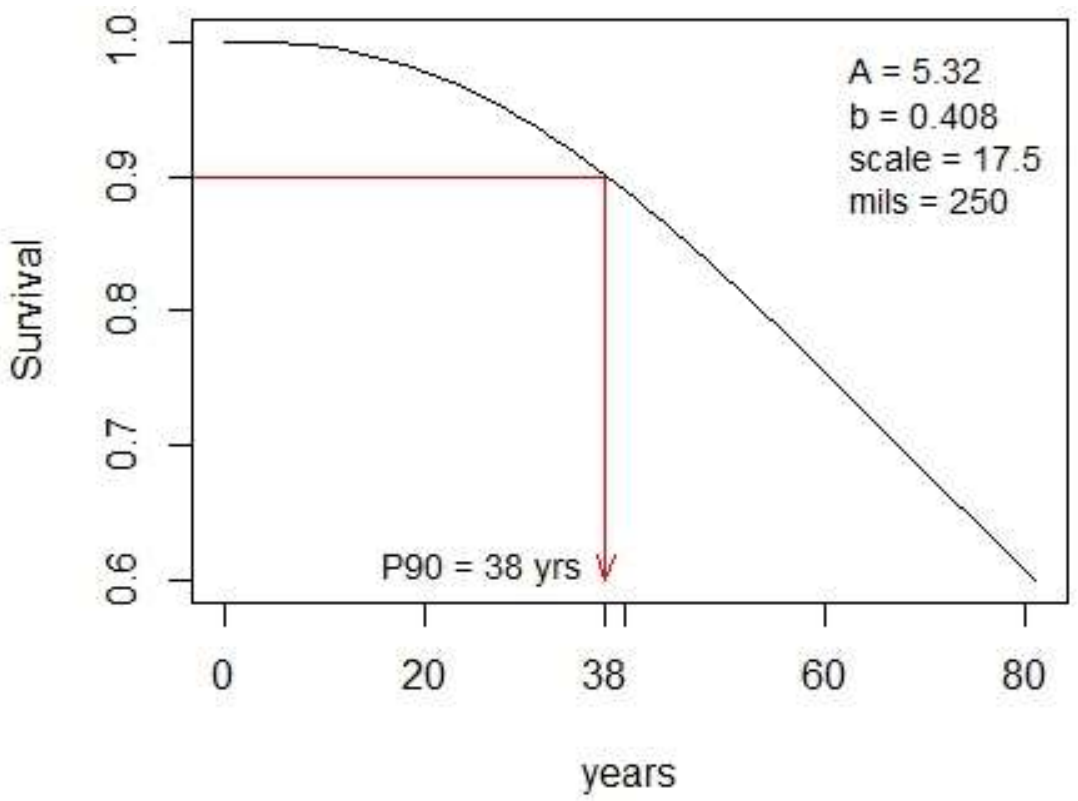



| year | Surviving % |
|---|---|
| 0 | 100 |
| 10 | 99.8 |
| 20 | 95.9 |
| 40 | 58.7 |
| 60 | 19.8 |

# A *Survival Curve* Traces the Fraction Surviving

An as yet uninspected AST with 250 mil bottom thickness is in a population of tanks with 20 year corrosion rate A = 5.32 mils/yr, power law b = 0.408, and noise intensity s = 17.5 mils/yr.

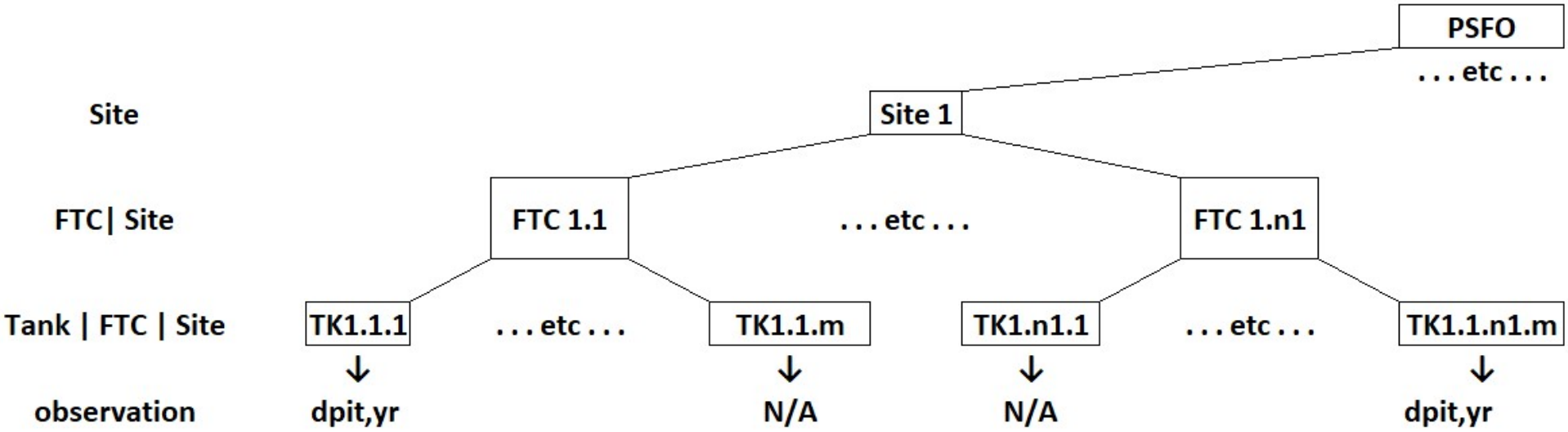
There is 90% probability that the tank bottom will not be perforated in the first 38 years of service.



# Where do we get A, b, and s?

- We need out of service inspection data for tanks fungible with the uninspected candidate tank.
- We use hierarchical random effects statistical analysis (e.g. empirical Bayes or Bayes empirical Bayes software.
- Levels of the hierarchy are
  - PSFO : Petroleum Storage Facility Operator
  - site : Storage facilities managed by PSTO
  - FTC | site : Fungible tank clusters at this site
  - tank | FTC | site : tanks in this FTC at this site

# Hierarchical Data from a Directed Acyclic Graph




Is analyzed by RJags [8]; the output is an estimated survival curve for each fungible tank cluster.

# Prototype app

The app finds fungible "control" tanks. For an uninspected "candidate" tank.

Using data from the controls it estimates the survival function of the candidate tank.

**Survival Forecast for candidate tank based on 2 control tank(s)**

Analyst: *A.N. Analyst* Date: 4/9/2018

Before you start: Click here for instructions.

| | | | | | | |
|---|---|---|---|---|---|---|
| Candidate terminal (click) | *Site of the tank* | | Control Tanks | | | |
| Candidate tank (click) | *I.D. of the tank* | | Enter Control Tolerances | | | |
| Candidate Tank Info | *Year built:* | *2011* | ± | 15 | year cand built | |
| | *Diameter:* | *180 ft* | ± | 10 | % cand diameter | |
| | *Bot. new/repair:* | *2011* | ± | 50 | yr cand bot new/rep | |
| | *2011 thickness* | *250 mils* | | | *Click to remove a control* | |
| Source of Controls (click) | | | *Seleted Control Tanks* | | | ↓ |
| Number of control tanks: | 2 | | *Fungible tank 1* | | built 1999 | |
| | | | *Fungible tank 2* | | built 2003 | |

| Year | Survival rate |
|---|---|
| 2021 | 97% |
| 2031 | 90% |
| 2041 | 83% |

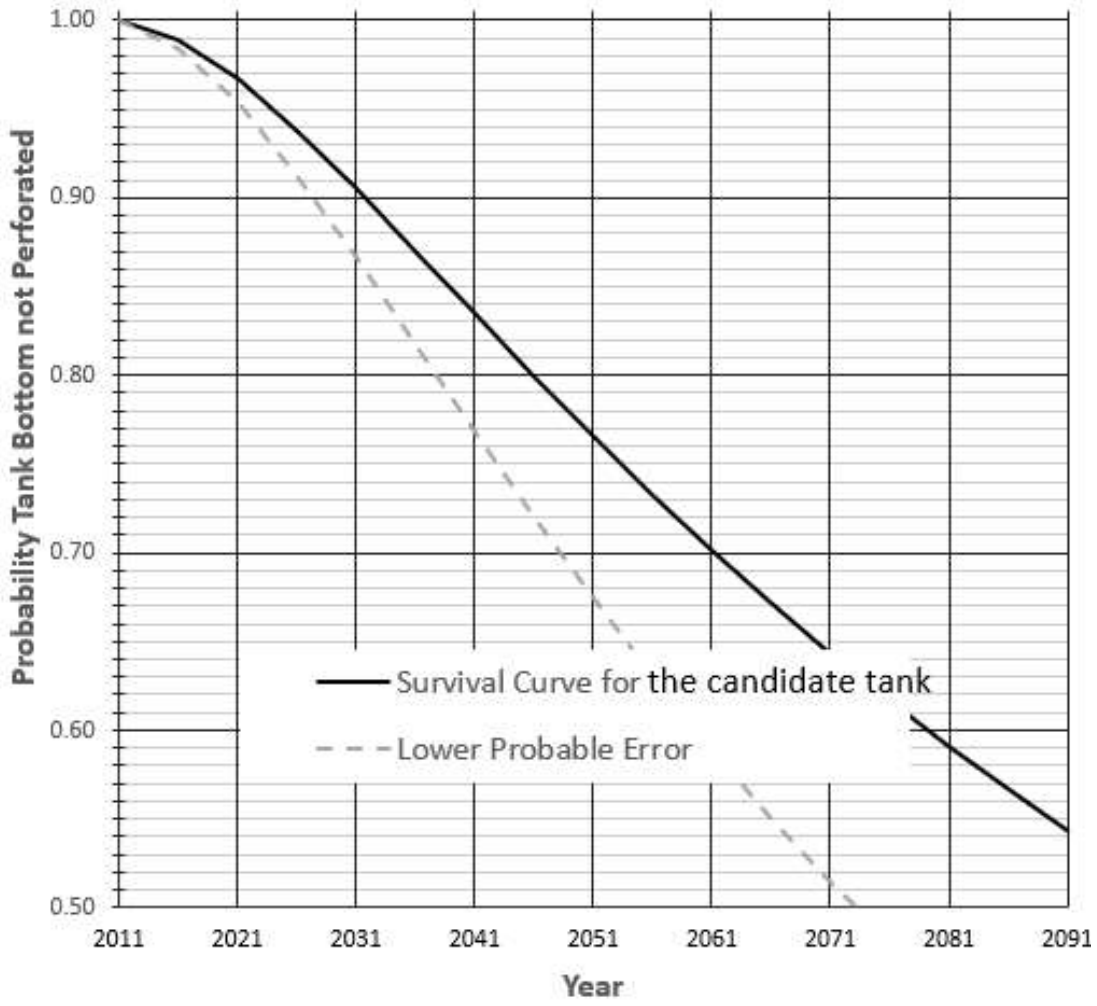
**Predicted Survival Times**

| | |
|---|---|
| 90th Percentile | 2032 |
| 95th Percentile | 2024 |
| 85th Percentile | 2039 |
| Average Linear Corrosion Rate | 9 mpy |
| Straight Line to 100 mils | 2028 |

# Estimated Survival Function

There's 75% confidence that the true survival curve is above the dotted line. So the chance of surviving 20 years could be less than 90%.

We need more and better data on factors that influence corrosion to reduce that uncertainty.



# A minimum data set (MDS) for Corrosion

The term Minimum Data Set comes from healthcare. It is defined as "A list of names, definitions and sources of data items needed to support a specific purpose."

Some purposes of a Corrosion MDS:

- What measure of amount corrosion best relates to risk of failure?
  - Average mass loss
  - Maximum pit depth
  - Other

- What controllable factors influence the amount of corrosion
  - Construction Details
    - Site preparation
    - Materials
    - Welding methods
    - other
  - Interventions
    - Cathodic Protection
    - Lining
    - Cleaning
    - Repair techniques
    - other
  - Product history

- What uncontrollable factors influence the amount of corrosion
  - Soil chemistry & moisture
  - Bacteria
  - Climate
  - Foundation
- How reliable are ultrasonic and other tank bottom corrosion measures
  - Are/can/should they be standardized?
  - Do vendors adhere to ASTM E797? Do they calibrate? Do they run duplicate scans?
  - Do different vendors produce comparable measures?
  - Can “ground truth” be determined

# How can API help improve corrosion data quality.

- API could sponsor a retrospective tank bottom corrosion study?
- Better, API could sponsor a prospective study with formal data measurement and collection protocols to (a) provide the minimum data set and (b) improve the consistency and accuracy of the date

# What's Next?

- Unlikely there will be the will and discipline for a concerted systematic effort to collect data properly for the purpose of better prediction of tank bottom corrosion rate models.
- However, this model can be used for any company that wishes to have a model that is technically sound and defensible that uses all of the information currently known in the industry combined with the companies data using principle of Bayesian Data Analysis.
- For more information, contact Philip Myers at phil@pemyconsulting.com or 9250-302-6707

# Notes

[1] Melvin Romanoff, Underground corrosion, N BS circ. 579, U.S. Government Printing Office, Washington , D. C. (1957).

[2] Data at 17 years were collected at low corrosion sites and give a biased picture of 17 year corrosion rates. At those sites, no data was collected at 10 years, so the 10 year data are biased toward high corrosion.

[3] Richard E. Ricker, Analysis of Pipeline Steel Corrosion Data From NBS (NIST) Studies Conducted Between 1922-1940 and Relevance to Pipeline Management. [J. Res. Natl. Inst. Stand. Technol. 115, 373-392 (2010)]

# Notes (continued)

[4] Theoretical justification: Fig 6, “Stable pitting corrosion of stainless steel as diffusion-controlled dissolution process with a sharp moving electrode boundary.” Corrosion Science 49 (2007) 319–346.
Experimental justification: Section 5, of [3]

[5] W. J. Schwertferger, “Soil Resistivity as Related to Underground Corrosion and Cathodic Protection,” JOURNAL OF RESEARCH of the National Bureau of Standards- Co Engineering and Instrumentation Vol. 69C, No. I, January-March 1965,

# Notes (continued)

[6] In R, the statistical programming language, the function truncreg allows fitting linear models to a dependent variable with some truncated values. https://www.rdocumentation.org/packages/truncreg/versions/0.2-4

[7] Mahmoodian, M. and Alani, A. (2013). "Modeling Deterioration in Concrete Pipes as a Stochastic Gamma Process for Time-Dependent Reliability Analysis." J. Pipeline Syst. Eng. Pract., Volume 5, Issue 1.

[8] Andrew O. Findley, " Using JAGS in R with the rjags package, " http://blue.for.msu.edu/CSTAT_13/exercises/exercise-1/ex-1.pdf