ELECTRIC POWER RESEARCH INSTITUTE

Interim Guidance for Determining Corrosion Rates for Evaluating FFS of Buried Pipe

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EPRI/NRC Meeting

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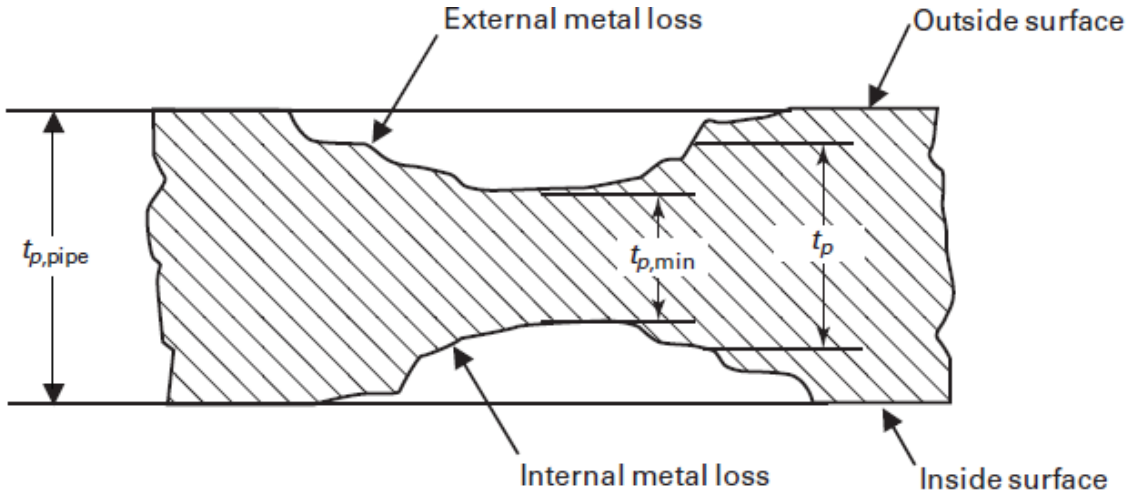
Background

- ASME Code Case N-806 provides fitness-for-service rules for evaluating degraded buried pipe
- Rules require determination of the predicted rates of metal loss on both the internal surface and the outside surface during the evaluation period
  - Responsibility of the Owner
- The rate to account for concurrent internal and external corrosion, as applicable, at the affected location



Objectives: Scope

- Provide interim guidance to plant owners as to how to determine corrosion rates for use in FFS and remaining life evaluations
  - Topical Report that complements Code Case N-806
- Scope:
  - Buried pipe
  - Soil side and fluid side
  - Carbon steel and stainless steel materials
  - Use results to improve inspection guidance to plants
- Excludes
  - Other materials
  - Cracking, fouling, uncommon mechanisms
  - Encased pipe

Why Interim?

- Most of the soil side corrosion data is found in NBS Circulars C401 (published in 1933), C450 (published in 1945), and C579 (published in 1957, author was Melvin Romanoff)
- C579 study consisted of 6 sets of duplicates, at ~60 sites throughout the US (varying soil compositions, but not quantified)
- Limitations included:
  - Pipe not grounded
  - Mostly iron and steel pipe
  - No welds
  - No CP
  - Mostly uncoated
  - Only short sections of pipe were buried (6” – 12”)
- Additional tests underway to evaluate these effects; use results to update guidance; 3 year project

Use of Guidance

- Guidance intended for FFS evaluations of inspected locations
- Important that accurate inspection data be obtained
  - Separate ID from OD degradation
  - Maximum pit depth and average wall loss
  - Sufficient length of pipe be inspected
  - Pipe inspected 360º
  - Welds/joints be inspected
  - Proper inspection method be used
    - E.g., pits in SS welds can have a small surface opening
  - Inspections follow a written procedure
- Corrosion rates from applicable test stations or other sources can be used in-lieu-of this guidance

ID Degradation

- Most buried pipes have portions that go above ground
- Guidance will be to take repeat measurements of above ground segments that have similar conditions (material, joints, temperature, flow rate, water treatment, etc)
- Identify both:
  - Maximum penetration (e.g., pit depth)
  - Average wall loss
- Combining OD and ID wall loss is discussed later in presentation

Corrosion Loss Prediction for Fitness for Service Assessment of Buried Pipes

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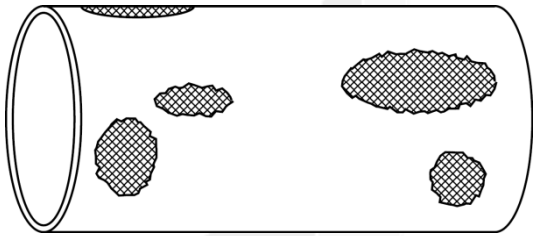
EPRI, AECL and University of Waterloo

Overview

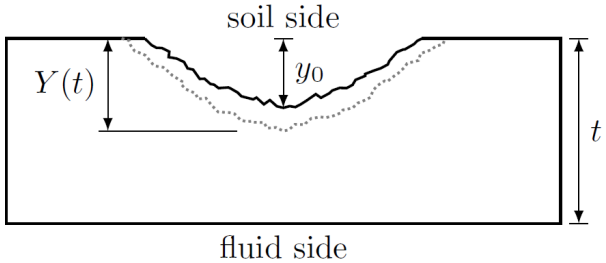
- **Assessment of time to reach to a critical thickness limit as per the FFS requirement**
  - Problem description - Corrosion flaws
  - Pitting affects the leak integrity
  - Mass loss affects the structural integrity
- **Probabilistic modeling of soil-side corrosion**
  - Regression model – Steady State Rate
  - Stochastic process model
- **Statistical data analysis and results**

Source of Data

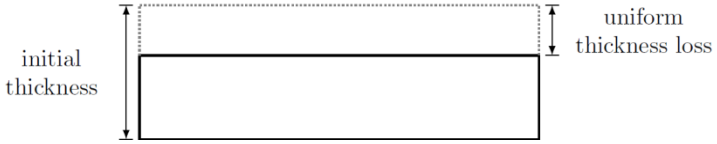
- **Short (6”-12” long) pipe sections (1.5”-3” dia)**
  - Small samples buried at 70+ sites across US over a period of 20+ years
- **A pipe sample with many pits**
  - Extract two types of data



(1) Maximum pit depth

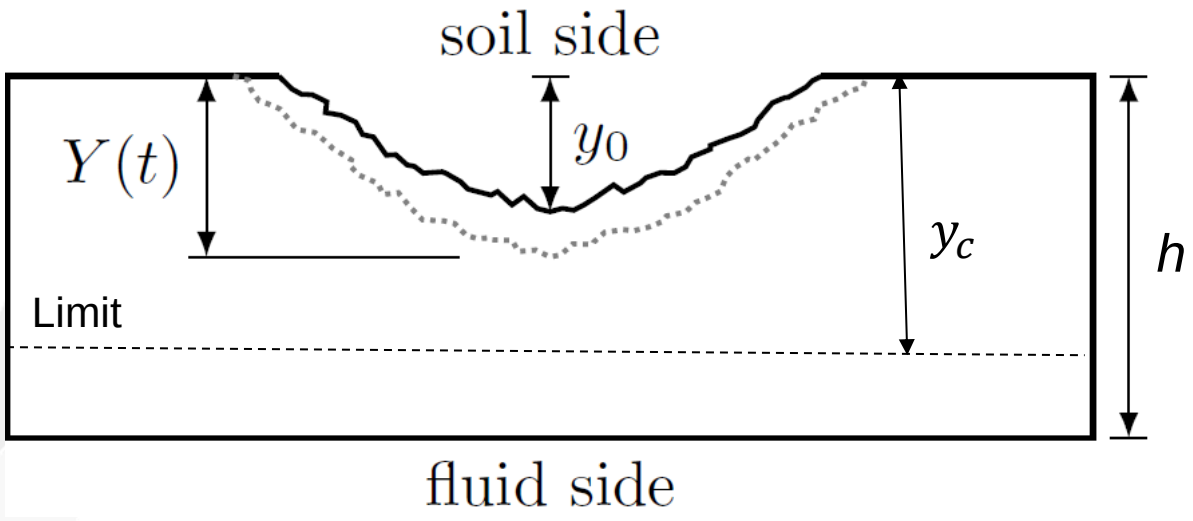


(2) Equivt. uniform thickness loss



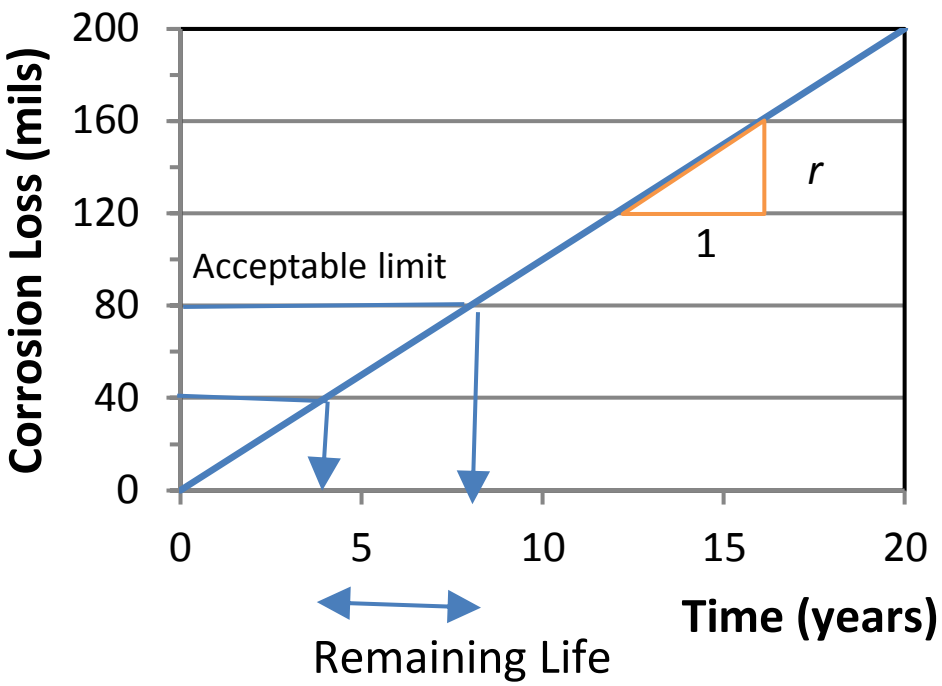
Basic Terminology

- $Y(t)$: Corrosion penetration at time t, a random variable
- y_0 : Current wall thickness loss (at the time of inspection)
- y_c: Acceptable limit of the wall thickness loss
- h : Pipe wall thickness



Deterministic Approach – Rate Model

- **Implicit Idea**
  - Degradation process is linear in time at a fixed rate = *r*
- **Time to leakage = time at which the penetration exceeds a limiting value ($Y(t) > y_c$)**



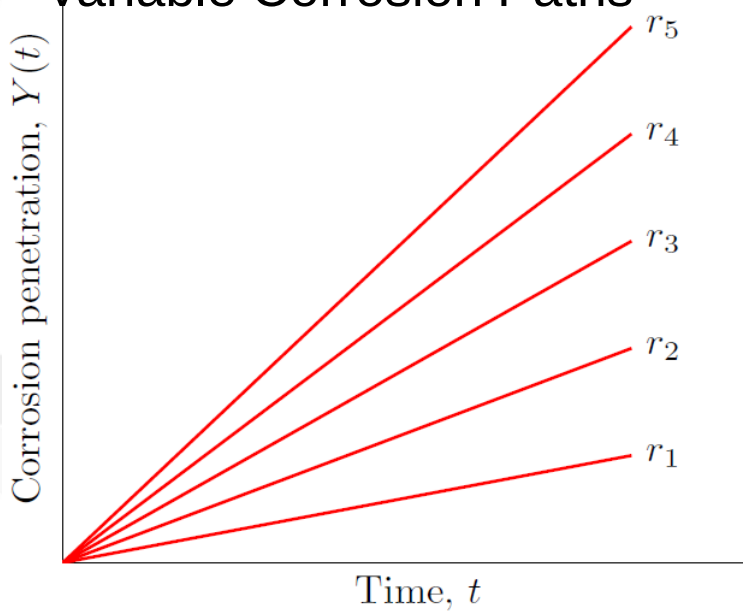
Time to leakage

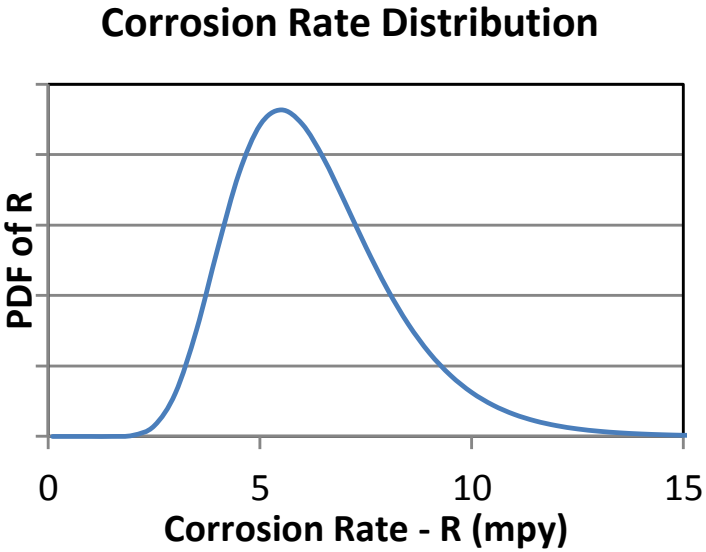
$$= \frac{acceptable\ loss\ (y_c) - current\ loss(y_0)}{Rate\ of\ corrosion}$$

Extension: Probabilistic Approach

- **Corrosion rate is a random variable with a probability distribution**
  - Linear model of corrosion loss is implicit
- **The rate varies from flaw to flaw and pipe to pipe operating even in a similar environment**

Variable Corrosion Paths





Prediction of Time to Reach a Critical Thickness (y_c)

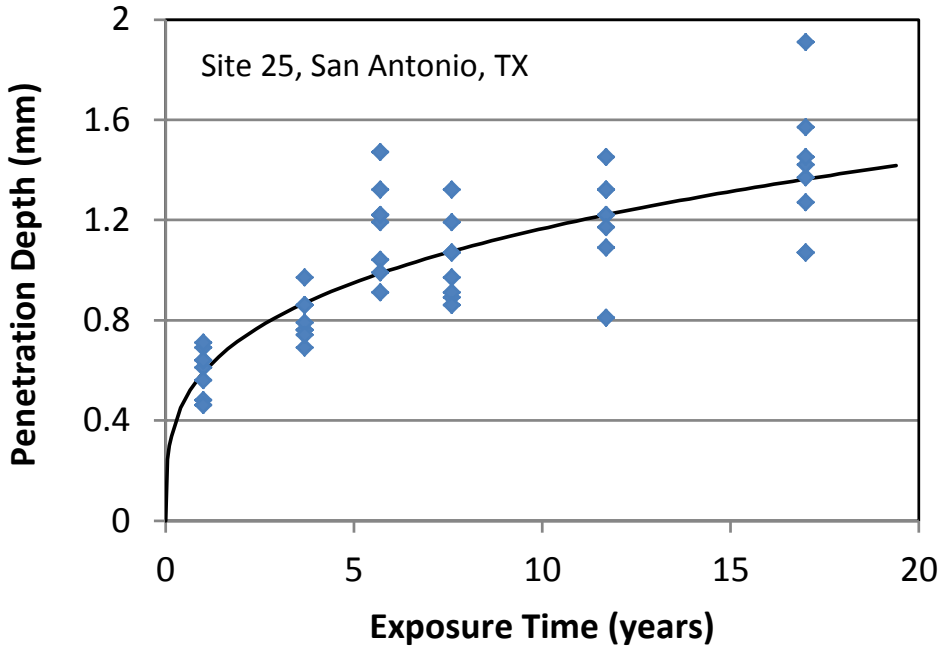
- **Time to reach y_c is a random variable: *T***
- **Probability distribution of *T* is related to the distribution of pitting rate – *R***
- $P[T \leq t] = P[Y(t) > y_c] = P[Rt > y_c]$
- $F_T(t) = 1 - F_R(\frac{y_c}{t})$
- **Instead of a full probabilistic analysis, the use of an upper bound rate is more practical**
  - Using an upper bound, 80th percentile, of rate *(R)* implies that actual remaining exceeds the estimated life **with 80% probability**

Underground Corrosion: Data

- **National Bureau of Standards (1922 – 1939)**
  - Bare steel pipe sections buried underground corrosion
  - 60+ soil sites across the U.S.
  - Average characterization of the soil chemistry and environmental conditions
- **Material: 6 different types of carbon steel**
  - 1.5” dia, 145 mils thick, 6” long pipe sections
  - 3” dia, 216 mils thick, 6” long pipe sections
- **Time dependent data consist of**
  - Mass loss: average of 2 samples of each material retrieved from each site periodically
  - Maximum penetration depth : avg. of 2 samples of each material retrieved from each site periodically

A Typical Sample

- Maximum penetration depth over time plot
- Large variability in the data
- A nonlinear nature of the localized corrosion process was conceptualized

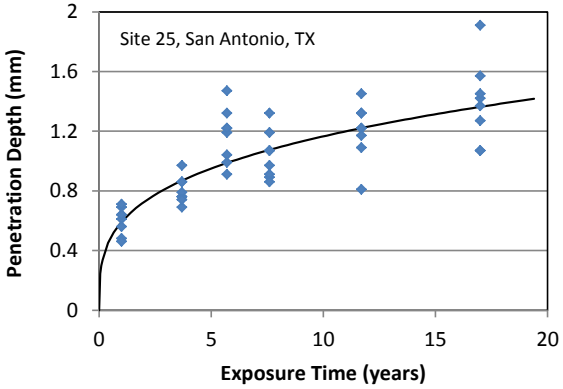


Nonlinear Corrosion Process

- **Romanoff study (1957) postulated a nonlinear law of localized pitting corrosion**
  - $Y(t) = at^n$
- **The pitting rate is a function of time (non-stationary process)**
  - **<u>Tangent</u>** rate ($\frac{dY(t)}{dt}$): slope of the tangent at a point
  - **<u>Secant</u>** rate ($\frac{Y(t)}{t}$) : slope of a chord joining a point & origin
- **Which rate to use?**
- **Modeling of uncertain and non-stationary nature of pitting process is a key analytical task**
  - Probabilistic model and statistical calibration

Statistical Prediction of Pitting

- **What will be the growth in the pit depth during the evaluation period?**
  - Easy to answer in a linear process
- **To answer this in a nonlinear process, we need**
  - The time of pit initiation (not known)
  - Equation of the curve (varies from site to site and soil to soil)
- **This investigation tackles both issues**
  - Statistical modeling of corrosion process
  - Steady state rate of corrosion



Previous Work

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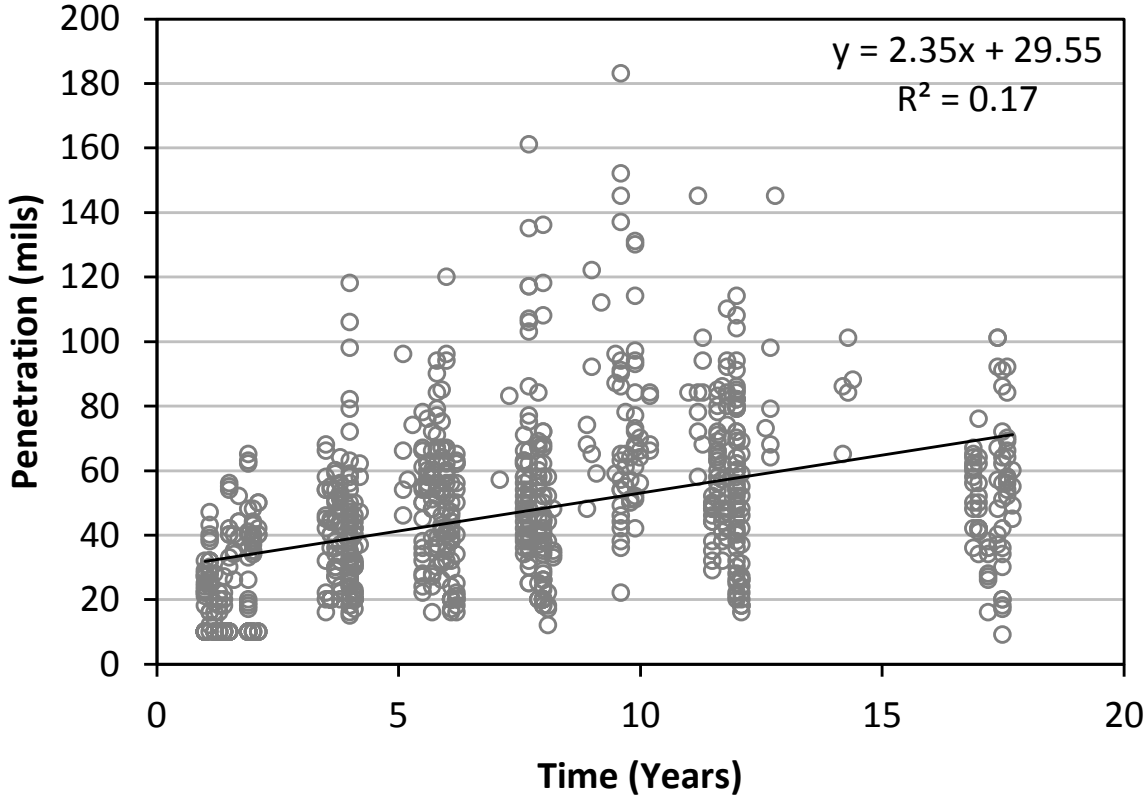
NBS Study (1922-1939)

- **All the data for carbon steel pipes samples**
  - How to explain large scatter in the data?
  - Explore correlation with various factors



Factors Affecting Corrosion

1. **Aeration**
   - Access of moisture and oxygen to the metal
   - It depends on physical characteristics of soil
2. **Electrolyte**
   - Facilitates the flow of current
   - Soli chemistry: Soluble salts, resistivity, acidity, moisture
3. **Soil texture**
   - Sand, clay, silt, loam, peat & muck
4. **Electrical Factors**
   - Size, number and location of anodic areas
   - Properties of the metal

NBS Study (1922-1939)

- **Lognormal regression model**
  - $lnY(t) = \ln a + n \ln t$
  - "*n*" is logarithmic rate of corrosion
- **Correlation between "*n*"and parameters related to soil & environment was analyzed**
  - Resistivity, moisture, pH, acidity, soil chemistry
- **No meaningful correlation was found**

Lack of Correlation: Reasons

- **In a laboratory setting, the effect of individual factors on corrosion can be controlled**
- **Underground corrosion depends on time dependent interaction of all the factors**
- **NBS data contained a ONE TME characterization of the environment of burial sites (chemistry, aeration, temperature and precipitation)**
- **Data ignored**
  - Spatial variability in the characterization of soil chemistry
  - Seasonal variation in the environmental
- **Parameters do not represent actual conditions present in the vicinity of the pipe sample**

A Reanalysis of NBS Data (2007)

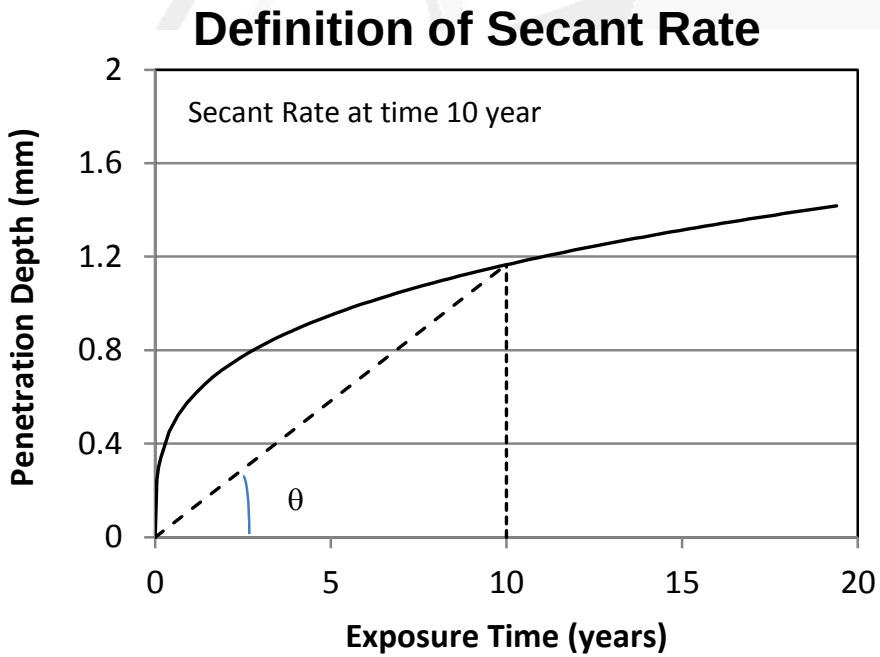
- **NIST-IR-7415 (2007) by Ricker carried out statistical analysis of data given in Romanoff study**
  - Nonlinear regression modeling
- **This study also confirmed a lack of crisp correlation between corrosion rate and other parameters**
  - Discussed reasons for lack of correlation
  - Parameters related to the soil environment and chemistry did not represent real condition in the vicinity of samples
- **The analysis of (secant) corrosion rate is problematic**

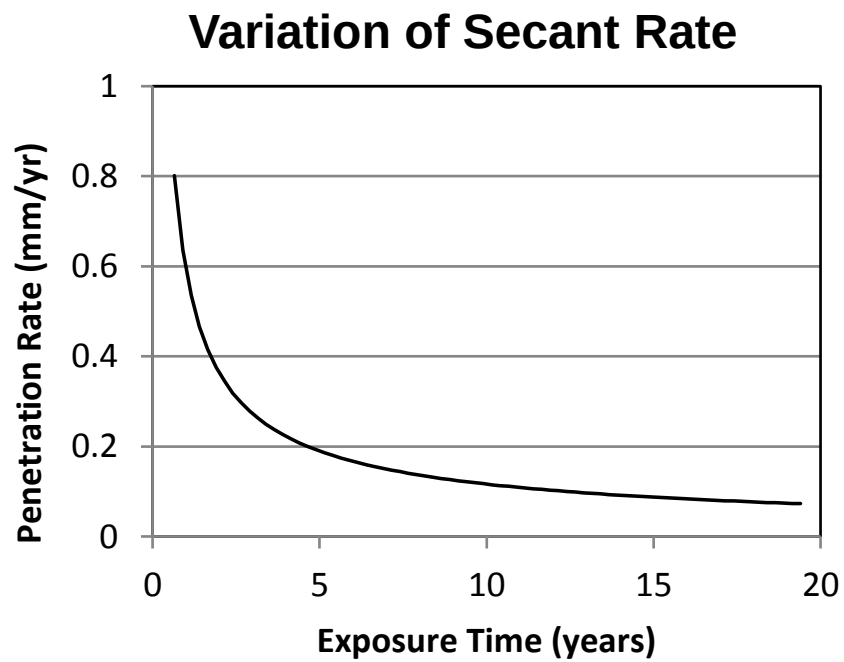
Default Rate: ANSI/NACE SP0502-2010

- **Default pitting rate of 0.4 mm/year (16 mpy) is recommended**
  - 12 mpy for locations with CP
- **This rate represents the upper 80% confidence level of <u>maximum</u> pitting rates for long-term (up to 17 year) duration**
  - Precise details of data and statistical analysis techniques are not given in the Standard
  - It appears that maximum pitting RATE data from the Romanoff's study were pooled and fitted by a distribution
  - Pooling of (secant) rates data is an additional source of sizable variability

Secant Rate of Pitting: Remarks

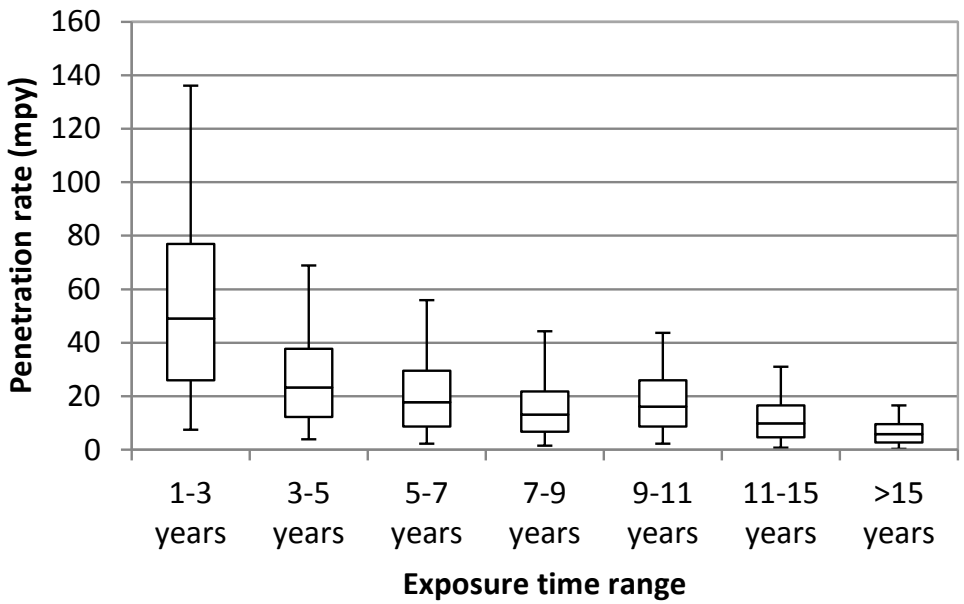
- **Secant rate varies by several orders of magnitude with the exposure time**





Secant Rate Variation : Data

- **Data from Romanoff study shows a large variation in secant rate with the exposure time**
  - The rate has large variability in early life
  - Variability reduces with exposure time, as expected



Pooling of (Secant) Pitting Rate Data

- **A naïve pooling of secant rates is <u>incorrect</u>**
  - Rates are non-stationary with very large variation over the exposure period
  - Pooling of rate will introduce large and <u>"artificial" variability</u> in the data
  - The nature of pitting process is sensitive to soil texture and chemistry, which should be taken into account in the statistical analysis

API 581: Recommended Rates

- **Soil Side corrosion rate = base rate modified by a set of multiplicative factors**
- **Factors to account for resistivity, temperature, CP and coating**
- **Three base rates are given (Table 2.B.12.2)**
  - 1 mpy (sand), 5 mpy (silt) and 10 mpy (clay)
  - Resistivity factor varies from 1.5 to 0.6
- **The basis for the estimation of the base rate is not discussed at all**

Summary

- **Data related to soil side corrosion under realistic conditions are limited**
  - The NBS study is the most comprehensive study
  - A large data set was generated during the time of development of modern statistical methods
- **Standards have recommended base line or default rates**
  - 80th percentile of the distribution as an upper bound rate
  - Conceptual modeling and prediction issues are not clearly addressed

Present Investigation

- **Statistical analysis of pitting and mass loss data by Regression models**
- **Objective**
  - To estimates the statistical upper bounds of pitting rate and equivalent uniform thinning rate for various groups of soils
- **Scope**
  - Analysis of carbon steel data (0.8 to 0.15 %C)
  - Cast iron and stainless steel will also be included in the report

Data Analysis and Results

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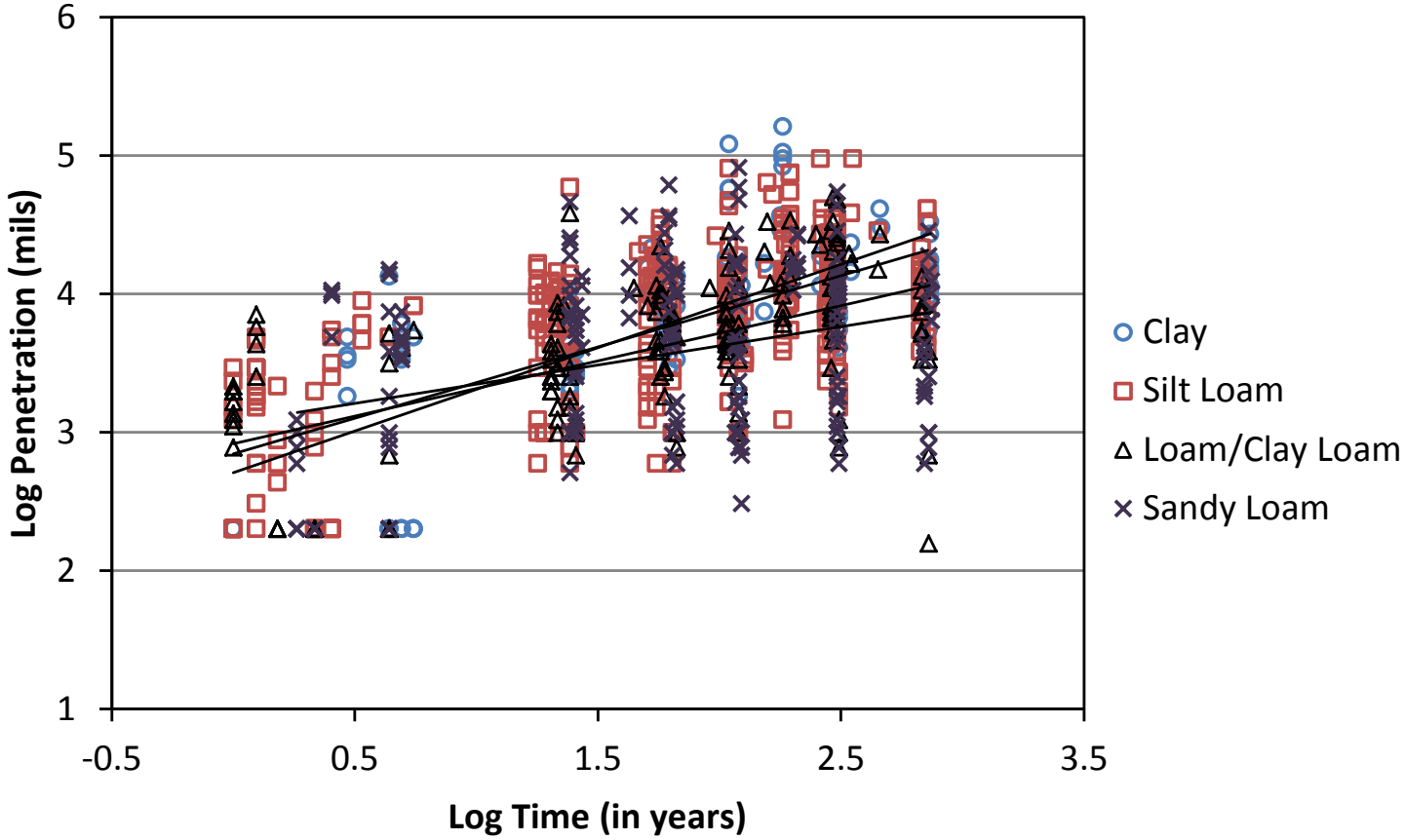
Basic Ideas

- **Localized corrosion rate exhibit erratic variations in early stages (< 5 year)**
  - After this, corrosion growth reaches a steady state
- **Prediction of Time to reach critical thickness should be based on the steady state of corrosion**
  - Existing piping system, if corroding, are expected to be in a steady state of pitting process
- **There is no point in seeking a correlation with a long list of parameters**
  - Conditions in the vicinity of pipe are stochastic, which continue to vary over the service life
- **A better approach is to estimate the rate for broader classifications of soil**
  - Texture, aeration and chemistry

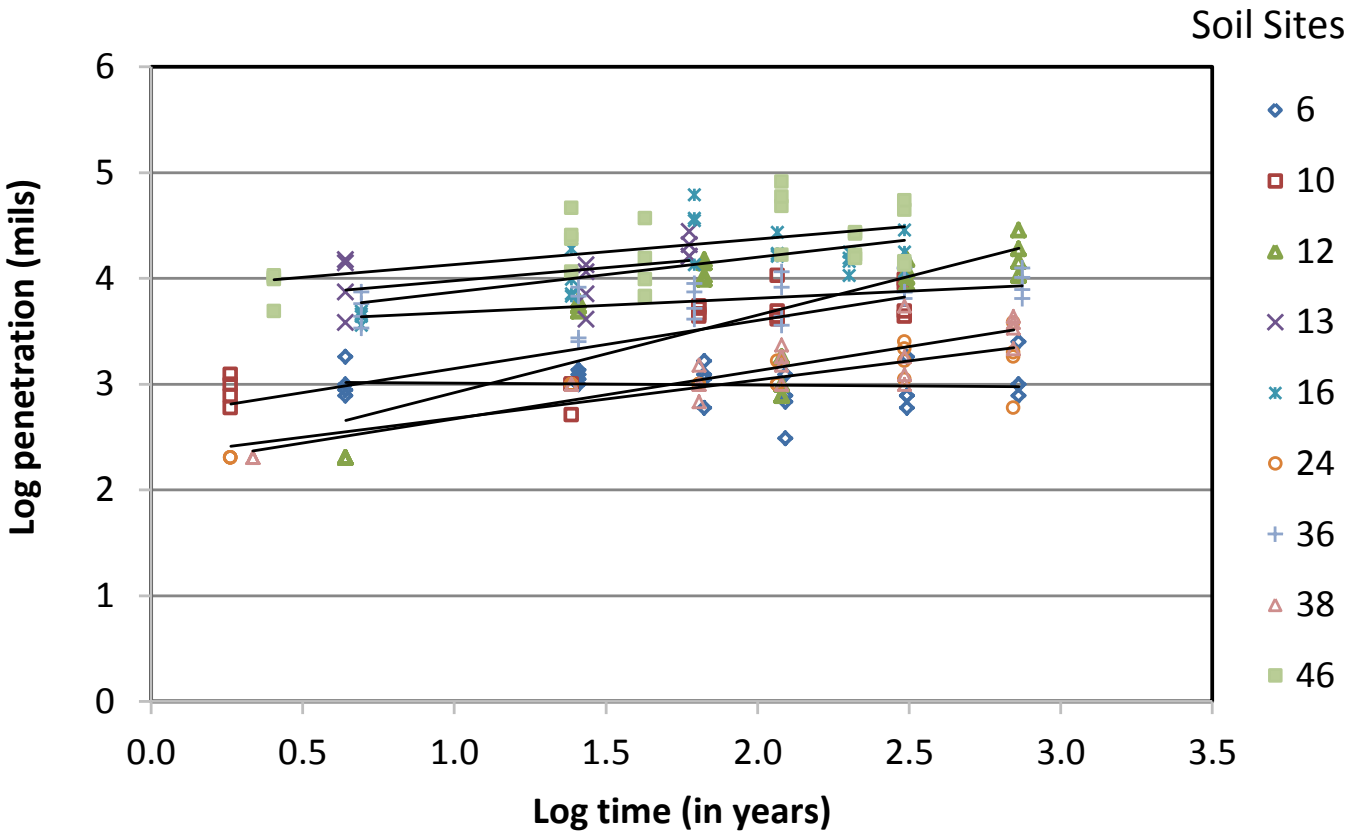
Soil Groups within the Data

- **Carbon steel data can be divided into groups based on the soil texture**
  - Groups have different trends



Trends within a Group

- **In a group, such as sandy soil, trends vary from soil site to site**
  - Pitting rate is variable in spite of similar texture



Proposed Modeling Approach

- **Logarithmic regression of corrosion penetration (in mm) over time**

$$\boldsymbol{Ln\big(Y(t)\big) = ln(a) + nln(t) + \varepsilon}$$

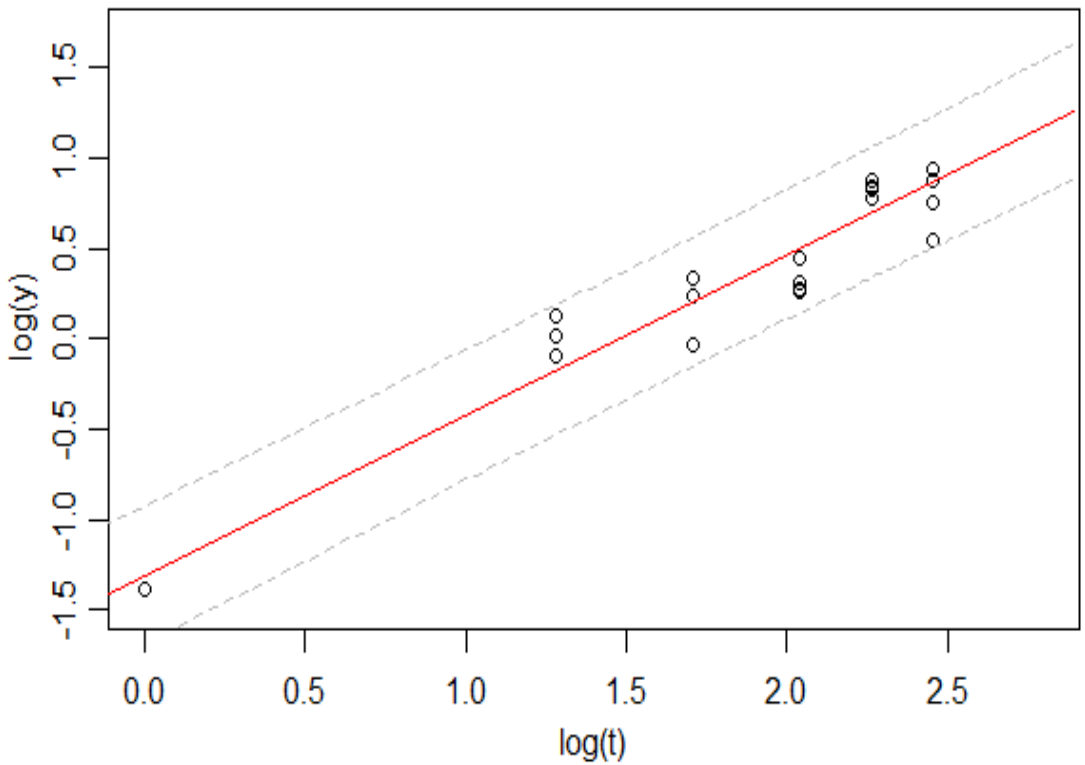
  - The level of analysis is a matter of modeling
- **Single level regression model**
  - Pool all the data for a group (like sandy soil)
  - Determine the upper prediction interval
  - Slope of the upper bound is the estimated rate
- **Two level regression model**
  - Inspired by “random coefficient regression” model
  - Analyze data from each site and estimate the rate
  - Combine “site” rates into a single “group” distribution

Data Analysis

- **Data**
  - Carbon steel pipe samples in Tables 13 and 15 in Romanoff (1957)
  - Six varieties of steel
  - Data from 60+ soil sites (sites 1 to 70, not all sites included due to censoring, as well as duplicate numbering)

Step - 1

- **Linear regression in logarithmic coordinates**
  - Including all data (also the early life data)
  - Estimate overall slope (logarithmic pitting rate)

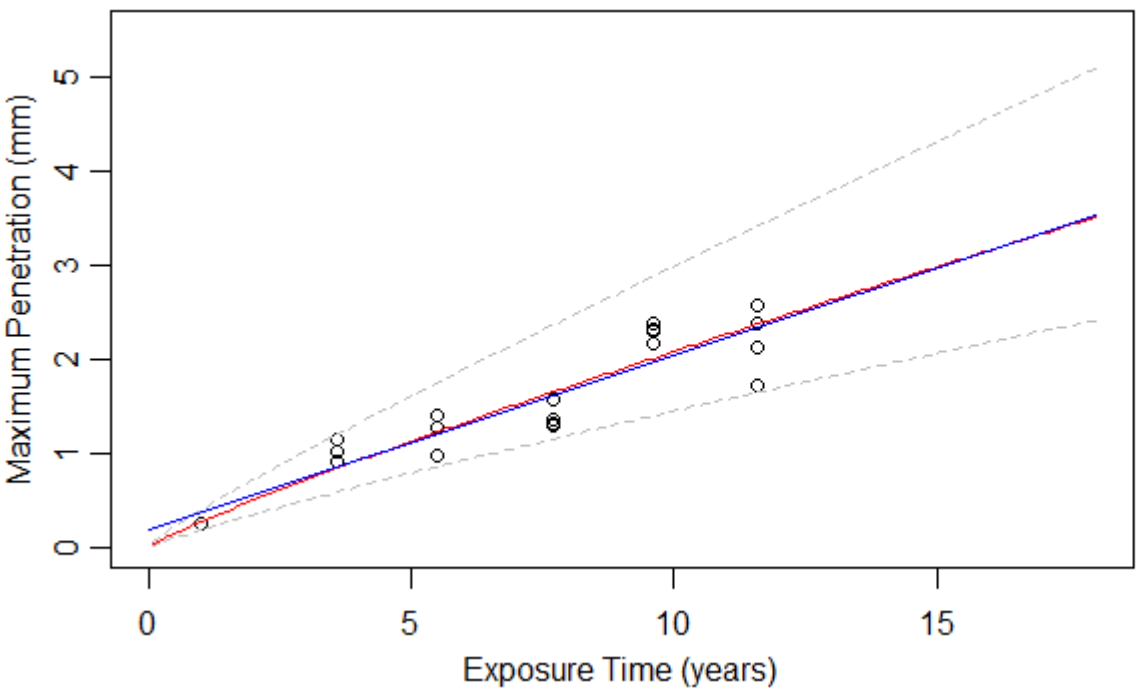


Site 1 - Cleveland, OH
Allis Silt Loam (Poor)
Resist: 1220
pH: 7
Moist: 28.6

N: 24
Slope: 0.887
Intercept: -1.309
R2: 0.95
St.Error: 0.169

Step -2: Steady State Rate

- **Plot the data and regression line ($y = at^n$) in the original coordinates**
- **Steady state rate = slope of the chord joining pit depths at *t* = 5 & *t* = 15 years**
  - Slope of initial transient period (< 5 years) is ignored



Site 1 - Cleveland, OH
Allis Silt Loam (Poor)
Resist: 1220
pH: 7
Moist: 28.6

Steady state rate = 7.2 mpy

Steady State Rate: Basis

- **The concept is inspired by the idea of a "stable" corrosion rate" used in the cathodic protection (CP) literature**
- **The minimum current required for CP is related to the average current density associated with the corrosion process [Schwerdtfeger 1964]**
  - Corrosion rate in early stages (< 3 years) is quite intense but decreasing over time.
    - To use this in designing a CP will be highly inefficient
  - The idea of using a "stable" corrosion rate reached after 5 years of exposure was adopted
- **Stable rate was calculated by using pitting data obtained from only 5 and more years of exposure**

Steady State Rate: Basis

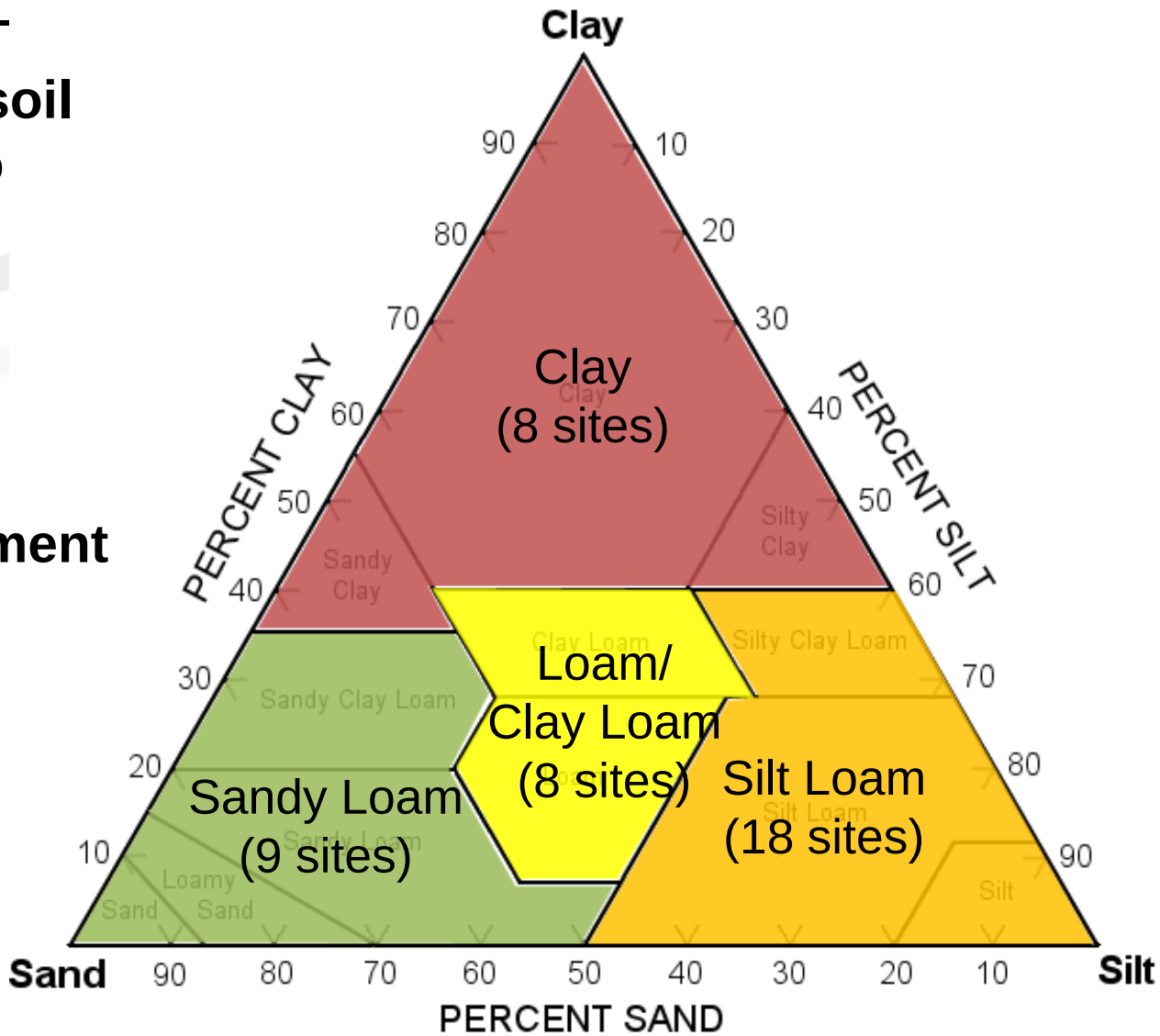
- **The idea of a long term rate of corrosion was also echoed in Loagn and Taylor (1934) as:**
- **"*There are indications that the rate of corrosion decreases with time in most soils because of more stable trench conditions or the formation of corrosion products.*"**
- ***"The rate of decrease in general diminishes with time, indicating that a fixed rate of corrosion may ultimately be reached*"**

Steady State Rate: Remarks

- **In the proposed method, all the data are used in the logarithmic regression (1st step)**
- **In the estimation of steady state rate, slope of the data between 0 and 5 years is ignored**
- **Steady state rate is a reasonable approximation**
  - Since in most cases $n < 1$, the corrosion path is almost linear after 5 years
- **Steady state assumption means that the time of initiation of corrosion is not required**
- **The process is progressing at a constant rate**
  - A conservative approach

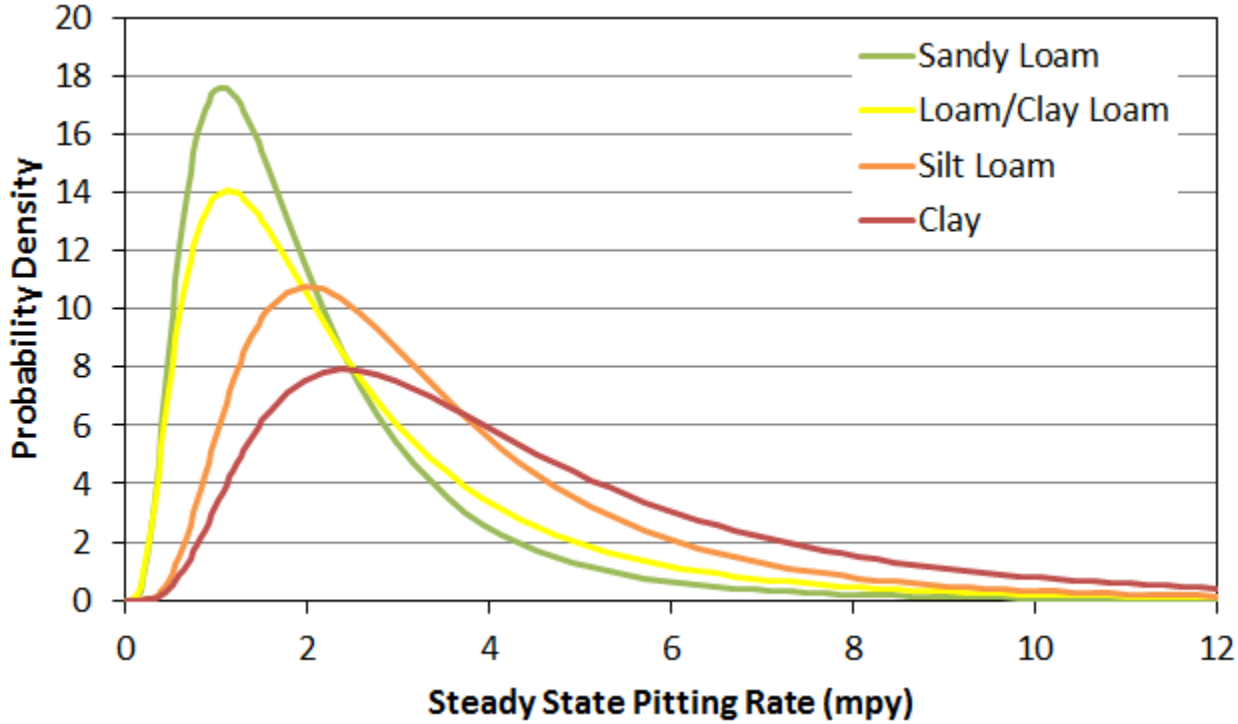
Soil Groups Based on Texture

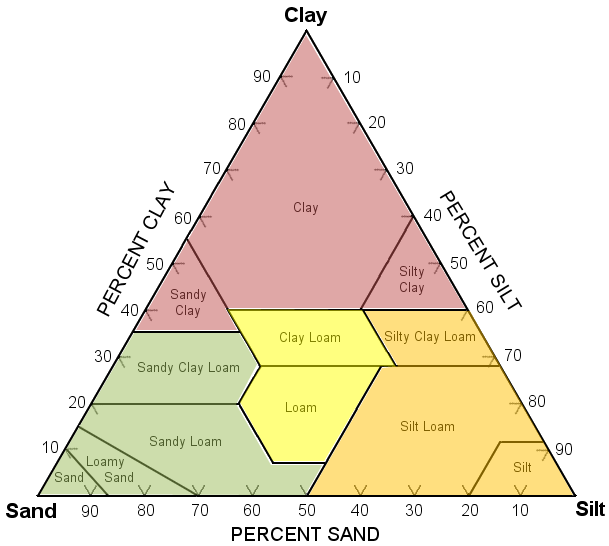
- **Group data from soil sites according to SOIL TEXTURE**
  - 4 different groups
- **These groups will provide a practical approach to assessment**



Pitting Rate Distribution

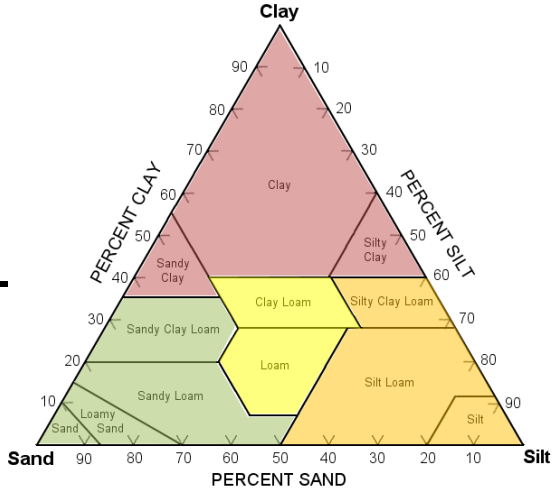
- For each soil group, steady state rates from various stations were pooled and analyzed
- The Log-Normal distribution fits the rate quite well for ALL soil texture groups





Overall Results

- Steady State Pitting Rates in mpy
- Carbon steel material



	Clay	Silt Loam	Loam/ Clay Loam	Sandy Loam
Average	4.6	3.5	2.6	2.1
Median	3.7	2.9	2.0	1.7
%tiles				
80	6.5	4.8	3.7	2.9
90	8.7	6.3	5.2	3.9
95	11.1	7.8	6.8	5.0

Summary of Results

- **Consider 80th percentile of the rate as an upper bound rate**
  - Similar to ANSI/NACE 2010
- **Steady State Rates**
  - Clay: 7 mpy
  - Silt-Loam: 5 mpy
  - Loam-Clay Loam: 4 mpy
  - Sandy-Loam: 3 mpy
- **<u>These rates are somewhat comparable to API 581 values</u>**
  - 1 mpy (sand), 5 mpy (silt) and 10 mpy (clay)

Other Soil Classifications

- **Two other classifications Romanoff (1957)**

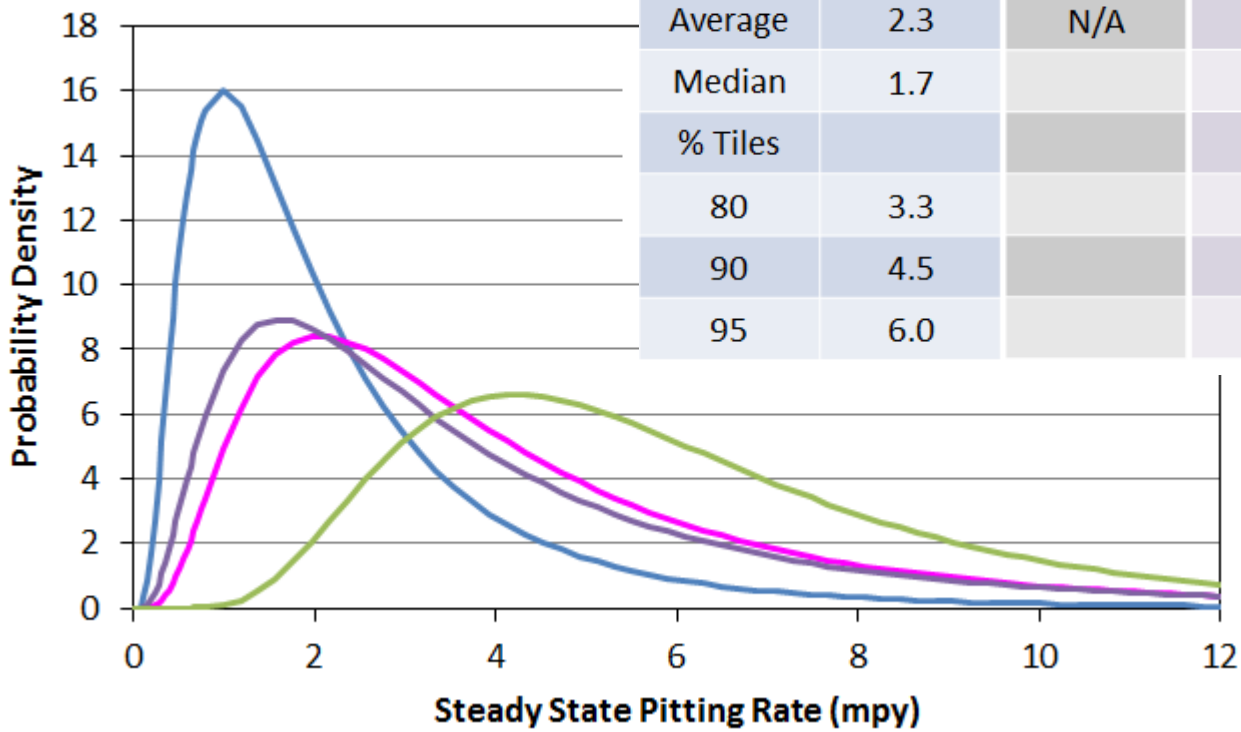
1. **Soil chemistry**
   - Inorganic and organic soli, Oxidizing and Reducing conditions, Acidic and Alkaline
2. **Soil aeration**
   - Good, Fair, Poor and Very Poor

- **The steady state rate has been estimated for these groups as well**
  - Log-normal distribution provides a good fit in all cases

Results by Soil Chemistry

- **Steady State Pitting Rates (in mpy)**

	Inorganic Soils				Organic Soils
	Oxidizing		Reducing		Reducing
	Acid	Alkaline	Acid	Alkaline	Acid
Average	2.3	N/A	4.4	4.2	6.1
Median	1.7		3.4	3.0	5.4
% Tiles					
80	3.3		6.2	5.9	8.2
90	4.5		8.4	8.4	10.3
95	6.0		10.9	11.2	12.3

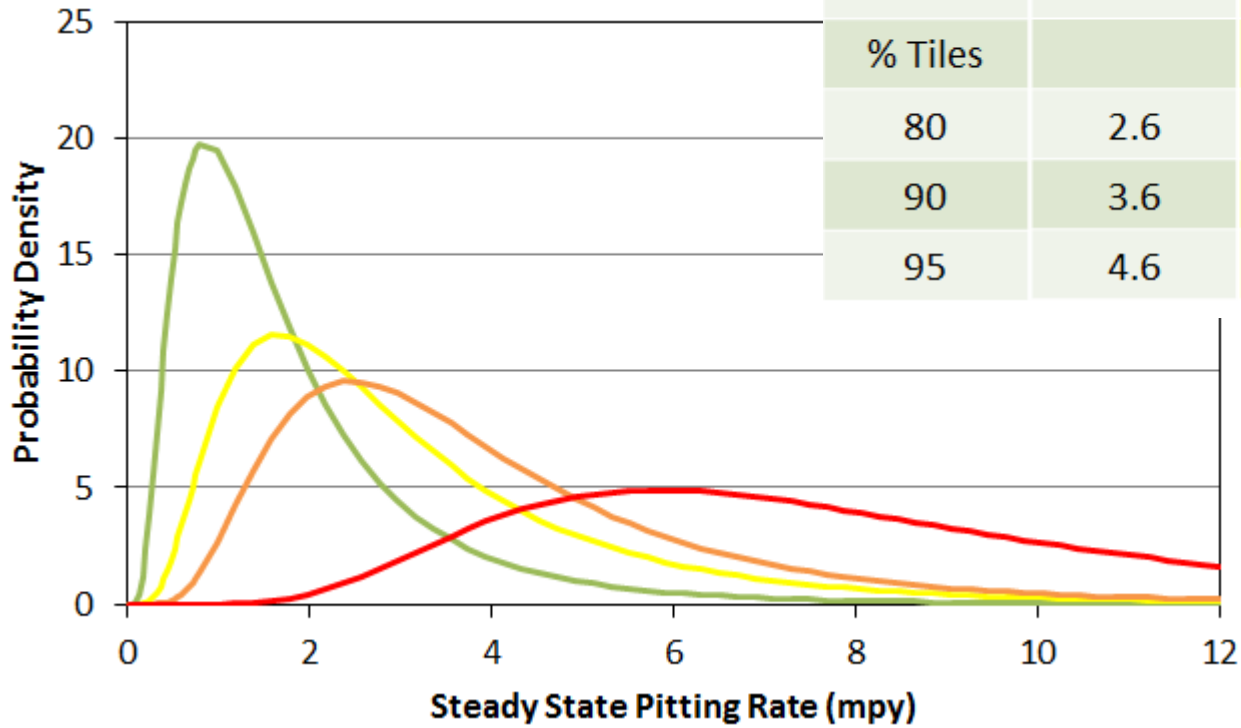


Organic Soils group consists exclusively of sites with Peat, Muck, and Tidal Marsh

Results by Soil Aeration

- **Steady State Pitting Rates (in mpy)**

	Good	Fair	Poor	Very Poor
Average	1.8	3.2	4.0	8.3
Median	1.4	2.6	3.4	7.4
% Tiles				
80	2.6	4.5	5.5	11.2
90	3.6	6.0	7.0	13.9
95	4.6	7.6	8.6	16.5



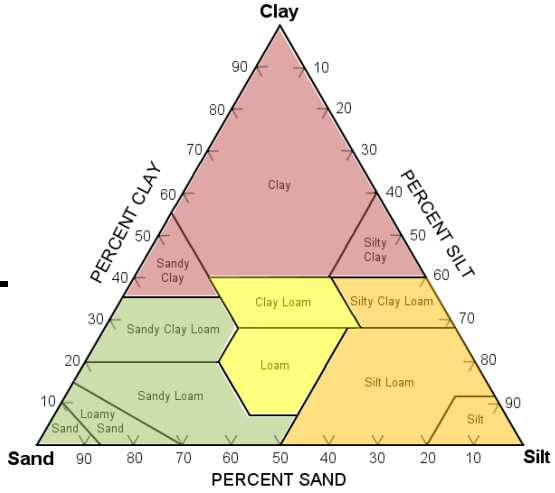
Very Poor aeration group includes sites with Clay, Peat, Muck, and Tidal Marsh

Analysis of General Mass Loss Data

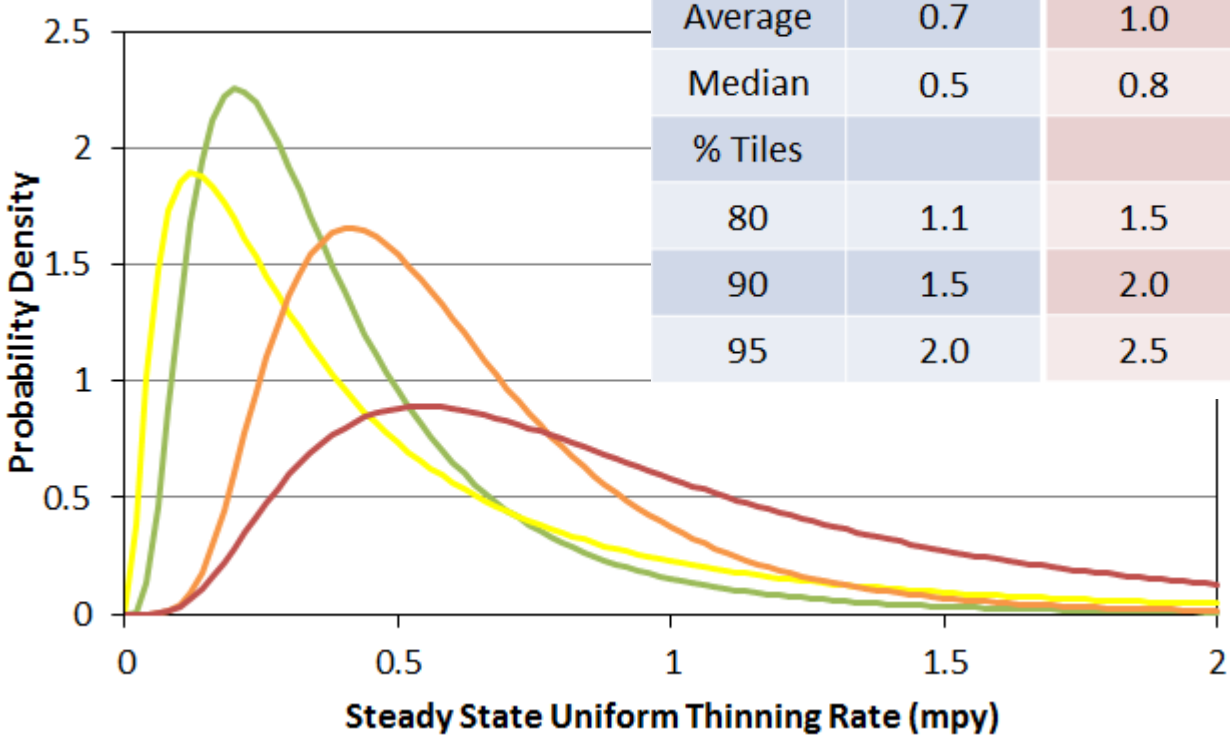
- **Romanoff (1957) report gives the mass loss data for each of the test specimens**
  - i.e., difference in original weight of pipe section and the retrieved sample weight after cleaning and removal of corrosion products
- **The weight loss data were converted into an <u>equivalent uniform thickness loss</u> based on specimen geometry and density**
- **Statistical modeling was done as before**
  - Distribution of uniform thinning rate

Results by Soil Texture

- **Steady State Uniform Thinning Rates (in mpy)**



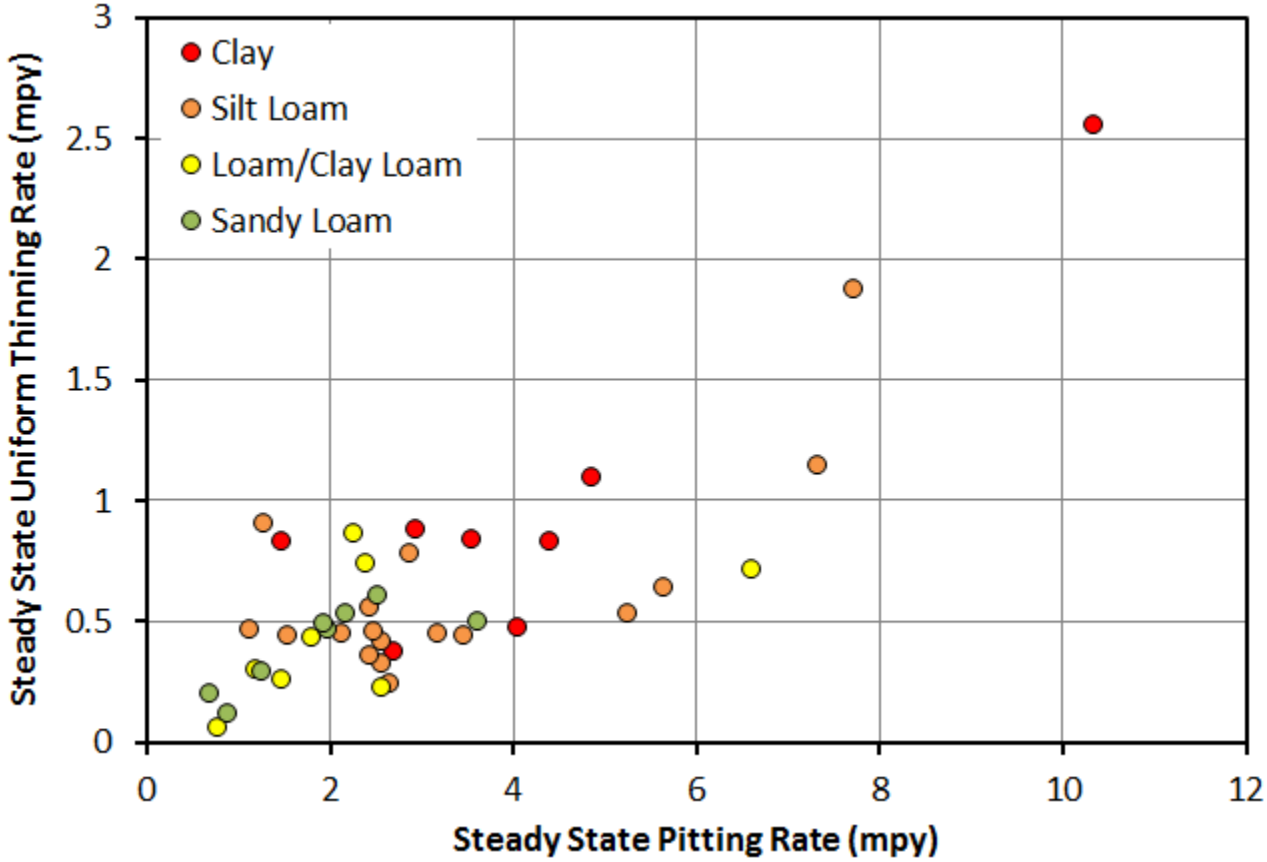
	ALL	Clay	Silt Loam	Loam/ Clay Loam	Sandy Loam
Average	0.7	1.0	0.6	0.6	0.4
Median	0.5	0.8	0.5	0.3	0.3
% Tiles					
80	1.1	1.5	0.8	0.8	0.6
90	1.5	2.0	1.0	1.3	0.8
95	2.0	2.5	1.2	1.8	1.0



Differences between the groups are less distinct

Pitting vs. Thinning Rates

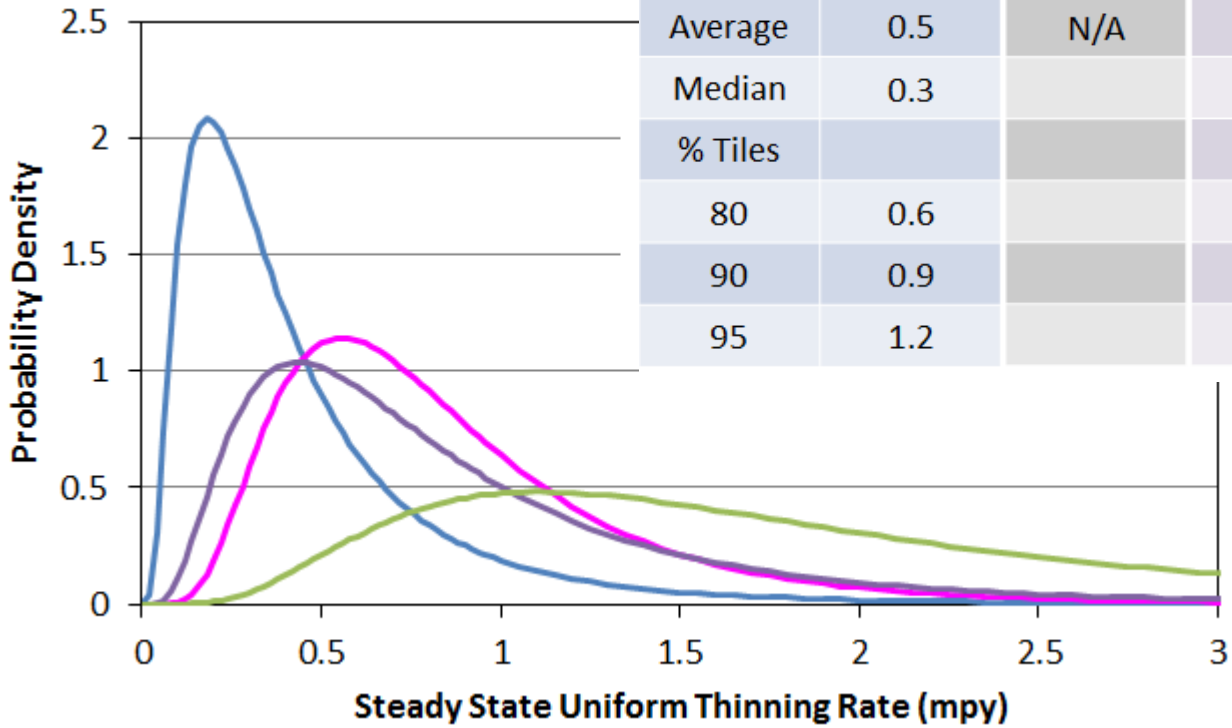
- **Pitting rate is about 4 or 5 times greater than the uniform thinning rate**



Results by Soil Chemistry

- **Steady State Uniform Thinning Rates (in mpy)**

	Inorganic Soils				Organic Soils
	Oxidizing		Reducing		Reducing
	Acid	Alkaline	Acid	Alkaline	Acid
Average	0.5	N/A	0.9	0.9	2.0
Median	0.3		0.7	0.7	1.6
% Tiles					
80	0.6		1.2	1.3	2.7
90	0.9		1.5	1.7	3.6
95	1.2		1.8	2.2	4.5

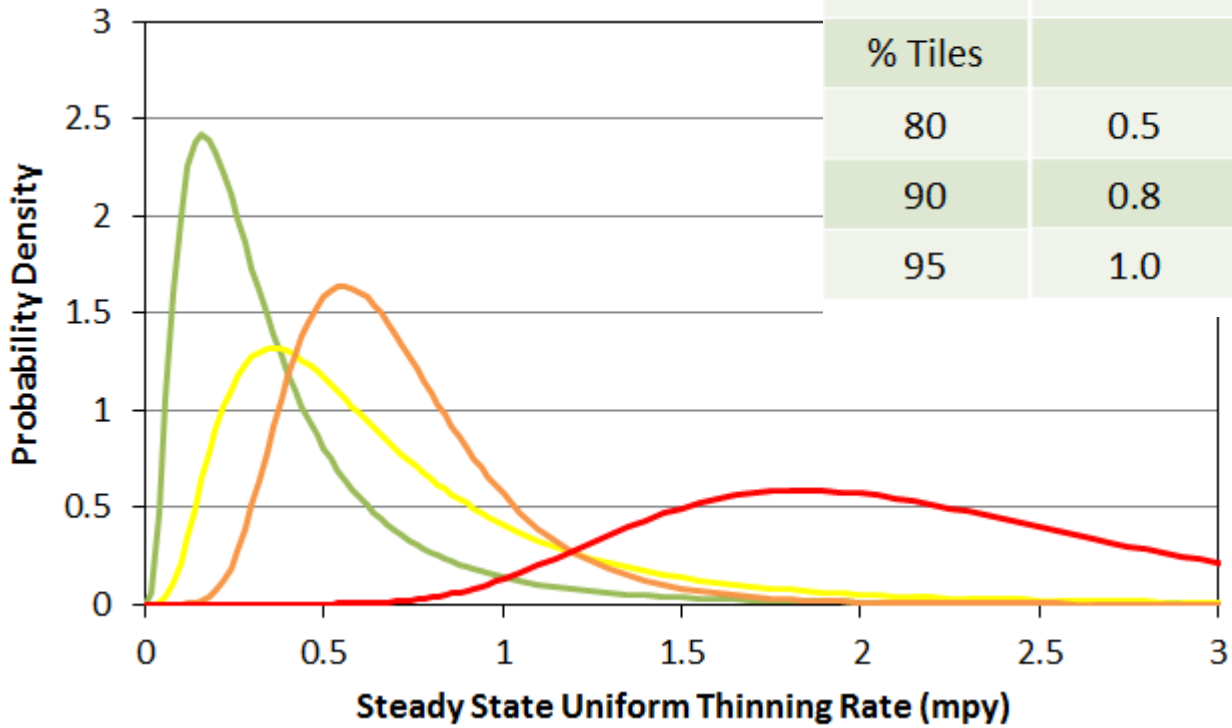


Organic Soils group consists exclusively of sites with Peat, Muck, and Tidal Marsh

Results by Soil Aeration

- **Steady State Uniform Thinning Rates (in mpy)**
  - Very poorly aerated soils have much higher general corrosion rates

	Good	Fair	Poor	Very Poor
Average	0.4	0.7	0.7	2.2
Median	0.3	0.6	0.7	2.1
% Tiles				
80	0.5	1.0	0.9	2.8
90	0.8	1.3	1.1	3.2
95	1.0	1.7	1.3	3.7



Very Poor aeration group includes sites with Clay, Peat, Muck, and Tidal Marsh

A Schematic of Inspection & Assessment Approach

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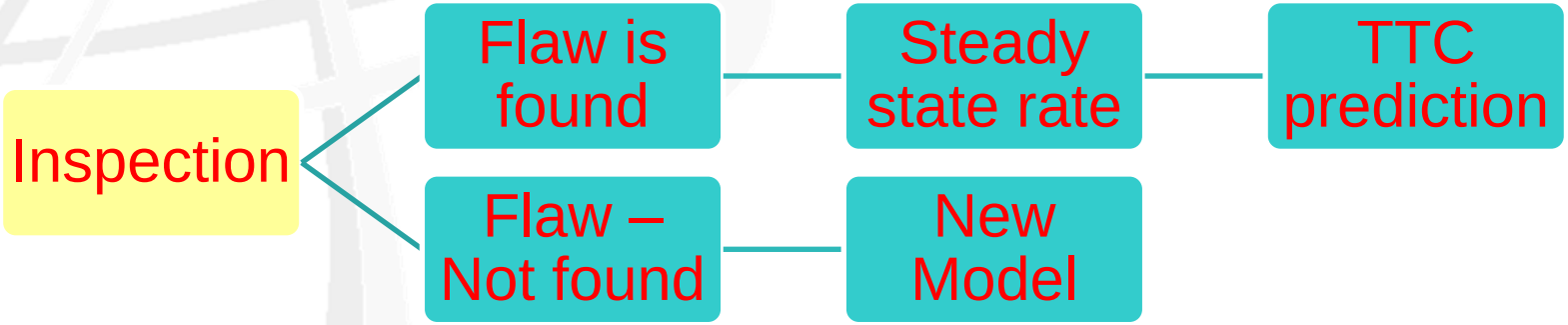
Inspection & Assessment Process -1

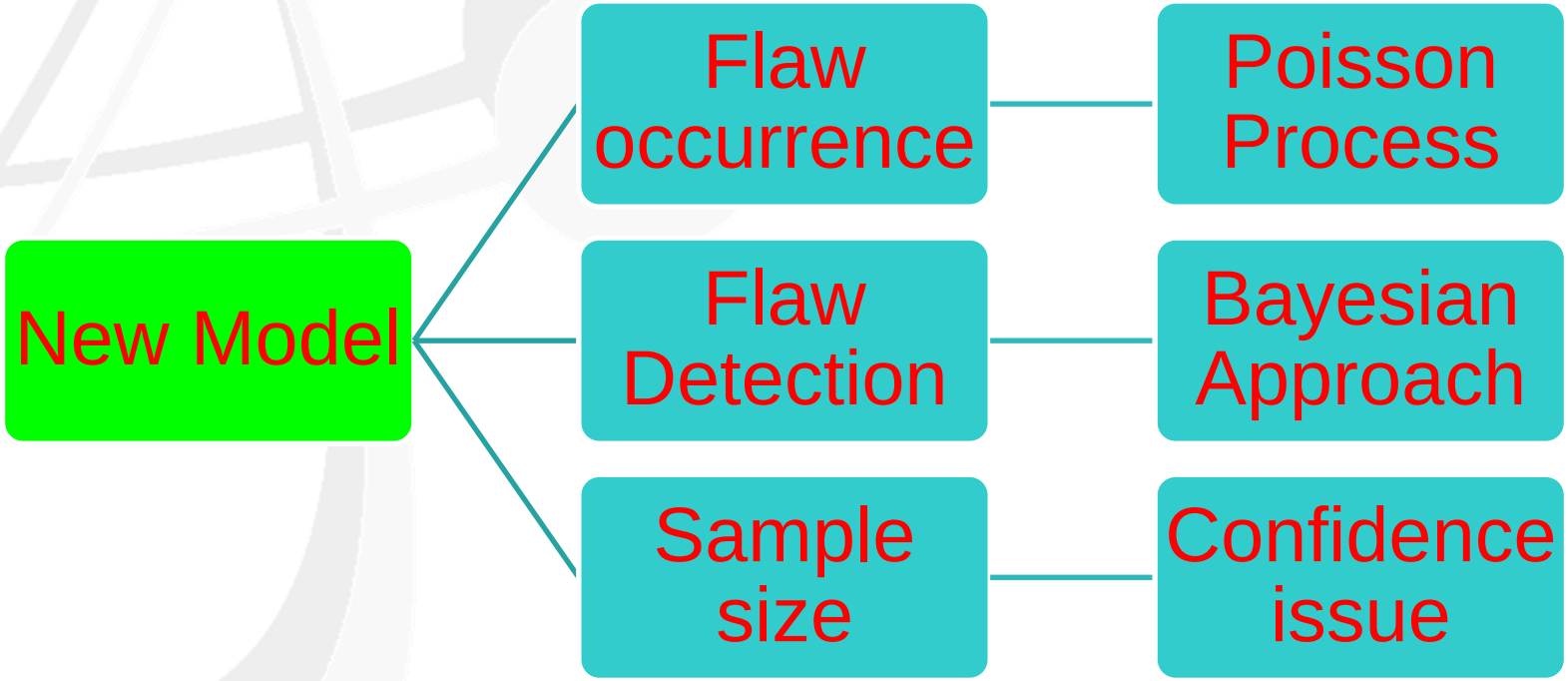


TTC: Time to critical thickness

Basic Premise: Detected flaws are under stable growth state

Inspection & Assessment Process -2

Inference about degradation process in uninspected pipe sections



Procedure-1

- **Inspection of a pipe section discovers a localized corrosion flaw**
  - Measure the current depth (y_0) and compare with an acceptable limit (ASME Standard) (y_c)
  - Select an evaluation period *(t)*
  - Determine the soil texture and other relevant information

1. **Pitting Rate**
   - Select an upper bound rate ($r_{0.8}$) for a given soil texture
   - Predicted depth $y(t) = y_0 + r_{0.8} \times t$
   - Acceptable if $y(t) > y_c$

Procedure - 2

- **Inspection does NOT discover any localized corrosion flaw**
  - This implies that pipe coating and CP protection are functional al at the inspected location
- **Pipeline condition at un-inspected locations have to be inferred**
  - What is the probability of corrosion initiation?
  - What is the expected number of flaws
  - How many additional sections to be inspected?
- **Different probabilistic tools are needed for this situation**
  - They are not the part of this project

Other Issues

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1. Combination of OD & ID Rates

- **Corrosion rates from soil side and fluid side need to be combined for the assessment**
- **Combined rate <u>cannot</u> be an arithmetic sum of the upper bounds fluid side and soil side pitting rates**
  - Coincidence of two extreme values is less probable
- **Technical Solution**
  - Sum of two distributions of the rates (convolution) must be carried out and then find an upper bound value
- **Approximate combination rules for two stochastic processes have been developed**
  - In the structural design, combination of snow and wind loads on the structure – two extreme values are NOT added

Combination of OD & ID Rates

- **Practical solution**
  - Average of one stochastic mechanism should be added to upper bound of the second mechanism
    - e.g., 80% probability pitting rate from soil side and average wall loss from ID
    - ID wall loss can be estimated from the inspection data

2. Other Cases

- **Coated pipes**
- **Cast iron pipes**
- **Stainless steel pipes**

  - NBS Data will be used in the statistical analysis

Summary

- **Statistical analysis of soil side corrosion data has been confounded by large variability**
- **The rate cannot be correlated well with soil properties and electro-chemical parameter**
  - Data are not representative of the real stochastic variations conditions
- **Prediction of time to reach a critical thickness**
  - Based on steady-state rate of corrosion
- **Results: Steady state rate (80th percentile)**
  - Pitting rate
  - Uniform thinning rate

Summary of Results

- **80th percentile of the Steady State Rates in mpy**

Texture	Pitting	Uniform Thinning
Sandy Loam	2.9	0.6
Loam/ Clay Loam	3.7	0.8
Silt Loam	4.8	0.8
Clay	6.5	1.5

Aeration	Pitting	Uniform Thinning
Good	2.6	0.5
Fair	4.5	1.0
Poor	5.5	0.9
Very Poor	11.2	2.8

Chemistry	Pitting	Uniform Thinning
Inorganic Soils		
Oxidizing		
Acid	3.3	0.6
Alkaline	N/A	N/A
Reducing		
Acid	6.2	1.2
Alkaline	5.9	1.3
Organic Soils		
Reducing		
Acid	8.2	2.7

Additional Slides

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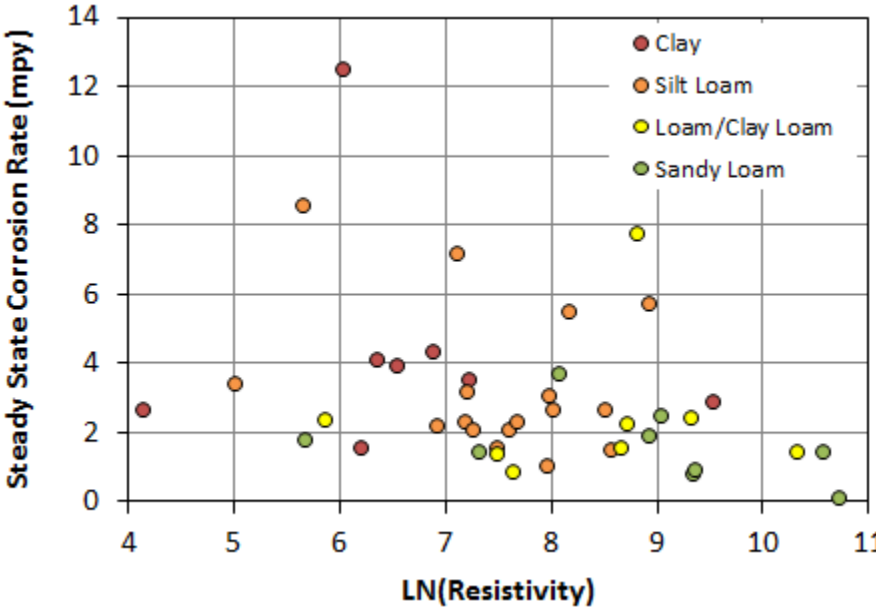
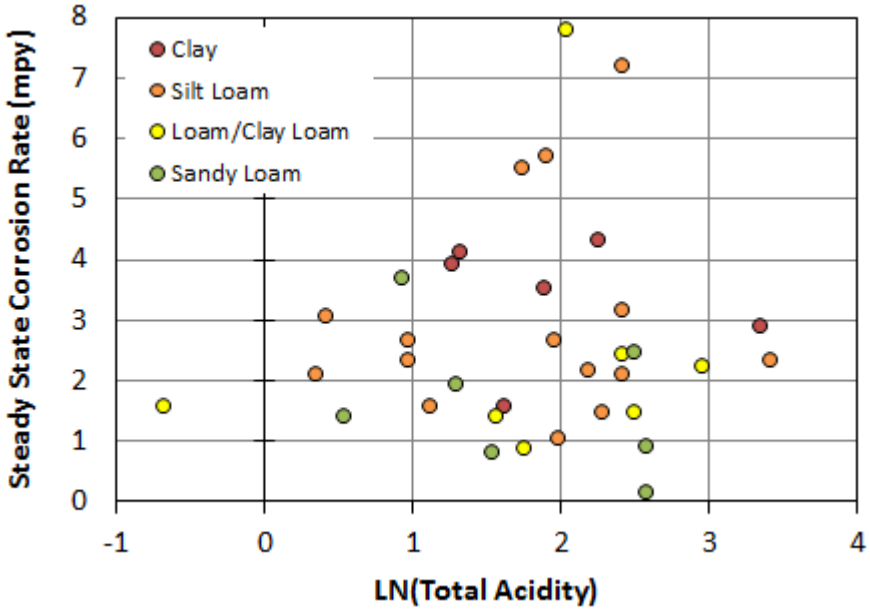
Correlation Study-1

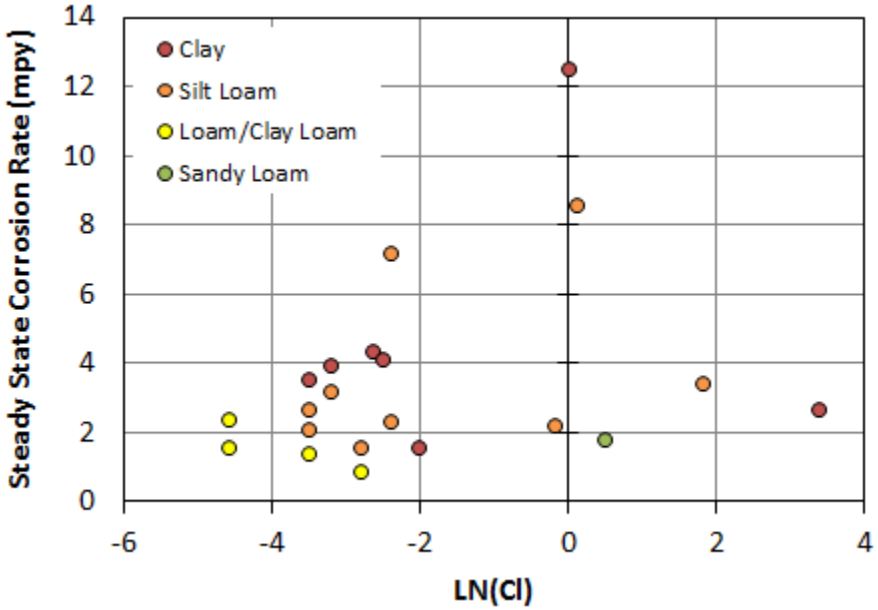
- **Steady state rate does not correlate well with various covariates (as expected)**
  - Resistivity and Total acidity

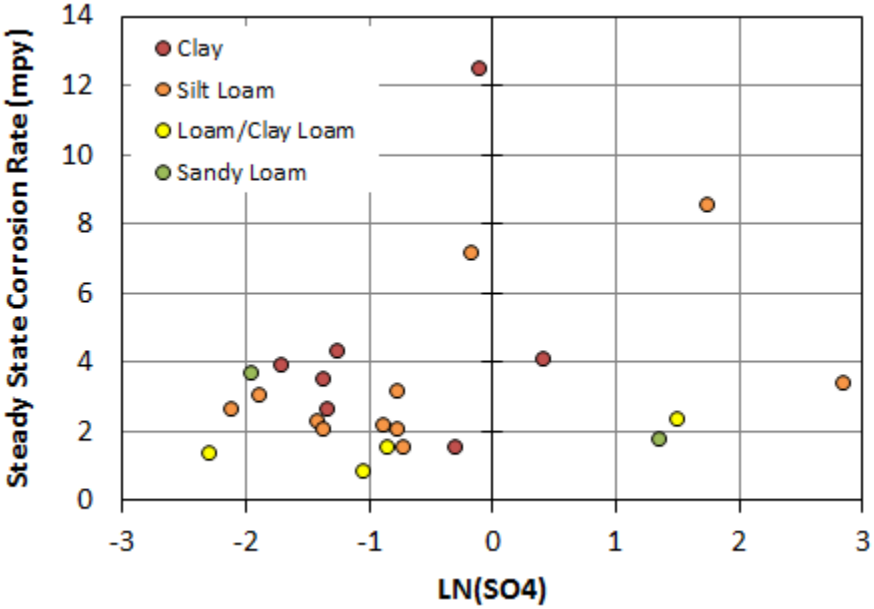




Correlation Study-2

- **Steady state rate does not correlate well with various covariates (as expected)**
  - Chloride and sulphate

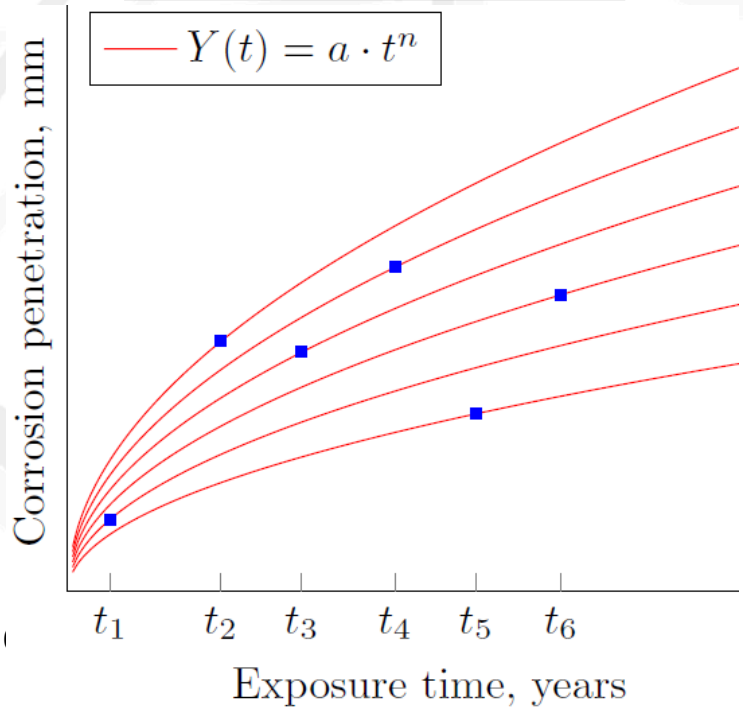




Implication of Sampling Procedure

- At a soil site, buried pipes were sequentially retrieved over a 17 year period (6×2 = 12 samples/dig)
- Data were collected from separate paths of corrosion process (non-monotonic nature of data)

Corrosion loss data



Calculated corrosion rates