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

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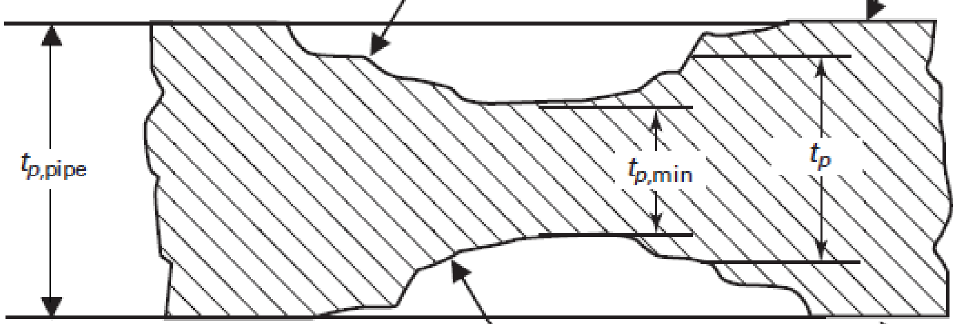
Background

- 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



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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 44 sites throughout the US (varying soil compositions, but not quantified)
- Limitations included:
  - Pipe not grounded
  - Iron and steel pipe only
  - No welds
  - No CP
  - Mostly uncoated
- Additional tests underway to evaluate these effects; use results to update guidance

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

Corrosion Loss Prediction for Fitness for Service Assessment of Buried Pipes

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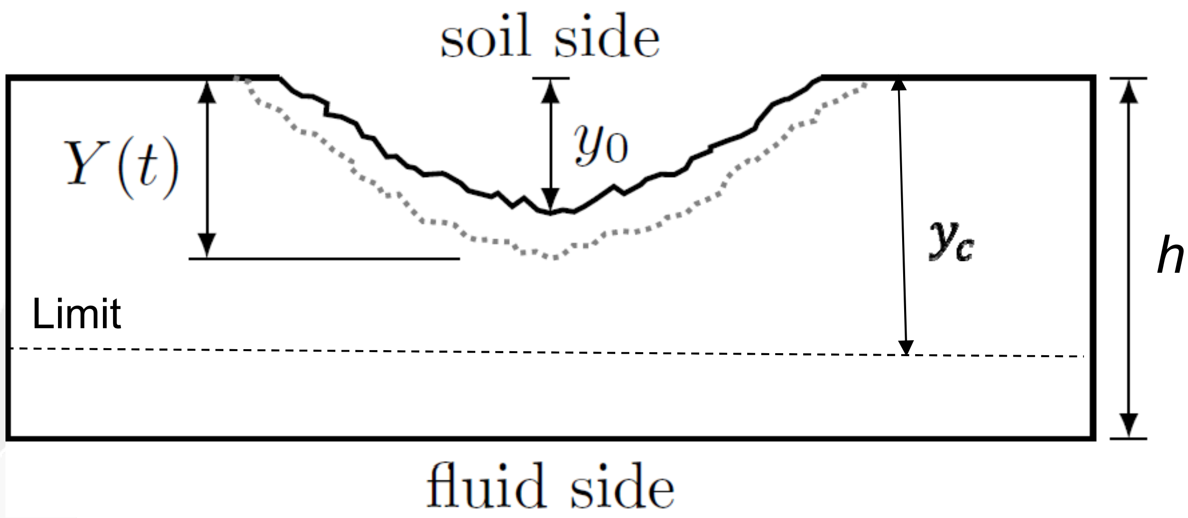
Overview

- **Remaining Life Assessment**
  - Problem description - Corrosion flaws
  - Fitness for service assessment
- **Probabilistic modeling of soil-side corrosion**
  - Regression model – Steady State Rate
  - Stochastic process model
- **Statistical data analysis**
- **Application to Fitness for Service (FFS)**

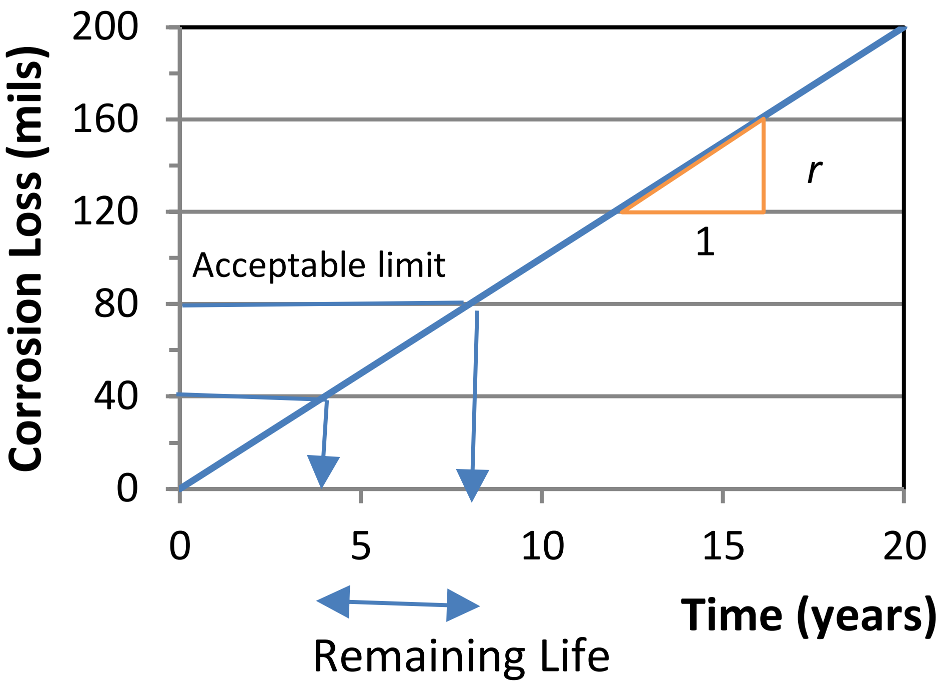
Basic Terminology

- $Y(t)$: 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*
- **End of Life = time at which the wall thickness loss exceeds the acceptable limit ($Y(t) > y_c$)**



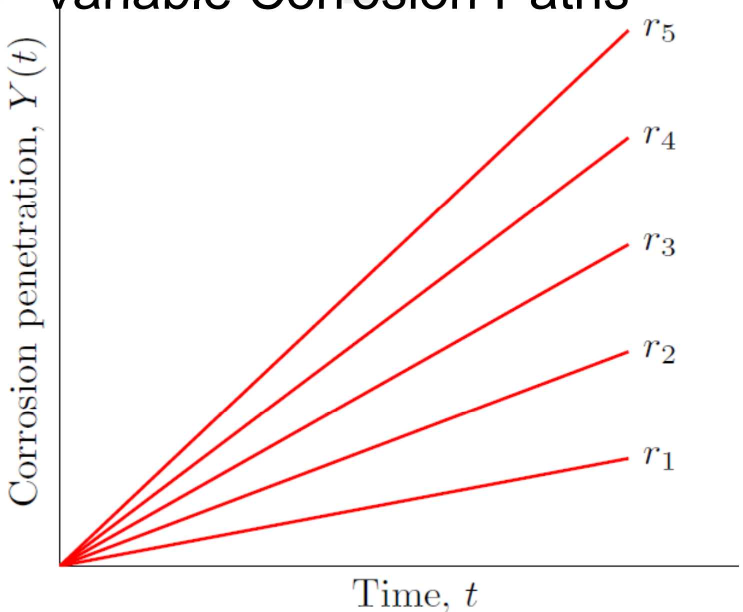
Remaining life

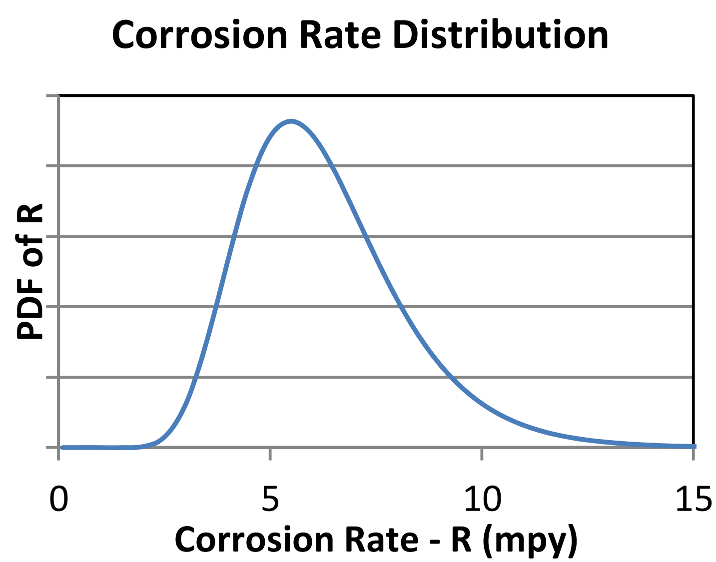
$$= \frac{acceptable\ loss\ (y_c) - current\ loss (y_0)}{Rate\ of\ corrosion}$$

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





Remaining Life Prediction

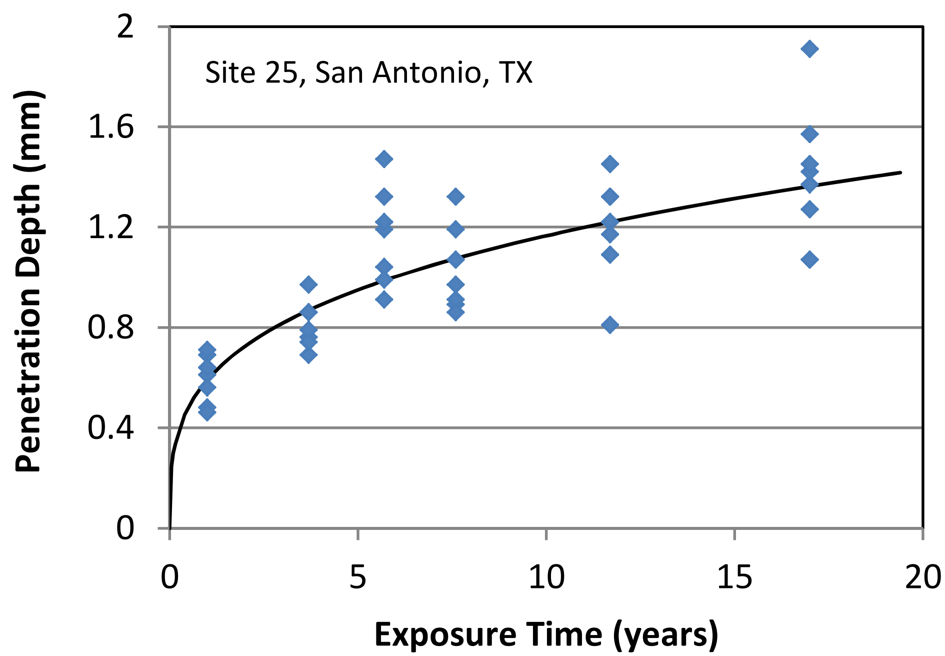
- **In the linear corrosion loss model, remaining life estimation is straightforward**
- **Remaining lifetime is a random variable: *T***
- **Probability distribution of lifetime is related to the corrosion rate – *R***
- $P[T \leq t] = P[Y(t) > y_c] = P[Rt > y_c]$
- $F_T(t) = 1 - F_R(\frac{y_c}{t})$
- **Use of an upper bound 95th percentile rate *(R)* will lead to the 5th percentile of the remaining life (*T*)**
  - **The estimated life time is associated with 95% exceedance probability**

Underground Corrosion: Data

- **National Bureau of Standards (1922 – 1939)**
  - Bare steel pipe sections buried underground corrosion
  - 47 soil sites across the U.S.
  - Average characterization of the soil chemistry and environmental conditions
- **Material: 8 different ferrous pipe alloys and steel**
  - 1.5" dia, 0.145" thick, 6" long pipe sections (4 alloys)
  - 3" dia, 0.216" thick, 6" long pipe sections (4 alloys)
- **Data consist of**
  - Mass loss: average of 2 samples retrieved
  - Maximum penetration depth : avg. of 2 samples retrieved

A Typical Sample

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

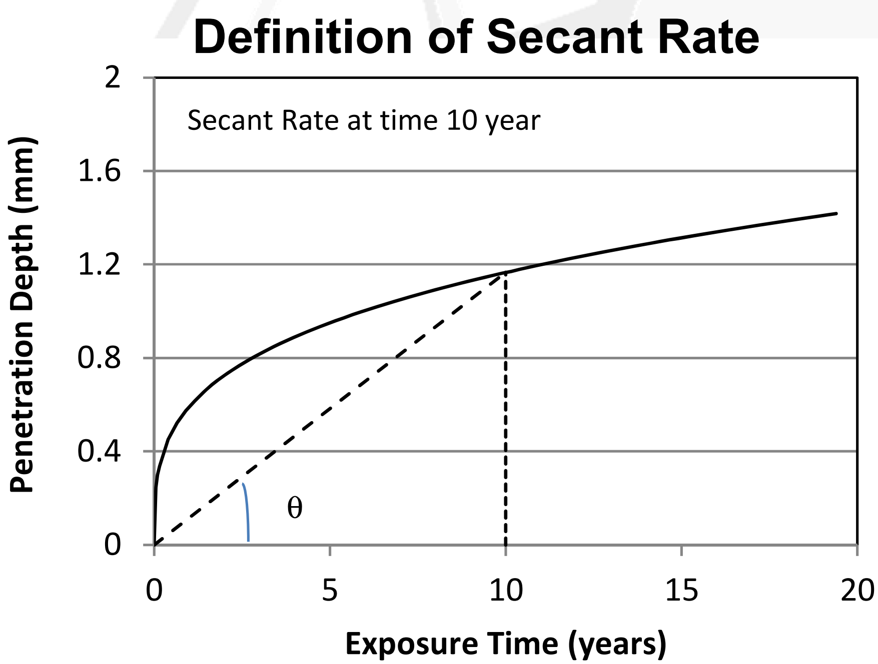


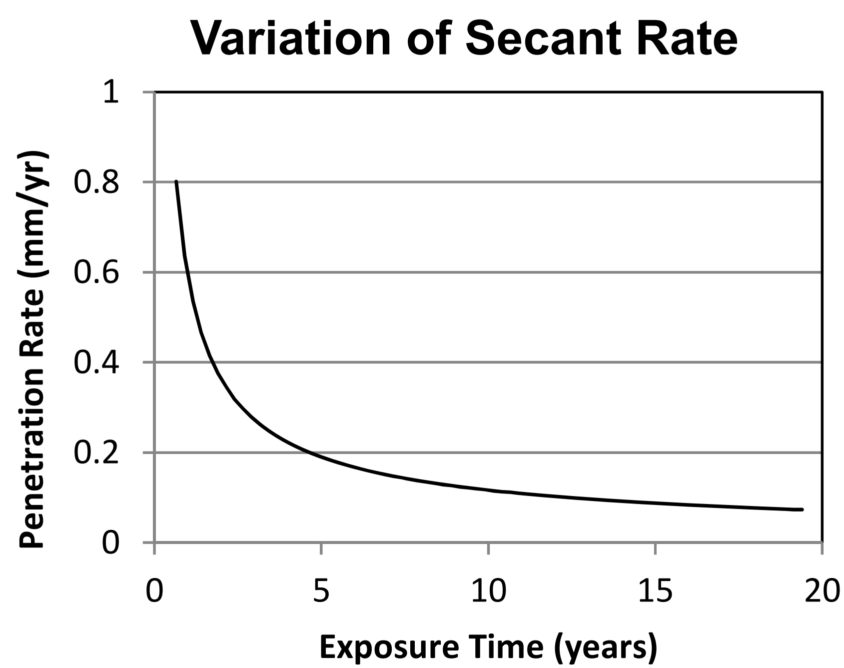
Nonlinear Corrosion Process

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

Secant Rate

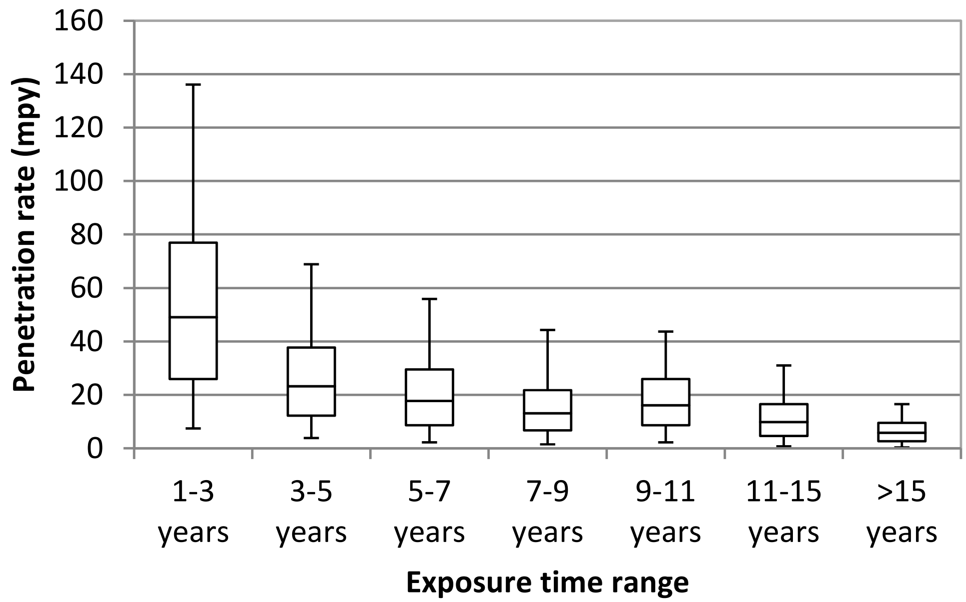
- **Secant rate varies by several orders of magnitude over the exposure time**





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



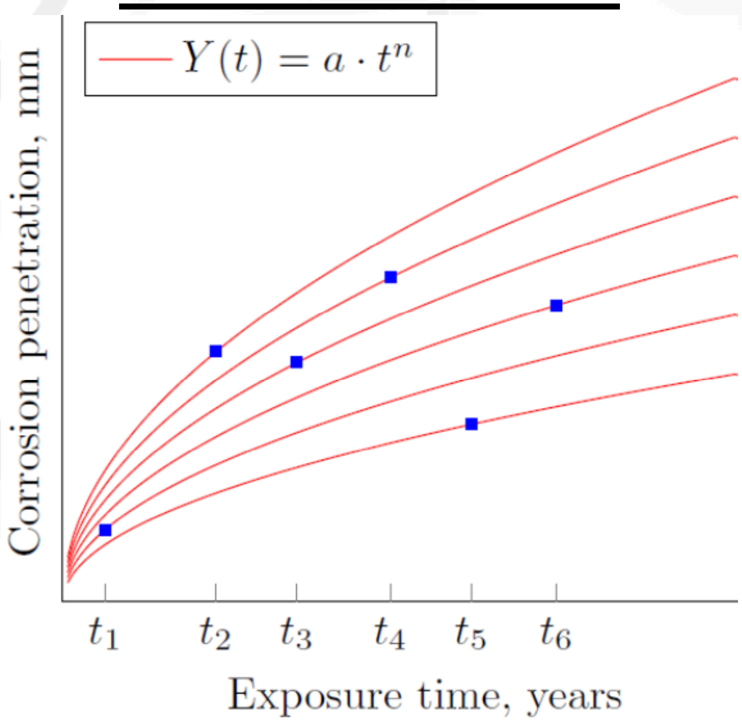
Use of Secant Rate

- **A sample from a soil site in NBS study**
  - typically 8×6 = 48 values of maximum corrosion penetration
- **In many studies, these data were converted into (secant) rates and used in statistical analysis**
  - Seeking correlation with soil properties
- **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” scatter</u> in the data

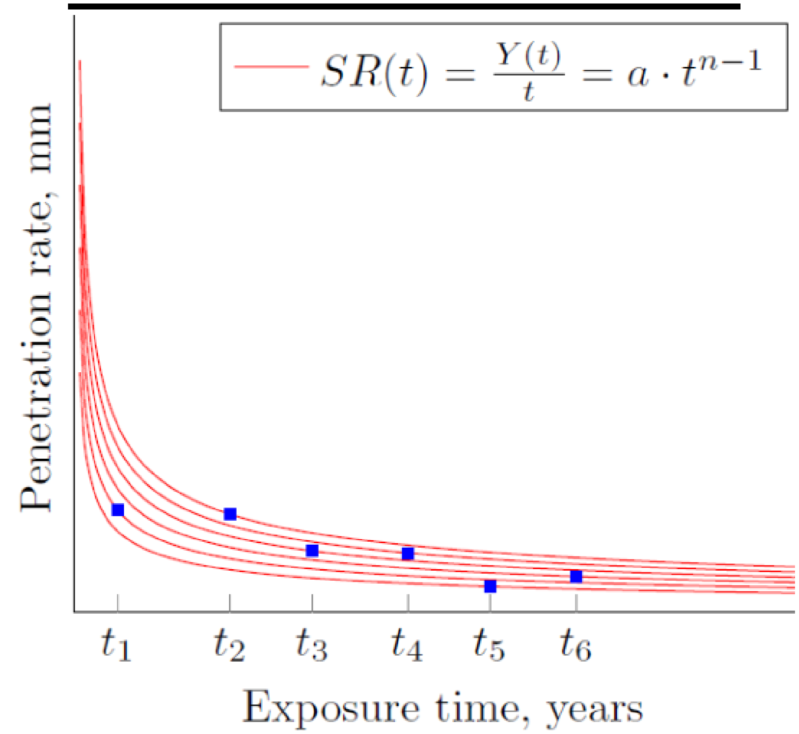
Implication of Sampling Procedure

- **At a soil site, buried pipe sections were sequentially retrieved over a 17 year period**
- **Data were collected from separate paths of corrosion process (non-monotonic nature of data)**

Corrosion loss data



Calculated corrosion rates



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. **Electrical Factors**
   - Size, number and location of anodic areas
   - Properties of the metal
4. **Other factors**
   - Backfill material, bacterial action
   - Welds
   - Coating, cathodic protection
   - Connection to ground grid

Probabilistic Modeling

- **Complexity in modeling of non-stationary process**
  - The origin of the process and equation of the path are required for prediction purposes
  - Time dependent changes in mean and variance need to be modelled

1. **Statistical regression of rate (or depth) over a variety of parameters (moisture, resistivity etc.)**
   - Tried by many researchers in the past
2. **Stochastic cumulative process model**
   - The approach has not been applied to this problem
   - Gamma process model of non-linear degradation

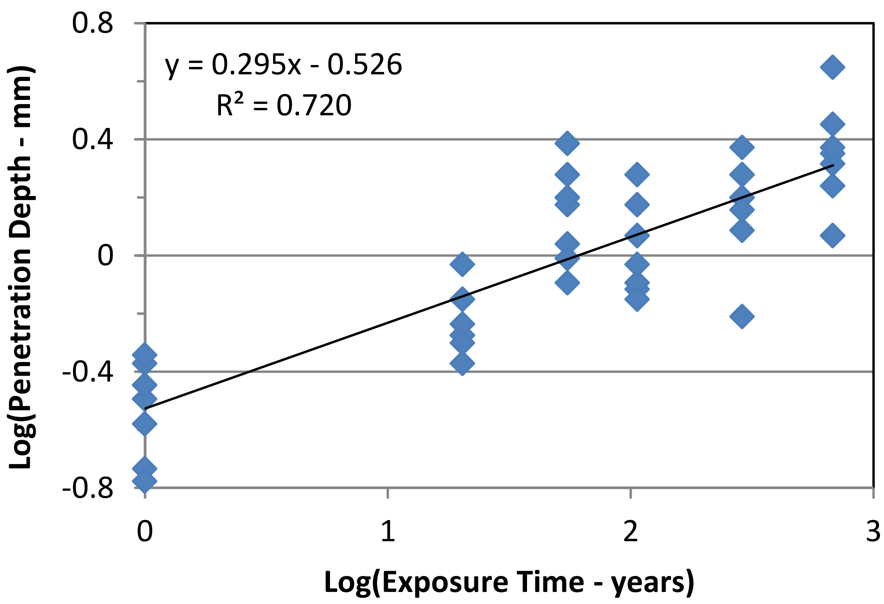
Previous Work on the Estimation of Corrosion Rate

NBS Study (1922-1939)

- **Data analysis in early 1940s and 50s in reports of Logan and Romanoff**
- **Investigated correlation between rate and parameters related to soil & environment**
  - Resistivity, moisture, pH, acidity, soil chemistry
- **Lognormal regression model**
  - $lnY(t) = \ln a + n \ln t$
  - "*n*" is logarithmic rate of corrosion
- **Large scatter in the data could not be explained**

Example

- **Soil site 25 (San Antonio, TX), logarithmic regression model**
  - Parameters: *a* = 0.59, *n* = 0.29
- **Logarithmic rate "*n*" was estimated for all the sites**
- **Analysis did NOT discover any meaningful correlation of "*n*" with covariates**



Lack of Correlation: Reasons

- **In a laboratory setting, the effect of individual factors on corrosion can be described with a greater confidence**
- **Underground corrosion in reality is an intricate and time dependent interaction of all the factors**
- **NBS data contained an average characterization of the environment of burial sites (temperature and precipitation)**
- **Data ignored variability in the characterization of soil chemistry at a given site**
  - Also ignored seasonal variation in the environmental
- **Parameters do not represent actual conditions present in the vicinity of the pipe sample**

Lack of Correlation

- **Quotes from Logan, Ewing and Yeoman (1928)**
- "*The relations between soluble salts and rates of corrosion and pitting, is no more satisfactory than those for hydrogen ion values*"
- "*The lack of consistency in the data may be because the data available do not show the salts in solution <u>in the soil adjacent to the specimens</u> at the time corrosion was occurring*"
- **"Lack of correlation" has been a well known problem and a source of frustration among analysts and engineers**

A Reanalysis of NBS Data

- **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 prediction of remaining life was not addressed**

Default Rate: ANSI/NACE SP0502-2010

- **Default pitting rate of 0.4 mm/year (16 mpy) is recommended**
- **This rate represents the upper 80% confidence level of maximum pitting rates for long-term (up to 17 year) duration**
  - Precise details of data and statistical analysis techniques are not given
  - It appears that rate data from different studies (incl. Romanoff's study) were pooled and fitted by a distribution
  - Pooling of (secant) rates data may be a source of considerable variability, as discussed before

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 detailed study
- **Researches have attempted to come up with “best estimates” of the corrosion rate**
- **Standards have recommended base line or default rates**
  - 80^{th} percentile of the distribution as an upper bound rate
  - Limited discussion about the nature of corrosion process and a suitable method of analysis

Path Forward

- **This project investigates methods for probabilistic modeling of the localized corrosion process, followed by the statistical estimation**
- **Two broad approaches are investigated**

1. **Regression model**
   - for the estimation of steady state corrosion rate
   - Simple approach for practical applications
2. **Stochastic process model**
   - Conceptually a more formal & rigorous approach
   - More involved method from a practical view point

Regression Model: Steady State Rate of Corrosion

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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
- **Remaining life prediction can be based on the steady state rate of corrosion**
  - Existing piping system, if corroding, are expected to be in a steady state of localized corrosion
- **There is no point in seeking a correlation with a long list of parameters**
  - Supporting data do not exist
- **Corrosion rate distribution should be estimated for broader classifications of soil**
  - Texture, aeration and chemistry

Proposed Model

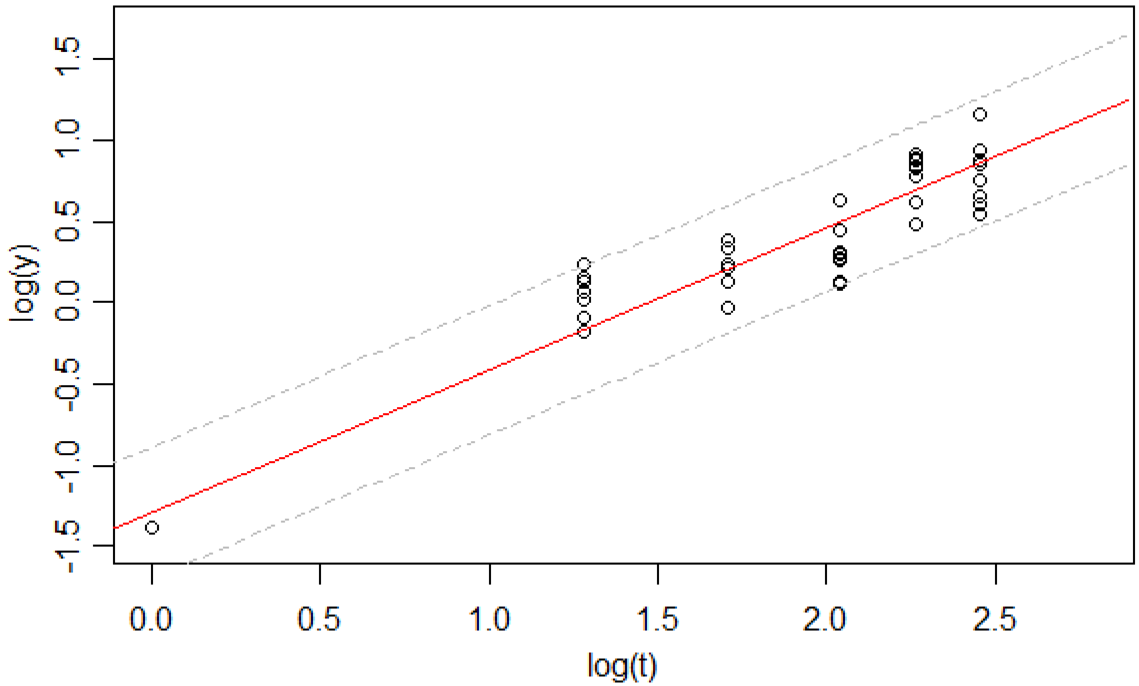
- **Logarithmic regression of corrosion penetration (in mm) over time**

$$Ln(y(t)) = ln(a) + nln(t) + \varepsilon$$

- **Data**
  - Ferrous pipe samples in Table 13 in Romanoff (1957) and carbon steel pipes N and S from Table 15
  - Sites 1 to 70 (not all sites included due to censoring, as well as duplicate numbering)
- **Fit regression model to the data from each soil site**

Example

- **The regression fit is approximately linear in logarithmic coordinates**

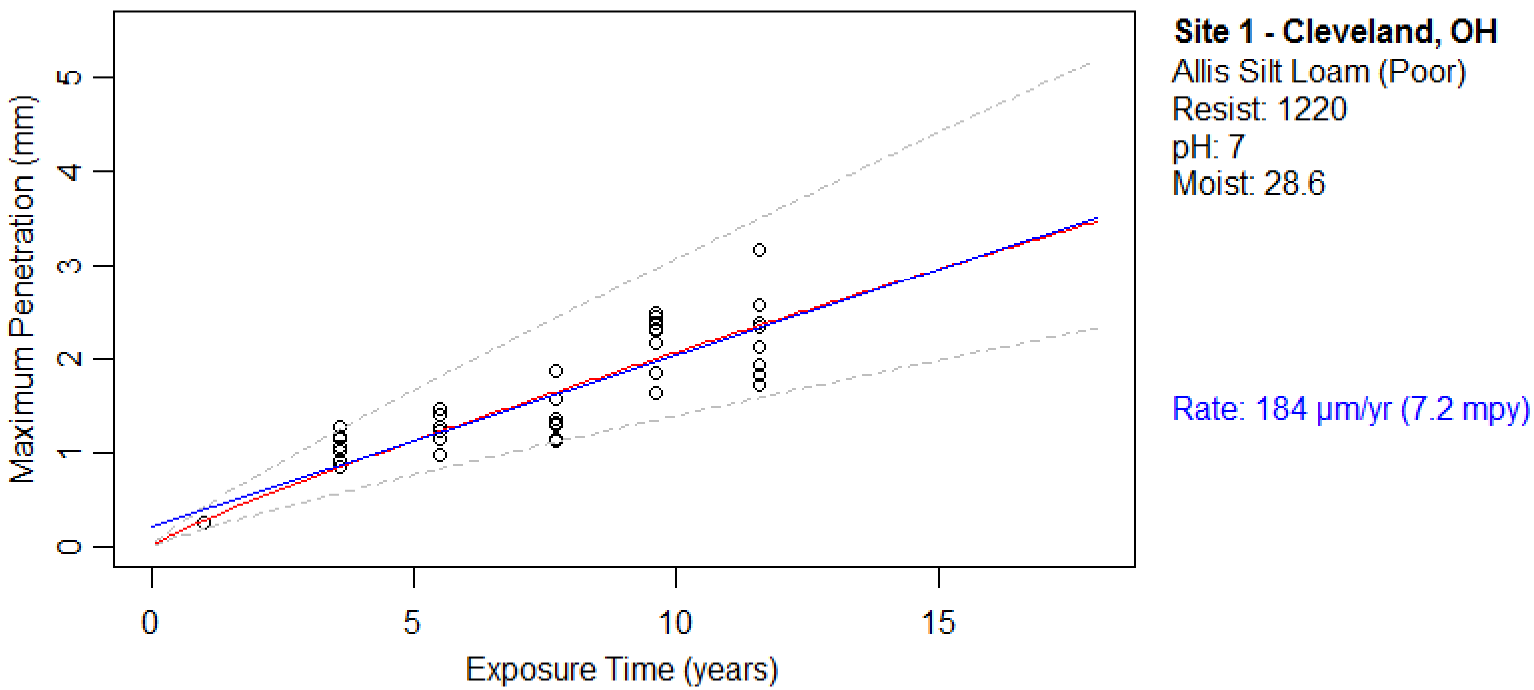


Site 1 - Cleveland, OH
Allis Silt Loam (Poor)
Resist: 1220
pH: 7
Moist: 28.6

N: 48
Slope: 0.880
Intercept: -1.296
R2: 0.94
St.Error: 0.193

Steady State Rate

- **The steady state rate is defined as the slope of the chord joining penetration depths at *t* = 5 years and *t* = 15 years**
  - The initial transient period (< 5 years) is ignored
  - Example: steady state rate = 0.184 mm/year (7.2 mpy)

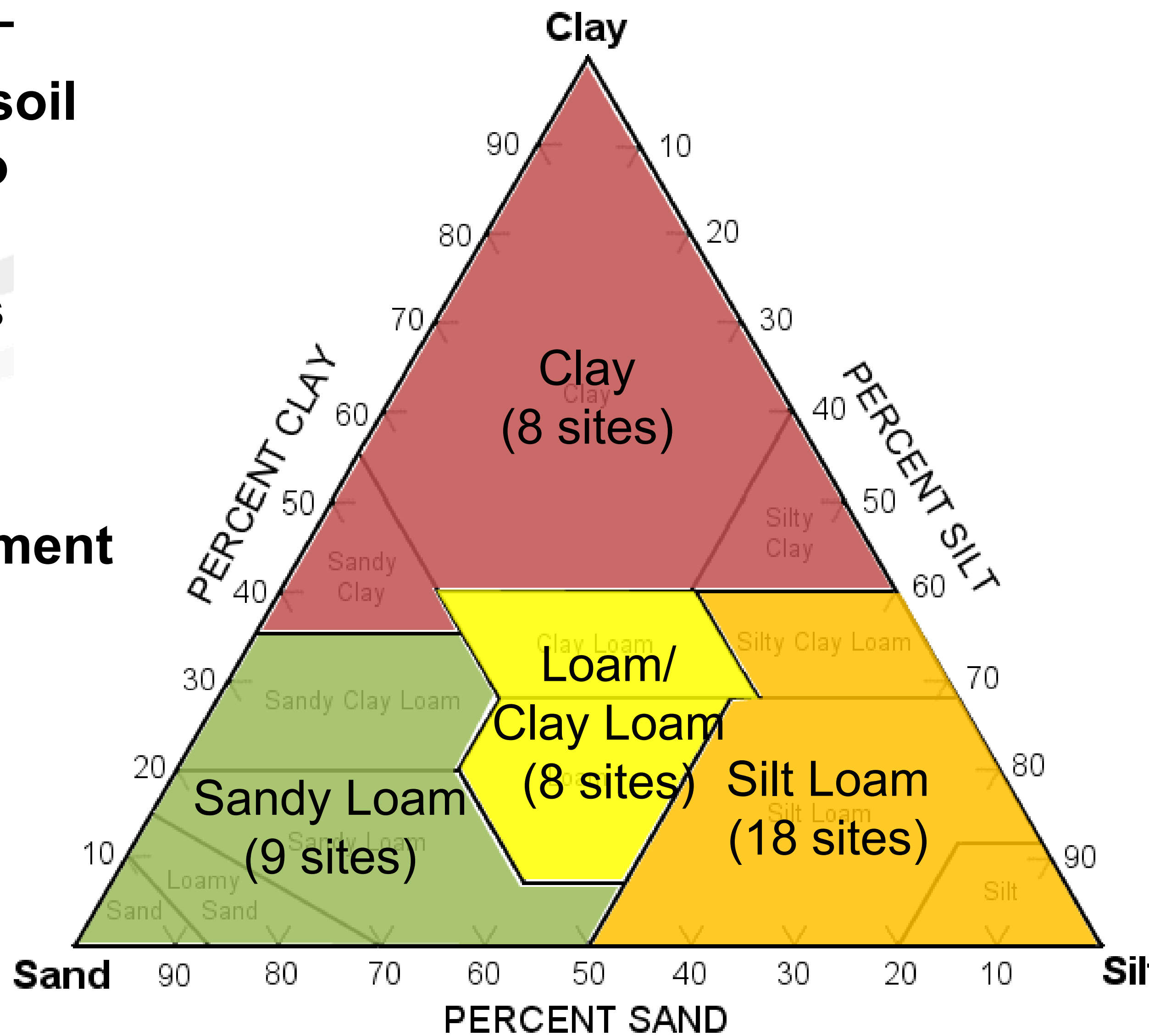


Implication of the Steady State Assumption

- **Steady state rate is a conservative approximation of actual rate of corrosion**
  - Recall the nonlinear corrosion loss model $y = at^n$
  - "n" is reflective of the intensity of the corrosion process
- **Steady state rate**
  - In case of $n \approx 1$, almost equal to the slope of the actual corrosion path
  - In case of $n \ll 1$, higher than the actual slope of the path
- **In corrosive soil, $0.5 < n < 0.7$**
  - Steady state approach is closer to the actual behaviour
- **In non-corrosive soil, $0.2 < n \leq 0.5$**

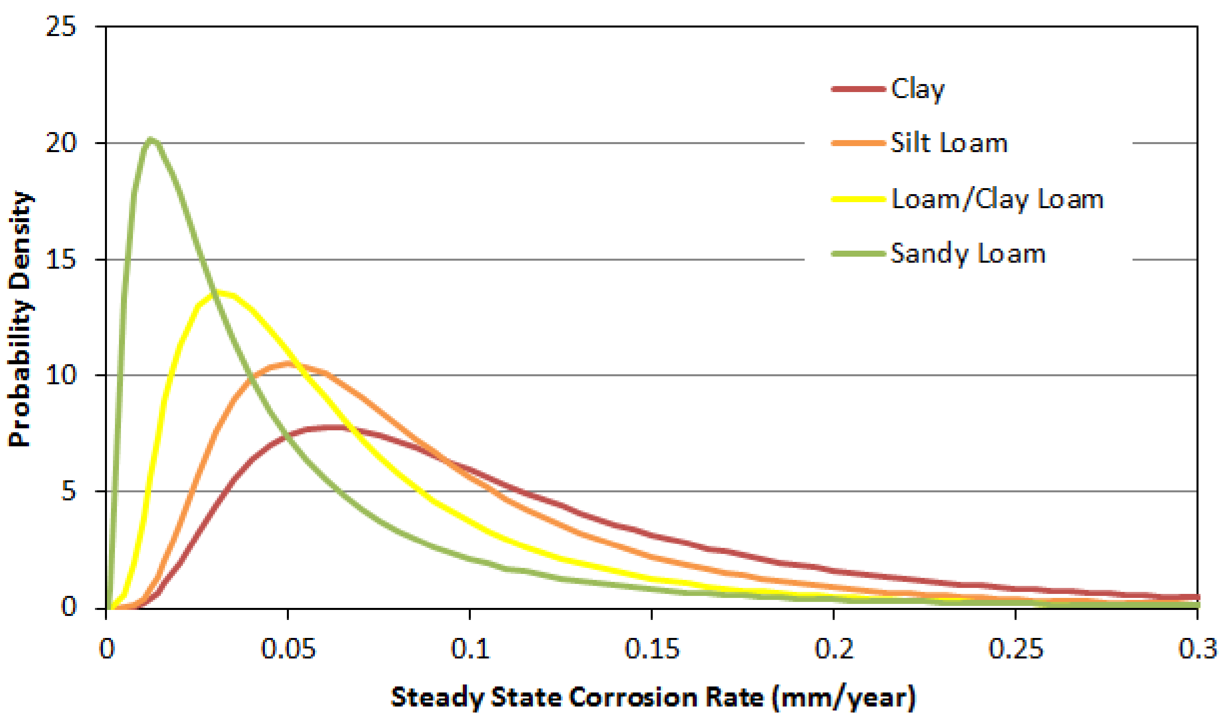
Soil Groups Based on Texture

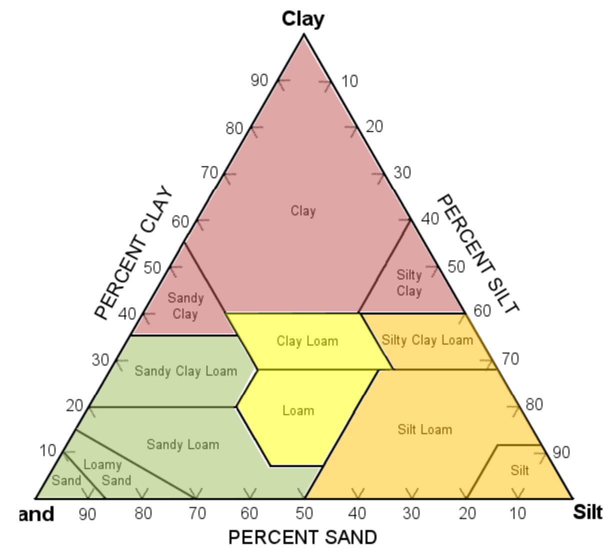
- **Group data from soil sites according to SOIL TEXTURE**
  - 4 different groups
- **These groups will provide a practical approach to assessment**



Corrosion Rate Distribution

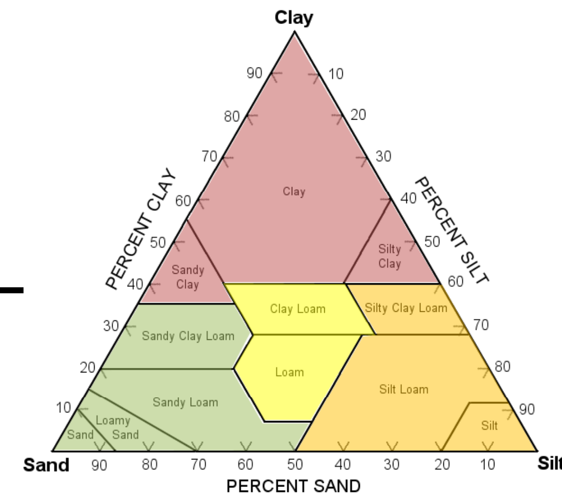
- For each soil group, steady state rates from various stations were pooled and analyzed
- The Log-Normal distribution fits the rate quite well for ALL soil texture groups





Overall Results

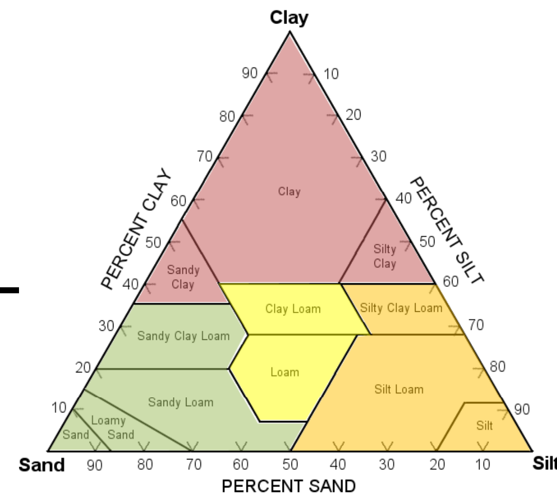
- **Steady State Rates in mm/yr**



	ALL	Clay	Silt Loam	Loam/ Clay Loam	Sandy Loam
Average	0.091	0.120	0.089	0.068	0.053
Median	0.065	0.096	0.074	0.052	0.033
% Tiles					
60	0.080	0.113	0.086	0.063	0.042
70	0.100	0.136	0.102	0.077	0.055
80	0.130	0.168	0.125	0.096	0.075
90	0.186	0.225	0.164	0.132	0.116
95	0.250	0.287	0.206	0.172	0.166
99	0.438	0.453	0.315	0.280	0.327

Overall Results

- **Steady State Rates in mpy**



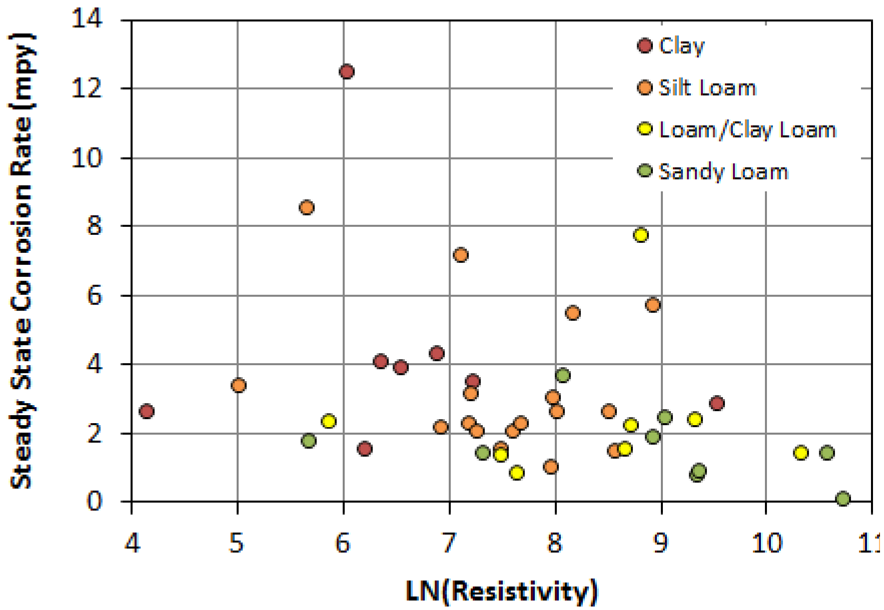
	ALL	Clay	Silt Loam	Loam/ Clay Loam	Sandy Loam
Average	3.6	4.7	3.5	2.7	2.1
Median	2.6	3.8	2.9	2.1	1.3
% Tiles					
60	3.2	4.5	3.4	2.5	1.7
70	3.9	5.3	4.0	3.0	2.2
80	5.1	**6.6**	**4.9**	**3.8**	**3.0**
90	7.3	8.9	6.5	5.2	4.6
95	9.9	11.3	8.1	6.8	6.6
99	17.2	17.8	12.4	11.0	12.9

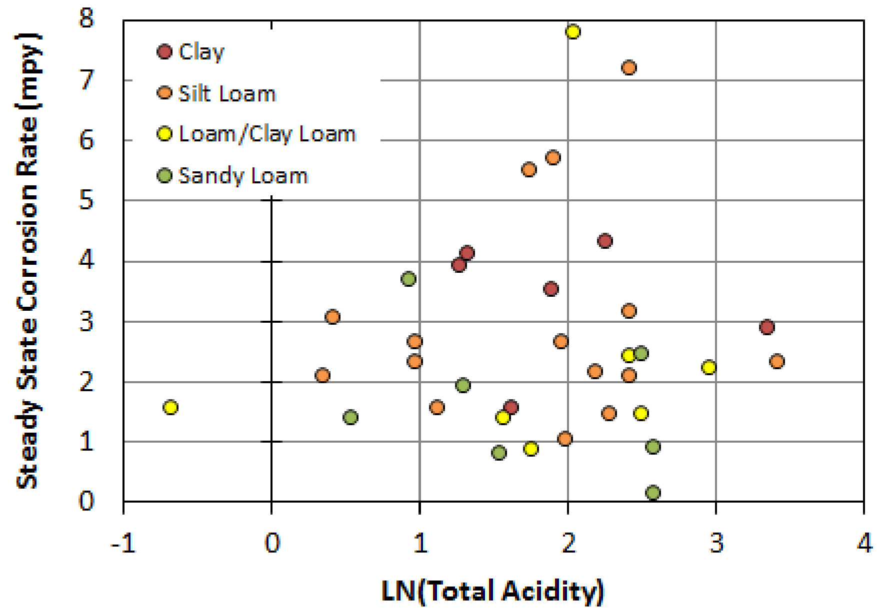
Summary of Results

- **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)

Correlation Study-1

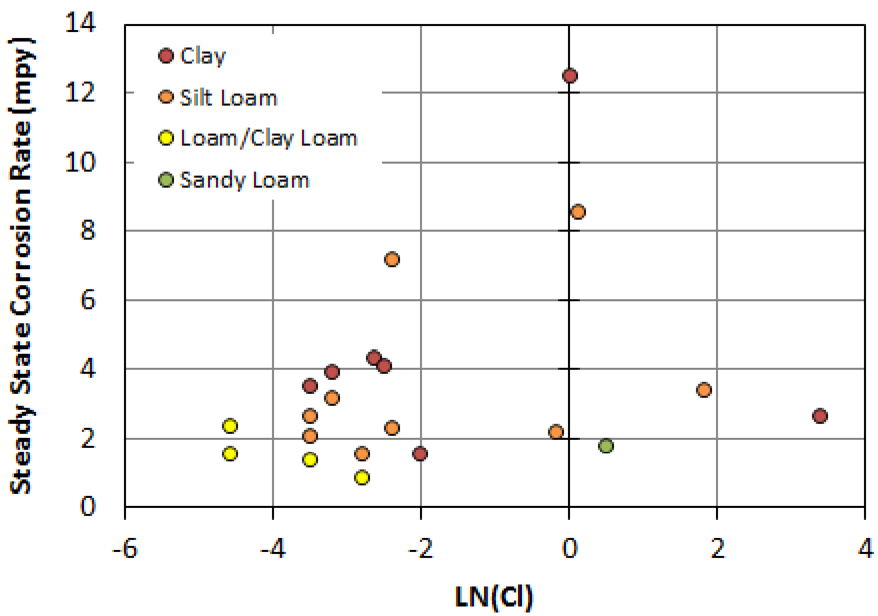
- **Steady state rate does not correlate well with various covariates (as expected)**
  - Resistivity and Total acidity

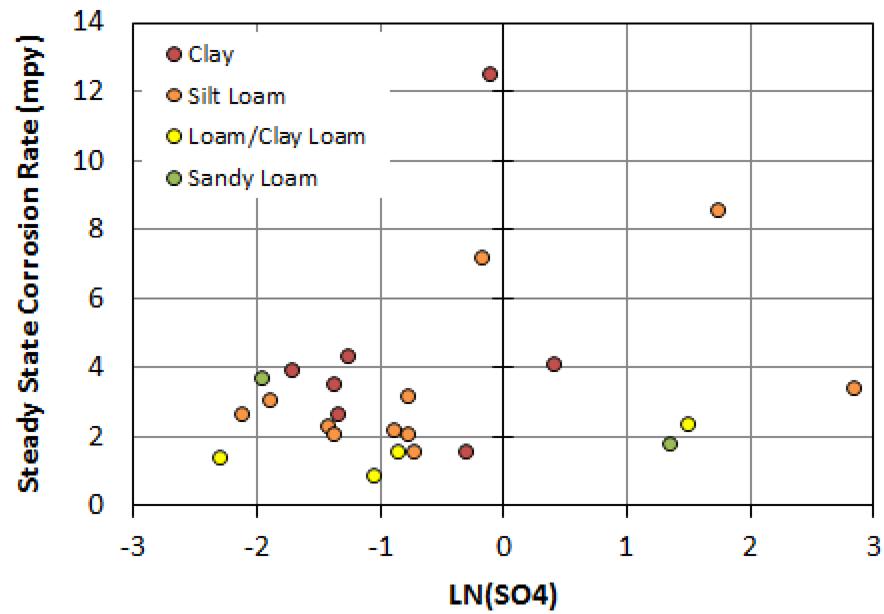




Correlation Study-2

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





Other Soil Classifications

- **Three basic classifications Romanoff (1957)**

1. **Soil composition**
   - Group I – VI, Pacific Coast and Poorly Drained
   - Based on soil texture (silt, clay, sand)
2. **Soil chemistry**
   - Inorganic and organic soli, Oxidizing and Reducing conditions, Acidic and Alkaline
3. **Soil aeration**
   - Good, Fair, Poor and Very Poor

- **The steady state rate can be estimated for these groups as well**

Limitations

- **Steady state rate is basically an <u>average</u> representative rate of corrosion**
- **Thus, the distribution of the rate for a soli group is the distribution of an average rate**
  - Results in an estimate of the “Average” Remaining Life
  - The estimated remaining life can be interpreted as an upper-bound Mean Life with 80% confidence
  - A fine point is that it is not the same as the “Remaining Life distribution (Not a holistic risk-informed approach)

Remarks

- **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
- **Given a large and confounding scatter in penetration depth data, this can be justified as a satisfactory approach**

Stochastic Process Model

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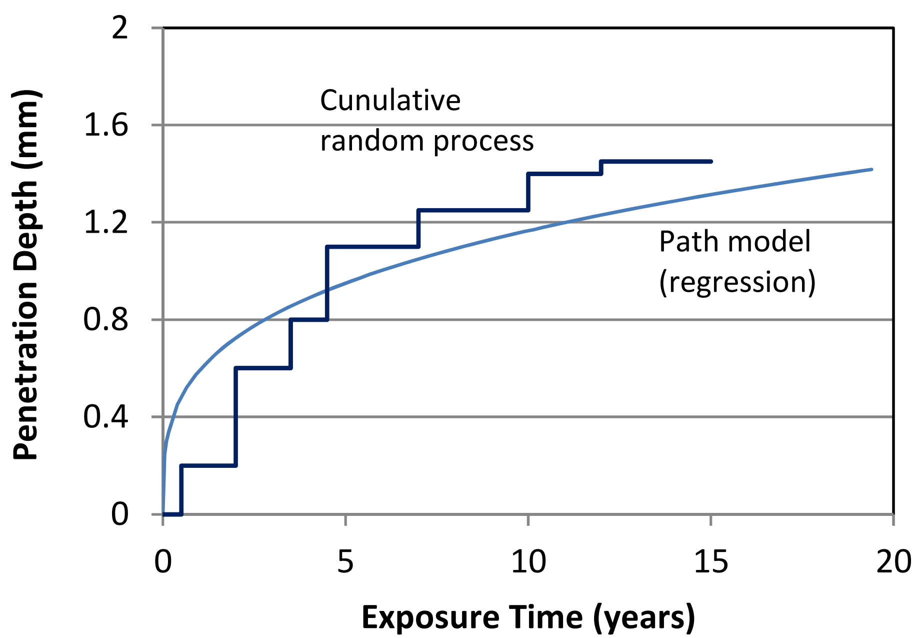
Corrosion: A True Stochastic Process

- **Electrochemical theory of corrosion process is well understood**
  - Corrosion occurs by loss of metal ions at anodic areas
- **Corrosion process is influenced by a wide variety of highly stochastic factors**
  - Process can be of intermittent, with highly variable intensity in any given stage
  - The intensity of corrosion in each stage can be highly variable and different from other stages of corrosion
- **Corrosion process is marred with temporal uncertainty during the exposure period**

Stochastic Cumulative Process

- **Degradation at any given time is a result of accumulation of degradation that took place in the past intervals**
  - Degradation as a sum of random increments
  - Random increments reflect variable conditions causing corrosion (different stochastic stages)



Cumulative Process

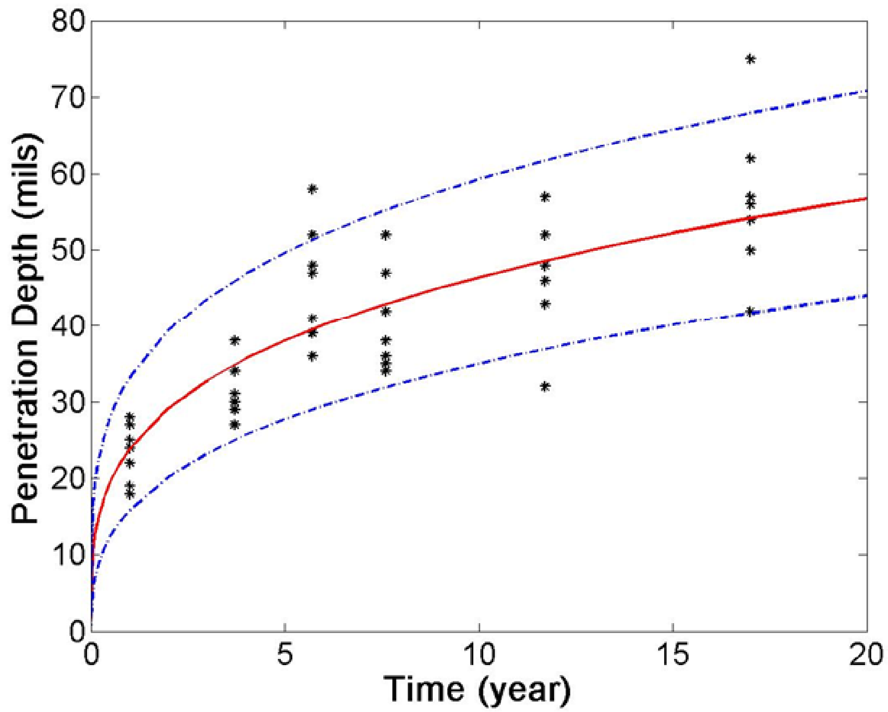
- **Cumulative degradation $Y(t)$ is a random variable**
  - Degradation increments, $X_k, k = 1, 2 \ldots.$, are also random variables
  - Overall degradation $Y(t) = X_1 + X_2 + \cdots . X_n$
  - Temporal uncertainty associated with evolution of degradation is retained in the model
- **Regression model is conceptually different**
  - It assumes that degradation path of a sample is given by a known equation
  - Future evolution of a sample path has no uncertainty
  - Each sample has different path, which gives the sampling uncertainty

Gamma Process Model

- **Total degradation is gamma distributed.**
  - Increments are also gamma distributed random variables
- **Model of corrosion process**
  - Mean corrosion depth as a function of time
  - $Avg[Y(t)] = \mu\,(t) = \beta a t^n$ (average path – nonlinear)
  - $Var[Y(t)] = \beta\mu(t)$ (variance of the process)
- **Statistical estimation**
  - Maximum likelihood method
  - All data including censored observations are included

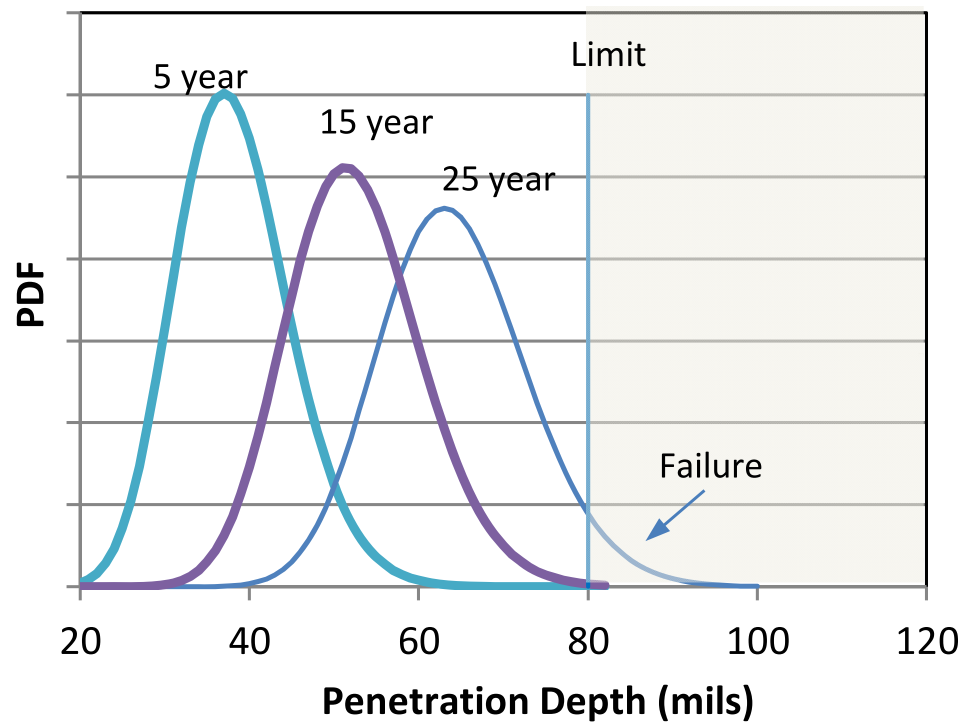
Example

- **Analysis of data from soil site 25 (San Antonio, TX)**
- **Parameters of gamma process model**
  - *a* =20.3, *n* = 0.29, β =1.18 mils
  - 95% prediction intervals are shown



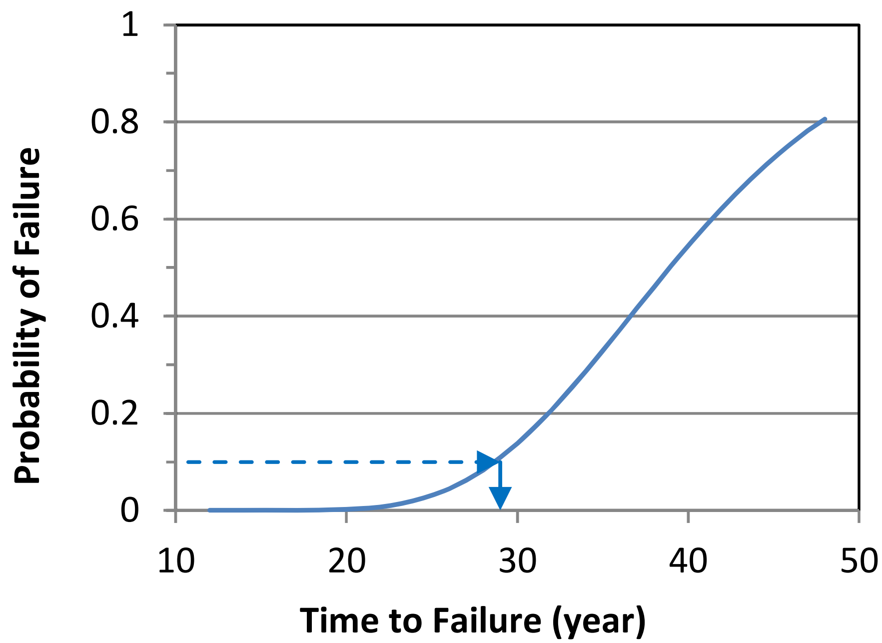
Flaw Size Distribution

- **What is the corrosion penetration depth after 5, 15 and 30 years?**
  - Overlapping Gamma distributions similar to the data
  - Distributions grow slowly since $n = 0.29, \ll 1$



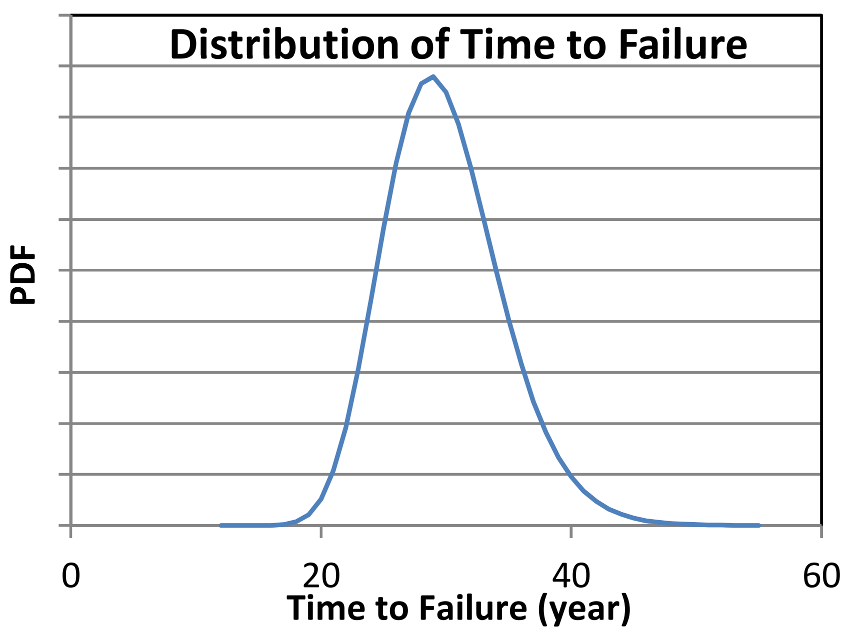
Application

- **Selection of next inspection interval**
  - Current flaw age 12 years, size 60 mils, y_{cr} = 80 mils
  - Probability of failure ≤ 0.10
  - Corresponding Time to next inspection: 29 years
  - Inspection interval of 17 years



Application-2

- **A corrosion flaw of depth 50 mils is discovered during an inspection at an of age 12 years**
- **Suppose maximum tolerable flaw depth is 110 mils**
- **Distribution of Time to Failure**
    - Time at which flaw depth exceeds the limit\



Mean time to failure: 28 years
10th percentile = 17 years

GP Parameters
a= 20.3, n = 0.4, β = 2.5

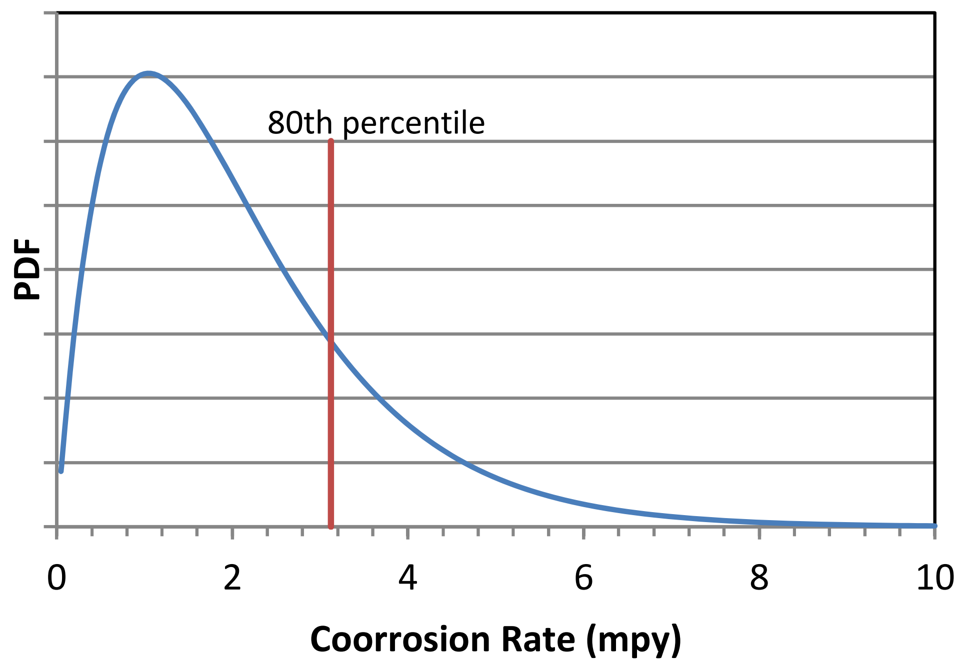
Remarks – Gamma Process (GP)

- **GP model needs the time of corrosion initiation (the origin)**
  - Being a non-stationary process
- **It can be assumed that flaw initiated some X years ago**
  - X = 5 years similar to the steady state rate model
- **Corrosion initiation time can as well be modelled as a random variable**
  - Additional complexity
  - Data about initiation time – breakdown of the coating
- **Assumption about some initiation time is “implicit” in most studies**
  - NBS study – starting time of test

Steady State Rate Distribution

- **Steady state rate can be inferred from Gamma Process model**
  - Steady state time interval: 5 to 15 years
  - Upper bound (80th percentile) = 3.1 mpy (fair drainage)

Corrosion Rate Distribution: Clay Loam)



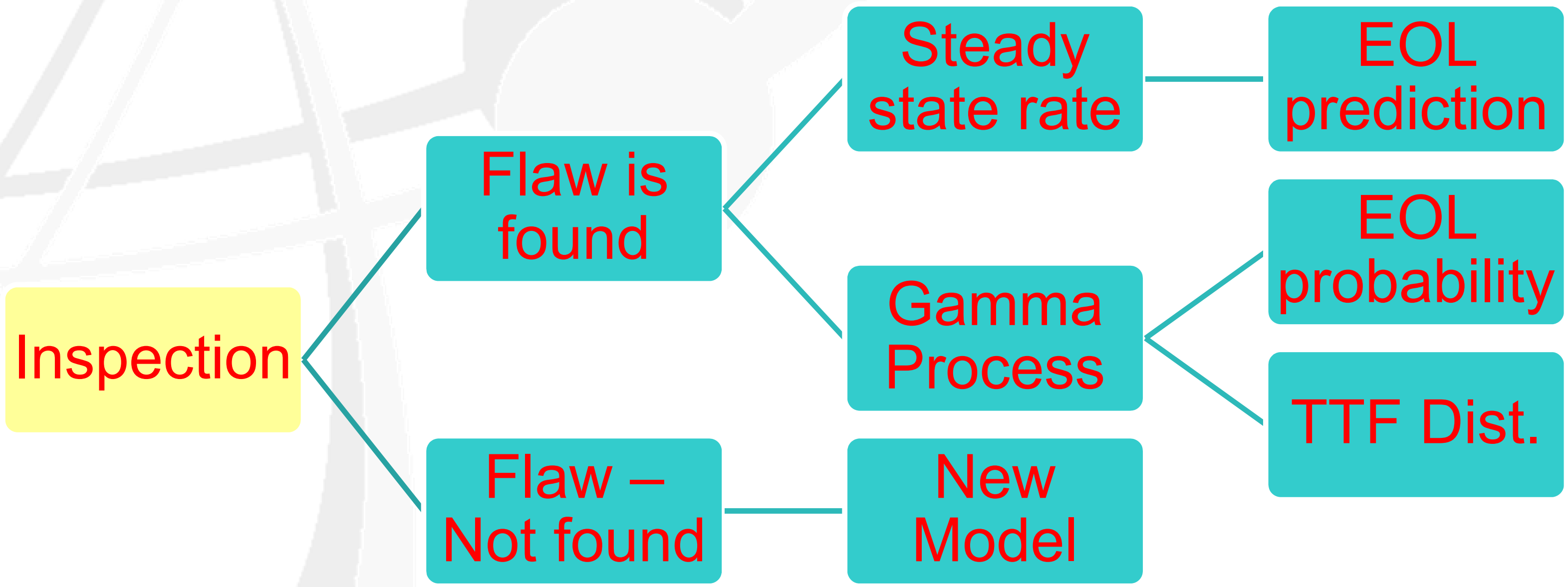
Remarks – Gamma Process

- **Gamma process is versatile in modeling a random degradation process like localized corrosion**
  - Conceptually accurate approach
  - Holistic risk-informed assessment
  - Statistical estimation is rigorously done
- **Can analytical complexity hinder practical applications?**
  - Not so much, since all the formulas can be programmed in Excel 2010
  - This model is widely used in the reliability literature, though less known to nuclear industry

A Schematic of Inspection & Assessment Approach

University of Waterloo

Inspection & Assessment Process -1



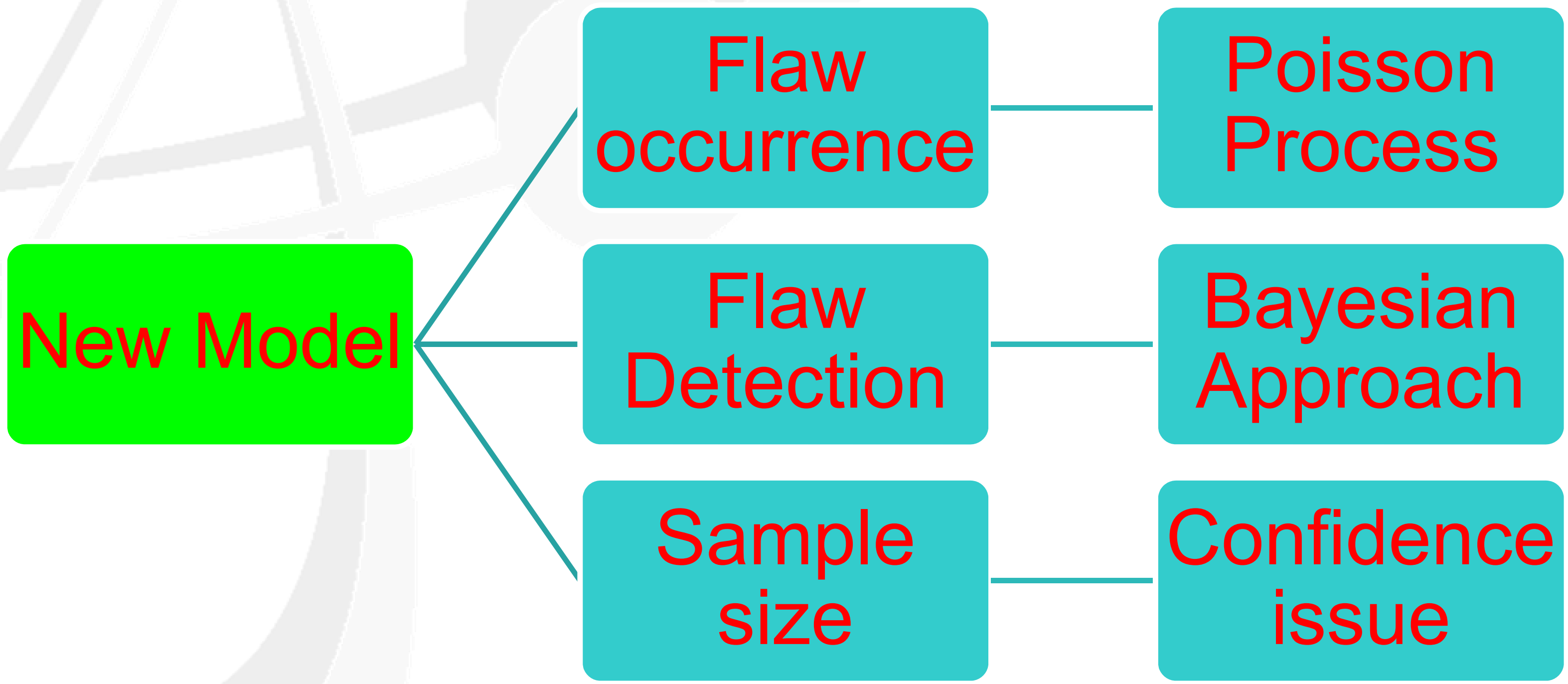
EOL: End of life
TTF: Time to failure

Basic Premise: Detected flaws are under stable growth state

Rapidly growing extreme flaws cannot be managed through inspection

Inspection & Assessment Process -2

Inference about degradation process is 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. **Steady State Model**
   - 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

- **Gamma process model**
  - Predict the full distribution of degradation in evaluation period
  - Predict the probability of non-compliance in the evaluation period ($P_f(t)$)
  - Condition acceptable if $P_f(t) < p_{cr}$
    - A limiting failure probability such as $p_{cr} = 0.1$
- **The expected number of flaw in "un-inspected" pipe sections can also be predicted by this model**

Procedure - 3

- **Inspection does NOT discover any localized corrosion flaw**
  - This implies that pipe coating and CP protection is functional 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**

Remarks

- **Assessment for leak integrity**
  - Based on localized penetration rate
  - Data analysis is extensively done
- **Assessment for structural integrity**
  - It will be based on the general corrosion loss
  - NBS data are available (Romanoff Report)
  - Data analysis and model developed are planned
- **Assessment for plant sites with potential soli contamination**
  - Example - Coastal plant sites with higher chlorides
  - Corrosion rate will be estimated from NBS soil site data similar to the plant in question

Other Issues

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 fluid side and soil side rates (or their upper bounds)**
  - These two rates are probabilistic quantities
- **Solution**
  - Sum of two distributions (convolution) must be carried out and then an upper bound value should be selected

2. Coated Pipes

- **Prediction of remaining life of coated pipes**
  - Coating prolongs the pit initiation
  - NBS Data are available to analyze time to initiation distribution
- **After the coating failure, the corrosion model based on bare ferrous pipe data can be used**
  - <u>It is a conservative approach</u>
  - In NBS Data, penetration depths in coated pipes were found to be much less than those in bare pipes (after 10 year exposure)
  - Does the “Area Effect” aggravate the corrosion rate?
    - Additional data analysis is required
    - Cathodic protection may compensate for this in real cases

2. Coated Pipes

- **A formal 2-stage process model can be developed**
  - *X*: random time to pit initiation, distribution $F_X(x)$
  - *Z(u)*: degradation growth after the initiation during time *u*
  - Total degradation distribution predicted at time *t*
  - Convolution: $F_Y(t) = \int_0^t F_Z(t-x)\,dF_X(x)$

3. Data from Test Stations

- **Using data from test stations**
  - Technology is available for in-situ measurement of corrosion rate
  - This rate data can be used directly for the remaining life estimation or time of next inspection
- **Direct Approach to FFS**
  - Collect a sufficiently large sample of “rate” data
  - Estimate a probability distribution of the rate
  - Estimate an upper bound rate (95th percentile) and use it for assessment
  - Define an optimal sample size to ensure a high confidence in the analysis

4. Sample Size Analysis

- **Adequate sample size can be estimated based on a selected criterion (Objective of FFS)**
  1. Width of confidence interval of average rate
  2. Tolerance interval at a selected confidence level
  3. the confidence about the estimated probability of failure or non-compliance
- **Bayesian Analysis**
  - Update the distribution of corrosion rate based on new measurements from test stations
  - A more formal and precise approach to determine the scope of the inspection campaign

5. Cathodic Protection

- **If inspection does not find any defects, the procedure discussed before should be used**
  - CP is effective at inspected locations
  - Estimate probability of potential degradation in other locations (as discussed earlier in the presentation)
- **If inspection finds a corrosion flaw, follow the procedure discussed before**
  - The corrosion rate estimated for bare pipes should be conservative (assuming area effect is not active)
  - In this case, the test station data would be most useful to provide site specific corrosion rate

6. Effect of Grounding Grid

- **Nuclear plant piping is connected to a grounding grid (copper grid) for protection**
  - The effect of grounding and its interaction with CP is not well understood
  - The aggravating effect of grounding on the corrosion rate is not known (data are lacking)
  - Pipe assessment can be based on the proposed procedures for the time being

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 condition
- **Remaining life prediction**
  - Based on steady-state rate of corrosion (Level 2)
  - Fully probabilistic approach – Gamma process (Level 3)
- **Results: Steady state rate (80th percentile)**
  - Clay: 7 mpy, Silt-Loam: 5 mpy, Loam-Clay Loam: 4 mpy and Sandy-Loam: 3 mpy

Summary

- **A fully probabilistic approach based on gamma process model is presented**
  - Analytical approach is derived & illustrated by an example
- **Approaches to address additional issues related to the assessment are conceptually developed**
  - Combination of OD and ID rates, Coated pipes, Use of test station data
  - Sample size selection for assessment work
- **Effect of copper grounding on the corrosion rate is under investigation**