the Energy to Lead

# Uncertainty in Risk Models

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**Gas Technology Institute**

- PHMSA RMWG
- Centerpoint Building, Houston, TX
- March 7th, 2017



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# Agenda

- Why do we need risk models?
- Uncertainty due to data quality
- How to score data quality
- Example of probabilistic risk model that includes uncertainty modeling: Aldyl A gas distribution systems
    - Identify the risk drivers
    - Make sense of the Causal factors and interactions
    - How to go about attaching numbers to the model
    - Material model
    - Sensitivity of the material model
    - Reference data
    - Test data for existing installations
    - Understanding the data
    - Models to address uncertainty
    - Model validation
    - Prediction
    - Forensics
    - Simplified model
- Questions + Discussion at any point during the presentation



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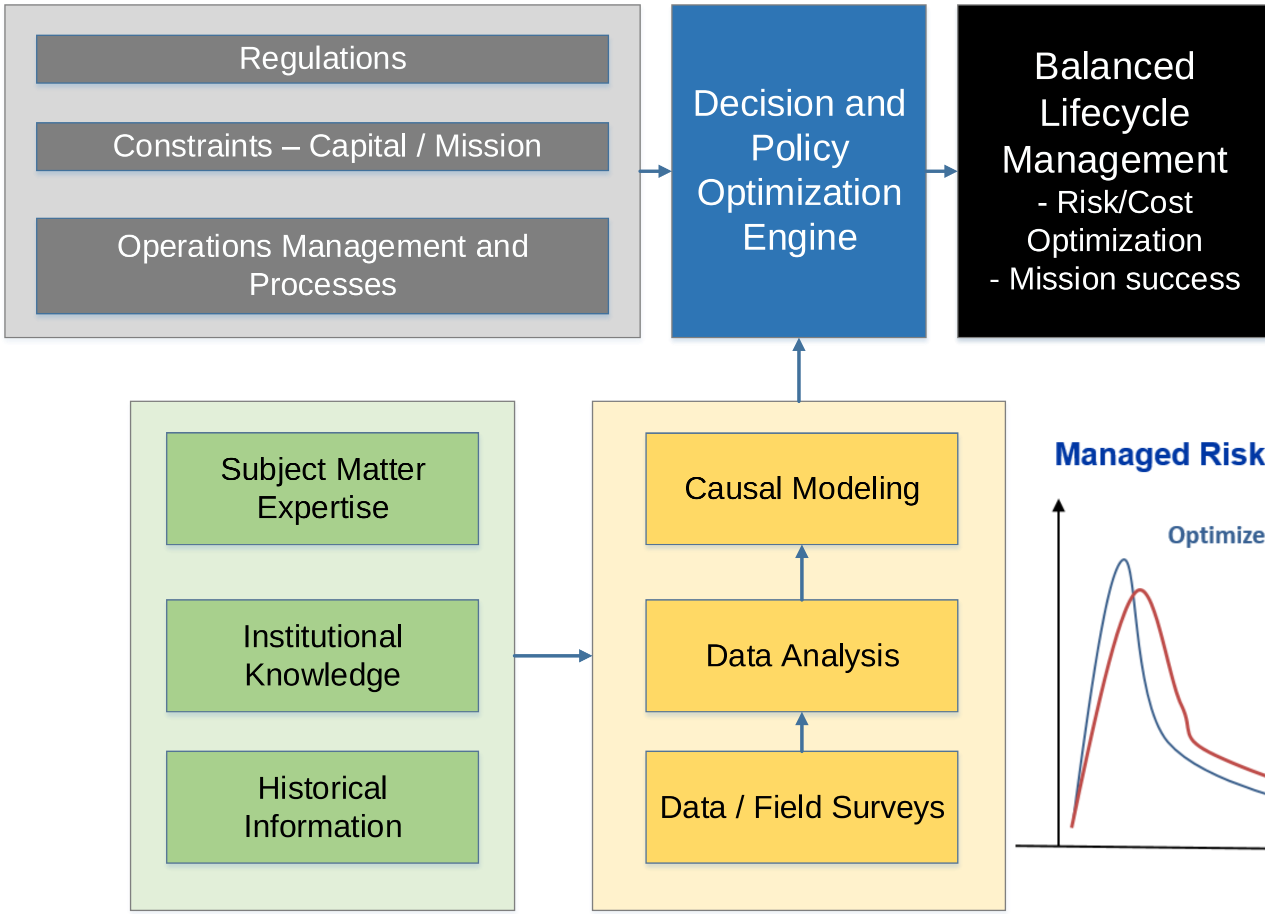
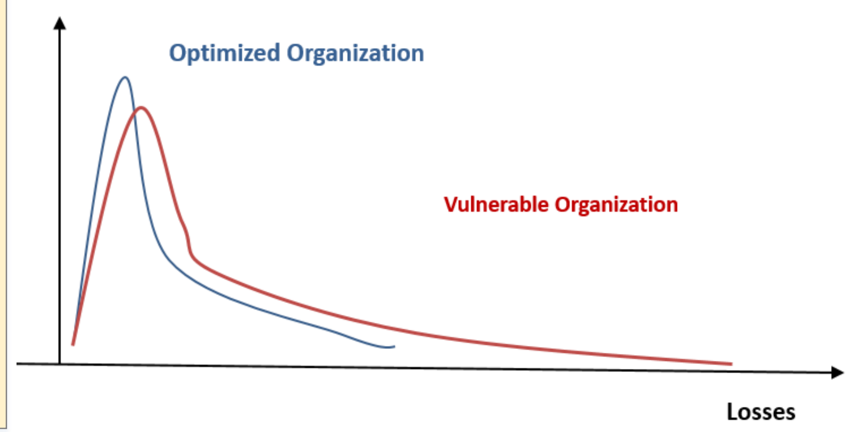
# Why Use Risk Models?




**Managed Risk vs. Catastrophic Losses**



# Data Pedigree

**Pedigree Levels**

The definitions and pedigree levels below are a generalization of the ASCE standard on quality to fit with the natural gas system asset and system classes. They were reconciled with the definitions of traceable, verifiable, and complete from advisory bulletins (ADB) and Notice of Proposed Rulemaking from DOT/PHMSA. The use of “reliable” by DOT/PHMSA is addressed in the Record Integrity definitions .

# Record Integrity

**Record Integrity Characteristics**

We have combined and taken a subset of information characteristics from GARP and ISO to develop four characteristics of Integrity: Authenticity, Compliance, Transparency, and Reliability. For each of these four characteristics one can establish one of five levels of agreement that a data/information record value has with the definitions: yes, partial, a conservative default value, no, and no info on data field.

# Authenticity

**Authenticity** - information has a reasonable and suitable guarantee of authenticity

- records need to be authentic, be what it purports to be
- have been created by the agent purported to have created it
- have been created or sent when purported
- prove that the origin, time of creation or transmission, and content are what they are claimed to be
- maintain the authenticity of records over time
- hardware, network infrastructure, software, and storage should be monitored for the systems that control the information and records
- have an acceptable audit trail
- is protected against unauthorized alteration
- any authorized annotation, addition or deletion to a record should be explicitly indicated and traceable.

# Compliance

**Compliance** - information program complies with laws and other binding authorities, as well as organization's policies

- information is entered into records in a manner/form consistent with the law
- records must be maintained in the manner and for the time prescribed by law, codes, and authorities

# Transparency

**Transparency** - documented in an open and verifiable manner, documents available to all personnel and appropriate interested parties

- records documentation should be written and recorded in a manner that clearly sets forth the information recorded
- records should be readily available to legitimately interested parties, in particularly to government authorities, auditors, and investigators, as well as the company representatives

# Reliability

**Reliability** - a reliable record is one

•whose contents can be trusted as full and accurate representation of the facts to which they attest

•which can be depended upon in the course of subsequent activities

# Simple Scoring of Data Quality Attributes

| Pedigree Level | Score |
|---|---|
| A | 15 |
| B or Default | 10 |
| C | 5 |
| D | 3 |
| No Info on Data Field | 1 |

| | Score | | | |
|---|---|---|---|---|
| Integrity Agreement | Authenticity | Compliance | Transparency | Reliability |
| Yes | 15 | 15 | 15 | 15 |
| Partial | 10 | 10 | 10 | 10 |
| Default Value | 5 | 5 | 5 | 5 |
| No | 3 | 3 | 3 | 3 |
| No Info on Data Field | 1 | 1 | 1 | 1 |

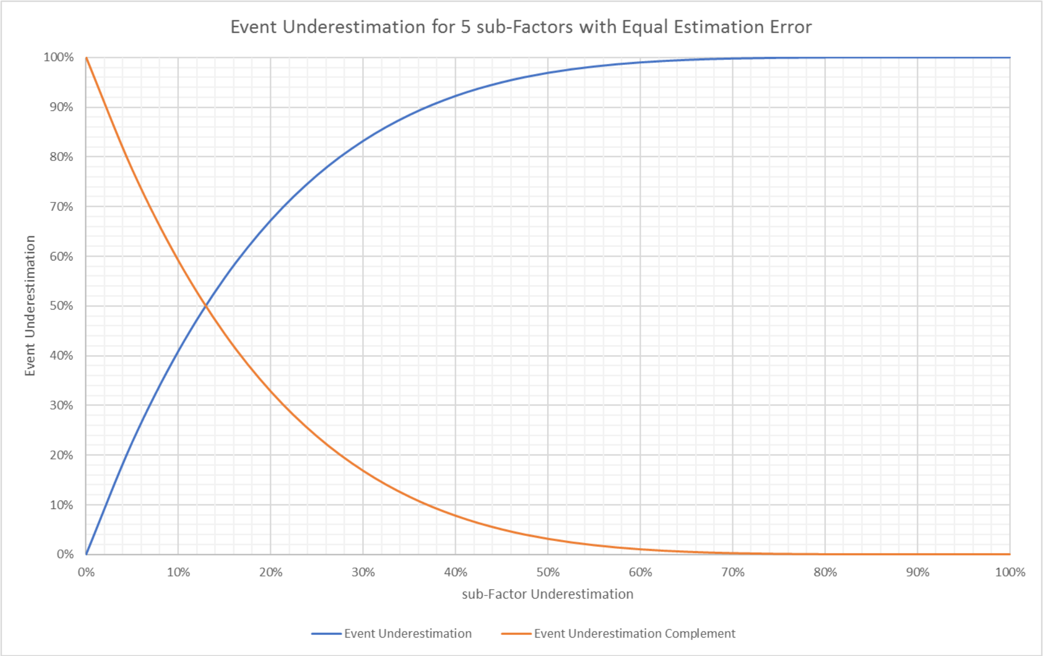
| Component | | Score / Level | Roll-Ups |
|---|---|---|---|
| Integrity | Authenticity | 10 | 12.5 |
| | Compliance | 15 | |
| | Transparency | 15 | |
| | Reliability | 10 | |
| Pedigree | | 10 | 10.0 |
| Weighted Score | | 75% Pedigree + 25% Integrity | **10.6** |

# Data Quality and Uncertainty

- It is not unusual to have five independent sub-factors in a catastrophic event
- The probability of occurrence for the catastrophic event if the each of the individual probabilities is p will be $p^5$
- If we underestimate each of the probabilities by 20% (80% certainty for our data for each factor), by how much will we underestimate the probability of occurrence of the event?

$Event\ Underestimation = 1 - 0.8^5$= 1-0.3278= 0.67

# Uncertainty Based Data Quality Score Suggestion

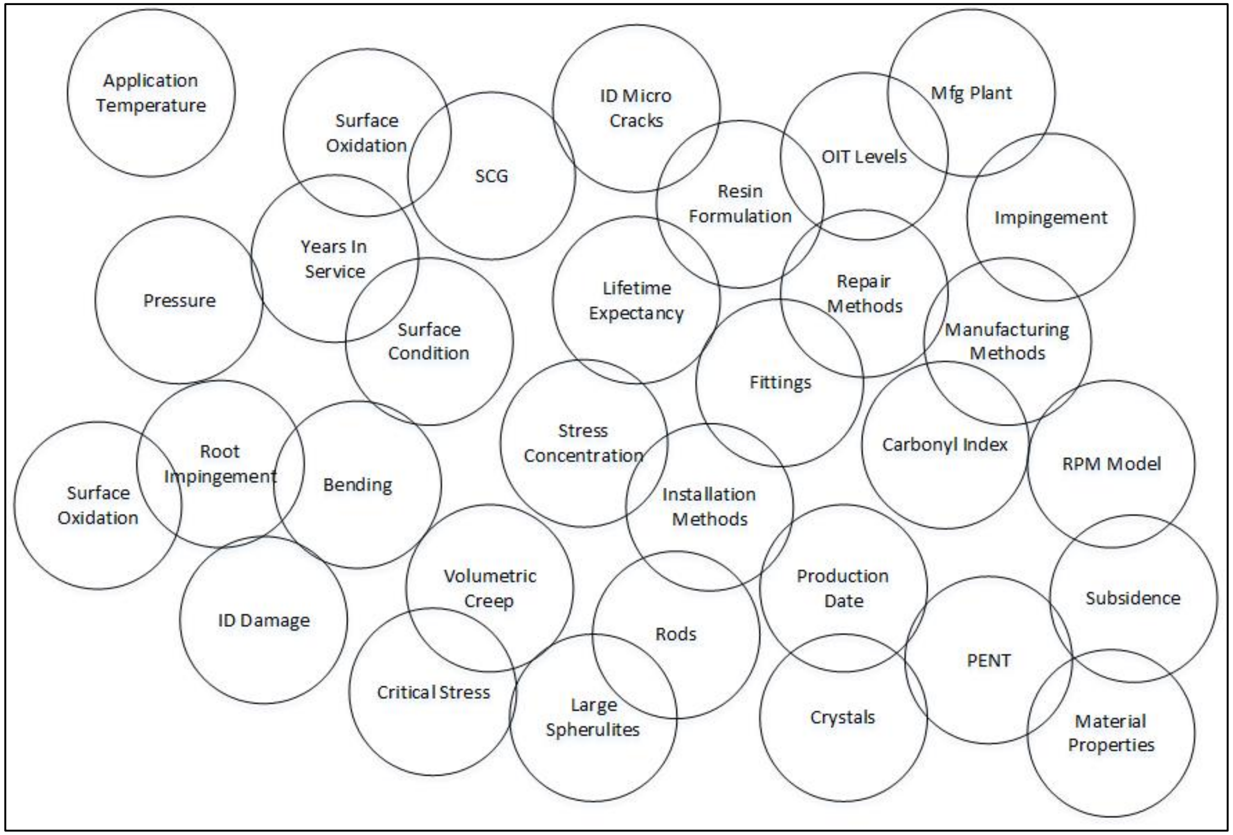



| Number of sub-Factors | 5 | | |
|---|---|---|---|
| sub-Factor Underestimation | Event Underestimation | Event Underestimation Complement | Revised Score for Data Quality |
| 0% | 0% | 1.0000 | 10000 |
| 5% | 23% | 0.7738 | 7738 |
| 10% | 41% | 0.5905 | 5905 |
| 15% | 56% | 0.4437 | 4437 |
| 20% | 67% | 0.3277 | 3277 |
| 25% | 76% | 0.2373 | 2373 |
| 30% | 83% | 0.1681 | 1681 |
| 35% | 88% | 0.1160 | 1161 |
| 40% | 92% | 0.0778 | 778 |
| 45% | 95% | 0.0503 | 504 |
| 50% | 97% | 0.0313 | 313 |
| 55% | 98% | 0.0185 | 185 |
| 60% | 99% | 0.0102 | 103 |
| 65% | 99% | 0.0053 | 53 |
| 70% | 100% | 0.0024 | 25 |
| 75% | 100% | 0.0010 | 10 |
| 80% | 100% | 0.0003 | 4 |
| 85% | 100% | 0.0001 | 1 |
| 90% | 100% | 0.0000 | 1 |
| 95% | 100% | 0.0000 | 1 |
| 100% | 100% | 0.0000 | 1 |

# What have we Touched on for Data Quality?

- Propagation of uncertainty
- Non-linear impact for ignorance

# Factors in Aldyl A Risk Assessment



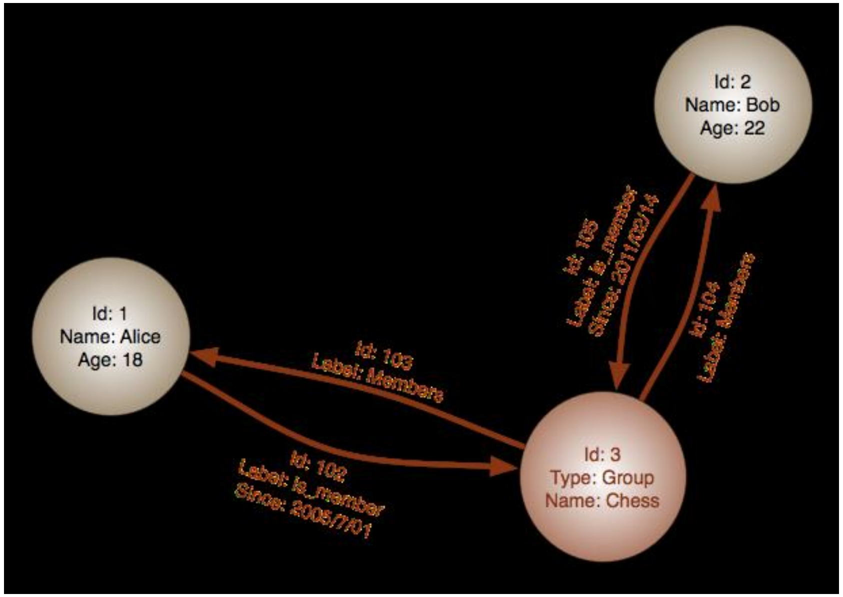

n=32

2^32=4,294,967,296

| Interacting Factors | Combinations |
|---|---|
| 2 | 496 |
| 3 | 4960 |
| 4 | 35960 |
| 5 | 201376 |
| Sum | 242792 |

# Semantics, Ontologies, Graphs (From Wikipedia)

**Semantics** (from Ancient Greek: σημαντικός *sēmantikós*, "significant")[1][2] is the study of meaning. It focuses on the relation between *signifiers*, like words, phrases, signs, and symbols, and what they stand for, their denotation

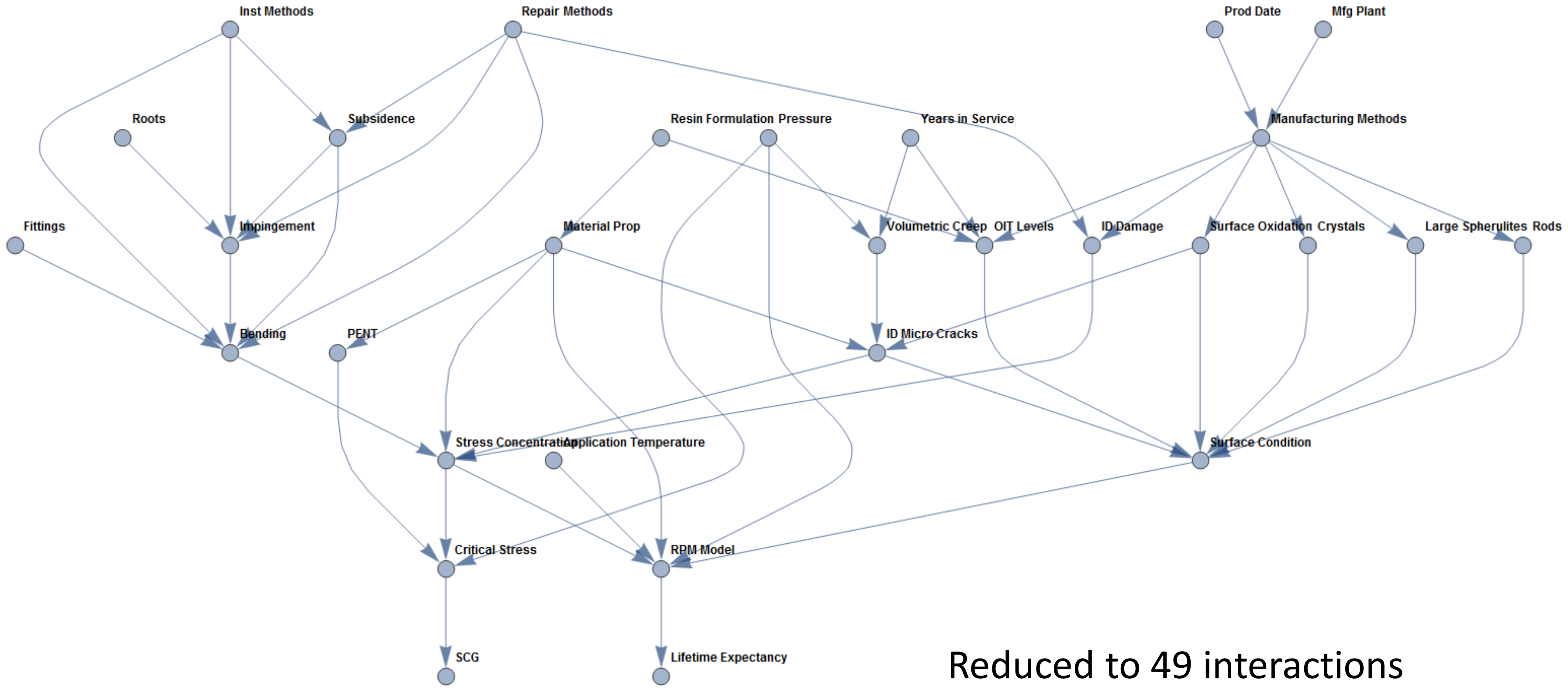



The term *ontology* has its origin in philosophy and has been applied in many different ways. The word element *onto-* comes from the Greek *ὤν*, *ὄντος*, ("being", "that which is"), present participle of the verb *εἰμί* ("be"). The core meaning within computer science is a model for describing the world that consists of a set of types, properties, and relationship types. There is also generally an expectation that the features of the model in an ontology should closely resemble the real world (related to the object).[3]

# Semantic Formulation in Mathematica

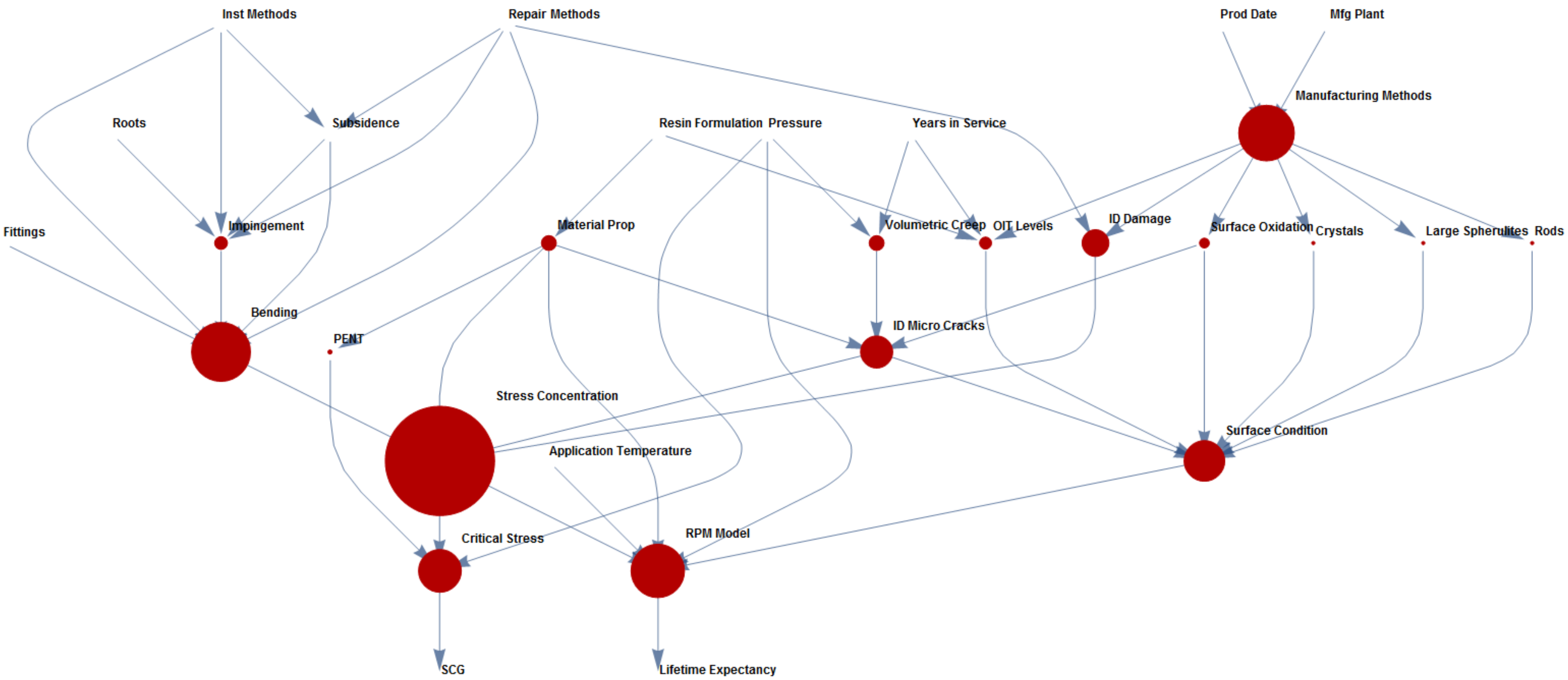
```
scgMap =
 Graph[{"Prod Date" ↔ "Manufacturing Methods", "Mfg Plant" ↔ "Manufacturing Methods",
   "Manufacturing Methods" ↔ "Crystals", "Manufacturing Methods" ↔ "Large Spherulites",
   "Manufacturing Methods" ↔ "Rods", "Rods" ↔ "Surface Condition",
   "Crystals" ↔ "Surface Condition", "Manufacturing Methods" ↔ "Surface Oxidation",
   "Large Spherulites" ↔ "Surface Condition", "Surface Oxidation" ↔ "Surface Condition",
   "Surface Oxidation" ↔ "ID Micro Cracks", "ID Micro Cracks" ↔ "Stress Concentration",
   "Material Prop" ↔ "PENT", "Repair Methods" ↔ "ID Damage",
   "Repair Methods" ↔ "Impingement", "Repair Methods" ↔ "Bending",
   "Repair Methods" ↔ "Subsidence", "Manufacturing Methods" ↔ "ID Damage",
   "ID Damage" ↔ "Stress Concentration", "Critical Stress" ↔ "SCG",
   "Pressure" ↔ "Critical Stress", "Bending" ↔ "Stress Concentration",
   "Stress Concentration" ↔ "Critical Stress", "Impingement" ↔ "Bending",
   "Fittings" ↔ "Bending", "Inst Methods" ↔ "Impingement", "Inst Methods" ↔ "Subsidence",
   "Inst Methods" ↔ "Bending", "Subsidence" → "Impingement", "Subsidence" → "Bending",
   "PENT" ↔ "Critical Stress", "Roots" → "Impingement",
   "Material Prop" ↔ "Stress Concentration", "Resin Formulation" ↔ "Material Prop",
   "Material Prop" ↔ "ID Micro Cracks", "Pressure" ↔ "Volumetric Creep",
   "Years in Service" ↔ "Volumetric Creep", "Volumetric Creep" ↔ "ID Micro Cracks",
   "ID Micro Cracks" ↔ "Surface Condition", "Surface Condition" ↔ "RPM Model",
   "Material Prop" ↔ "RPM Model", "Pressure" ↔ "RPM Model",
   "Stress Concentration" ↔ "RPM Model", "Manufacturing Methods" ↔ "OIT Levels",
   "Resin Formulation" ↔ "OIT Levels", "Years in Service" ↔ "OIT Levels",
   "OIT Levels" ↔ "Surface Condition", "Application Temperature" ↔ "RPM Model",
   "RPM Model" ↔ "Lifetime Expectancy"}, VertexLabels → "Name",
  VertexLabelStyle → Directive[FontFamily → "Arial", FontSize → 12, Bold],
  ImagePadding → 100, GraphLayout → "LayeredDigraphEmbedding"]
```

# Graph of Aldyl A Risk Model – The Aldyl A Gas Pipeline Risk Ontology

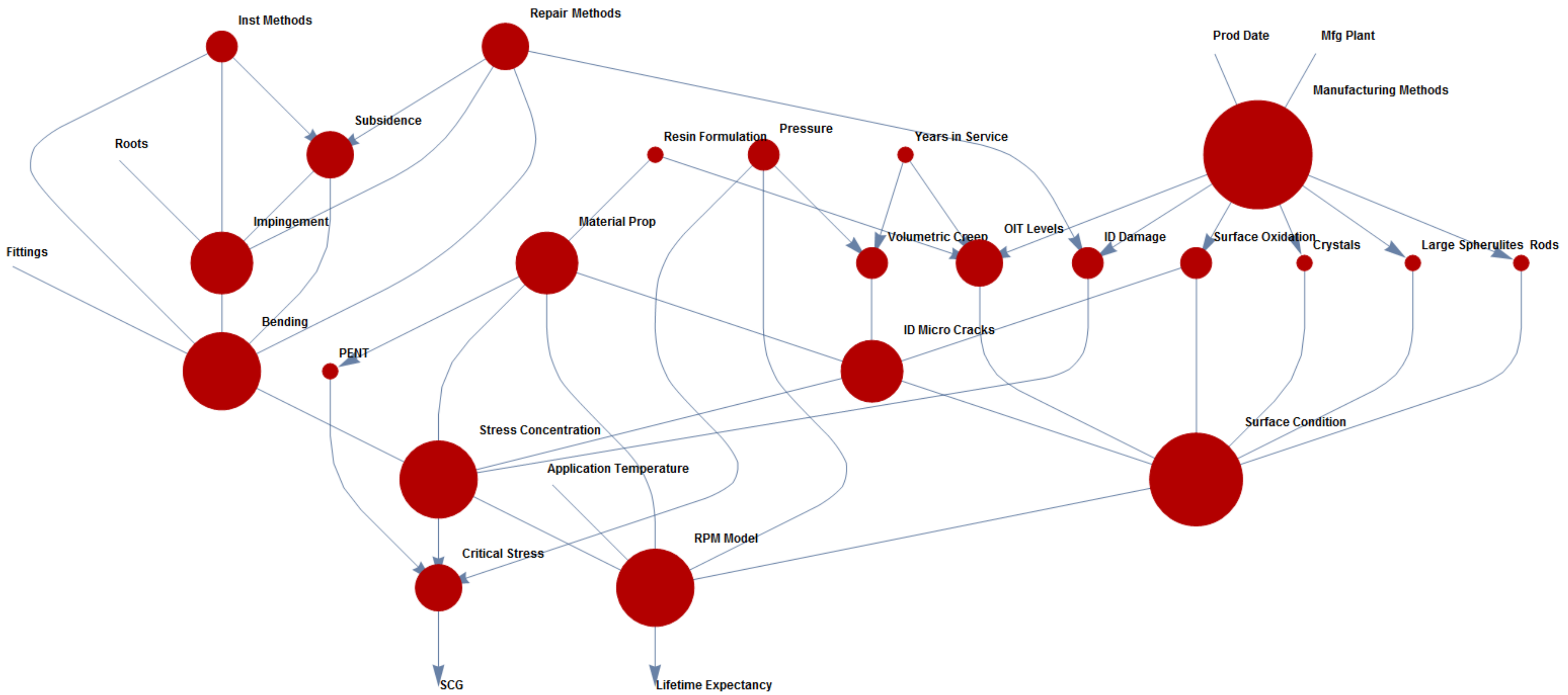



Reduced to 49 interactions
EdgeCount[scgMap]=49

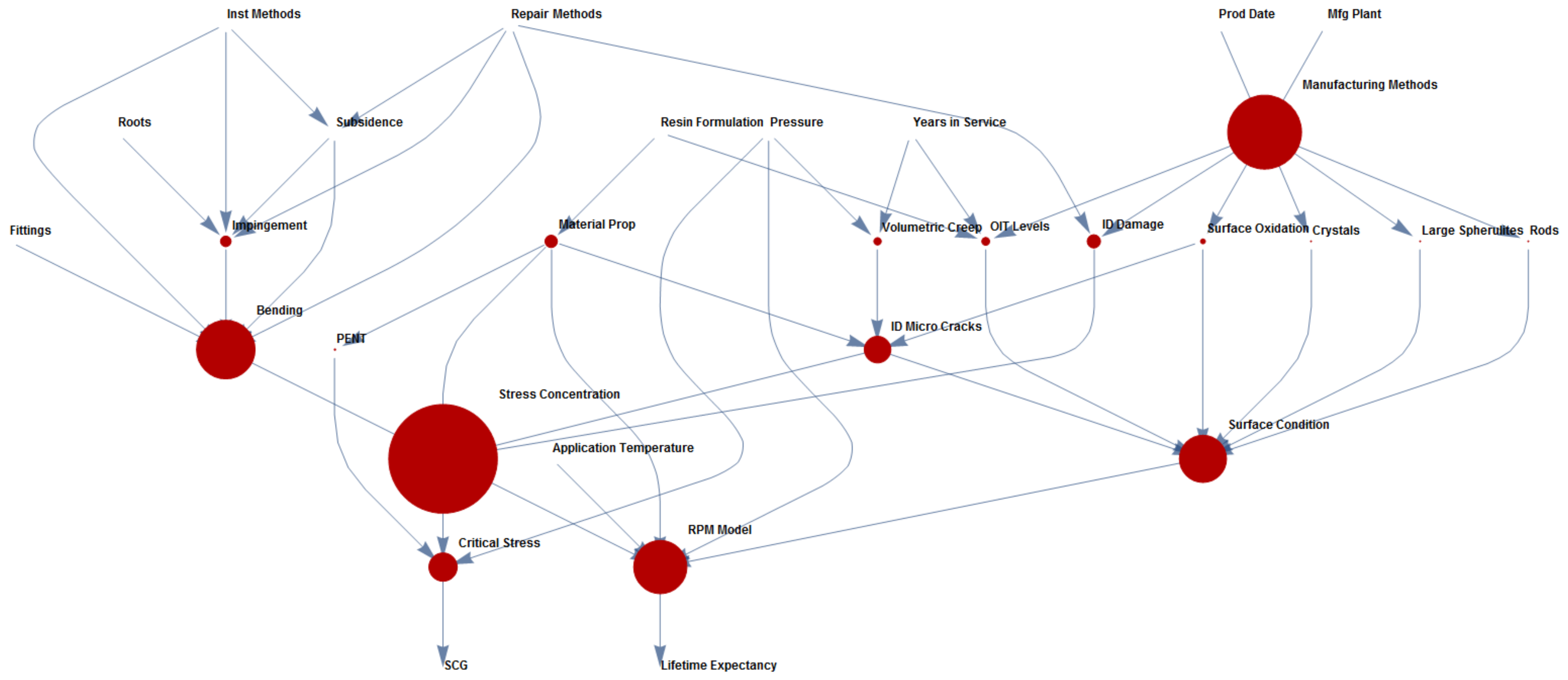
# Betweeness Centrality (BC)



# Degree Centrality (DC)



# Composite Ranking (DC*BC)



# Betweeness, Degree and Composite Ranking

| | |
|---|---|
| Stress Concentration | 51. |
| Bending | 27.5 |
| Manufacturing Methods | 26. |
| RPM Model | 25. |
| Critical Stress | 20. |
| Surface Condition | 19. |
| ID Micro Cracks | 15. |
| ID Damage | 12.5 |
| Volumetric Creep | 7. |
| Material Prop | 7. |
| Impingement | 6. |
| OIT Levels | 5.6 |
| Surface Oxidation | 4.6 |
| PENT | 2. |
| Rods | 1.6 |
| Large Spherulites | 1.6 |
| Crystals | 1.6 |
| Years in Service | 0. |
| Subsidence | 0. |
| SCG | 0. |
| Roots | 0. |
| Resin Formulation | 0. |
| Repair Methods | 0. |
| Prod Date | 0. |
| Pressure | 0. |
| Mfg Plant | 0. |
| Lifetime Expectancy | 0. |
| Inst Methods | 0. |
| Fittings | 0. |
| Application Temperature | 0. |

| | |
|---|---|
| Manufacturing Methods | 8 |
| Surface Condition | 7 |
| Stress Concentration | 6 |
| RPM Model | 6 |
| Bending | 6 |
| Material Prop | 5 |
| Impingement | 5 |
| ID Micro Cracks | 5 |
| Subsidence | 4 |
| Repair Methods | 4 |
| OIT Levels | 4 |
| Critical Stress | 4 |
| Volumetric Creep | 3 |
| Surface Oxidation | 3 |
| Pressure | 3 |
| Inst Methods | 3 |
| ID Damage | 3 |
| Years in Service | 2 |
| Rods | 2 |
| Resin Formulation | 2 |
| PENT | 2 |
| Large Spherulites | 2 |
| Crystals | 2 |
| SCG | 1 |
| Roots | 1 |
| Prod Date | 1 |
| Mfg Plant | 1 |
| Lifetime Expectancy | 1 |
| Fittings | 1 |
| Application Temperature | 1 |

| | |
|---|---|
| Stress Concentration | 306. |
| Manufacturing Methods | 208. |
| Bending | 165. |
| RPM Model | 150. |
| Surface Condition | 133. |
| Critical Stress | 80. |
| ID Micro Cracks | 75. |
| ID Damage | 37.5 |
| Material Prop | 35. |
| Impingement | 30. |
| OIT Levels | 22.4 |
| Volumetric Creep | 21. |
| Surface Oxidation | 13.8 |
| PENT | 4. |
| Rods | 3.2 |
| Large Spherulites | 3.2 |
| Crystals | 3.2 |
| Years in Service | 0. |
| Subsidence | 0. |
| SCG | 0. |
| Roots | 0. |
| Resin Formulation | 0. |
| Repair Methods | 0. |
| Prod Date | 0. |
| Pressure | 0. |
| Mfg Plant | 0. |
| Lifetime Expectancy | 0. |
| Inst Methods | 0. |
| Fittings | 0. |
| Application Temperature | 0. |

# What have we learned about a semantic/ontological approach?

- Very good at capturing subject matter expertise
- Lends itself to a causal description
- Provides a baseline Bayesian Network
- We see how information flows
- Can help identify critical variables/features
- We should be able see how uncertainty propagates through the system once we insert models to calculate conditional probabilities and attach numbers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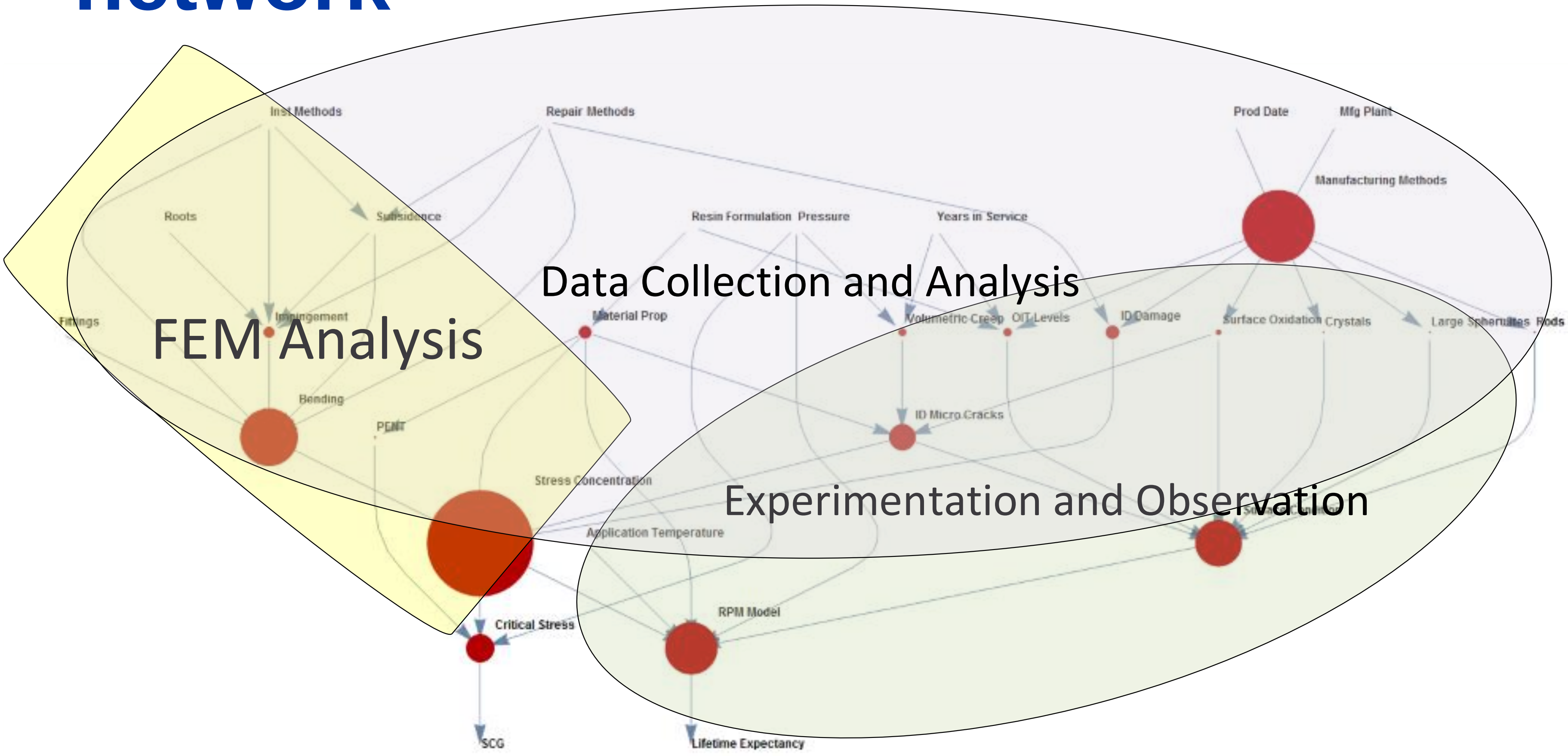
# How to attach numbers to the network



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# The Rate Process Method (RPM) Model for Aldyl A

**4.1 General model for the regression analysis according to ISO 9080**

The general 4-parameter model used in ISO 9080 is the following:

$$Log(t) = C_1 + C_2 \cdot \frac{1}{T} + C_3 \cdot Log(\sigma) + C_4 \cdot \frac{Log(\sigma)}{T} + e$$

*where*

| | | |
|---|---|---|
| $C_1$ to $C_4$ | *parameters used in this model* | |
| $t$ | *time to failure* | *[h]* |
| $T$ | *Temperature* | *[K]* |
| $\sigma$ | *Hoop stress* | *[MPa]* |
| $e$ | *error variable* | *Laplace-Gaussian distribution, with zero mean and constant variance (the errors are assumed to be independent)* |

The 4-parameter model shall be reduced to a 3-parameter model if the probability level of $C_3$ is greater than 0.05. i.e. $C_3 = 0$.

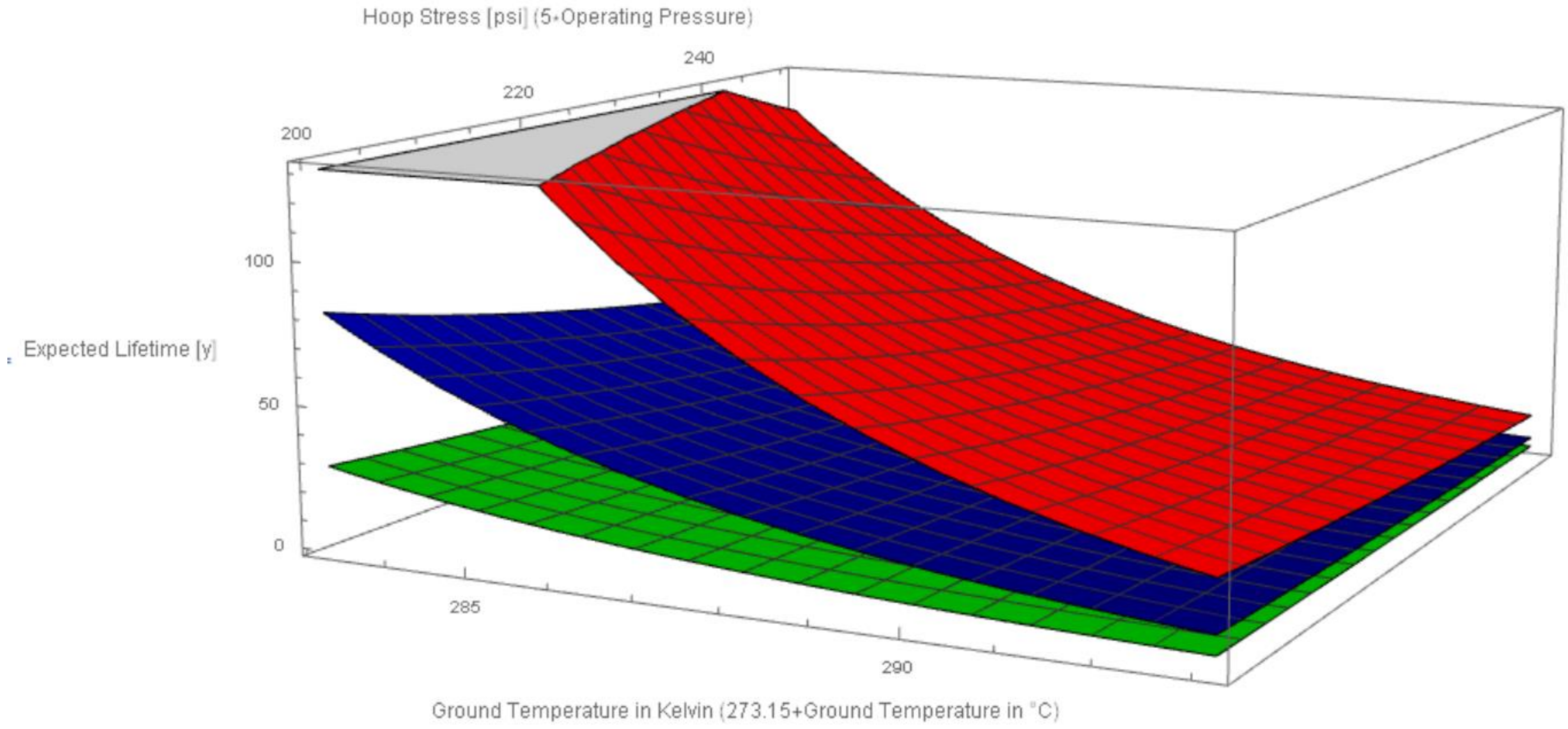
**Figure 16. The General RPM Model as Described by ISO 9080**

**Table 4. DuPont Control Model Parameters for 3 Parameter ISO 9080 Model**

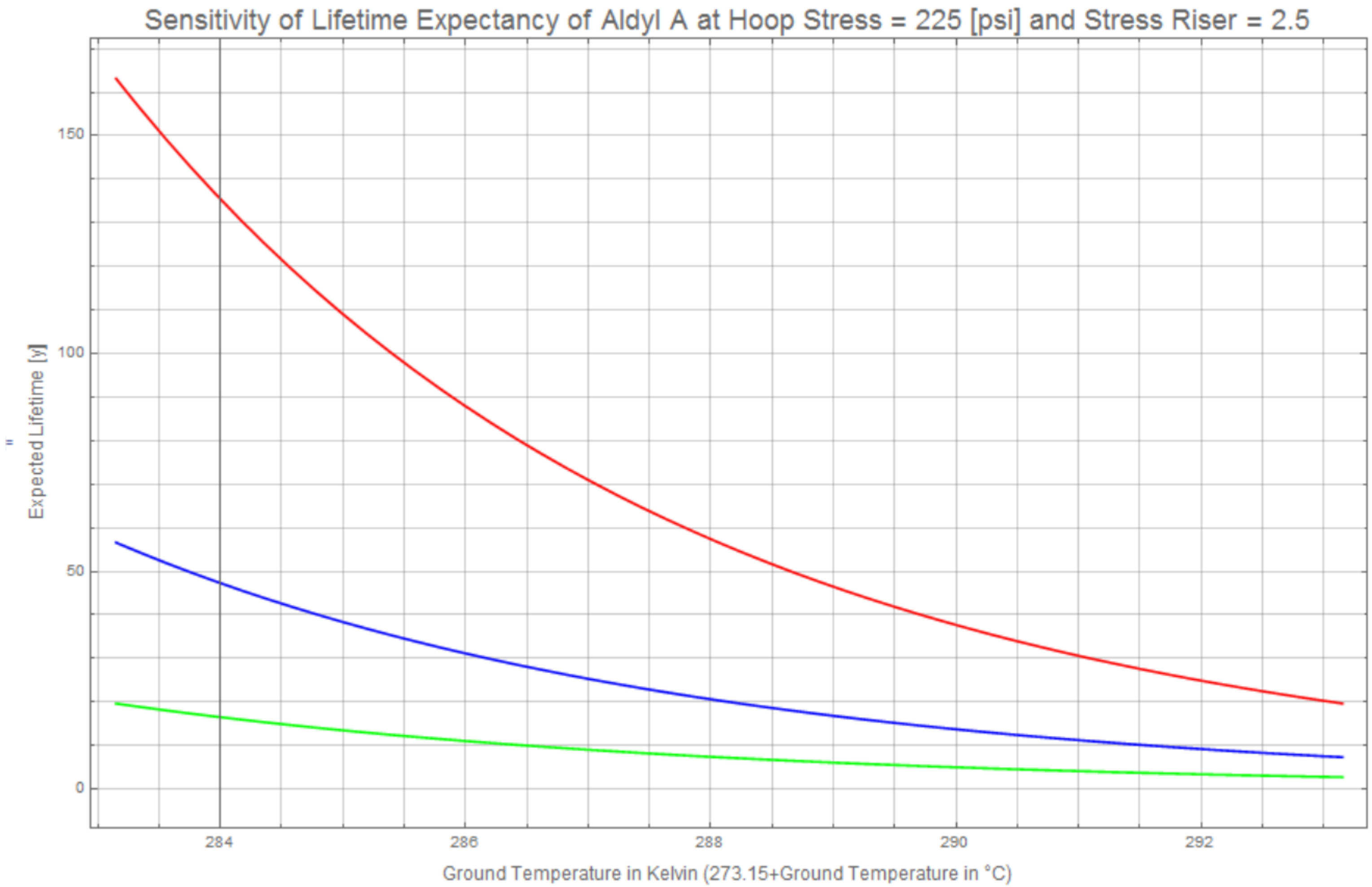
| Parameters | $C_1$ | $C_2$ | $C_4$ | $R^2$ | $R^2_{adj}$ | n | p | $\sigma^2$ |
|---|---|---|---|---|---|---|---|---|
| Value | -17.6172 | 9485.337 | -898.536 | 0.898 | 0.896 | 122 | 3 | 0.080944 |
| Standard Error | 0.703265 | 296.4989 | 33.90417 | | | | | |

| Covariance Matrix | | |
|---|---|---|
| 6.110133978 | -2487.297563 | 152.8993481 |
| -2487.297563 | 1086051.522 | -89681.8456 |
| 152.8993481 | -89681.8456 | 14201.01238 |

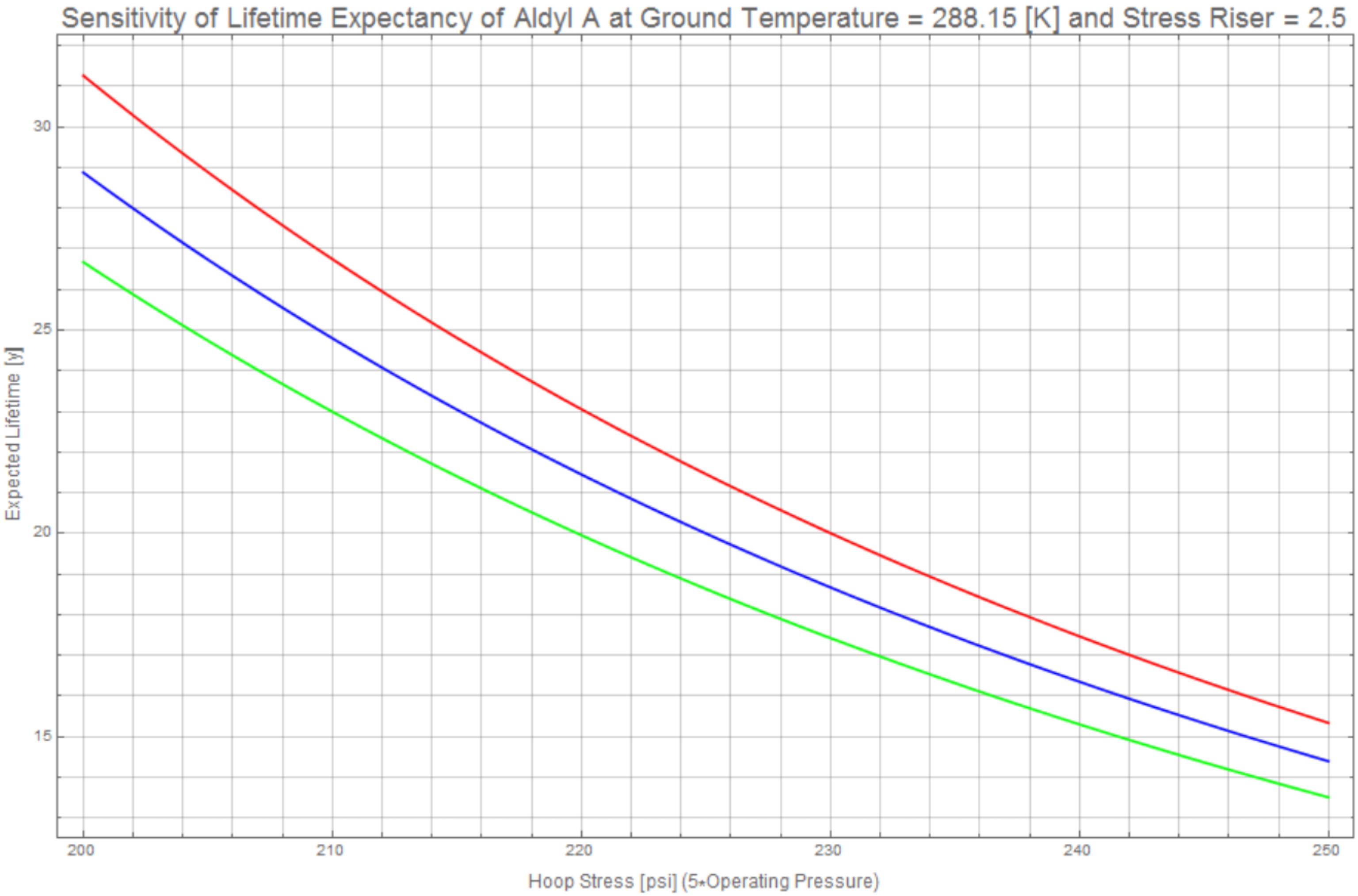
# RPM Model Sensitivity (Temperature, Stress)



# RPM Model Sensitivity to Temperature



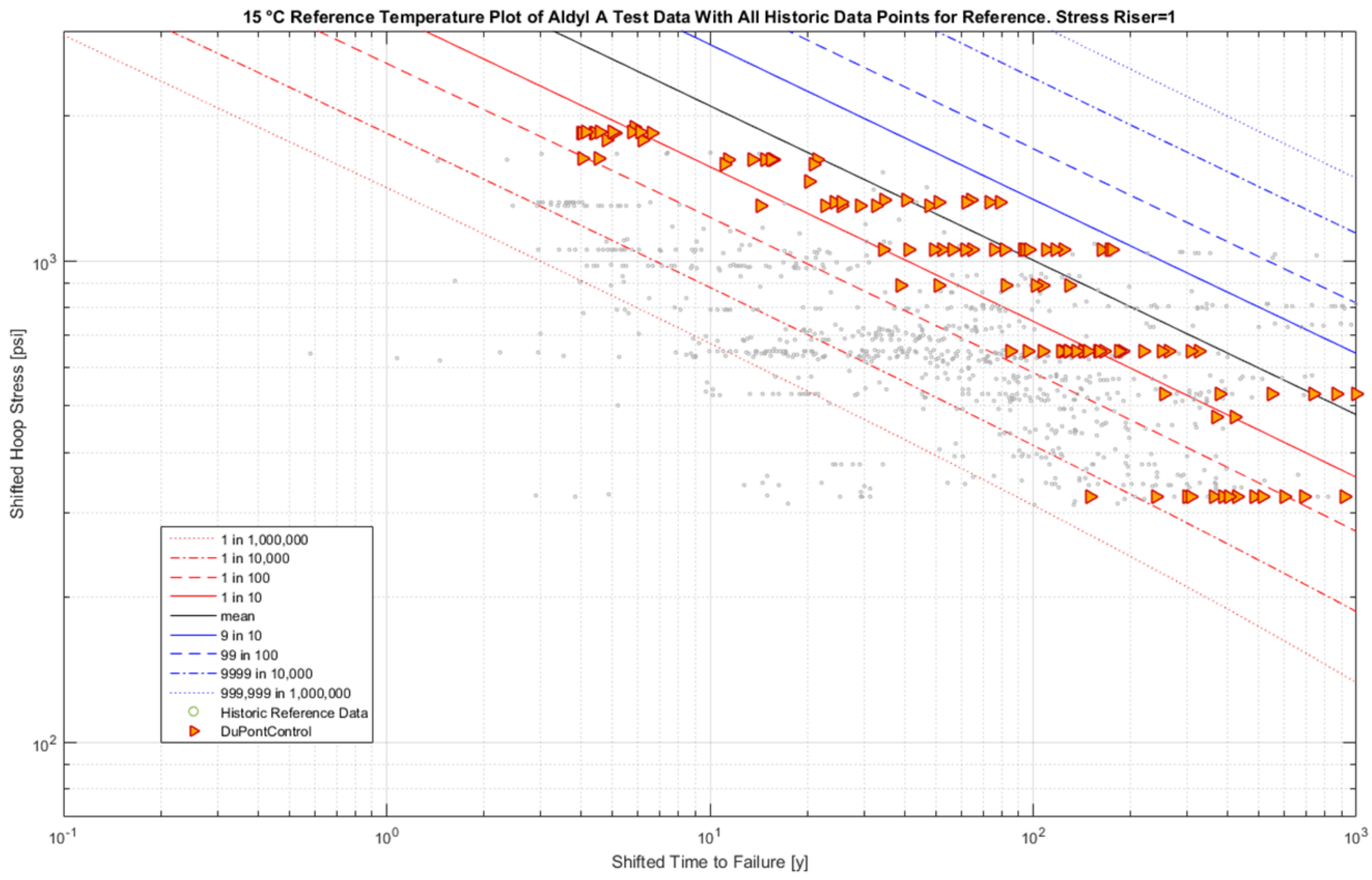
# RPM Model Sensitivity to Stress



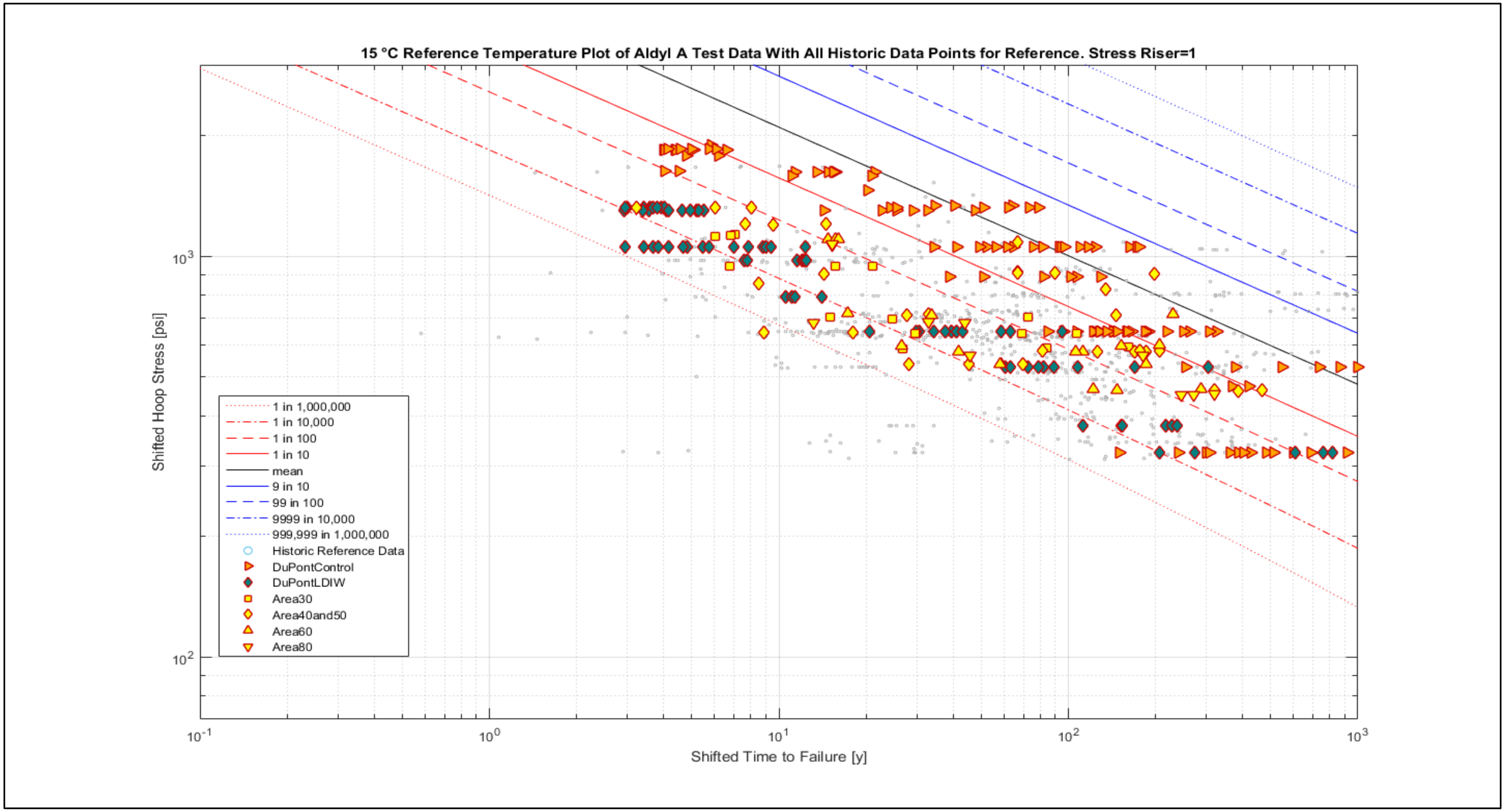
# What have we seen so far?

- We understand that application temperature is the dominant factor
- Stress is critical and has a non-linear effect

# Reference Data Underlying the RPM Model



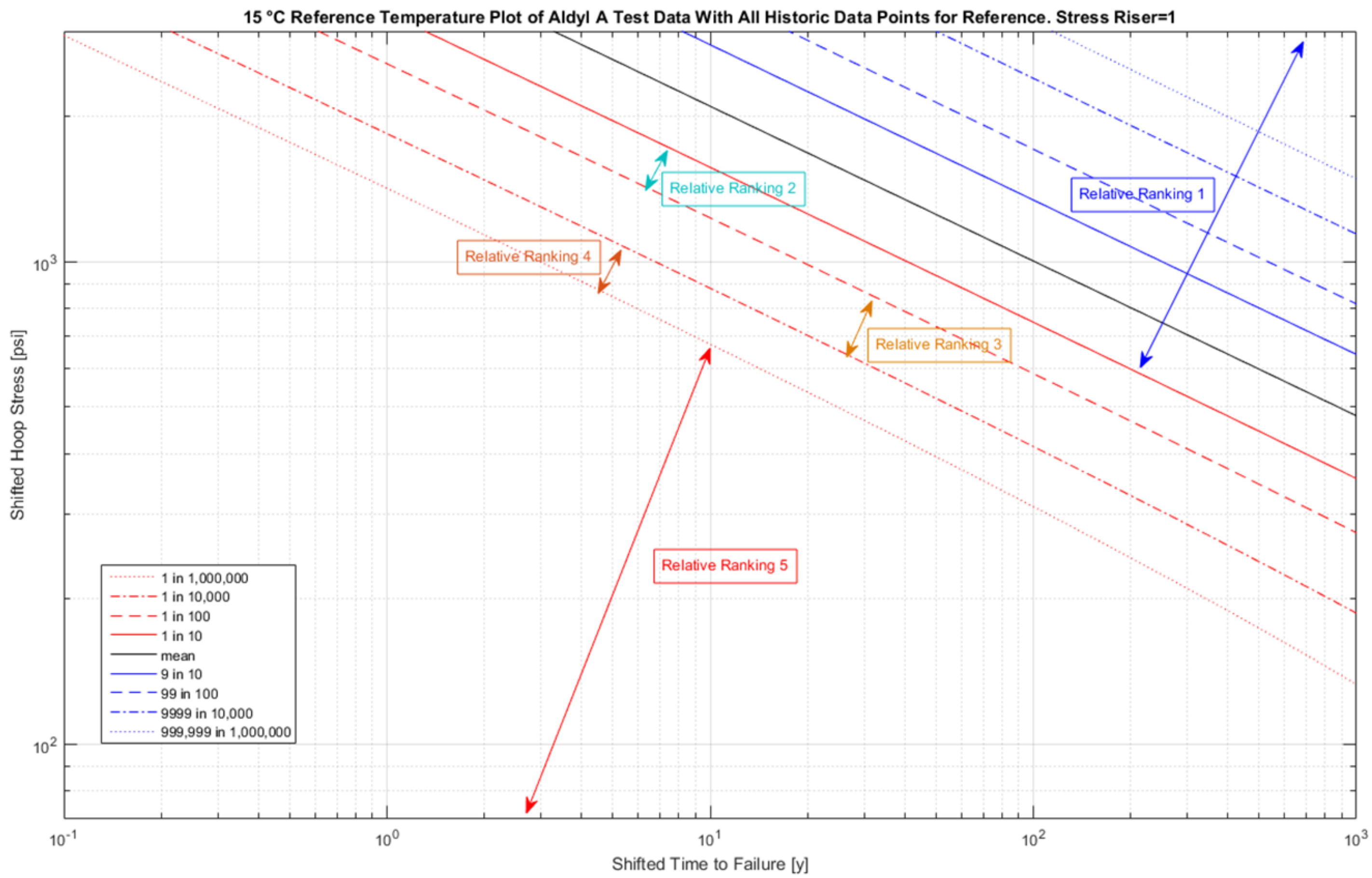
# Actual Installed Pipe Residual Lifetime



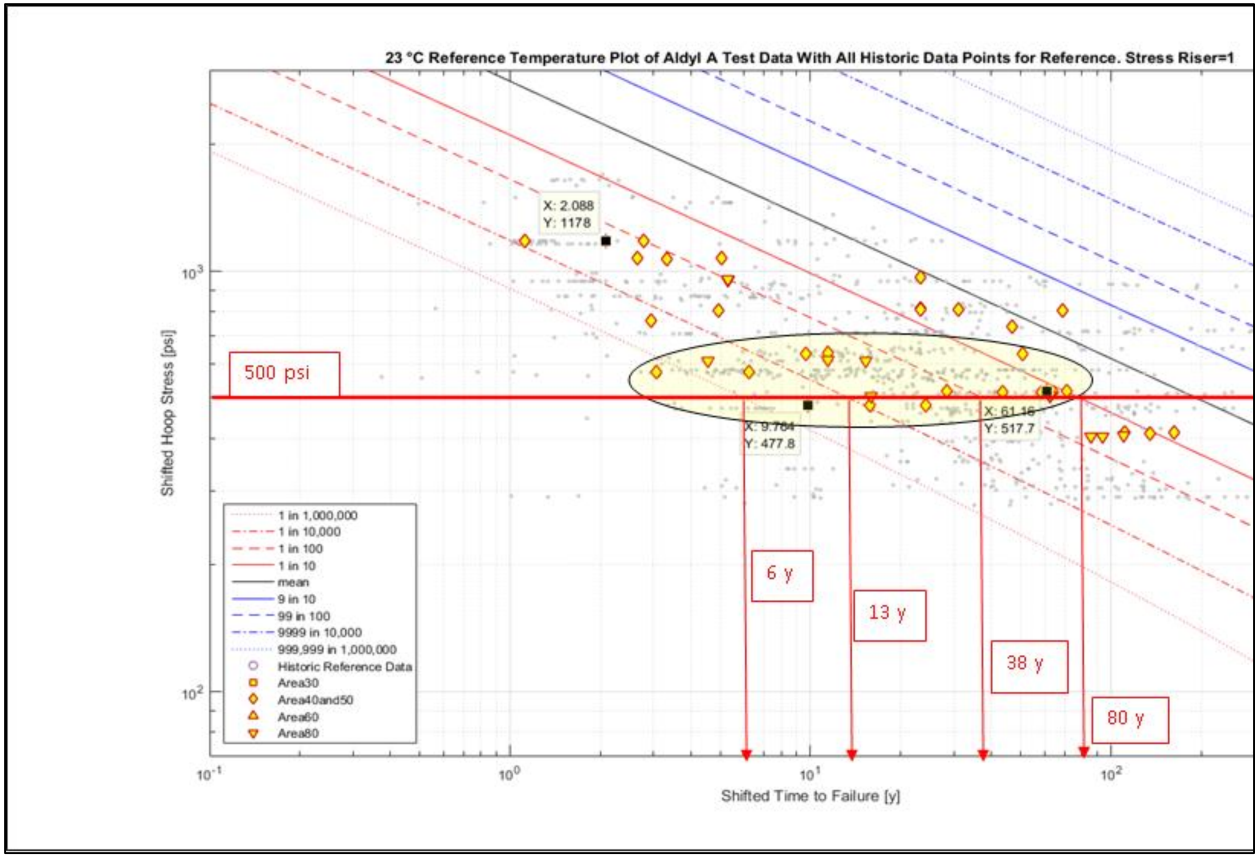
# What do we understand about the data?

- There is a large amount of uncertainty:
  - 250 fold variance relative to model mean at a given stress level
- Need to explain the variance and try to reduce uncertainty gor an input stress

# Probability Bands Translated to Relative Ranking

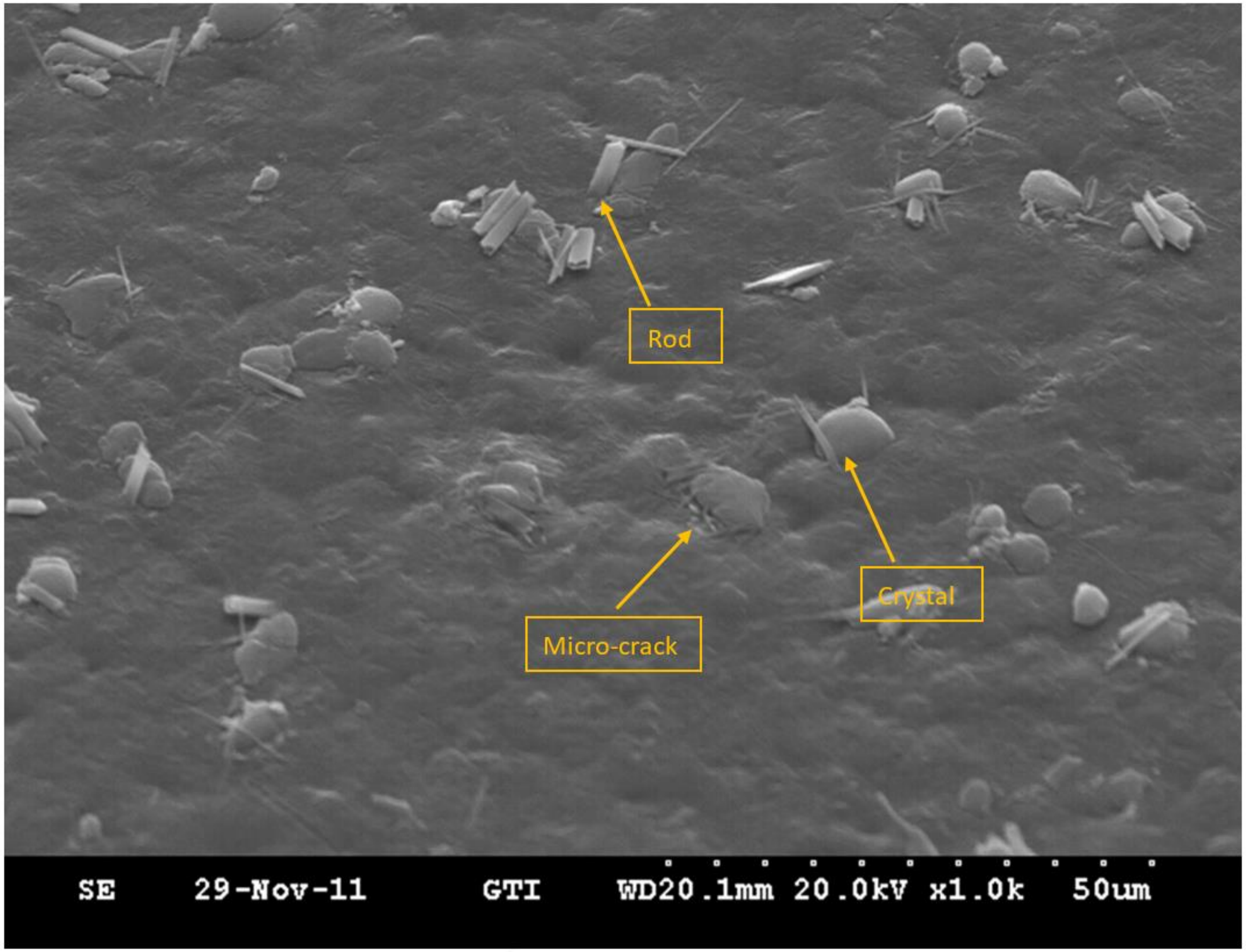


# Probability Bands Used to Reduce Uncertainty of Prediction

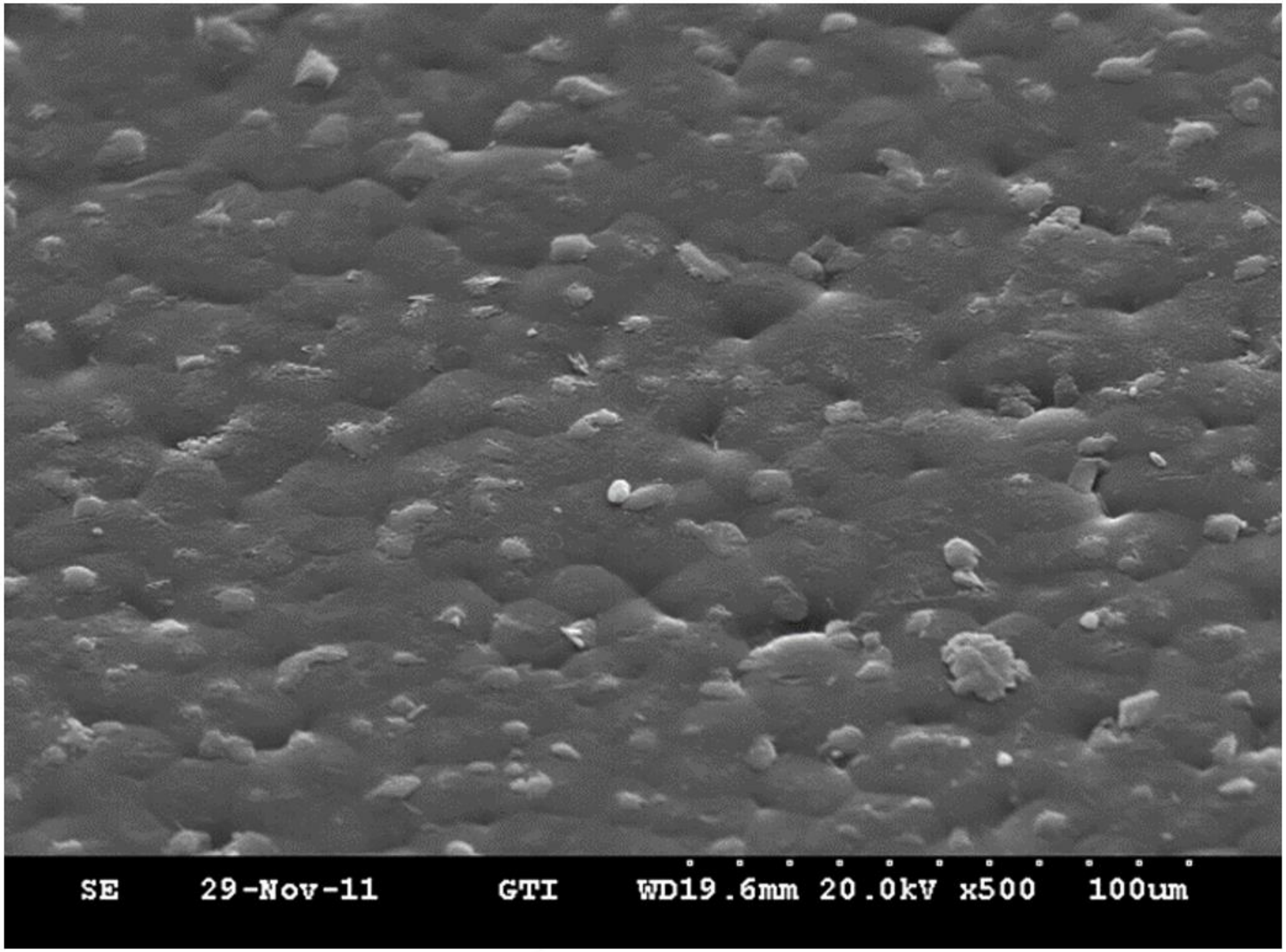



Uncertainty for all test data 250:1 at ~500 psi hoop stress relative to mean model prediction

# Inner Wall Risk Drivers



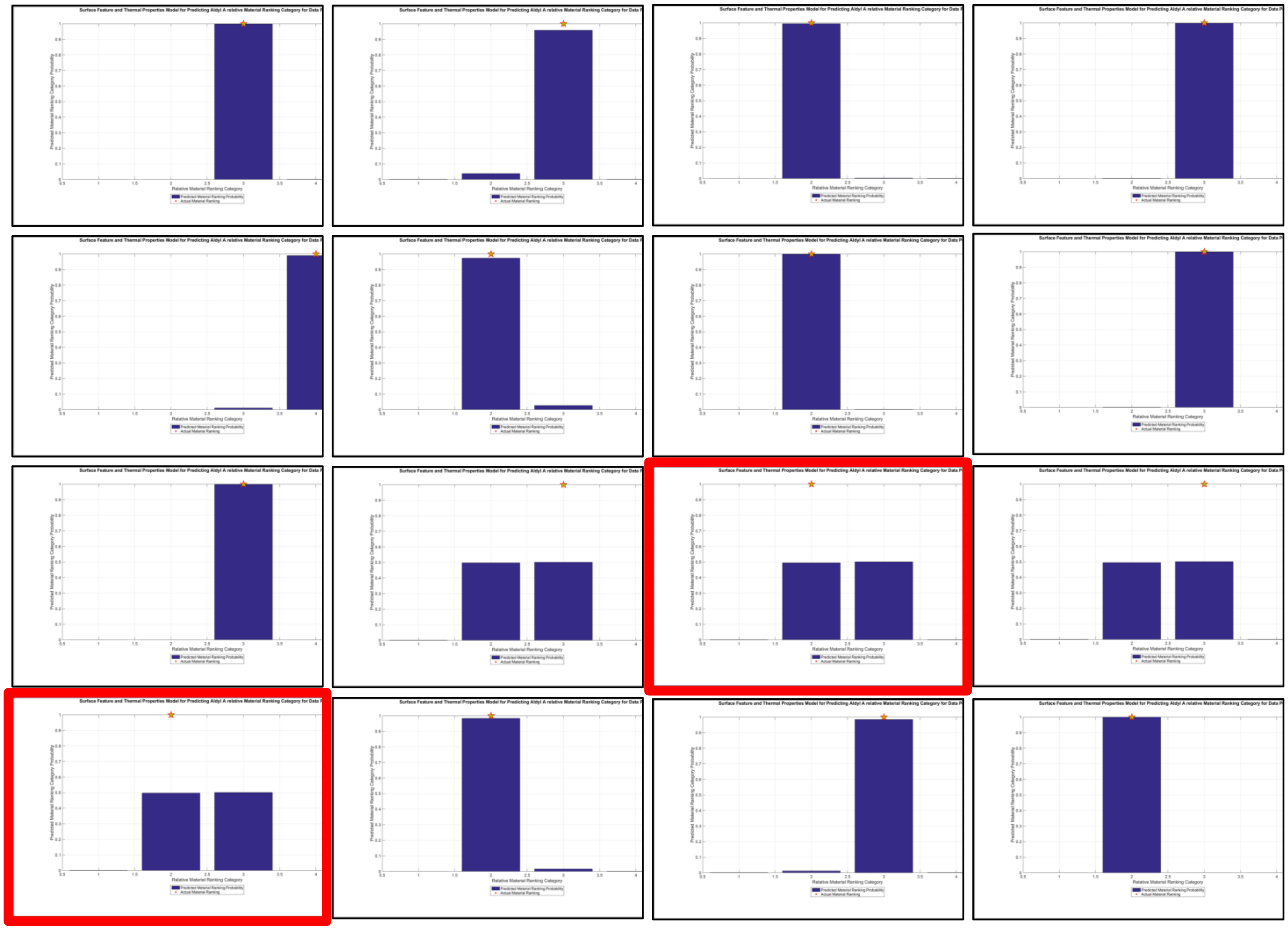
# Inner Wall Dimples



# Surface Feature to RPM Correlation

| Dimple | Micro Crack | Rod | Boundary Crystals | Surface Crystals | OIT | FTIR - CI | RPM Ranking | | Predicted RPM Ranking |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 1 | 2 | 3 | 5 | 3 | ✓ | 3 |
| 1 | 1 | 1 | 1 | 1 | 4 | 4 | 4 | ✓ | 4 |
| 1 | 0 | 1 | 1 | 1 | 2 | 3 | 3 | ✓ | 3 |
| 0 | 1 | 0 | 1 | 1 | 5 | 1 | 2 | ✗ | 3 |
| 1 | 1 | 0 | 1 | 1 | 5 | 1 | 3 | ✓ | 3 |
| 1 | 1 | 0 | 1 | 3 | 5 | 1 | 2 | ✓ | 2 |
| 0 | 1 | 0 | 1 | 1 | 5 | 1 | 3 | ✓ | 3 |
| 1 | 1 | 0 | 4 | 1 | 5 | 1 | 2 | ✓ | 2 |
| 0 | 1 | 1 | 1 | 1 | 3 | 1 | 2 | ✓ | 2 |
| 0 | 1 | 0 | 1 | 1 | 2 | 1 | 2 | ✓ | 2 |
| 1 | 1 | 0 | 3 | 1 | 1 | 2 | 2 | ✗ | 3 |
| 1 | 1 | 1 | 4 | 5 | 2 | 4 | 3 | ✓ | 3 |
| 1 | 1 | 0 | 3 | 2 | 1 | 3 | 3 | ✓ | 3 |
| 1 | 0 | 0 | 3 | 1 | 1 | 3 | 3 | ✓ | 3 |
| 1 | 1 | 0 | 3 | 1 | 1 | 2 | 3 | ✓ | 3 |
| 1 | 1 | 0 | 5 | 2 | 1 | 2 | 2 | ✓ | 2 |

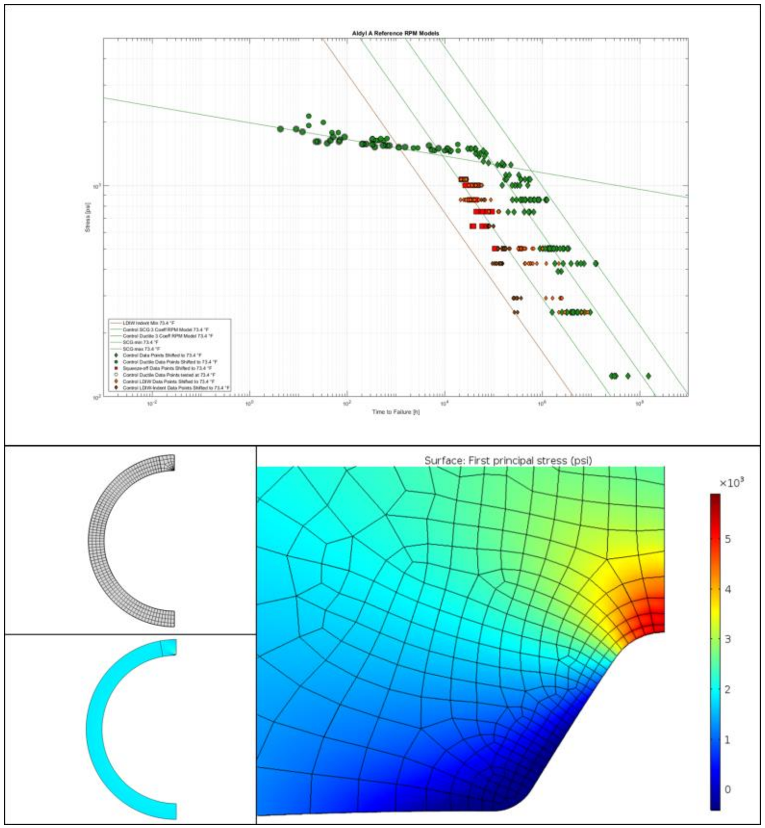
# Performance of Surface Correlation Model

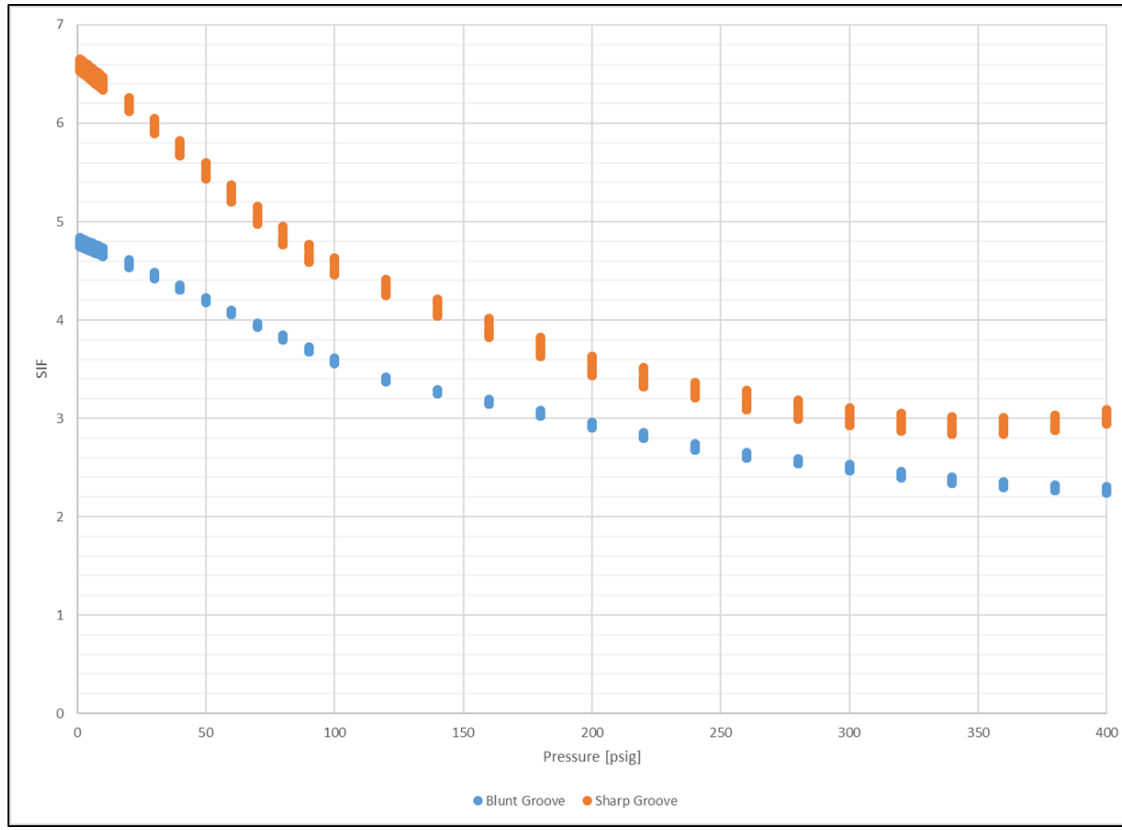


# What have we learned so far?

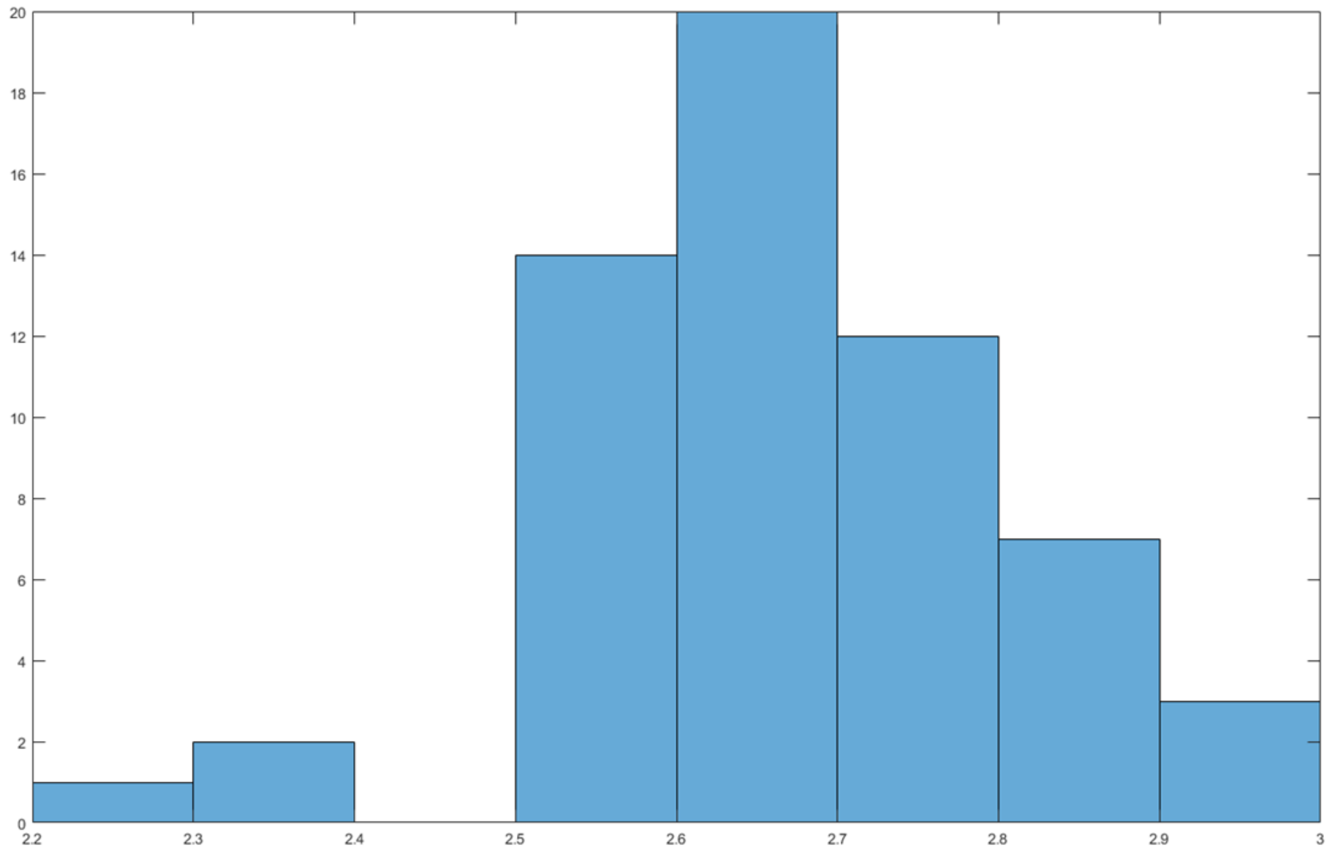
- We have a good model for linking surface features to long term performance
- Need to explore effect of stress risers

# Further Investigation into Drivers of Uncertainty in Test Data

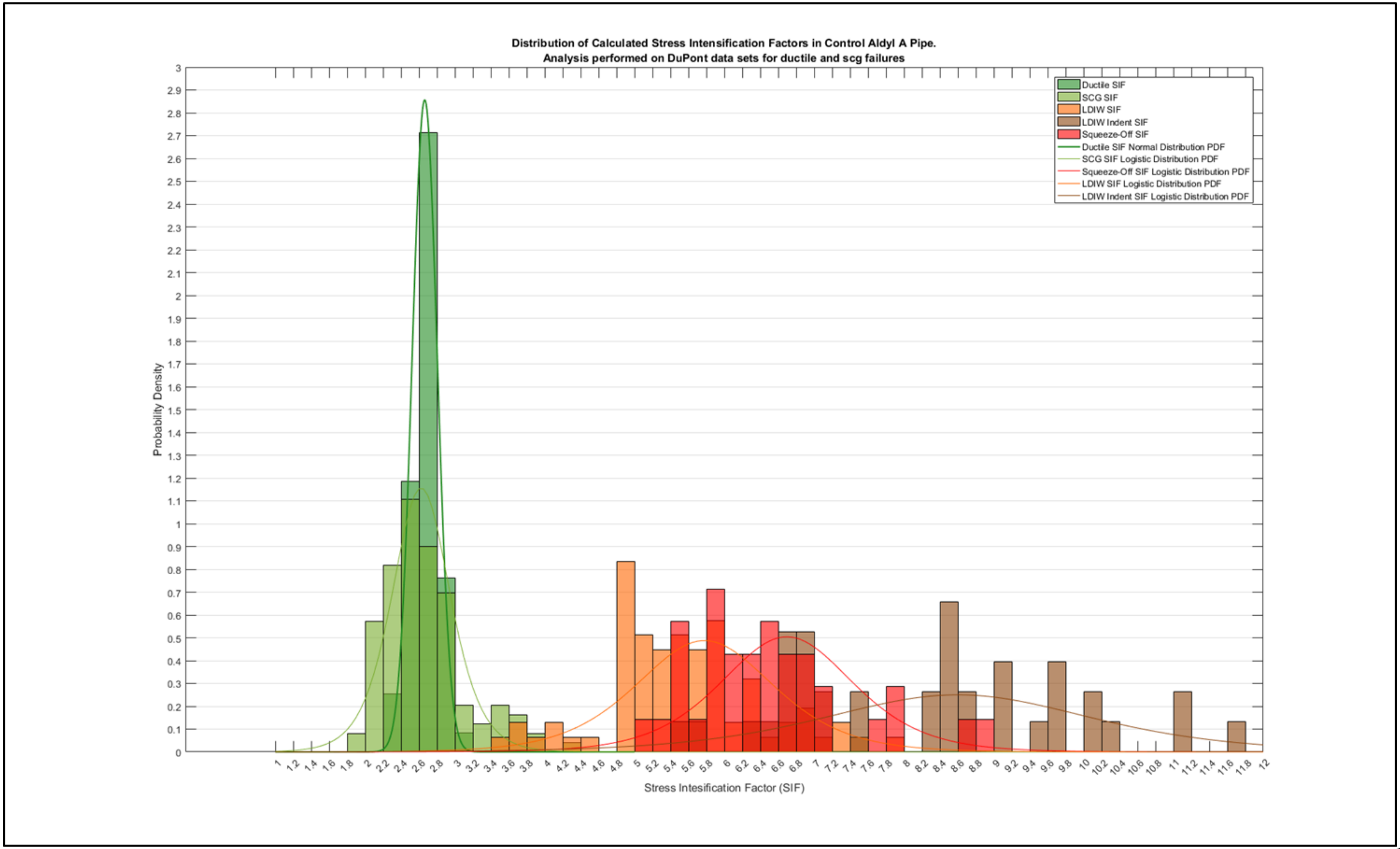


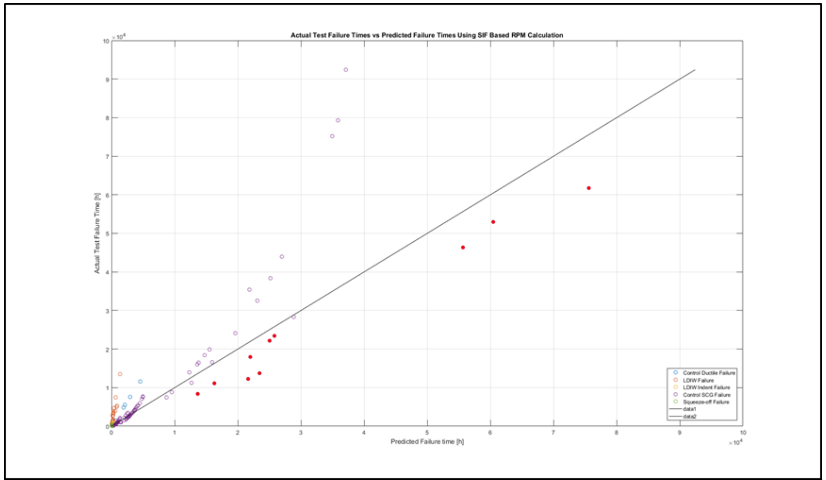
# Stress Intensification Factors (SIF) Inferred from Ductile Failure Data

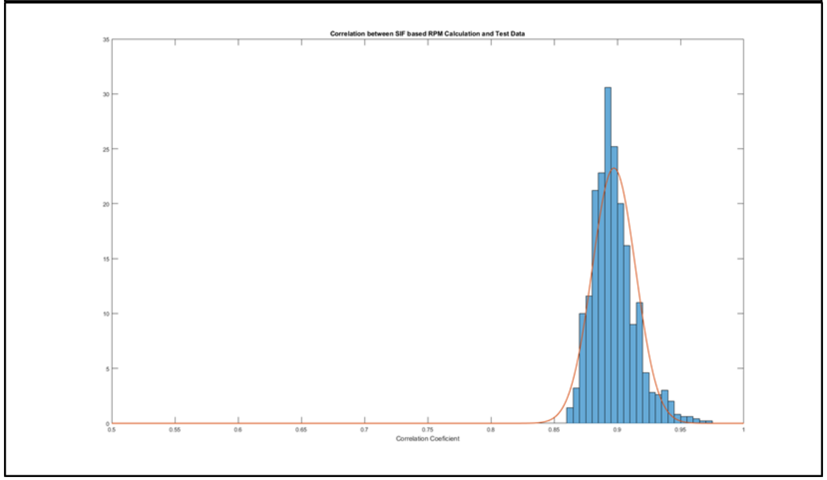


# Inferred SIF for DuPont Data Sets



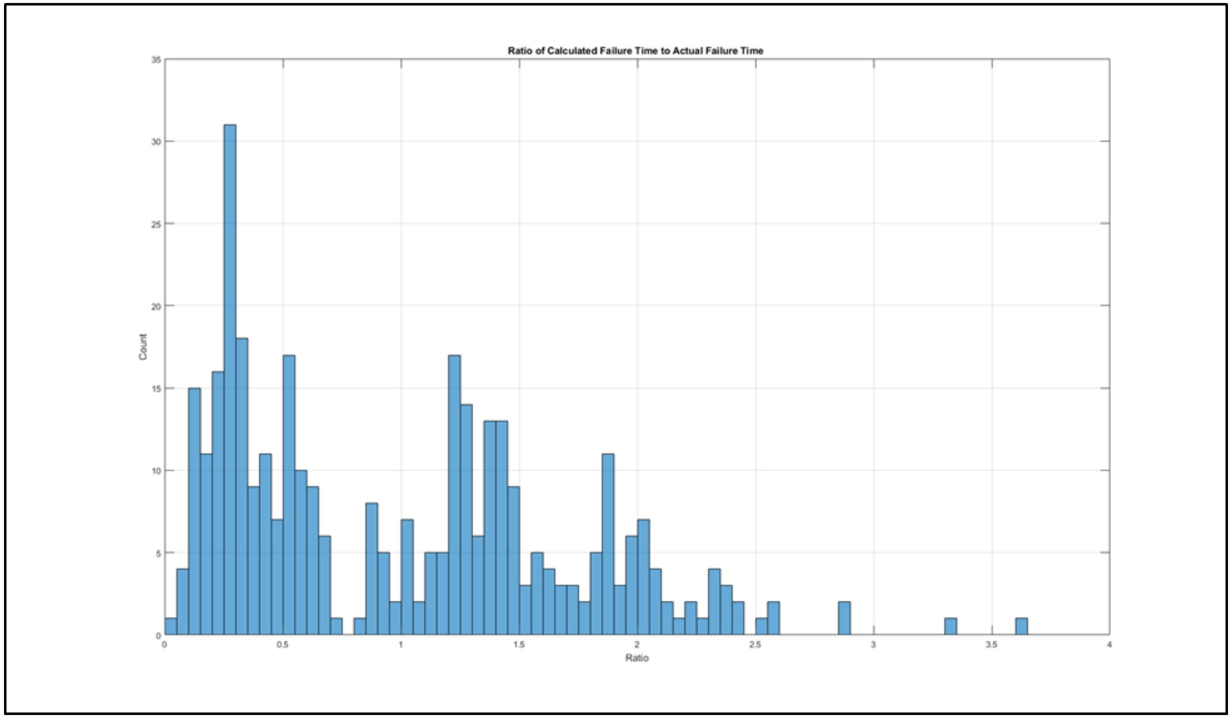
# Using Control Data Set and SIF to Predict All Failures




There were 351 validation points with 2.8% of results non-conservative predictions, therefore we can conservatively state that we have 95% confidence that the model predictions will result in a conservative lifetime prediction. Figure shows the actual correlation estimate distribution with mean value of 0.9

# Distribution of calculated failure times to actual failure times ratio

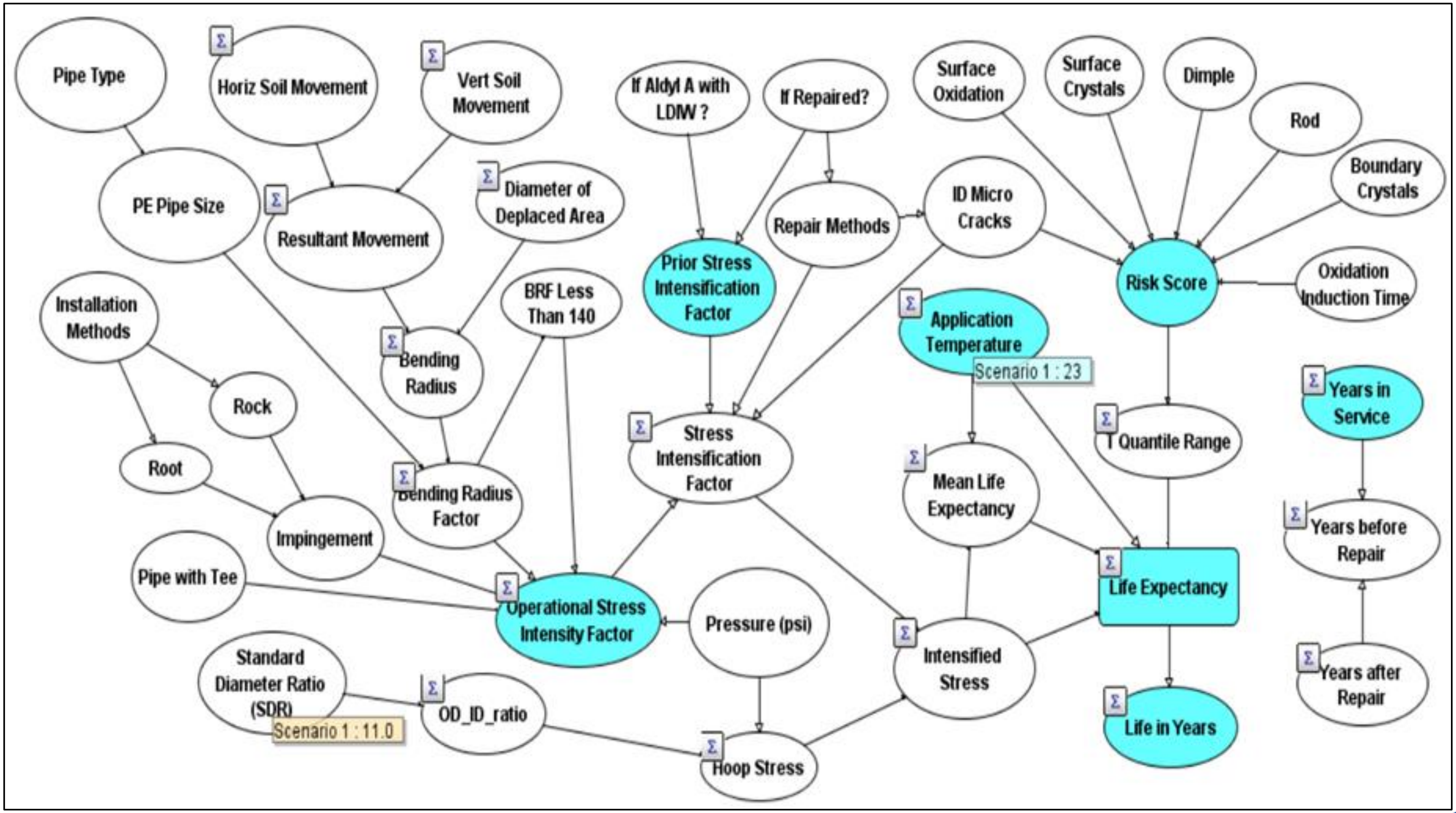



Uncertainty reduced from 250:1 to 3.6:1

# What have we added to our understanding of uncertainty in the models

- We have found plausible connections between Stress Intensification Factors (SIF) and the large variability in test data at a nominal hoop stress
- We have reduced the uncertainty by two orders of magnitude
- Ready to refine the Bayesian Network

# Refined Bayesian Network for Aldyl A Pipe in Gas Distribution Systems



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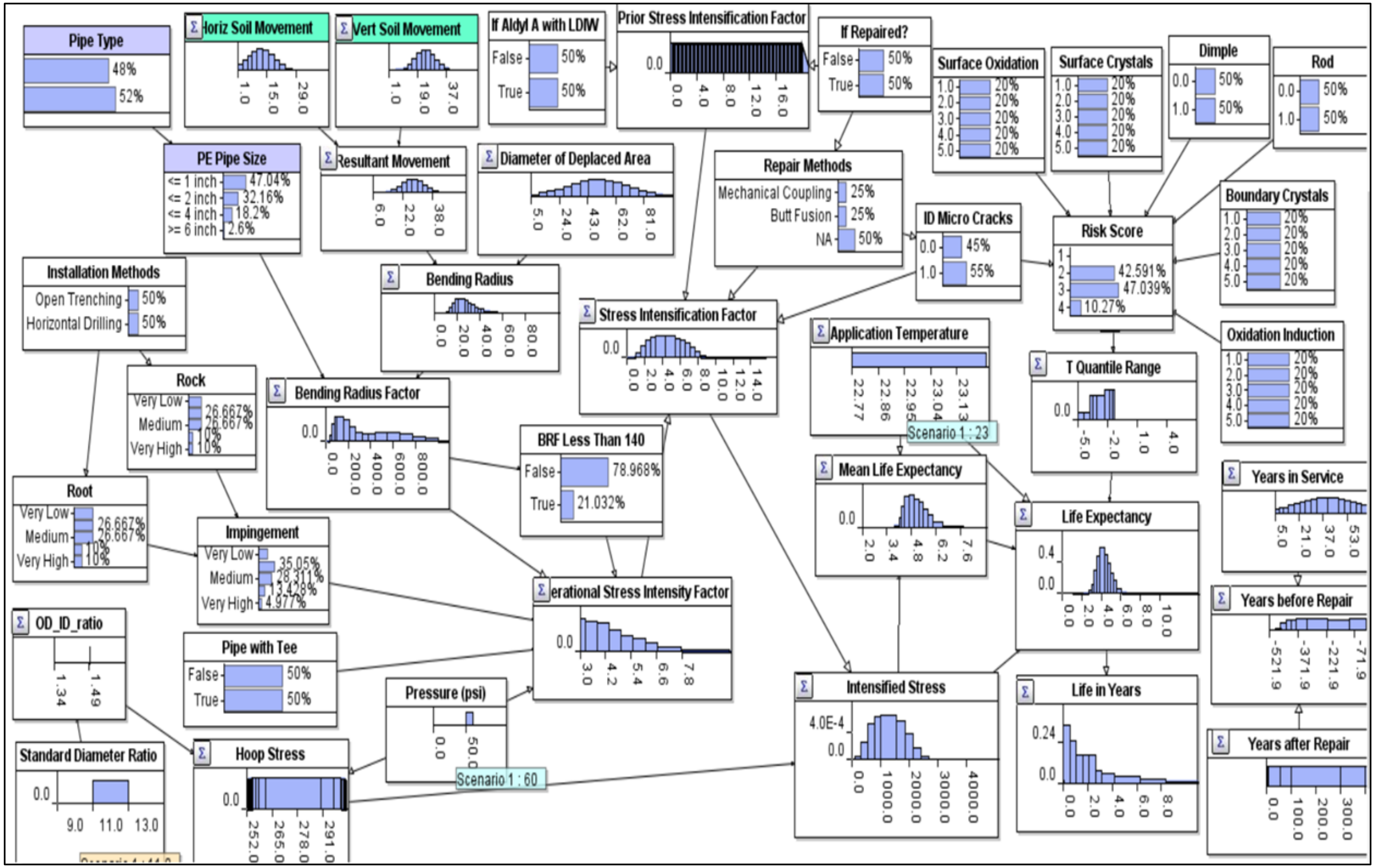
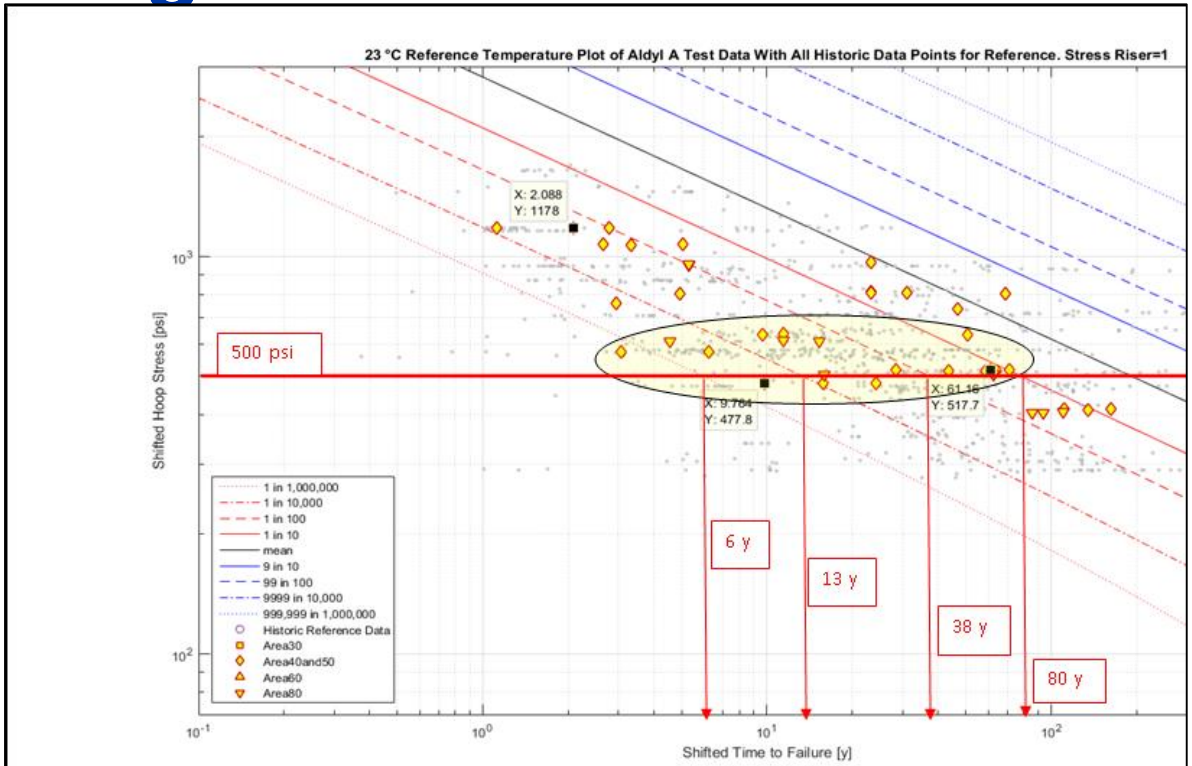
# Bayesian Network with Data

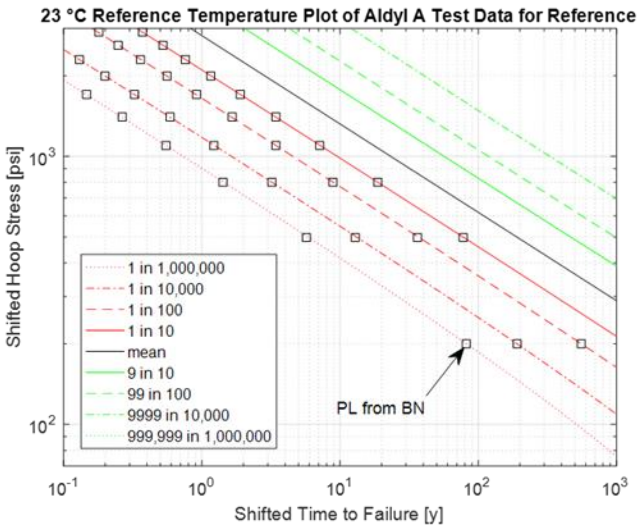


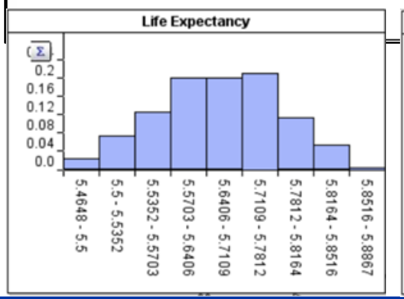
# Validation of Bayesian Network Against Inner Wall Surface Model

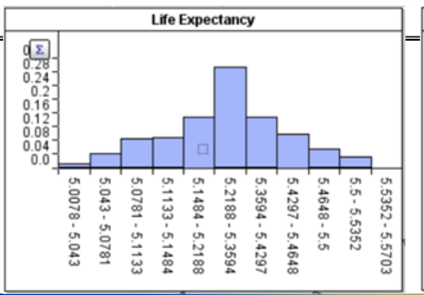
| Risk Score from Regression | Probability of Each Category | | | | Risk Score from network |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | |
| **3** | 7.40E-05 | 0 | 0.998062 | 0.001864 | **3** |
| **4** | 0.000179 | 0 | 0.010156 | 0.989665 | **4** |
| **3** | 0.000707 | 5.00E-06 | 0.998109 | 0.001179 | **3** |
| **3** | 0.001328 | 0.496864 | 0.501255 | 0.000553 | **3** |
| **3** | 0.001982 | 0.03762 | 0.958174 | 0.002224 | **3** |
| **2** | 6.00E-06 | 0.972903 | 0.027091 | 0 | **2** |
| **3** | 0.001328 | 0.496864 | 0.501255 | 0.000553 | **3** |
| **2** | 0.000366 | 0.982811 | 0.015212 | 0.00161 | **2** |
| **2** | 0.00032 | 0.993946 | 0.003589 | 0.002146 | **2** |
| **2** | 4.00E-06 | 0.997916 | 0.00208 | 0 | **2** |
| **3** | 0.002037 | 0.494501 | 0.501623 | 0.00184 | **3** |
| **3** | 0.001875 | 0.012431 | 0.984085 | 0.001609 | **3** |
| **3** | 0.000811 | 0.00141 | 0.997339 | 0.00044 | **3** |
| **3** | 7.60E-05 | 0.001317 | 0.998605 | 2.00E-06 | **3** |
| **3** | 0.002037 | 0.494501 | 0.501623 | 0.00184 | **3** |
| **2** | 2.00E-06 | 0.999757 | 0.000241 | 0 | **2** |

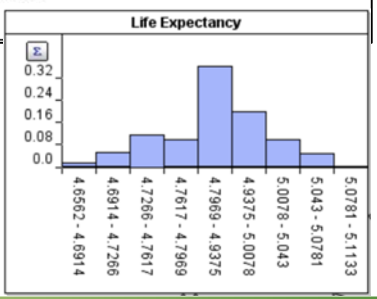
# Validation of Bayesian Network Against RPM Prediction Limits



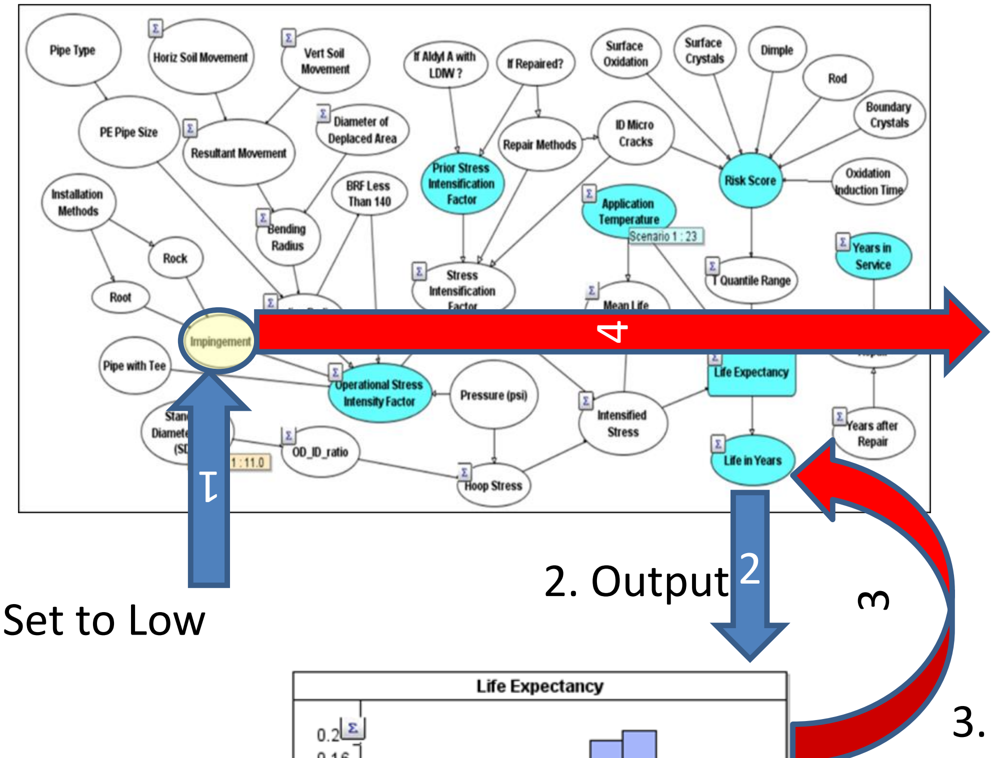



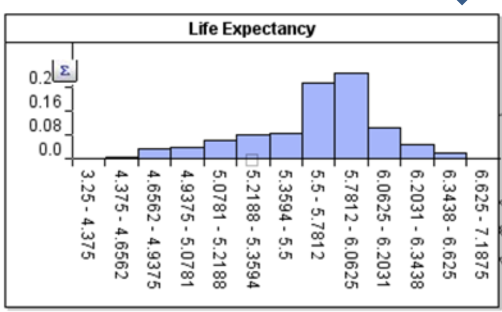

Mean life=53.1 years,
Mean life=21.7 years,
Mean life=8.7 years

# Forwards and Backwards Calculation – Certainty → Uncertainty



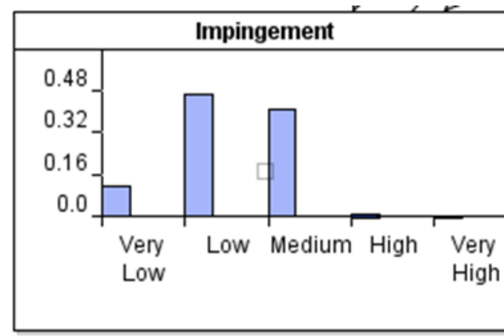

1. Set to Low

2. Output




3. Clear Impingement node and Force Life Expectancy to this Distribution

4. “Low” has the highest probability. The reason why its probability is less than 1 is because the mean value evidence can’t completely represent the distribution for the “Life Expectancy” node. Therefore, the distribution for impingement is not fully reconstructed.



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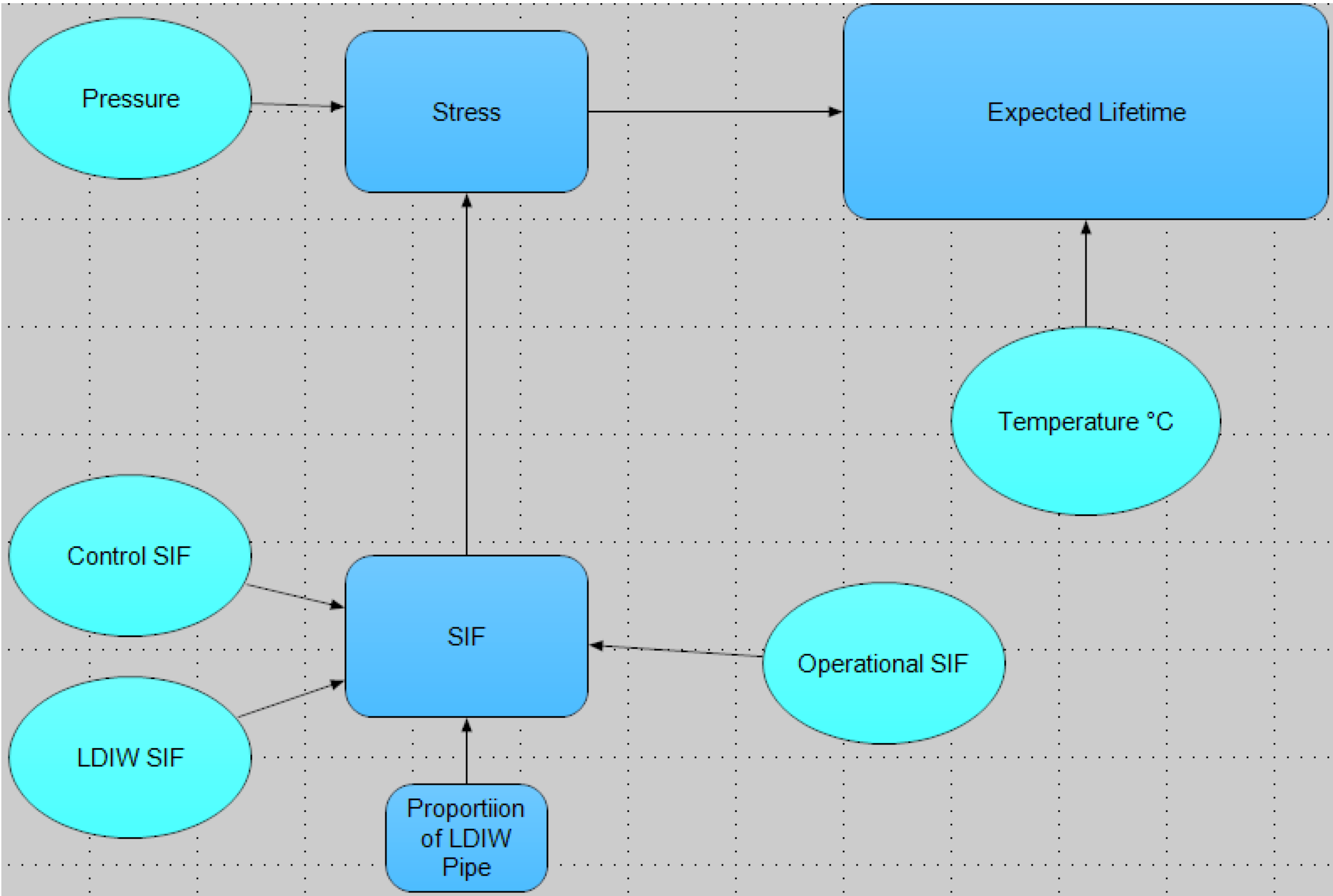
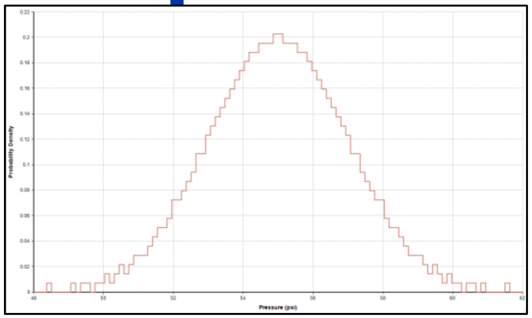
# What have we seen n the refined Bayesian Network

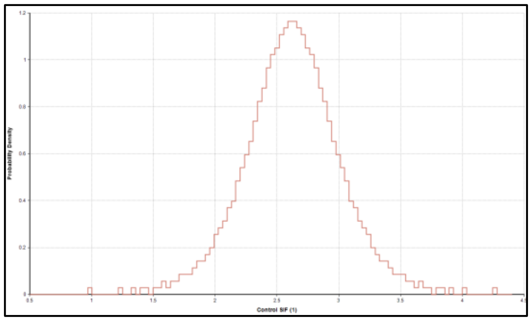
- Good description of Aldyl A performance
- Forward prediction of next state
- Backwards forensic diagnosis capabilities
- Can we simplify the model?

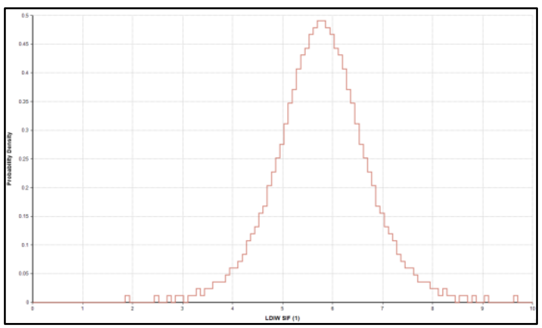
# Simplified Model for Aldyl A

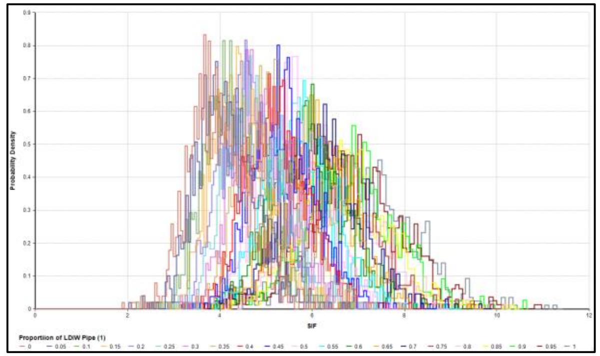


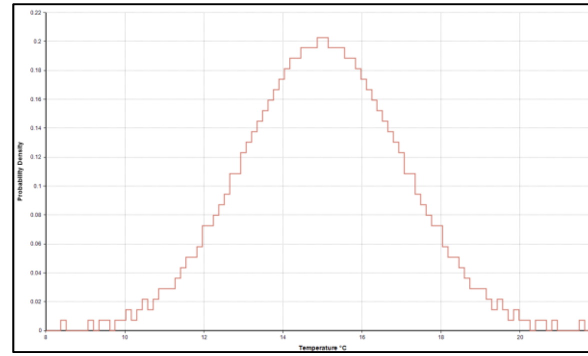
# Input Distributions at Installation



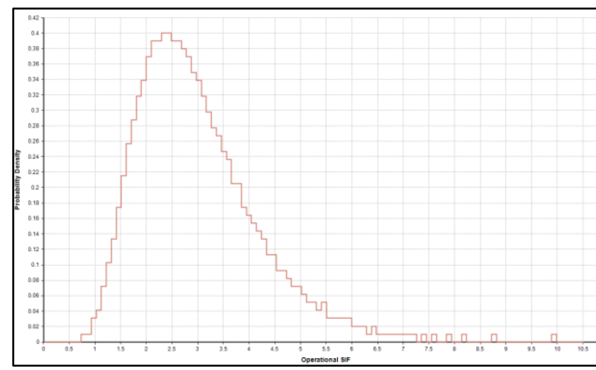



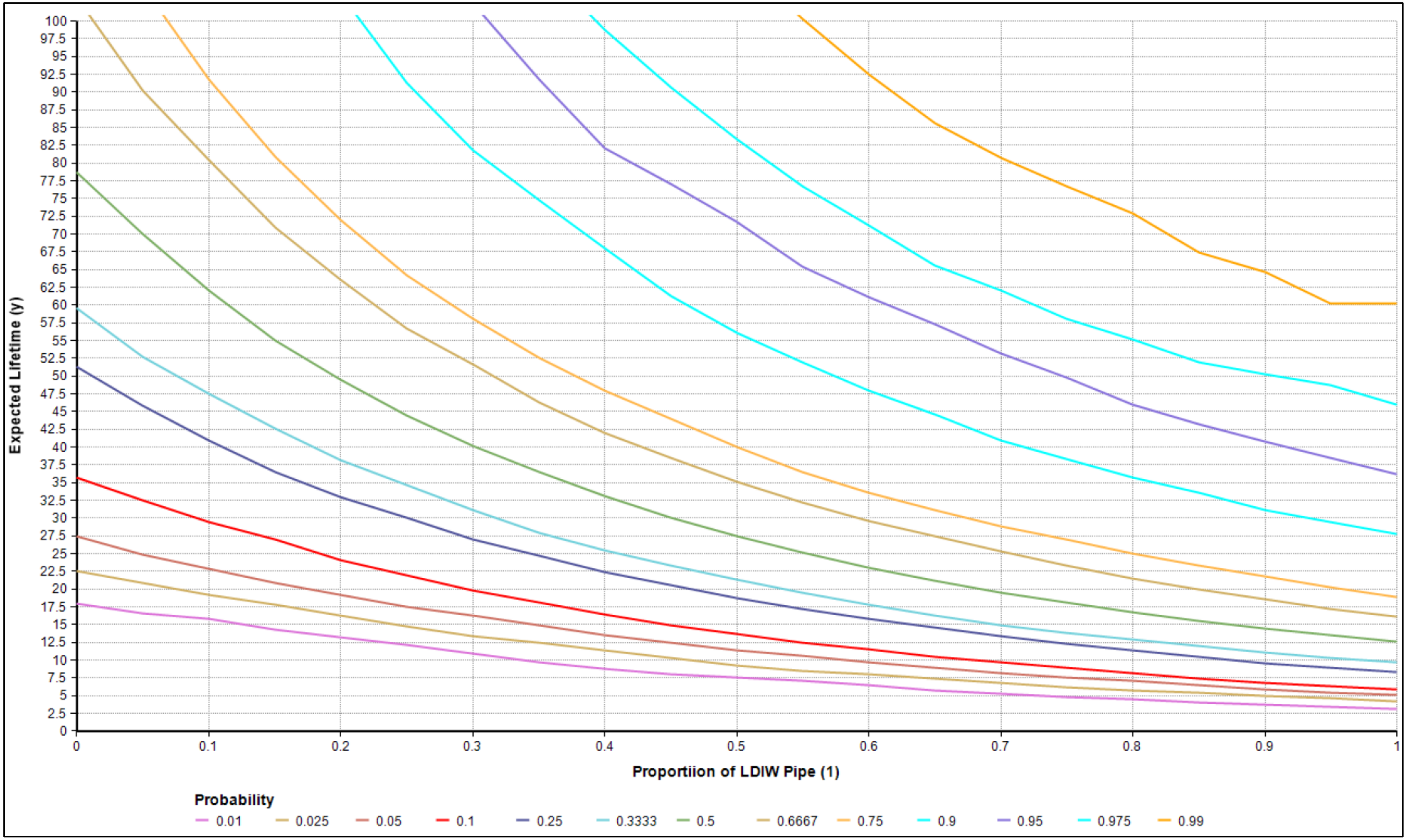



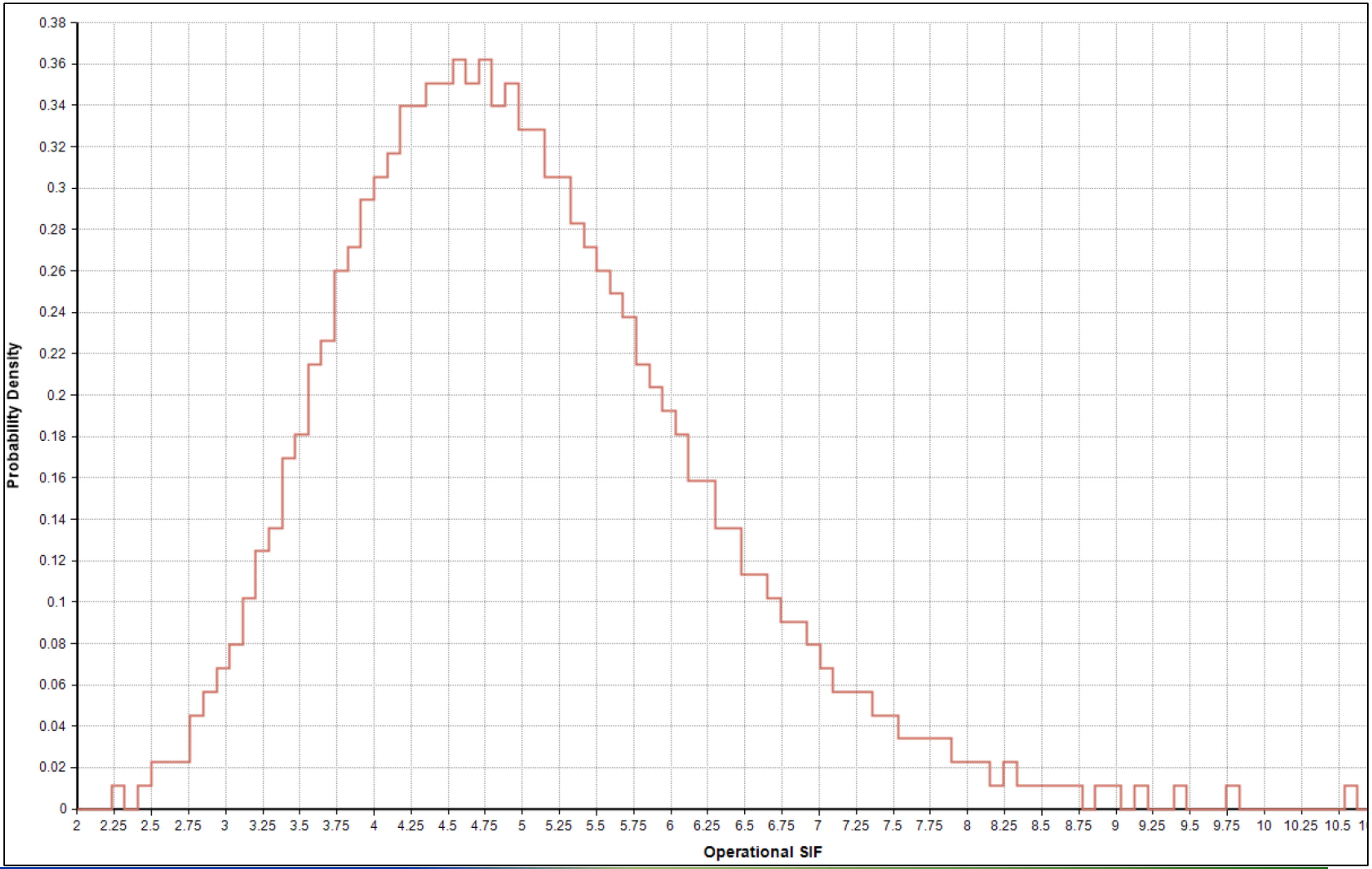

| |
|---|
| 0 |
| 0.05 |
| 0.1 |
| 0.15 |
| 0.2 |
| 0.25 |
| 0.3 |
| 0.35 |
| 0.4 |
| 0.45 |
| 0.5 |
| 0.55 |
| 0.6 |
| 0.65 |
| 0.7 |
| 0.75 |
| 0.8 |
| 0.85 |
| 0.9 |
| 0.95 |
| 1 |



# Lifetime Expectancy at Installation



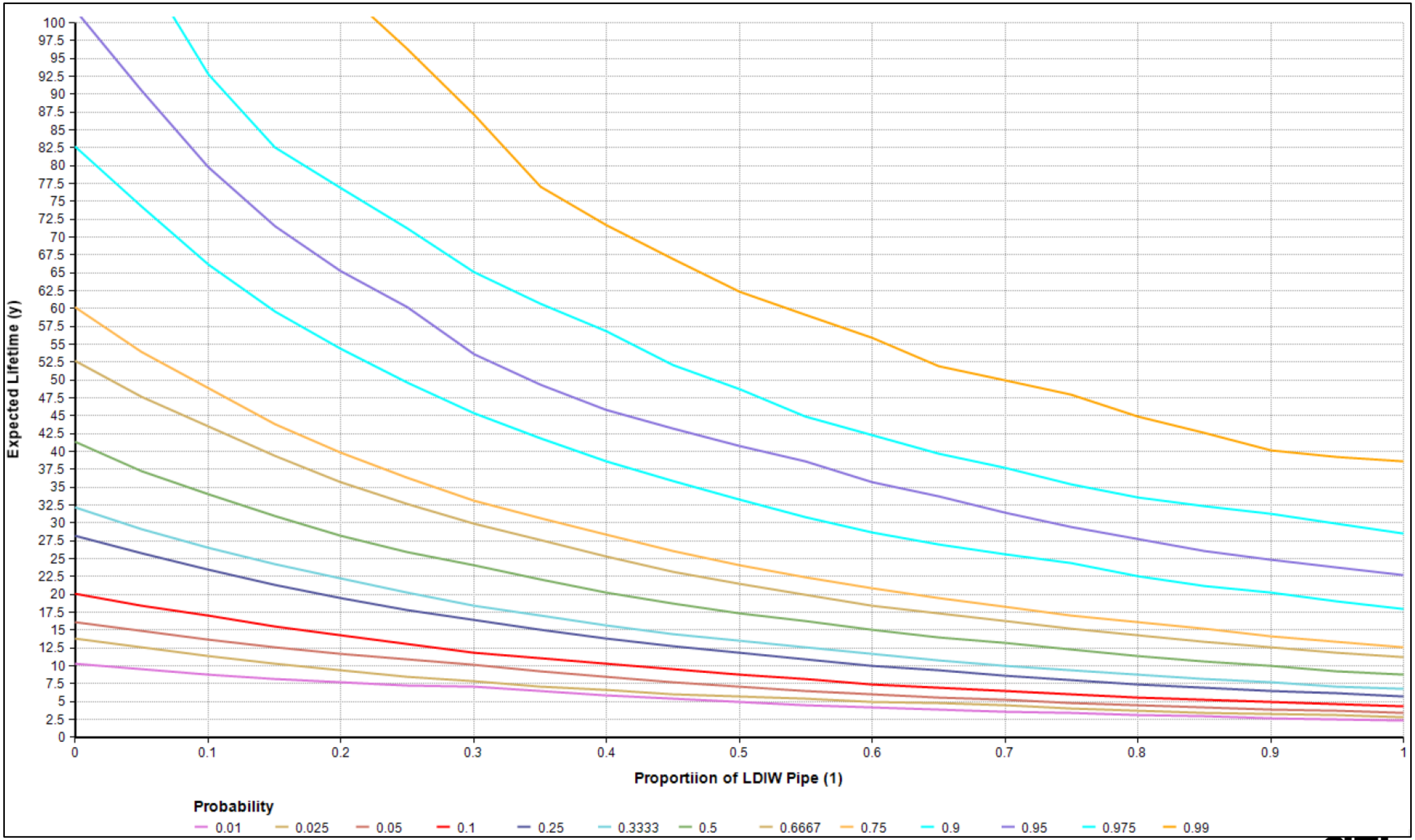
# Operational SIF Reflecting 40 years of Service



# So far so good

- Good description of variability in as installed condition
- How can we capture years in service?

# Expected Residual Lifetime After 40 years of Service



# Final comment on simplified model

- The equivalent SIF for years in service does a reasonable job in capturing degradation over time.

# Questions?