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H. H. Uhlig Corrosion Laboratory

Reliability Prediction for Naval Shafting Under Cyclic Loads

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Program Driver & Objectives

- **Driver-Ohio Replacement Program**
- **Objectives**
  - – Develop an Engineering & Science Based Probabilistic Determination of Shaft Life Including Uncertainty Estimates
    - Development of Required Inspection Intervals and Basis for These Intervals
  - – Identify and Quantify Advanced materials and/or Design Changes that would Alloy Extension of Inspection Intervals

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Shaft Life Extension Program-Areas of Thrust

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Modeling Path

General Literature Search

- General Corrosion of Steels
- Pitting/SCC of Steels
- Fatigue/Corrosion Fatigue of Steels
- Marine Shafting Research/Failure Analysis
- Classification Society Data (ABS, Lloyd's, DNV, etc.)

Modeling Literature Search

- General Modeling Approaches
  - Deterministic
  - Empirical (Weibull, etc.)
  - Probabilistic
- Pitting/SCC of Steels
- Fatigue/Corrosion Fatigue
- Available Models
  - AFGROW (www.afgrow.net)
  - Others
    - From Literature

Design

Characterization of System

- Physical
  - Materials
  - Geometry
  - Environment
    - Chemical,
    - Mechanical
- Problem Definition
- Workshop
  - Definition of System
  - Definition of Requirements
  - Week if 1/21/13?

Design Mods.

- Coatings (GRP)
- Spray (hot/cold)
- Weld Overlay

Experimental Path

New Materials

(Fe-Cr-Si), Other Coatings

Material Characterization

- Shaft Material
- Fe-Cr-Si
- Other

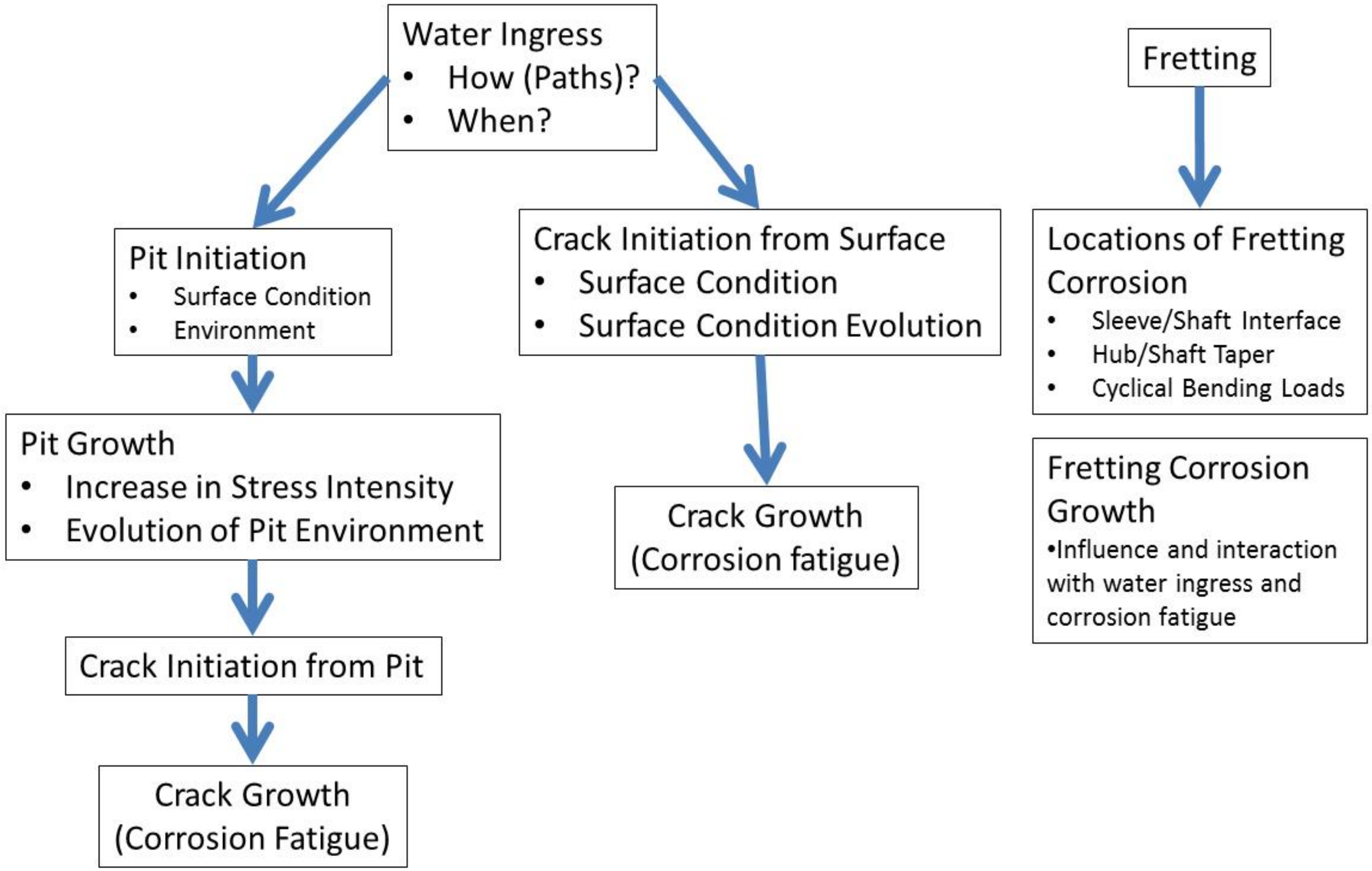
Tasks-Corrosion

- 1. Base Material
  - Polarization Tests
    - Measure Pitting Potential
    - Corrosion Current
- 2. Coupled To Shaft Steel
  - Measure Coupled Current
  - Measure Coupled Mixed Potential
- 3. Overlay on Shaft Material
  - Measure Electrochemical Parameters

Tasks-Mechanical

- 1. Tensile Properties
- 2. Fatigue (Air)
- 3. Fatigue (In Environment)
- 4. Abrasion, impact resistance

Modeling Components: Key Variables



Question

- **What if we Could ELIMINATE the Problem?**
  - Prevent Pitting-No Fatigue Crack Initiation
    - Prevent Water Ingress ("impossible"??)
    - Provide a Surface that Does Not Pit (not impossible???)

Benefits of Success

- Increased Inspection Interval-Reduces Required # of Hulls
- Elimination of Problem-Allows Expanded Operational Envelope
- Saves a TON of Cash

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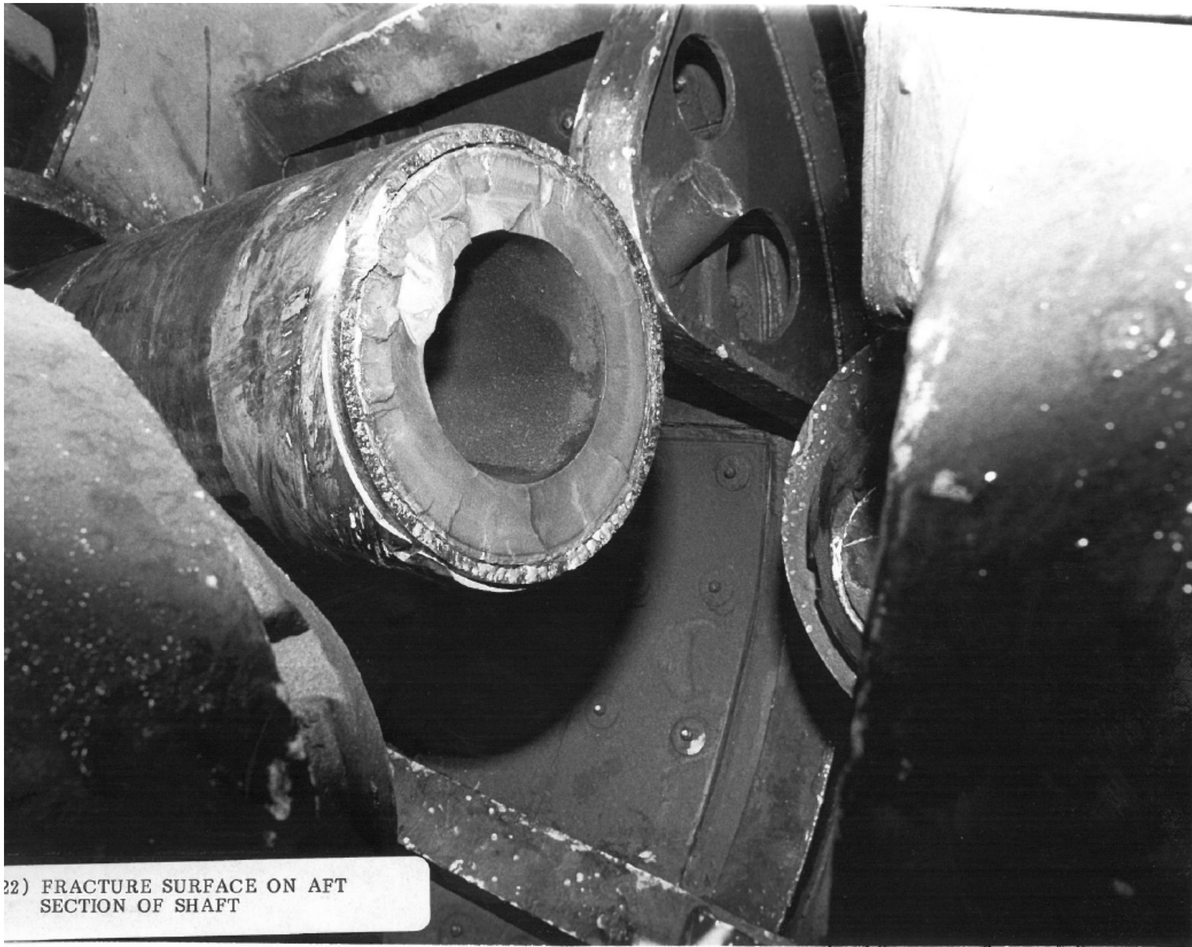
Submarine Shaft Life Project

Professor Ballinger
Professor Slocum
LCDR Jonart



Key Takeaways

- Uncertainty drives predictions for desired performance
- ORP shaft needs to stay dry for an order of magnitude longer than OHIO shaft

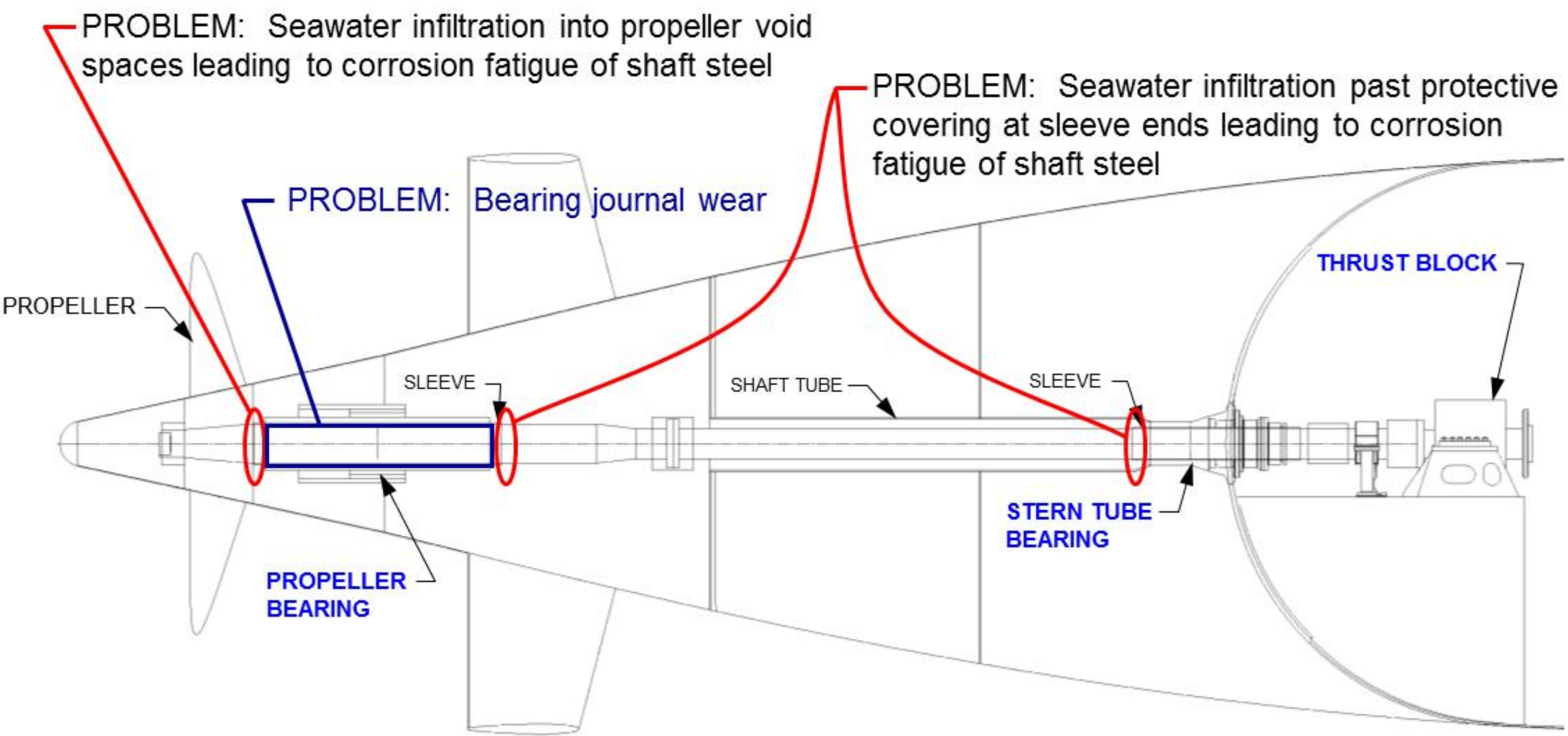
- Driver and problem
- Solutions and method
- Results

Project Driver

- **OHIO class**
  - Shafts inspected and refurbished at least every **6** years
  - Over 30 years of service without breaking a shaft
  - Class design service life was 30 years; recertified for 42
- **OHIO Replacement Program (ORP)**
  - Shafts inspected and refurbished at least every **12** years
  - Being designed for "OHIO-like" service life
- **Is this a problem?**

The Problem: Failure Locations

Corrosion Fatigue Initiated from Pits



"Shaft Life Advancements", W. H. Needham, Presentation at Shaft Life Advancement Industry Day, October 13, 2011.

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The Problem: Corrosion Fatigue Failure

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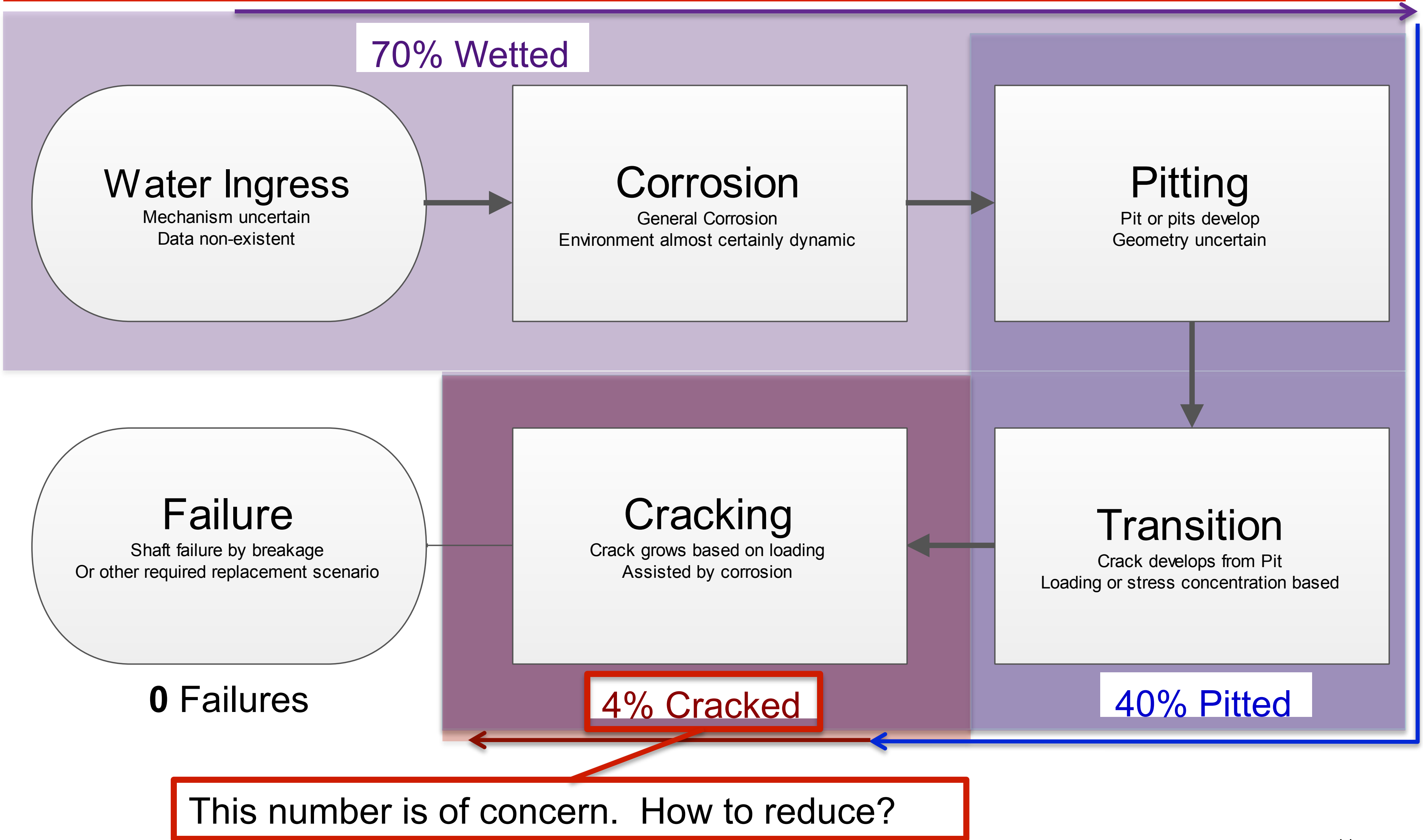

Solutions: How to Improve?

- **Material**
  - Stainless steel
  - Claddings
  - Preservatives
- **Shaft design**
- **Loading limits**
- **Prevent water ingress**
  - Mechanical systems (O-rings, seals, design)
  - Coatings
- **Housing around shaft**
- **Alternative propulsion**
- **Sensing**

Project evaluated these; My thesis focused on water ingress

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Corrosion Fatigue: Method

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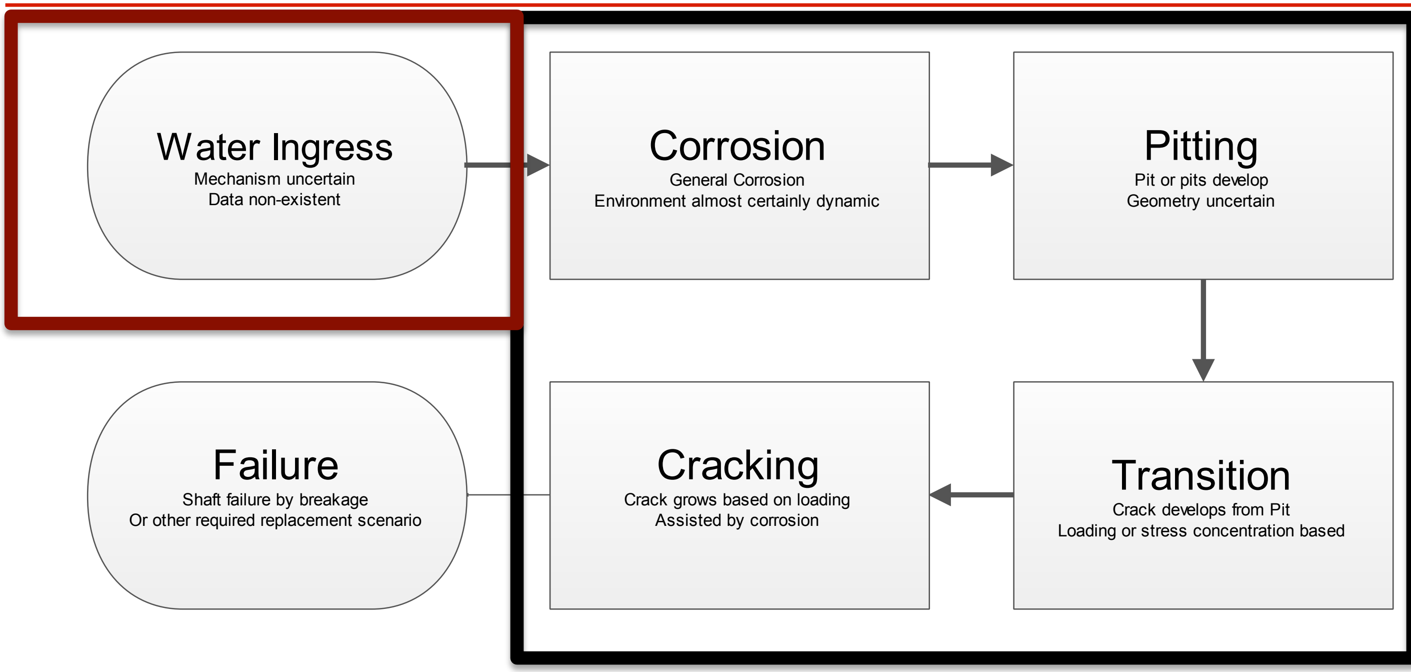


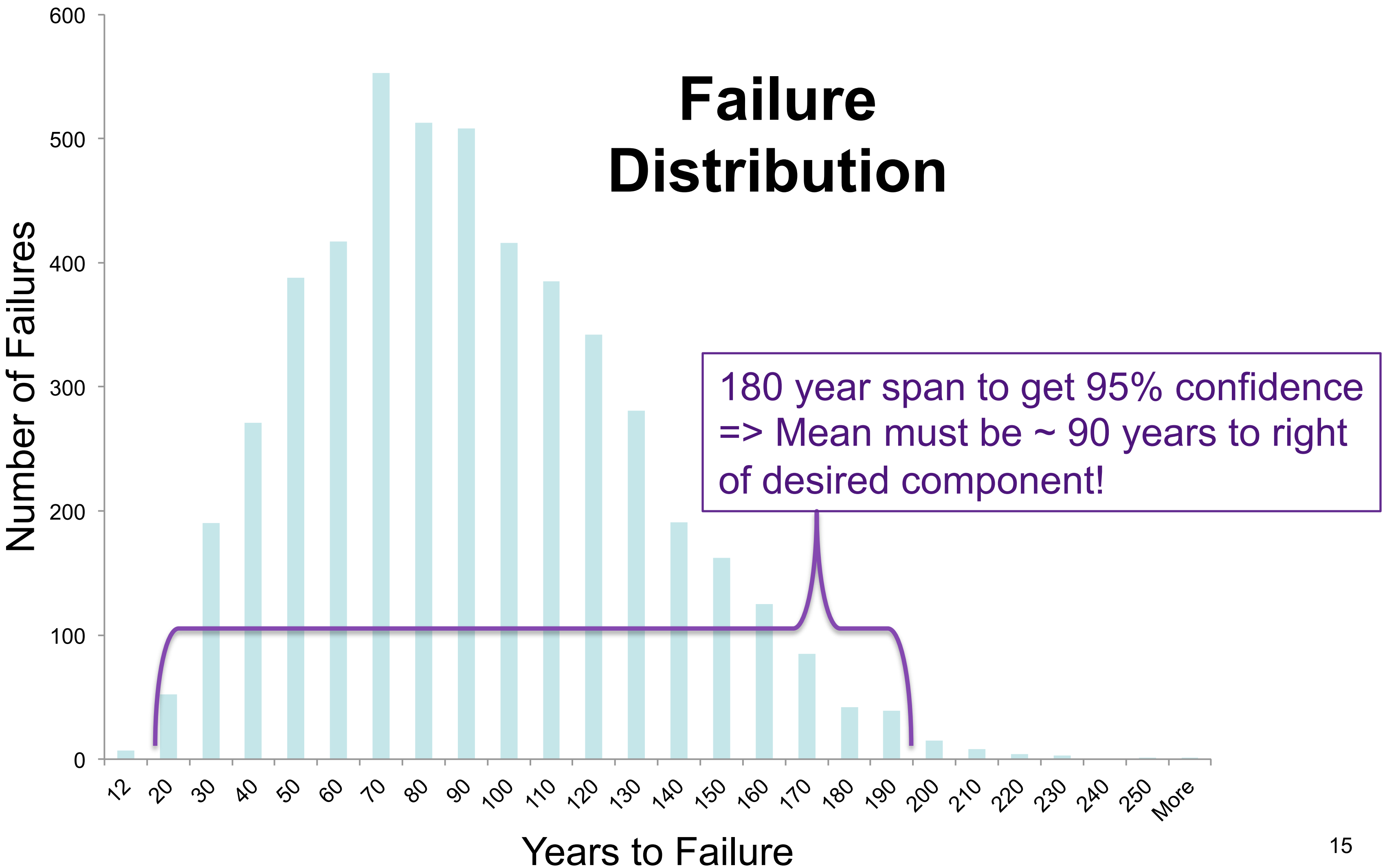
Target Values:
70% Wetted
40% Pitted
4% Cracked
0 Failures

- **Search literature for best model for each stage**
  - Pitting, transition, and crack models
  - Parameters from literature, testing, Navy specifications
- **Infer water ingress distribution**
  - Run Monte Carlo Simulation
  - Evaluate “goodness” by L2 Norm from OHIO target values
- Repeat for 12 year shaft life and evaluate

Results: Real Story for ORP: Uncertainty

- **Uncertainty comes from:**
  - Differences in physical environment
  - Variations in chemical environment
  - Differences in nominally similar materials, exposures, specimens
  - Temperature of corrosion environment (10°= 2x corrosion rate)
  - Loading
  - Built into each model (probabilistic)
  - Monte Carlo technique
  - Many more
- **Primary effect: widens distribution**
  - For given reliability, must push mean to right
  - Sensitivity of true control variables diminished

Uncertainty: Drastic Effect on Mean



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Results: Ohio Wetting

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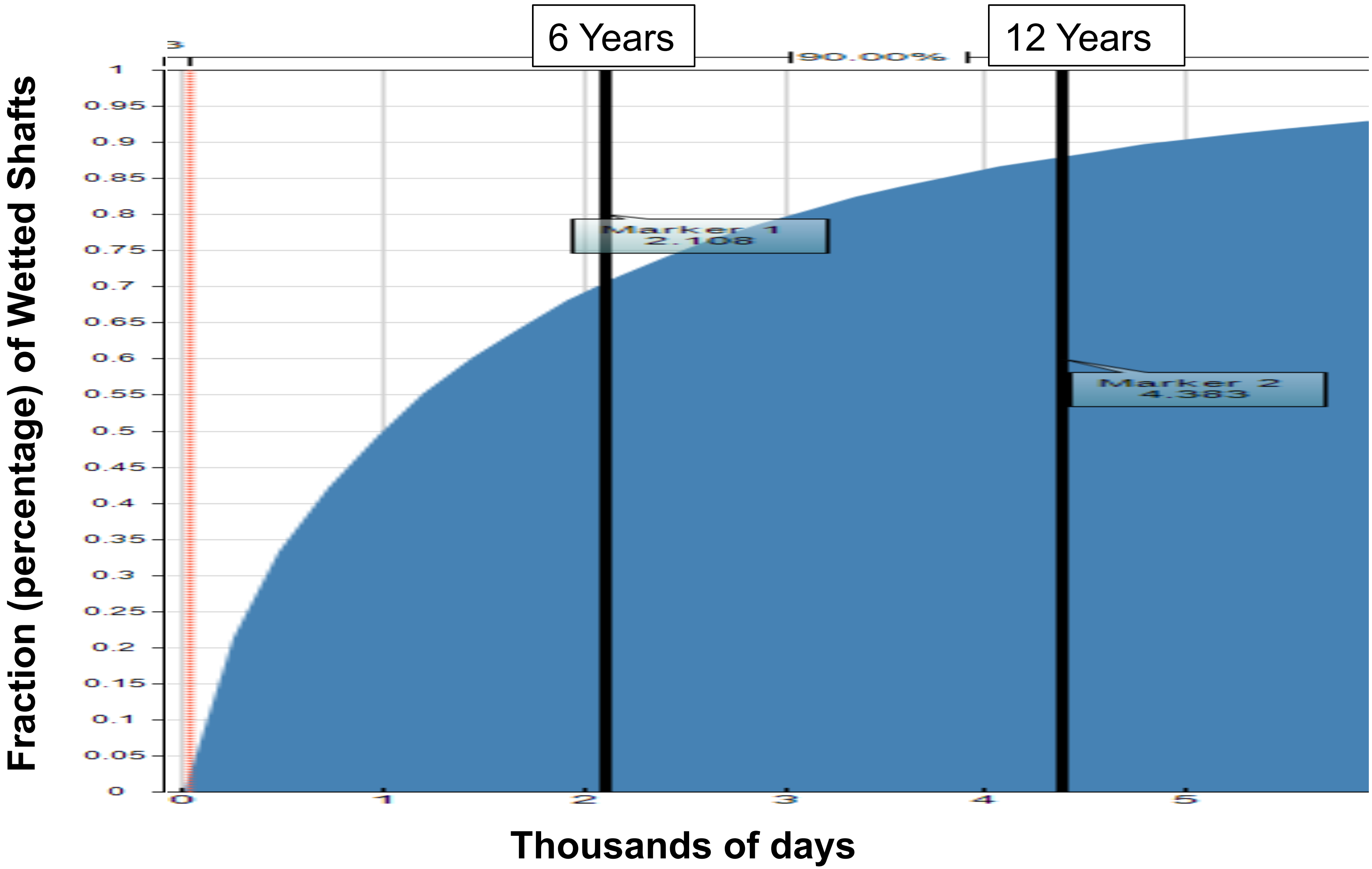
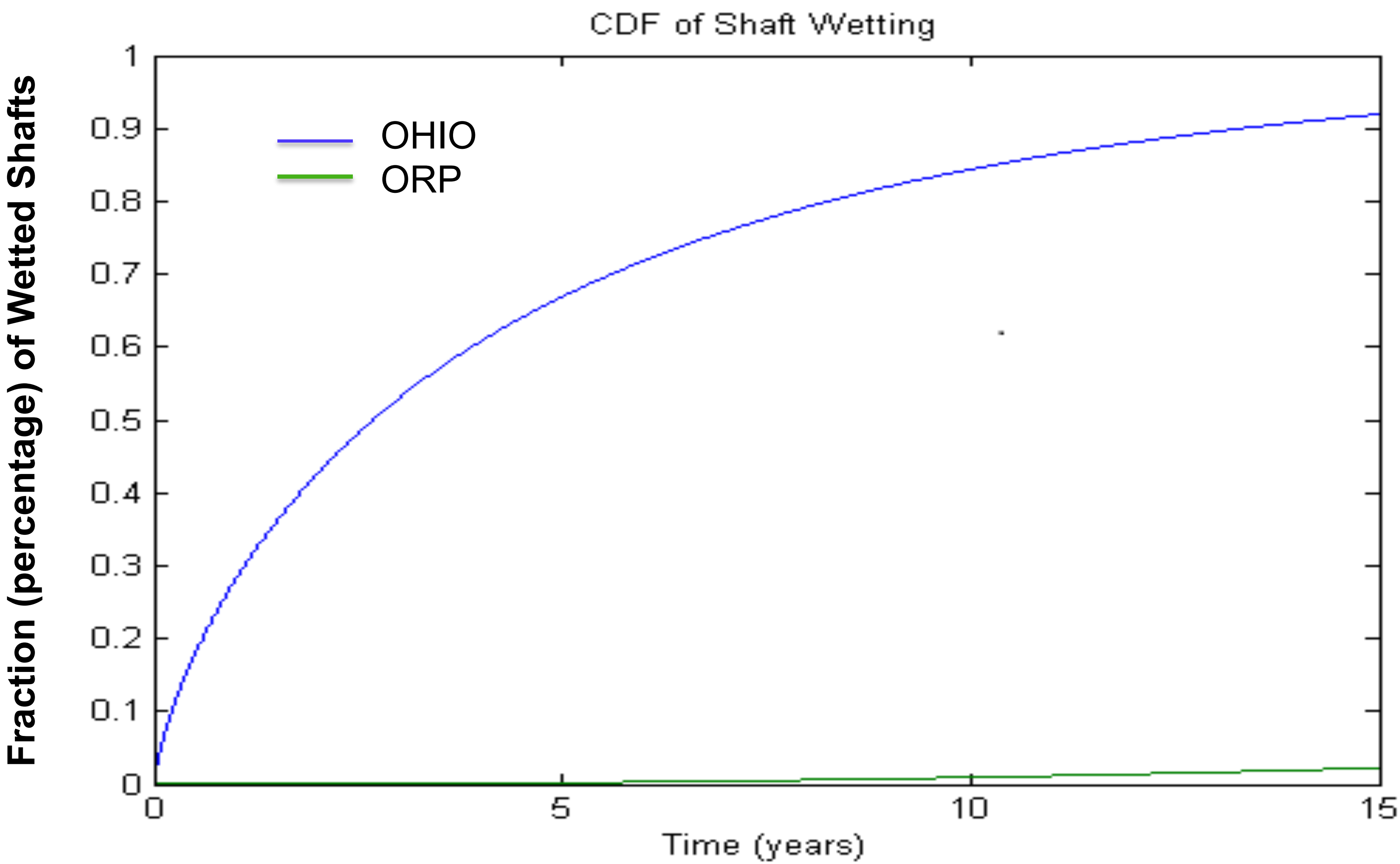


Results: Comparison



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Results: Comparison

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6 Years	OHIO	ORP
Wetted	71%	2.3%
Pitted	39%	0.04%
Cracked	5%	0
Failed	$\boxed{0 *}$	0

12 Years	OHIO	ORP
Wetted	87%	5.6%
Pitted	69%	0.3%
Cracked	59%	0.16%
Failed	45%	$\boxed{0*}$

This is the real performance desired

* Denotes that successive runs reveal about a 10% chance of having 1 failure in 60 service cycles

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Results: ORP

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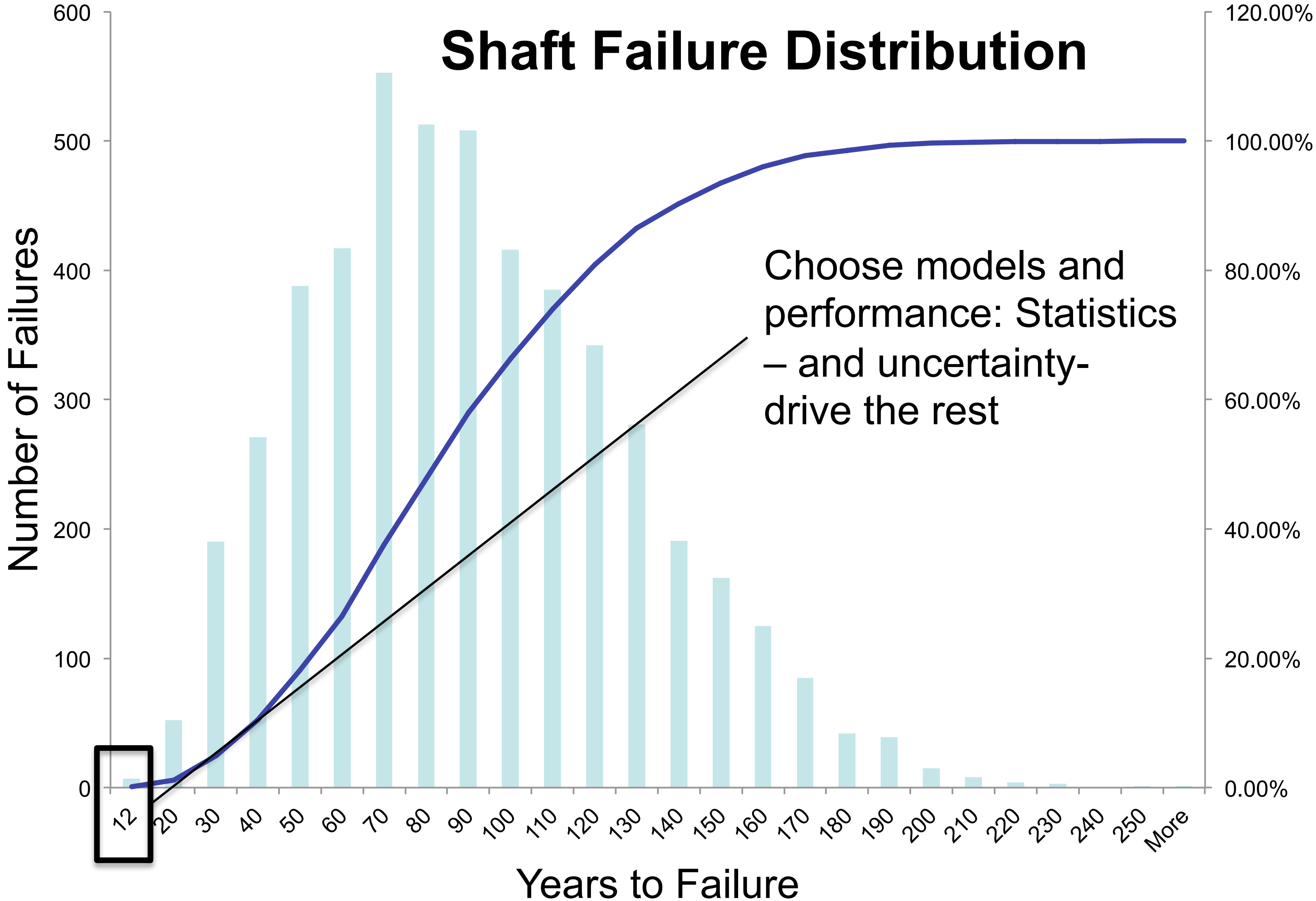

Results: Conclusions

- **Minimum L2 norm is Shape = 0.75**
  - Indicative of highly skewed water ingress
  - Reasonable physics would be O-ring failures or similar
- **Uncertainty becomes very large**
  - Drives problem for ORP predictions
  - Effectively eliminates desired reverse probability approach
- **Bottom line, though, is need to improve dry time by an “order of magnitude”**
- **Improved inspection data reduces uncertainty**
  - Levels of corrosion
  - Sizes, shapes, distribution of pits
  - Sizes and characteristics of cracks

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Results: Key Takeaways

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- **Uncertainty drives predictions for desired performance**
  - Solution: Improved inspection procedures and data
- **ORP shaft needs to stay dry much longer than OHIO shaft**
  - Solutions already being investigated and in some cases implemented
  - How to model and predict their effects
- **Without reducing uncertainty, may be challenging to defend reliability performance**
  - Solution: Break the failure chain elsewhere
  - Clad shaft to preclude pitting is one solution

Questions

and

Discussion