# Prognostics and Health Management in Petroleum Structures


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**Invited Talk at the**
**2015 Plant Maintenance & Reliability 6th Global Praxis**
**Interactive Technology Workshop**

17 February 2015

# Outline of the Talk

- Center for Risk and Reliability, University of Maryland
- Important Failure Mechanisms
- Examples of PHM
- Applications to the Petroleum Industry
- Conclusions

# Areas of Recent Focus at Center for Risk and Reliability (CRR)

- Probabilistic Physics of failure (PPoF, PHM, ADT, ALT)
  - Corrosion
  - Fatigue
  - Wear
  - Creep
  - Combinations
- PPoF Based Modeling of Structures and Systems
  - Agent-Based Computing
  - Simulations-Based Computing
  - Common Cause Failures
- Probabilistic Risk Assessment and Reliability Analysis
  - Risk Assessment and Management
  - Transportation Risk (CNGs and Pipelines)
  - Small Modular Reactors
  - Failure Data Collection and Analysis (small and large data, machine learning)
  - Modeling Reliability of complex components (Compressors, pumps, MOVs, etc.)



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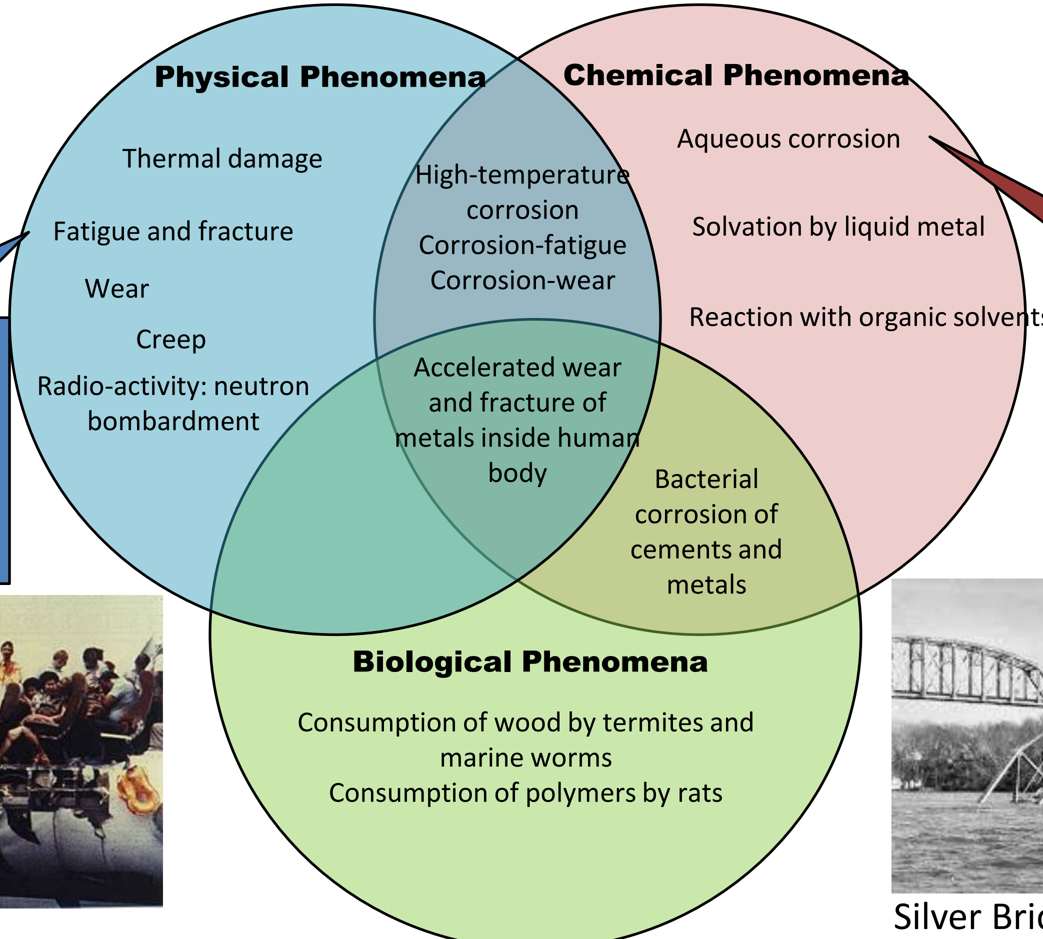
# Overview of Failure Mechanisms




According to the National Bureau of Standards, the costs associated with material fractures for 1978 in the Unites States was $119 billion or 4% of the Gross National Product.

According to the NACE, 2001, the direct cost of corrosion in the U.S. is $276 billion or 3.1% of the Gross Domestic Product.

Aloha Airlines accident, 1988

Silver Bridge collapse, 1967

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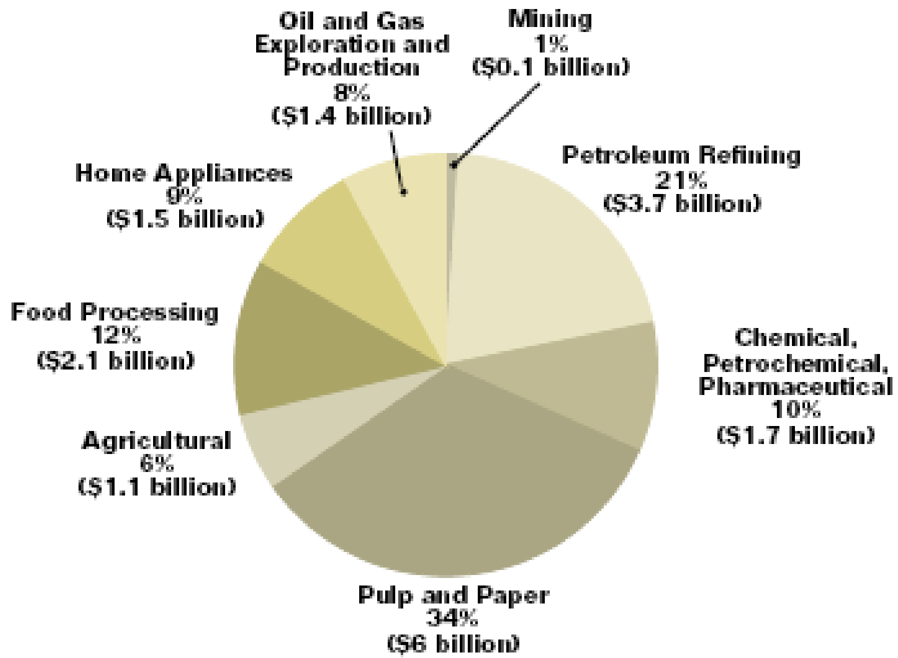
# Important Failure Mechanisms in the Petroleum Industry

| Failure Mode | Failure inducing agents | Sub-categories | Examples |
|---|---|---|---|
| **Fatigue** | Fluctuating stress/strain<br>Assisted by environment: temperature, humidity, oxidation, corrosion | High-cycle fatigue<br>Low-cycle fatigue<br>Thermal fatigue<br>Impact fatigue<br>Surface fatigue<br>Fretting fatigue<br>Corrosion fatigue<br>Creep fatigue | Airframes, pipelines, bridges, railroad structures, rotating shafts, turbine blades, pumps, bolts, gears, hip joint, welded structures, solder in electronic devices |
| **Corrosion** | Chemical or electrochemical reaction with environment<br>Assisted by stress, deformation, abrasion, wear | Direct chemical attack<br>Galvanic corrosion<br>Uniform corrosion<br>Pitting corrosion<br>Erosion corrosion<br>Crevice corrosion<br>Intergranular corrosion<br>Stress corrosion<br>Biological corrosion<br>Hydrogen damage<br>Corrosion fatigue<br>Dealloying corrosion | Pressure vessels, boiler tubes, pumps, compressors, bridges, crude oil storage tanks, airframes, marine structures, bolts, medical devices |
| **Wear** | Relative motion between mating surfaces<br>Plastic deformation<br>Assisted by environment: humidity, oxidation, temperature, corrosion | Adhesive wear<br>Abrasive wear<br>Fretting wear<br>Corrosive wear<br>Fatigue wear<br>Impact wear<br>Deformation wear | Pipe bends, seals, bearings, gears, disks and tapes, piston rings, nuclear machinery, drills, pump impellers, human teeth and joints |
| **Creep** | Plastic deformation due to stress and elevated temperature<br>Assisted by fluctuating stress/strain, corrosion | Creep fatigue<br>Creep corrosion | Boiler super-heaters, petro-chemical furnaces, reactor vessel components, gas turbine blades, aeroengines |

# Fact About Corrosion in Industries

- Corrosion is considered a significant factor in the failure and damage of metals
- Annual direct cost of  corrosion in U.S. oil and petrochemical industry= $6.8 billion
-  Mechanistic loads increase damage in the presence of Corrosion
- Pipelines are subject to mechanical stresses and harsh corrosive environments



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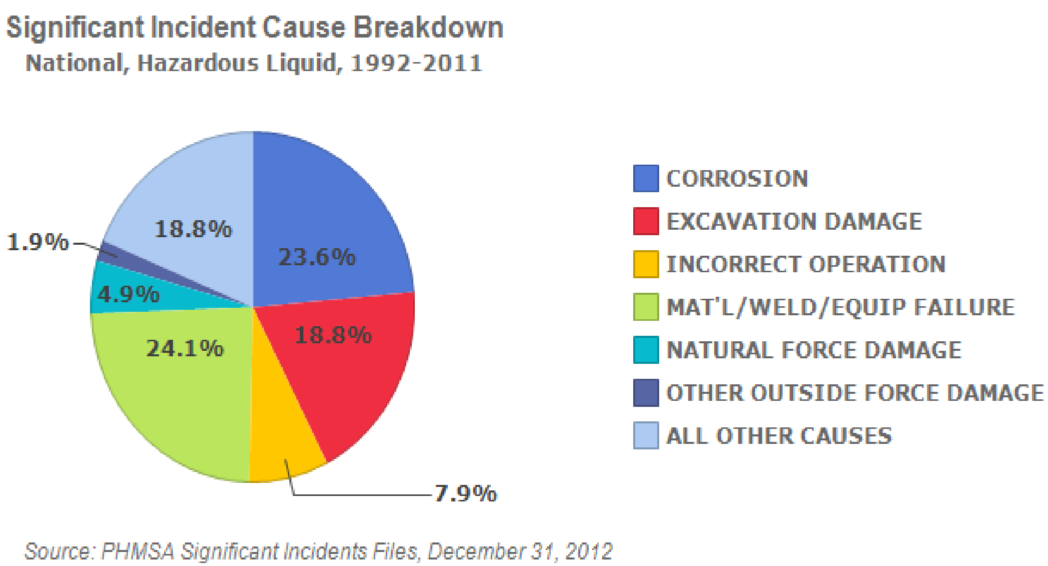
# Fact About Corrosion in Industries (Cont.)

- The 2010 Enbridge Spill in Michigan-U.S. was due to Corrosion-Fatigue (~$1B cost of clean up so far!).
- Why Mechanistic Failures are Important?
  - Preexisting cracks (pits, dents, weld flaws, cracks initiation due SCC, etc.)
  - Mechanical loads (tensile and cyclic)







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# UMD Approach to the Petroleum Industry PHM Application

- Define Conditions:
  - Understand needs and interests in the oil industry facility integrity management
  - Define accelerated test conditions that matches the operating field environment of the targeted facility
- Perform Experiments and Data Gathering:
  - Experiments to accelerate damage on representative materials
  - Analysis of data and associated uncertainties
  - Gather field data
- Develop Models:
  - Select Mathematical Model
  - Model Validation

Step 1
- Problem Definition
- Test Conditions Determination

Step 2
- Conduct the Experiments
- Field Data Gathering

Step 3
- Modeling & Validation
- Conclusions
- Recommendations

# Types of Corrosion

Forms of corrosion

- **Uniform Attack**
  Oxidation & reduction occur uniformly over surface.
- **Stress corrosion**
  Stress & corrosion work together at crack tips.
- **Erosion-corrosion**
  Break down of passivating layer by erosion (pipe elbows).
- **Selective Leaching**
  Preferred corrosion of one element/constituent (e.g., Zn from brass (Cu-Zn)).
- **Pitting**
  Downward propagation of small pits & holes.
- **Intergranular**
  Corrosion along grain boundaries, often where special phases exist.
- **Galvanic**
  Dissimilar metals are physically joined. The more anodic one corrodes. Zn & Mg very anodic.
- **Crevice**
  Between two pieces of the same metal. due to concentration difference

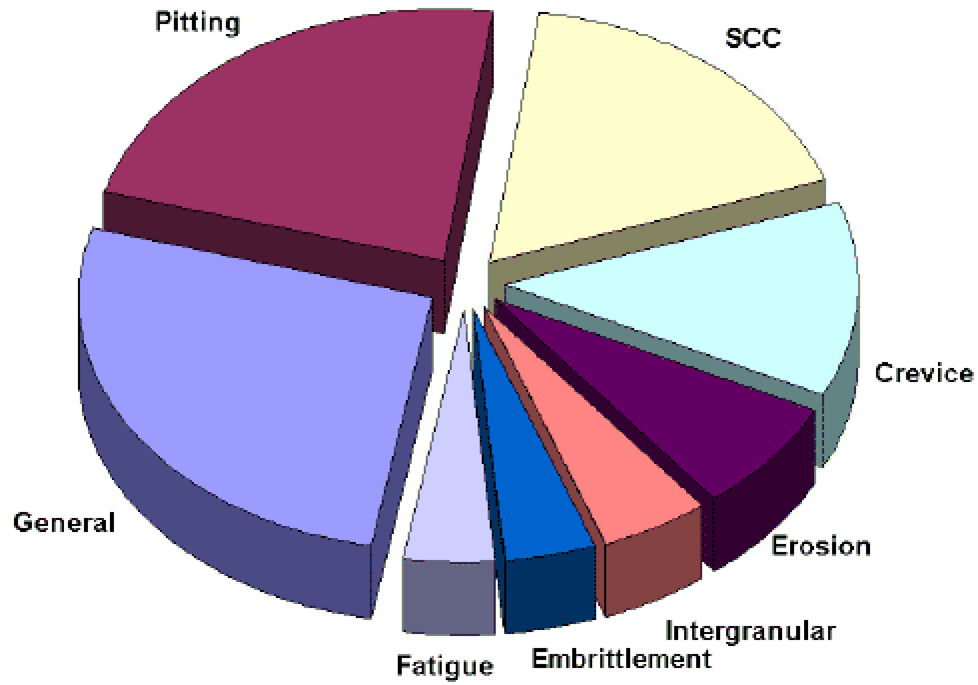
(Corrosion and Corrosion Control, H. Uhlig, et. al. 1997)

# Importance of Corrosion in PHM

- Waste of Material and Energy
- Economical Loss
  - Direct Loss
  - Indirect Loss
    - Shutdown
    - Loss of product
    - Loss of efficiency
    - Product contamination
    - Overdesign
- Environmental Impact/Health

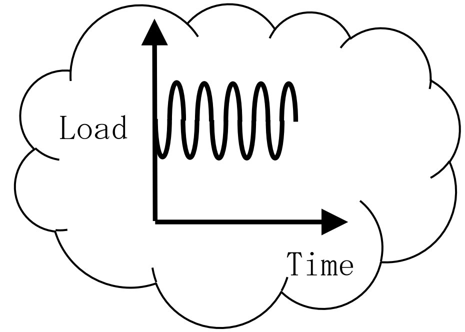
Different Types of Corrosion in a petrochemical Plant

Stress corrosion crack

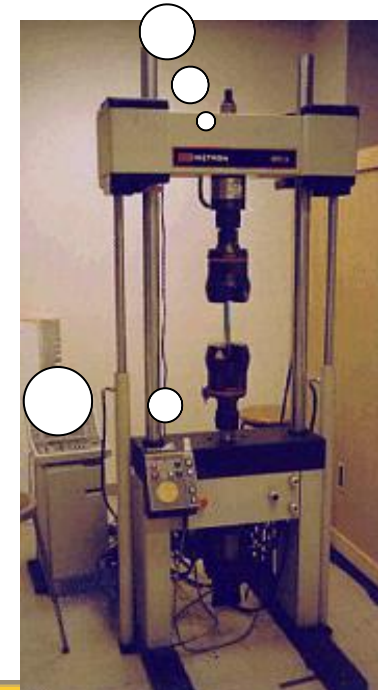



Data from major companied in France (www.corrosion-doctors.org)

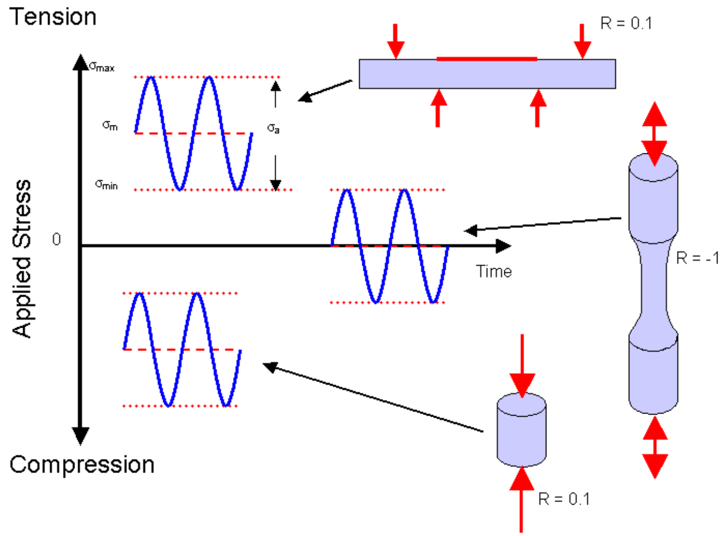
# Fatigue Failure in Facility Structures and Machinery

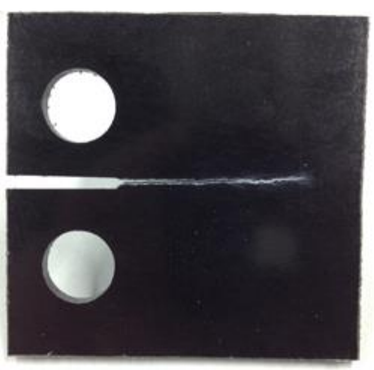



By common usage:
*Fatigue* refers to the behavior of materials under the action of repeated stresses or strains, as distinguished from their behavior under monotonic or static stresses or strains.



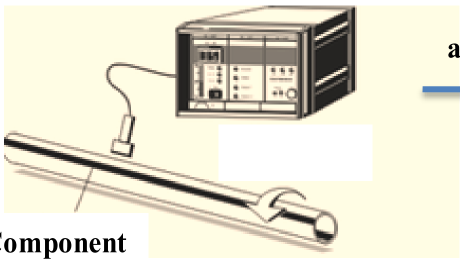
# Examples Fatigue Test & Specimens



# PHM in Oil Industry Considering NDT

Nondestructive equipment



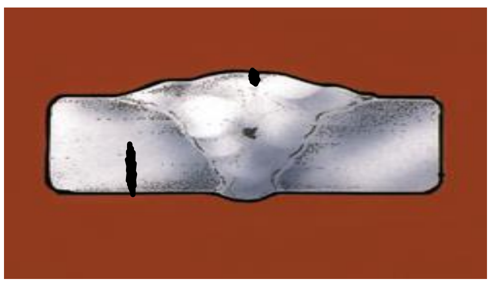
Component

Precision & accuracy

Response signal amplitudes

Analysis & processing

Defect size measurements



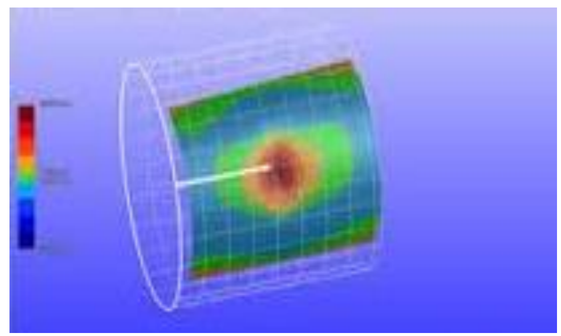


Photo Courtesy of Yxlon International

Assessment of Real Damage /Degradation

Incomplete and Uncertain Evidence of Damage

g(ρ)=Real Damage Density Distribution?
f(a)=Real Damage Size Distribution?

Evidence-Based
(NDT-Based Defect/Damage size and density)



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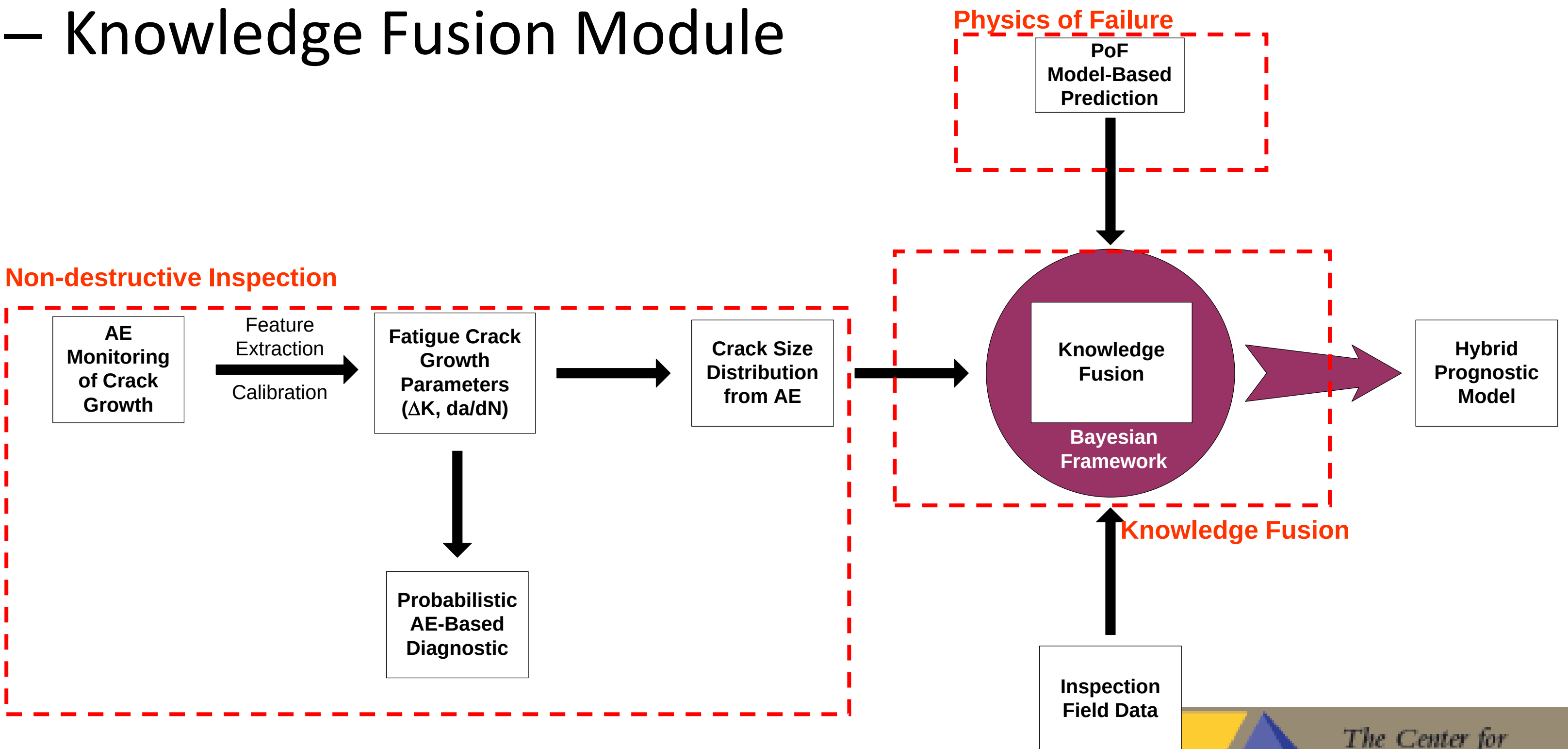
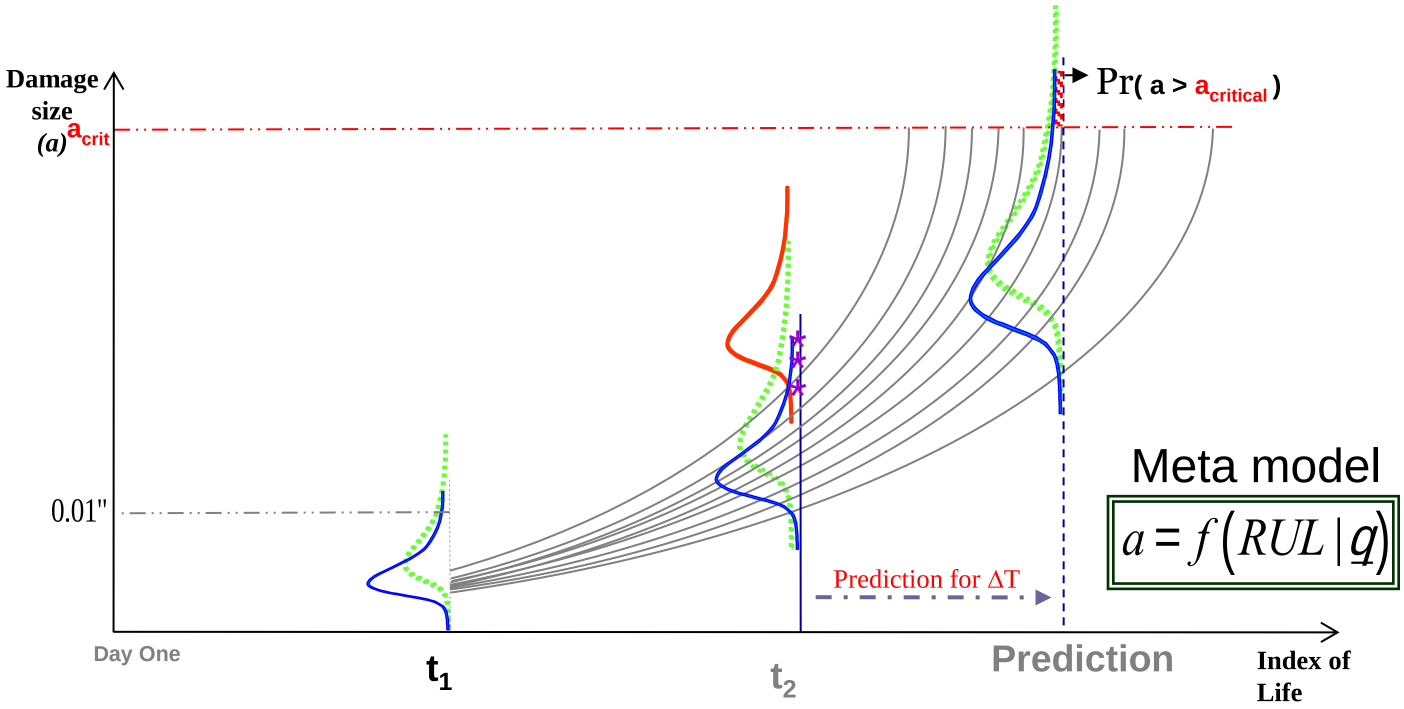
# Methodology USED

- Hybrid PHM consisting of the following modules:
  - Physics-of-Failure (PoF) Model
  - NDT-based structural integrity assessment
  - Knowledge Fusion Module



# Hybrid PHM Approach




**Damage Growth PoF Model**

**Field NDT**

**Field Inspection**

$$\pi(\underline{\theta} \mid \text{Evidence}) = \frac{L(\text{Evidence} \mid \underline{\theta})\, p(\underline{\theta})}{p(\text{Evidence})}$$

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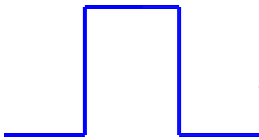
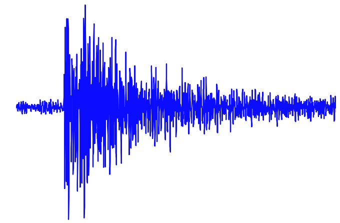
# Acoustic Emission Monitoring

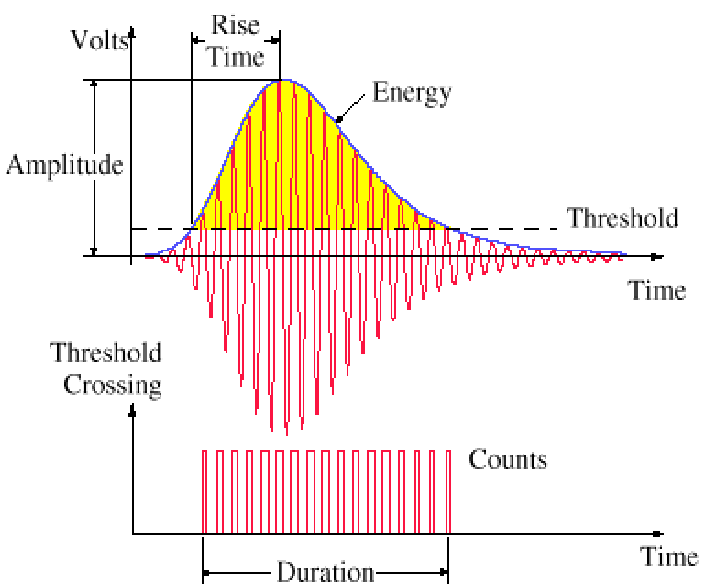
# AE for Fatigue Prediction

Signal at Source (Pulse) → Medium (Aluminum) → Sensor → Received AE Signal (Complex Waveform)



Deconvolution of the measured voltage signal from the sensor to evaluate the properties of the source event is extremely difficult.






# AE Features

- Amplitude
- Energy
- Rise time
- Counts (Threshold crossing)
- Frequency content
- Waveform shape





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# AE for Fatigue Prediction (Cont.)

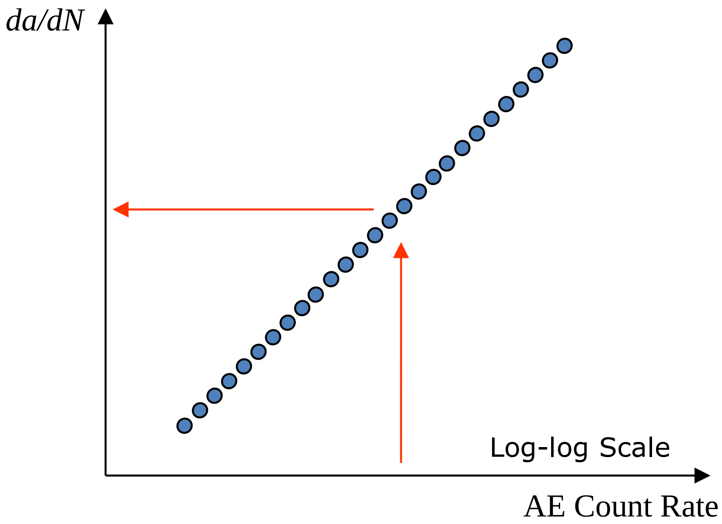
**Acoustic Emission**

- Amplitude
- Energy
- Rise time
- Counts
- Frequency
- Waveform

*correlation* →

**Fatigue**

- Crack Growth Rate
- ΔK=f(stress, crack size)

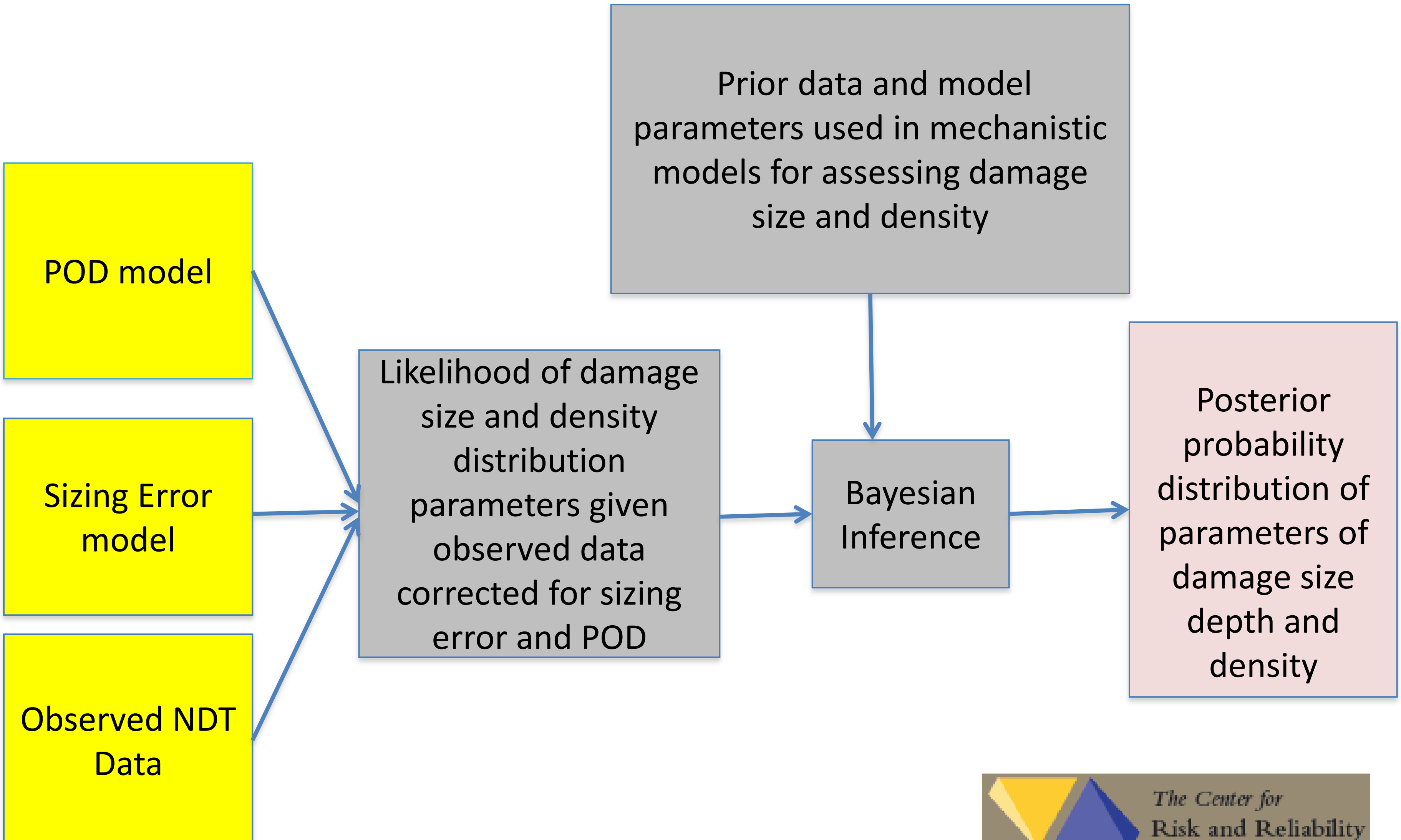



$$\log\left(\frac{da}{dN}\right) = \beta_1 \log\left(\frac{dc}{dN}\right) + \beta_2$$

One can estimate *da/dN*, given $\beta_1$, $\beta_2$ and AE count rate

[4] Bassim, M.N., St Lawrence, S. & Liu, C.D., 1994. Detection of the onset of fatigue crack growth in rail steels using acoustic emission. *ENG FRACT MECH*, 47(2), 207-214.

# Elements of Model Development: Bayesian Approach



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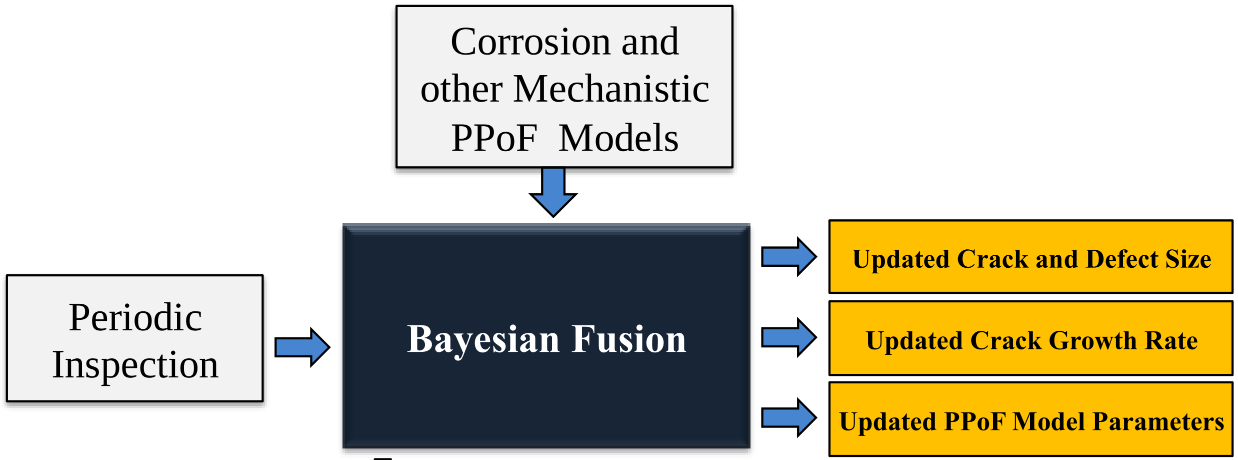
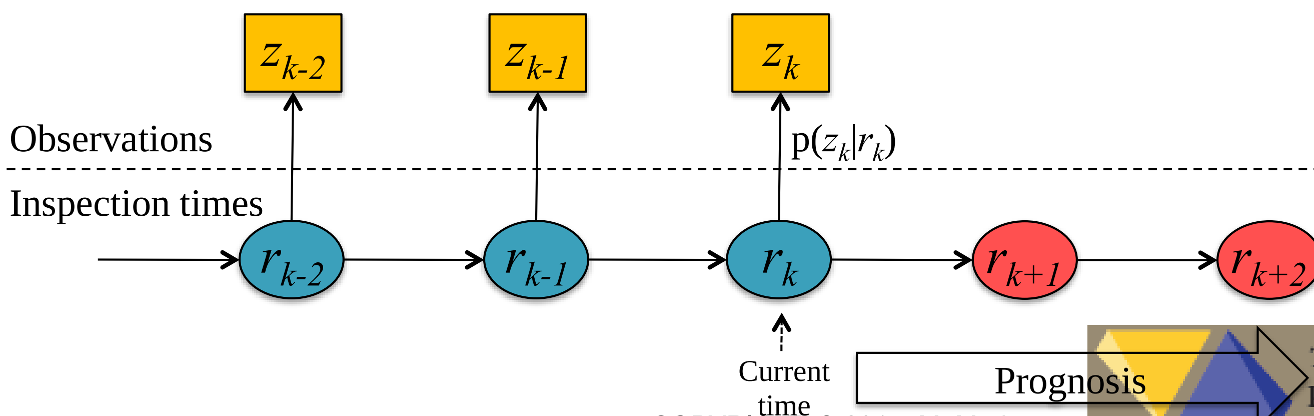
# Machine Learning and NDT Data Fusion in PHM




- Quantitative
- Probabilistic

- Formal framework
- Recursive (online fusion)
- Computationally feasible
- Multiple source

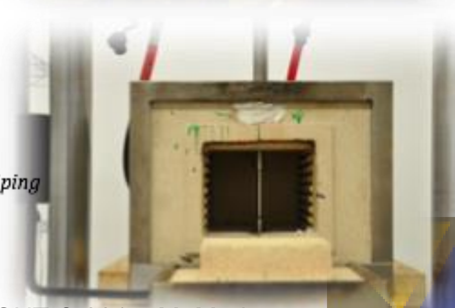


## Probabilistic Modeling of Failure Mechanisms


- MTS Uniaxial Fatigue Testing Machines
  - *Two-post and Four-post machines rating at ±100kN in tension or compression under static and cyclic conditions.*
  - *Fatigue Life Assessment Based on Energy Release*
  - *Fatigue Crack Initiation Based on Entropy Generation*

- Optical Microscopy for Short Fatigue Crack
  - *25 to 10X Microscope with C-mount adaptor for the video port. Magnification of 25X to 100X, can be increased to as high as 200X. Simultaneous visual and video viewing.*
  - *Short crack detection in fatigue*
  - *Visualization of crack growth*

- Acoustic Emission Technique for Crack Initiation and Growth
  - *Sensors and amplifiers to collect and amplify the signals, a data acquisition module to perform front-end filtration and record the signals, and a software module to visualize the data and to perform the required analysis such as feature extraction and source location.*
  - *Assessment of crack initiation*
  - *Large crack growth modeling*
  - *Information entropy analysis of AE signals for crack initiation*



- Heating Chamber for Creep Testing
  - *Exposure of specimen under controlled heat up to 700°C*
  - *Probabilistic modeling of creep*
  - *Fatigue-creep testing capability*

- Corrosive Medium Chamber
  - *Probabilistic corrosion-Fatigue model development in piping*
  - *Probabilistic pitting corrosion in pipes*
  - *Probabilistic stress corrosion in piping*



http://clarkdev.eng.umd.edu/modarres/index.php 301-405-5226 University of Maryland, College Park, MD 20742 USA

# Conclusions

- CRR Provides Most Up to Date Methods for PHM in the Petroleum Industry
- Strong Experimental, Model Development and Simulation Approaches to PHM
- Investments in PHM Corresponds to Multiples of Direct and Indirect Returns

# Thank you for listening

# Question?



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