Current Trends in Reliability Engineering Research

Lunch & Learn Talk
at
Chevron Company
Houston, TX

July 12, 2017

Mohammad Modarres
Center for Risk and Reliability
Department of Mechanical Engineering

Outline of this Talk

- Reliability Engineering Timeline
- Frontiers in Reliability Engineering
- Prognosis and Health Management (PHM)
- Reliability Science
- Conclusions

Timeline of Reliability Engineering

- Initiatives in 1950's
  - Weakest link
  - Advisory Group on the Reliability of Electronic Equipment (AGREE) DoD 1956-1958
  - Exponential life model
  - Reliability Block Diagrams
- Exponential Distribution Retreat in 1960's
  - Birth of Physics of Failure
  - Uses of other distributions
  - Reliability growth
  - Life testing
  - Failure Mode and Effect Analysis
- Logic Models: Fault Tree Analysis in 1970'S
  - Probabilistic Risk Assessment
  - Common Cause Failures
  - Uncertainty Analysis

Timeline (Cont.)

- Accelerated Life and Degradation Testing in1980's
- Rebirth of Physics-of-Failure in 1990's
  - Probabilistic Physics-of-Failure
  - Time Varying Accelerated Tests
  - Highly Accelerated Life Testing (HALT)
- Hybrid Reliability and Prognosis Models in 2000's
  - Combined Logic Models, Physical Models and Probabilistic Models (e.g. BBN)
  - Prognosis and Health Management (PHM) methods
  - Powerful simulation tools (MCMC, Recursive Bayes and Particle Filtering)
- Exploring Fundamental Sciences of Reliability in 2010's
  - Thermodynamics and Entropy
  - Data science and predictive Analytics (treating Big Data in reliability)
  - Autonomous systems and robots
  - Infrastructure and cyber-physical systems

Our Current Areas of Research in Reliability

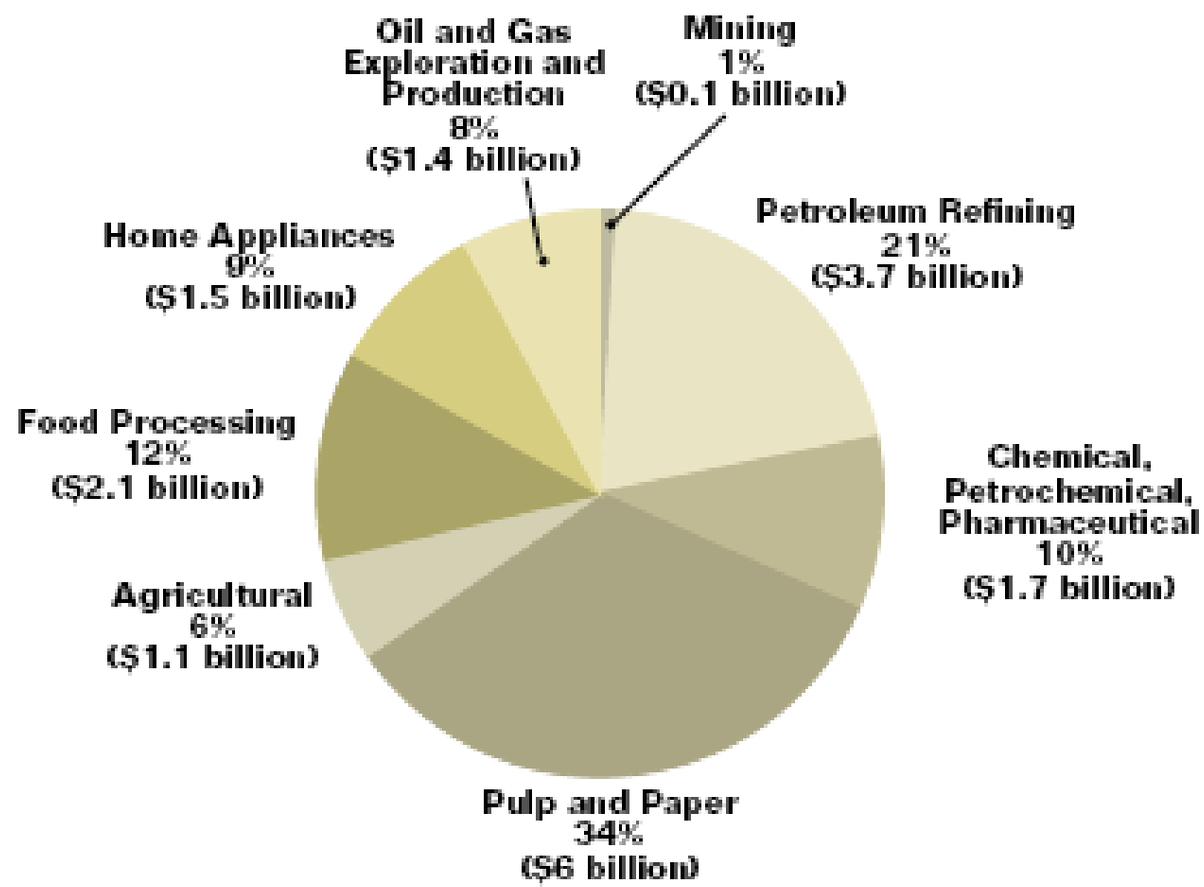
- Probabilistic Physics-of-Failure (PPoF)
  - More than 50-Years of History in PoF (More Recently PPoF)
  - Accelerated Reliability Testing for PPoF Model Development
  - Empirical Model for Unit-Specific Reliability Assessment
  - Simulation-Based Reliability
- Hybrid Reliability
  - Combined System Analysis Techniques: BBN, DBN, DFT, DET, Markov and Semi-Markov, FEM and FDM, FM, RBD, etc.
- Sensor-Based (Precursors) / Big Data Reliability Analysis
  - Data Fusion, Predictive Analytics, Deep Learning, Natural Language, Detection Probability, Measurement Models
- Fundamental Sciences of Reliability Engineering

Our Current Areas of Research in Integrity / Risk Assessment

- Infrastructure Safety-Security-Resilience (SSR)
  - Integrity of Complex Systems and Networks: Cyber-Human-Software-Physical (CHSP) Systems
  - Highly Connected Infrastructure Networks: Electricity, Gas, and Water Pose Major Societal Risks of Cyberspace Attacks
  - Risk Management and Resilience
  - Societal Disruption, Health, Safety and Resilience
- Life-Cycle Risks of Advanced Energy Systems
  - Pipeline and Conventional Fossil-Based Energy System integrity
  - Renewable Energy Systems
  - Nuclear Energy (Fission and Fusion)

Integrity of Energy Systems: Corrosion

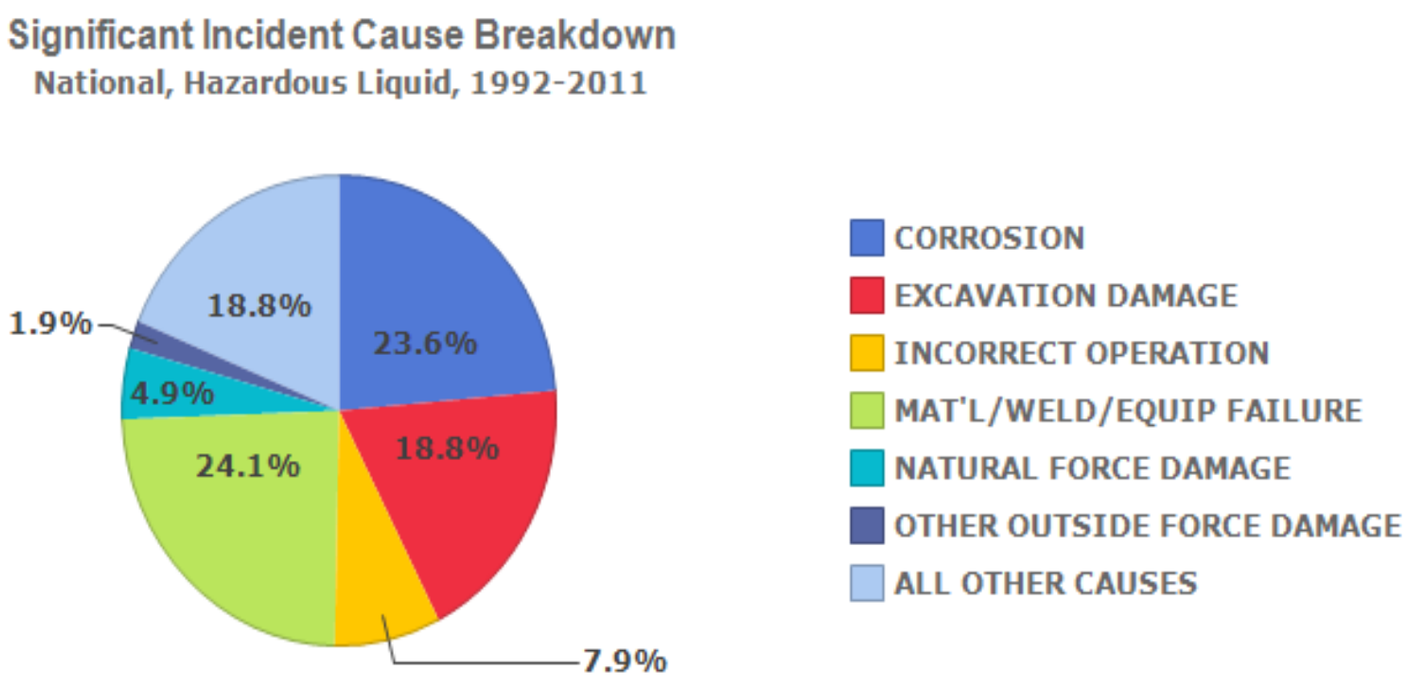
- Corrosion a major contributor to failure and damage in metals
- Annual direct cost of corrosion in U.S. oil and petrochemical industry= $6.8 billion[1]
- Mechanistic loads increase damage in the presence of Corrosion
- Pipelines are subject to mechanical stresses and corrosive environments



1. NAS, 2014

Integrity of Energy Systems: Corrosion (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 due to SCC, etc.)
  - Mechanical loads (tensile and cyclic)



Source: PHMSA Significant Incidents Files, December 31, 2012

UMD Approach to a Petroleum Industry PHM Application

- Define Conditions:
  - Understand needs of facility integrity management
  - Define accelerated test conditions that match operations
- Perform Experiments and Data Gathering:
  - Accelerate damage on representative materials
  - Analyze data and associated uncertainties
  - Supplement with field data
- Develop Models:
  - Physics of failure Model
  - Model Validation
  - Simulate Models

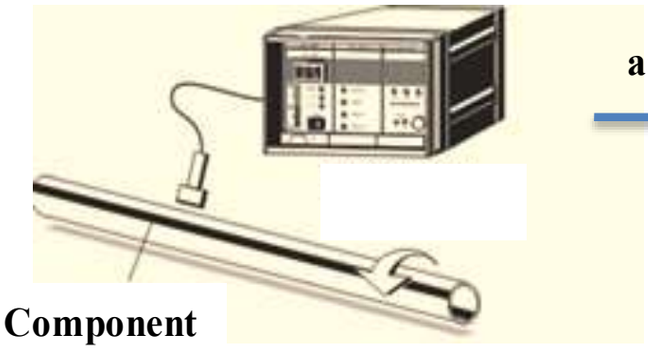
Step 1
- Problem Definition
- Test Conditions Determination

Step 2
- Conduct the Experiments
- Field Data Gathering

Step 3
- Modeling & Validation
- Simulate the Model
- Assess Health and Integrity

PHM in Oil Industry with NDT

Nondestructive equipment



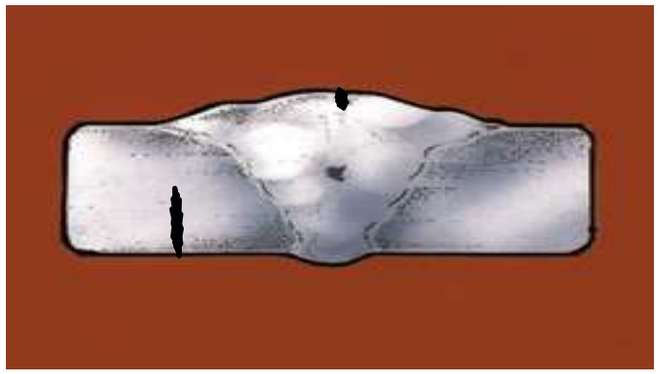
Component

Precision & accuracy →

Response signal amplitudes

Analysis & processing →

Defect size measurements



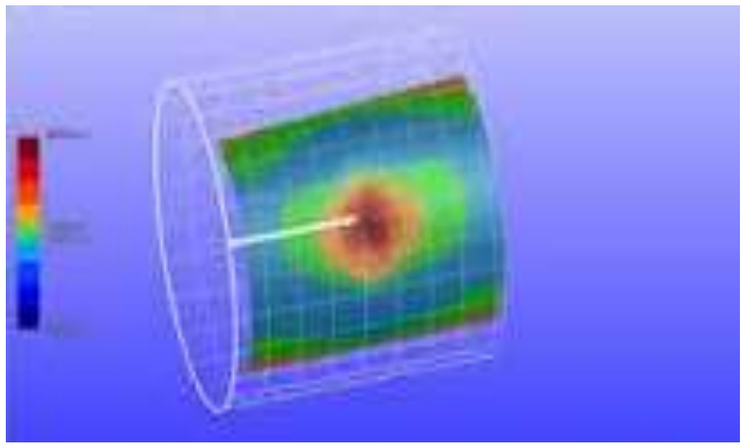


Photo Courtesy of Yxlon International

Assessment of True Damage

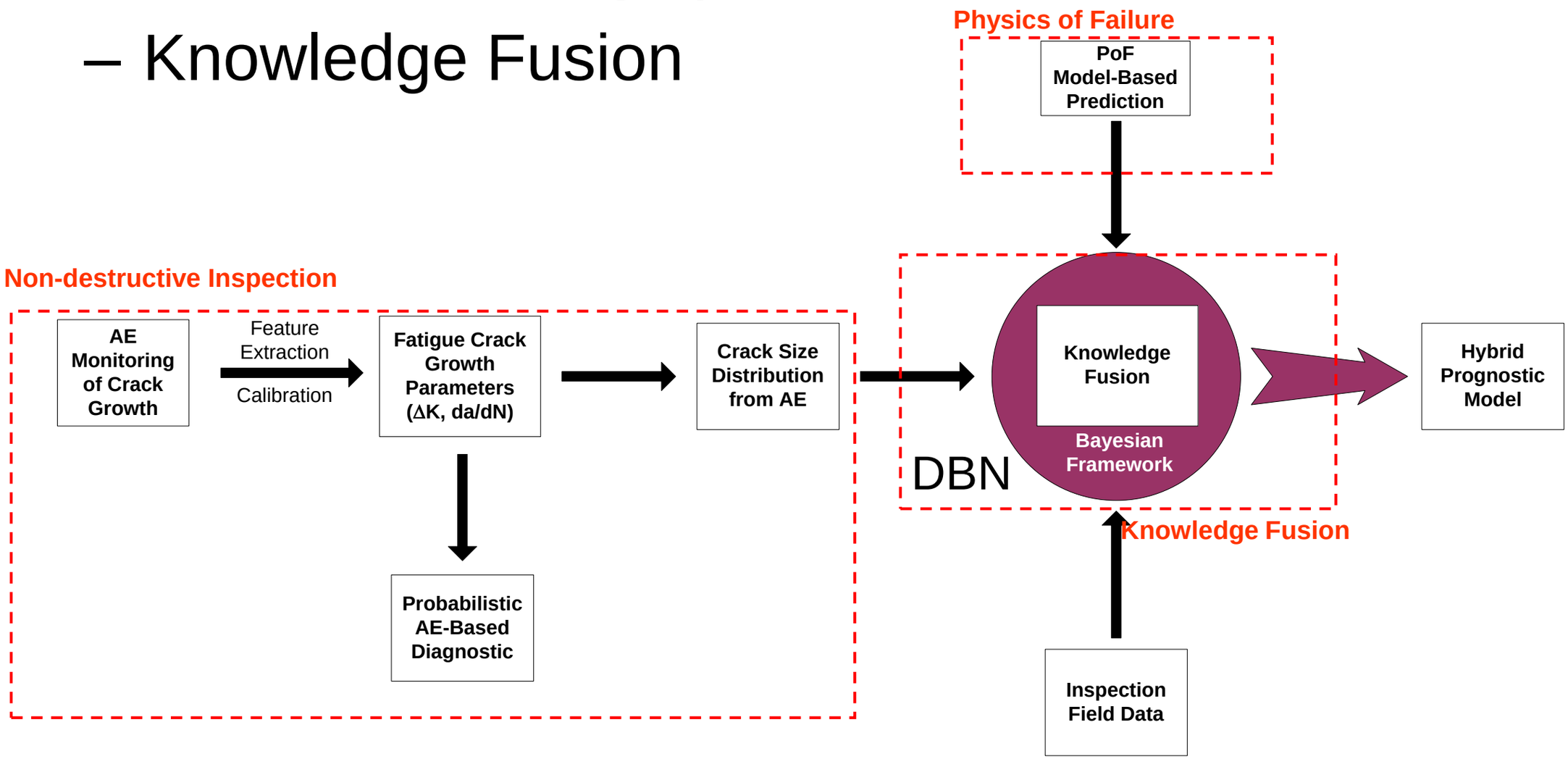
Incomplete and Uncertain Evidence of Damage

Damage Density Distribution
Damage Size Distribution

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

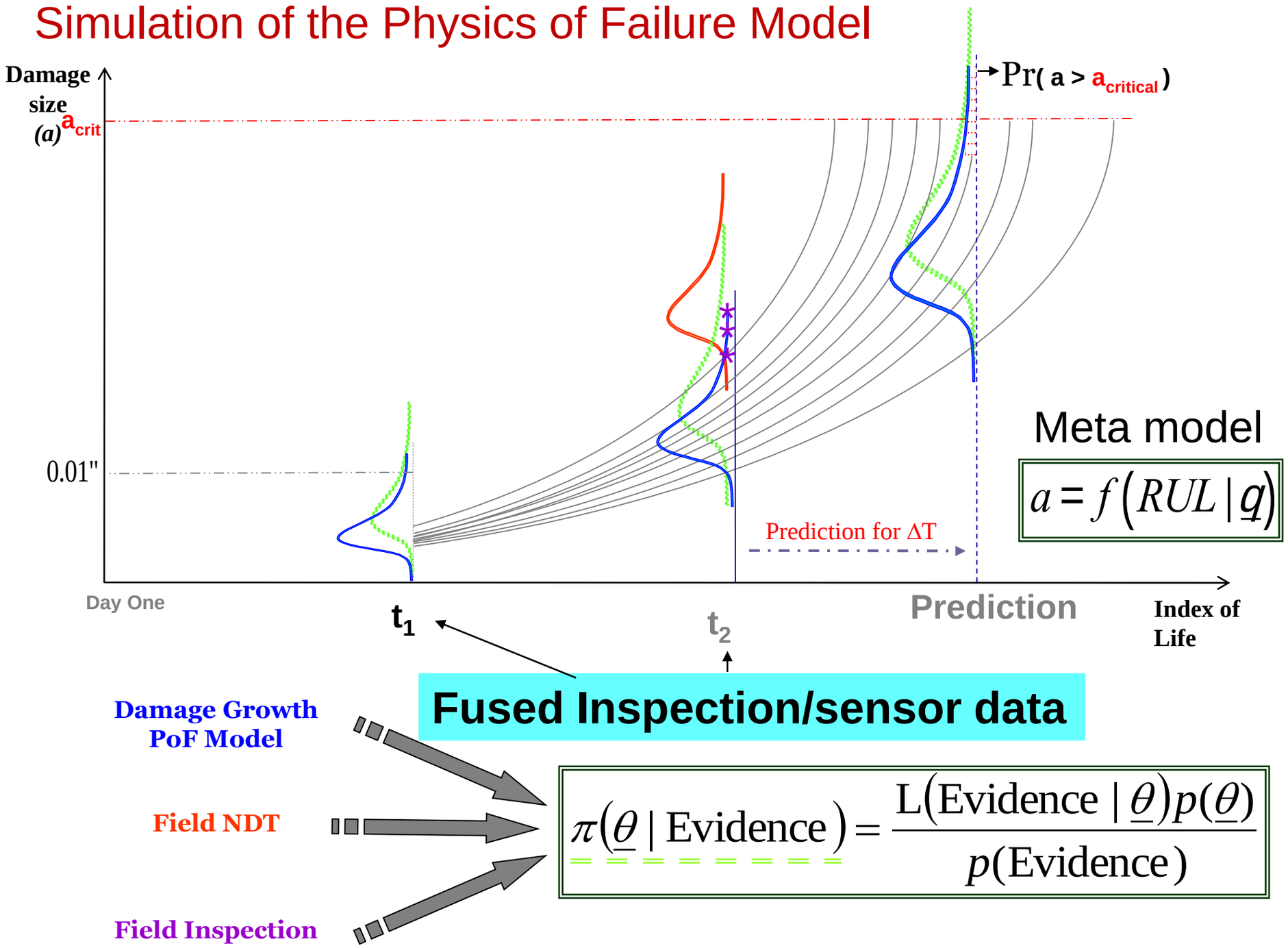
Hybrid HM Approach

- Consists of the following elements:
  - Physics-of-Failure (PoF) Model
  - NDT-based integrity assessment
  - Knowledge Fusion

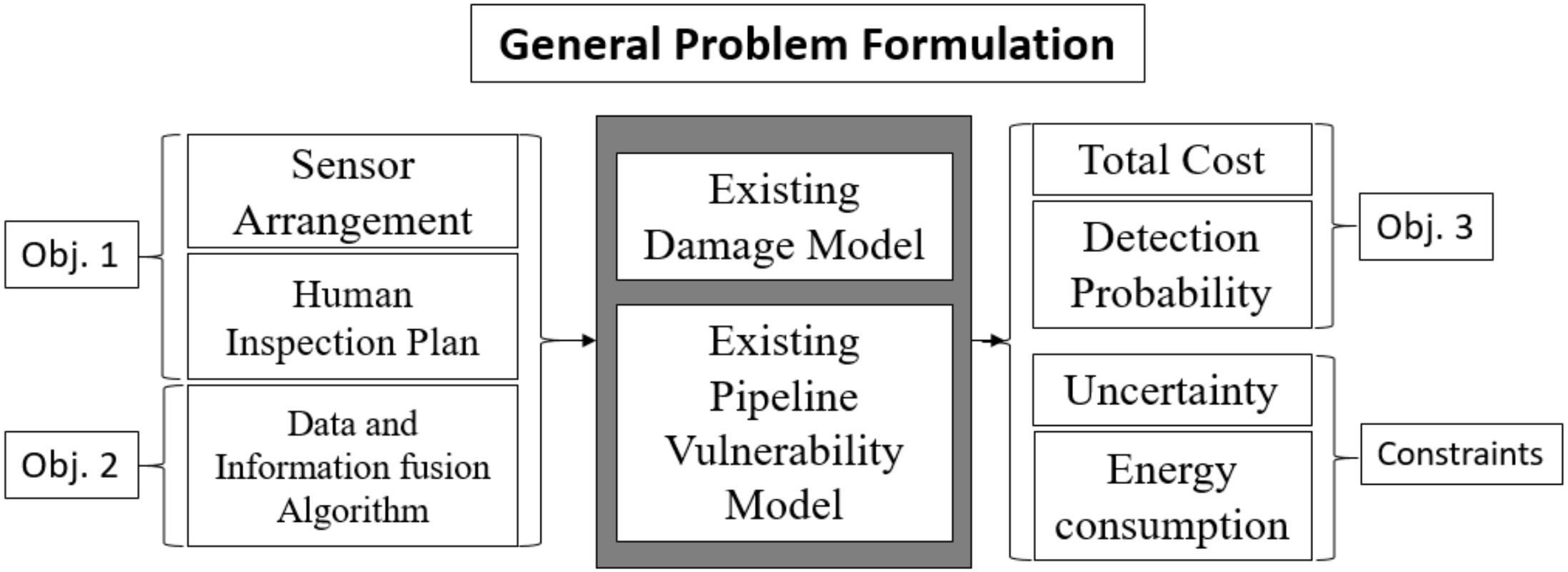


Hybrid PHM Approach (Cont.)

Simulation of the Physics of Failure Model



Overview of a Current Research in PHM



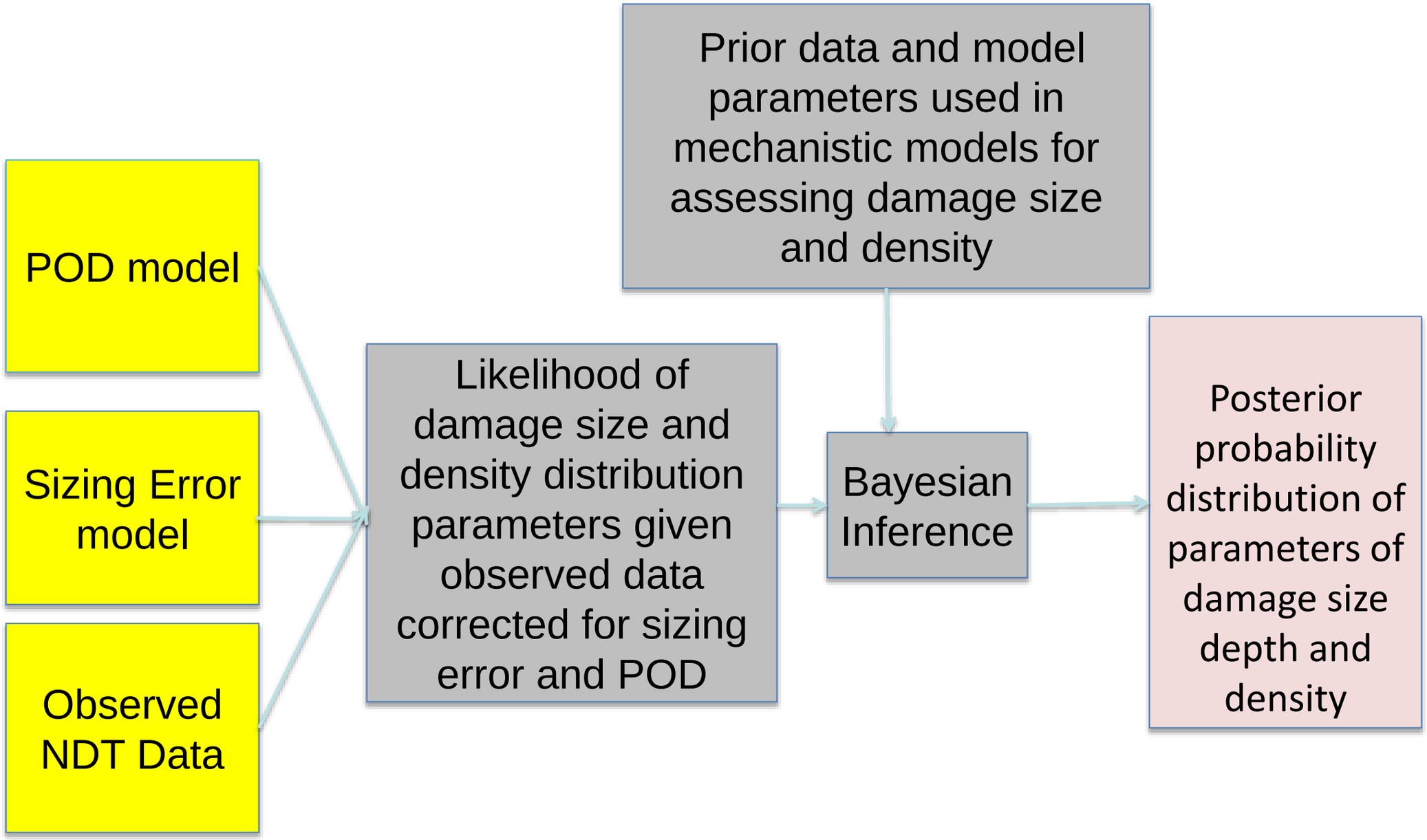
Objectives:

1- Develop data gathering approach for high-confidence remaining life estimation of pipeline systems

2- Assess reliability and prognosis of pipelines

Overview of a Current Research in PHM (Cont.)



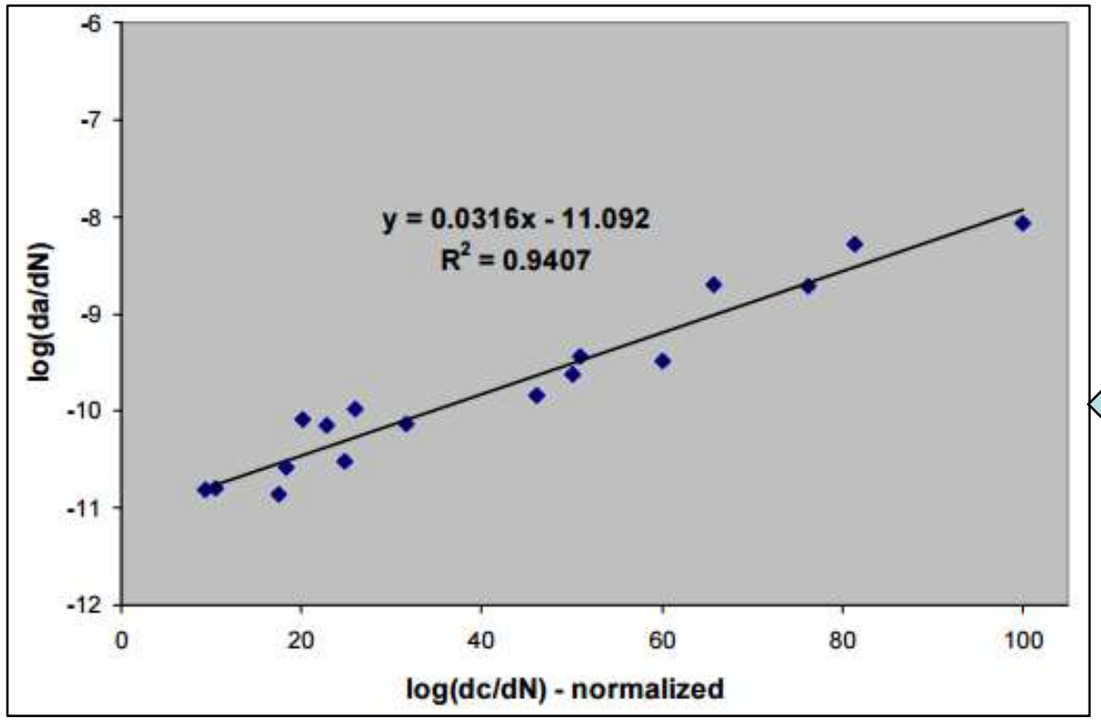


Example of a Sensor-Based Monitoring PHM

- Describe damage using the surrogate indicator: acoustic emission (AE)
- Process raw AE features to prediction fatigue damage
- Define damage and its endurance in the context of AE features
- Applications to Prognosis and Health Management (PHM) of structures

Example of a Sensor-Based Monitoring PHM (Cont.)

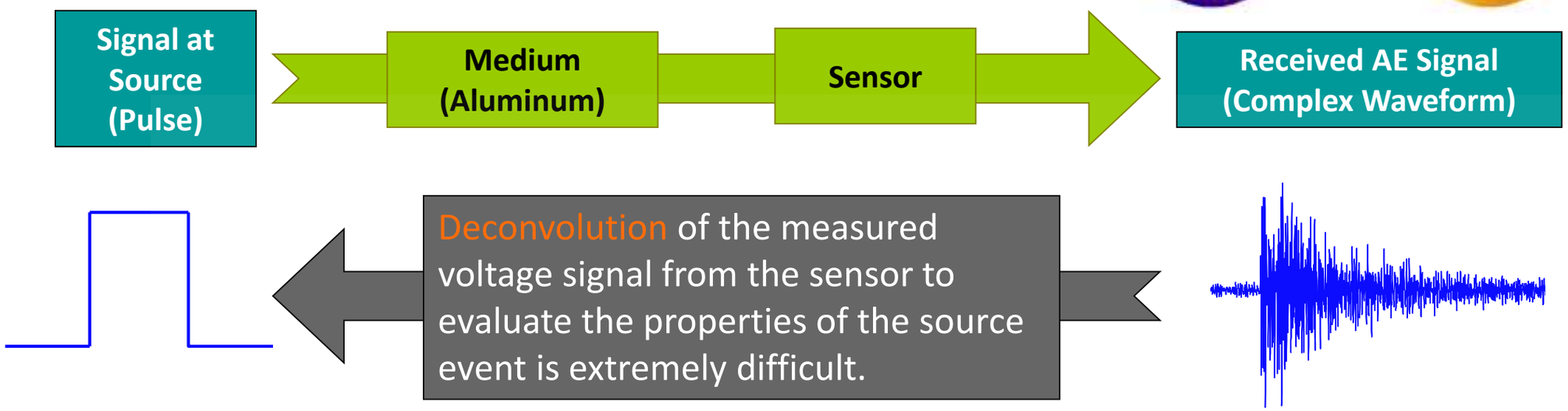
[1]

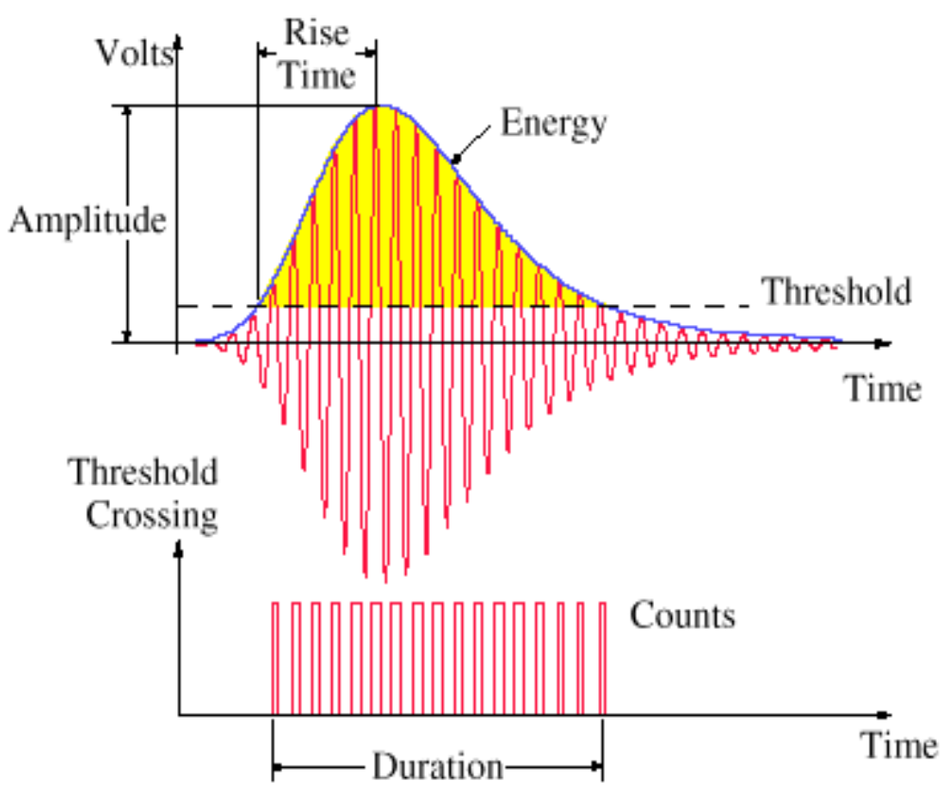


Crack growth correlation with an AE feature: AE count

[1] A. Kshtgar and M. Modarres, Acoustic Emission-Based Fatigue Crack Growth Prediction, Reliability and Maintainability Symposium (RAMS), 2013 Proceedings-Annual, p.1-5

Example of a Sensor-Based Monitoring PHM (Cont.)





AE Features

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

Example of a Sensor-Based Monitoring PHM (Cont.)

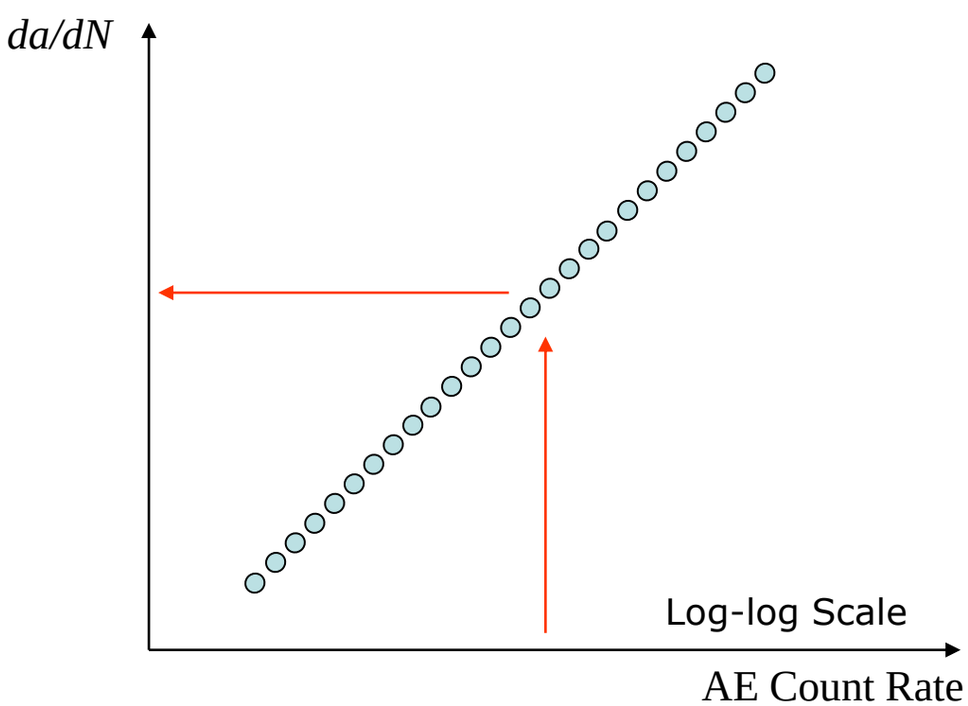
Acoustic Emission

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

correlation →

Fatigue

- Crack Growth Rate
- $\Delta K = f(\text{stress, crack size})$

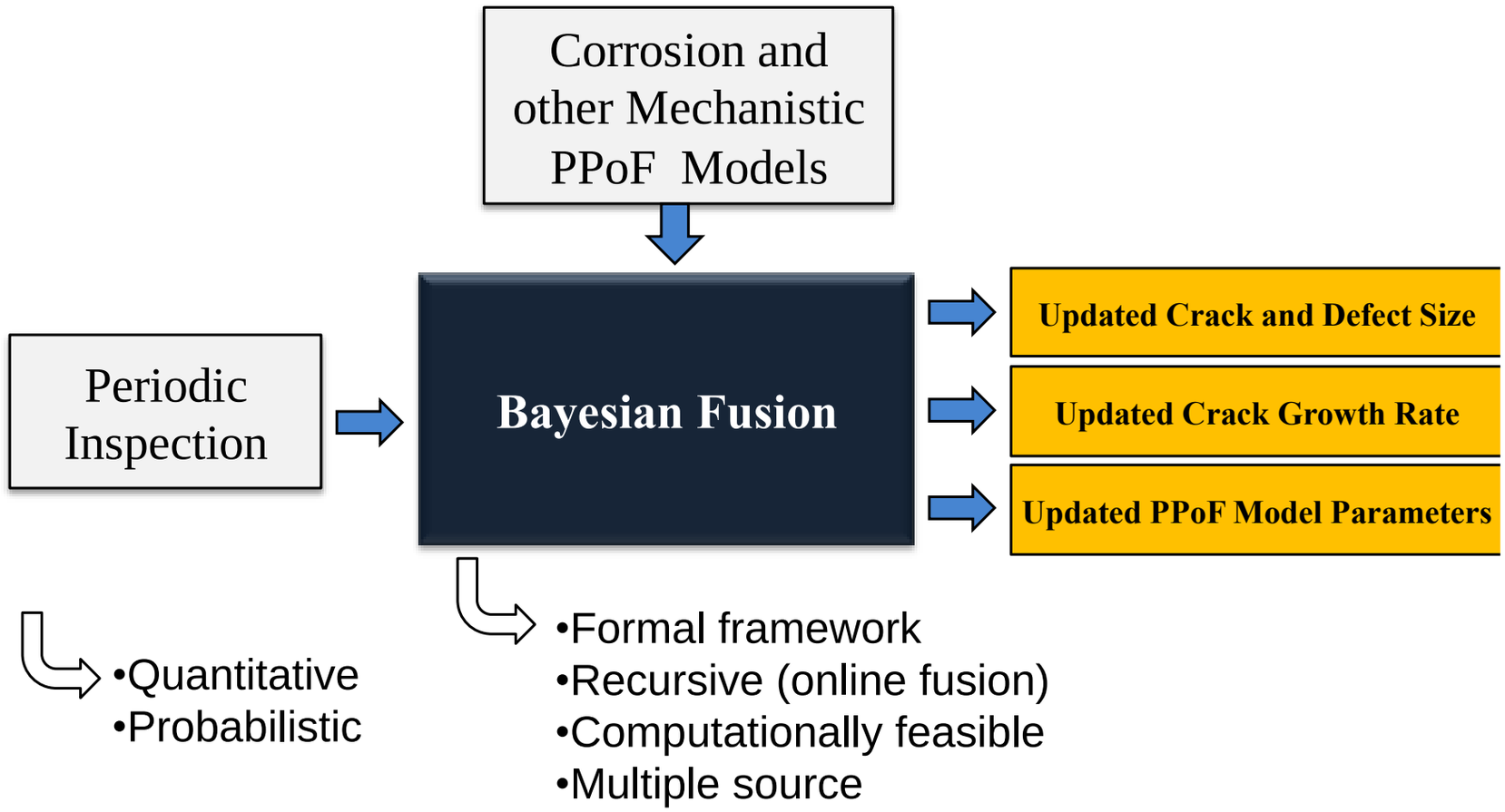


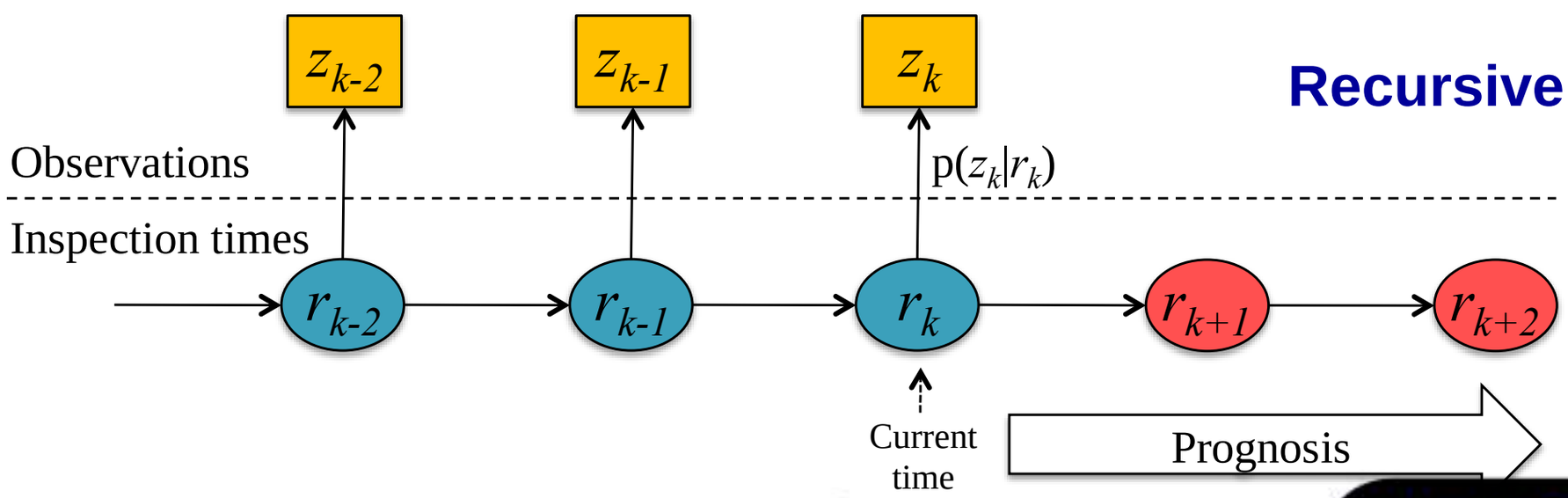
$$\log\left(\frac{da}{dN}\right) = \beta_1 \log\left(\frac{dc}{dN}\right) + \beta_2$$

One can estimate *da/dN*, given β_1, β_2 and AE count rate

[1] 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.

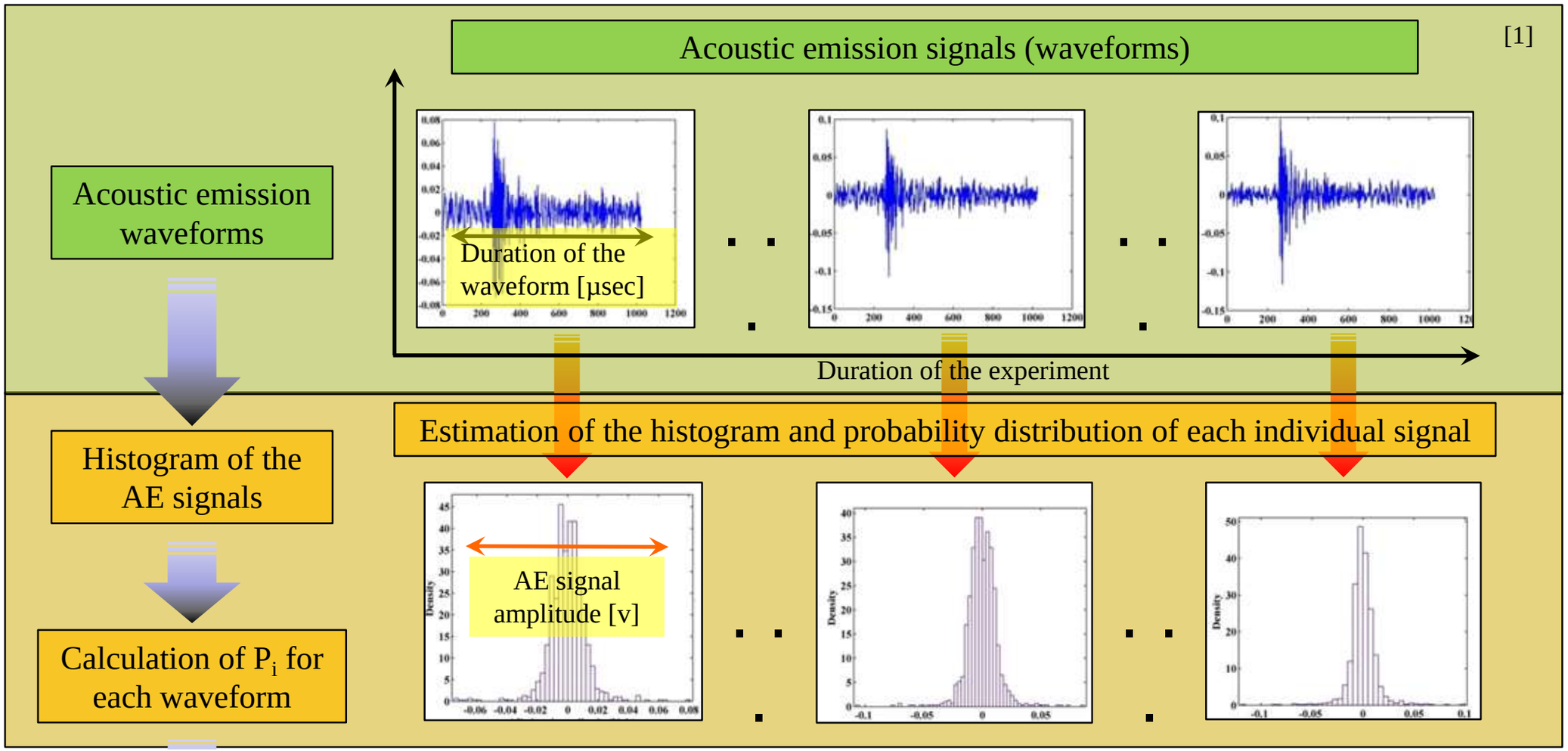
Example of a Sensor-Based Monitoring PHM (Cont.)





Recursive Bayesian

Example of a Sensor-Based PHM: Information Entropy



Probability distribution (P_i) → Entropy

$$S_I = \sum_{i=1}^{n} p_i \log_2\left(\frac{1}{p_i}\right) = -\sum_{i=1}^{n} p_i \log_2(p_i)$$

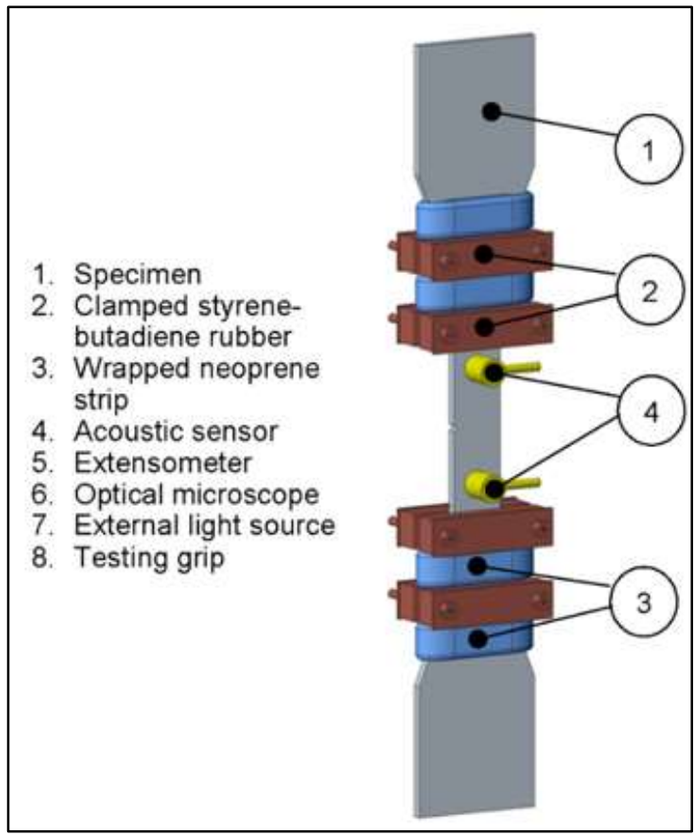
[1] Ali Kahirdeh, Christine Sauerbrunn, Mohammad Modarres, Proceedings of the 35th International Workshop on Bayesian Inference and Maximum Entropy Methods in Science and Engineering, MaxEnt_2015, Potsdam, NY, 2015

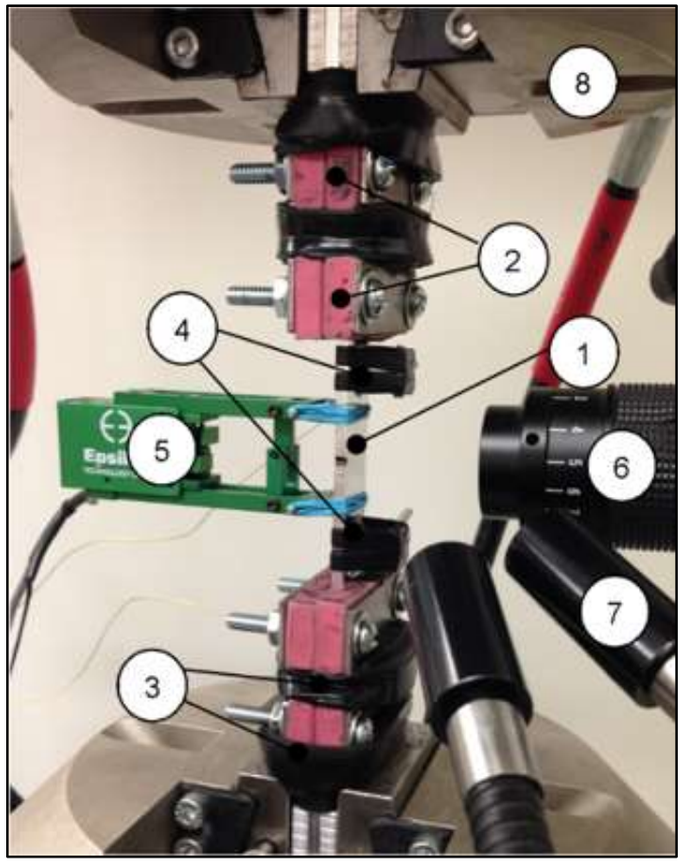
Example of a Sensor-Based PHM: Information Entropy

- Material / Specimen: Al alloy 7075-T6 / Dogbone ASTM E466

Element	Al	Zn	Mg	Cu	Cr	Fe	Mn	Si	Ti	V	Zr	Other
Composition (wt %)	89.7	5.7	2.6	1.4	0.20	0.15	0.08	0.06	0.02	0.01	0.01	0.05
Material Property	Ultimate Strength (MPa)				Yield Strength (MPa)				Elastic Modulus (GPa)			
Property Value	587				538				67.8			

[1]





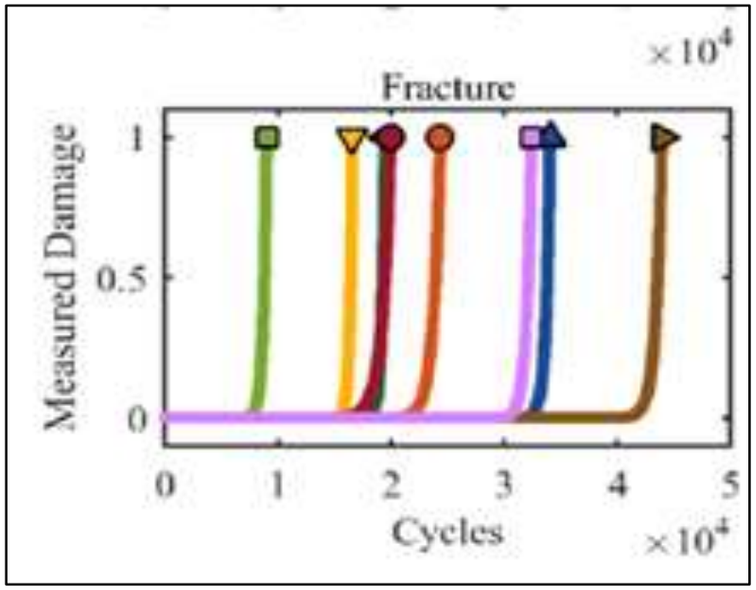
- Dogbone specimen with round notch (1 mm radius)
- K_t=2.61
- Eraser and neoprene rubber bands were used for mechanical damper for AE signal noise reduction

[1] Sauerbrunn, Christine M., et al. "Damage Assessment Using Information Entropy of Individual Acoustic Emission Waveforms during Cyclic Fatigue Loading." *Applied Sciences* 7.6 (2017): 562

Example of a Sensor-Based PHM: Information Entropy

- Reference damage is computed by using modulus degradation [1]

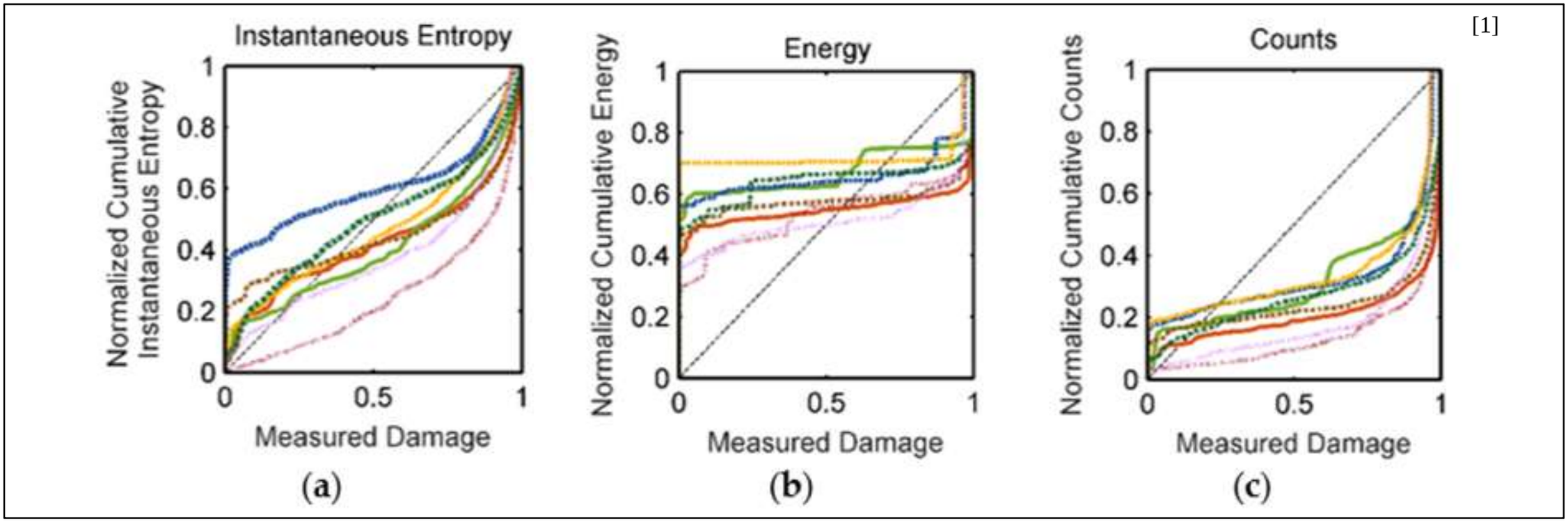
$$MDD^{*} = \frac{E_i - E_0}{E_f - E_0}$$

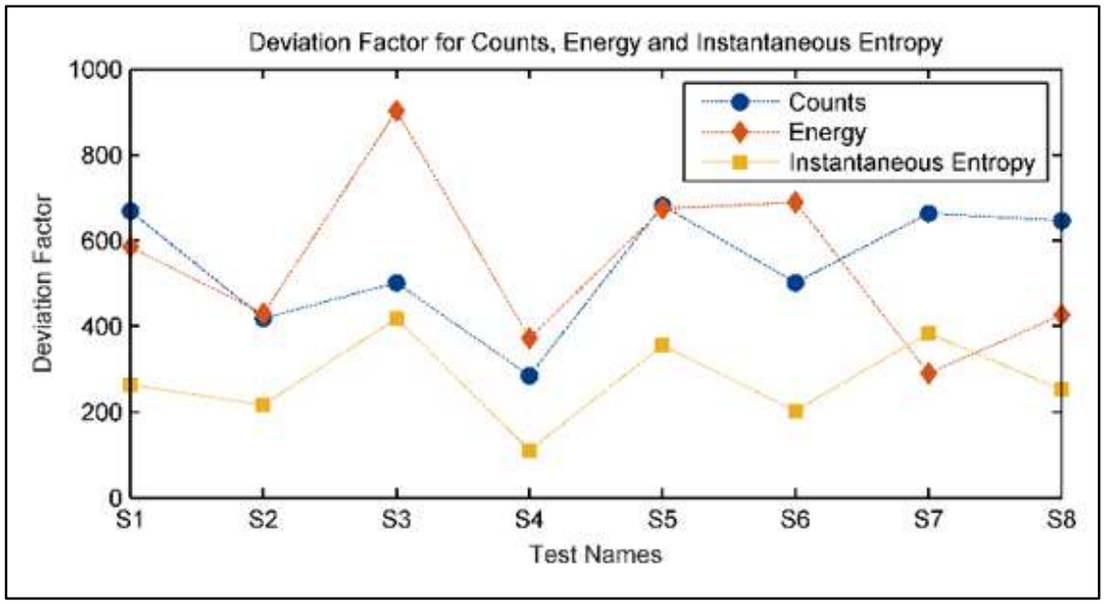


- MDD: Modulus Degradation Damage

[1] Christine M. Sauerbrunn, Evaluation of Information Entropy from Acoustic Emission Waveforms as a Fatigue Damage Metric for Al7075-T6, 2016, University of Maryland, Master of Science Thesis

Example of a Sensor-Based PHM: Information Entropy





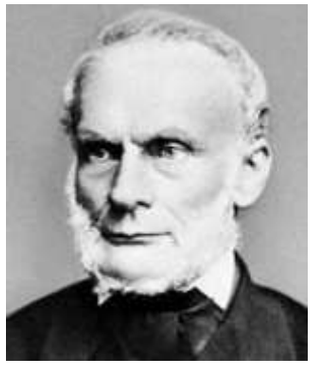
- The correlation results were evaluated with deviation factor
- The information entropy is closer than raw AE features

[1] Sauerbrunn, Christine M., et al. "Damage Assessment Using Information Entropy of Individual Acoustic Emission Waveforms during Cyclic Fatigue Loading." *Applied Sciences* 7.6 (2017): 562

An Entropic Theory of Damage: A Fundamental Science of Reliability

- Failure mechanisms leading to degradation share a common feature at a deeper level: ***Dissipation of Energy***
- Dissipation (or equivalently entropy generation)≅Damage

Degradation mechanisms → Damage → Dissipation energies → Entropy generation



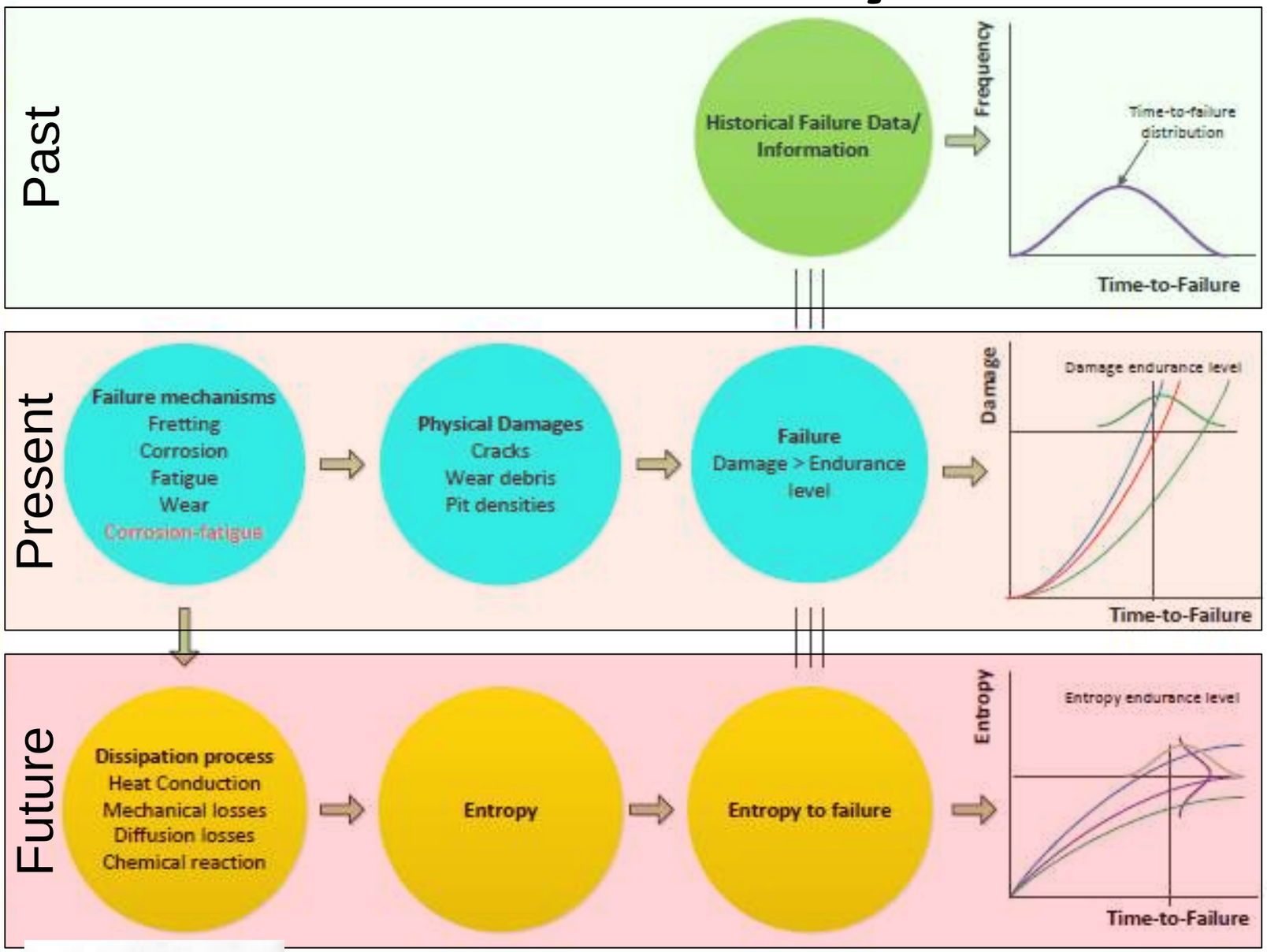
Rudolf Clausius
1822 –1888

Failure[1] occurs when the accumulated total entropy generated exceeds the entropic-endurance of the unit

- Entropic-endurance describes the capacity of the unit to withstand entropy
- Entropic-endurance of identical units is equal
- Entropic-endurance of different units is different
- Entropic-endurance to failure can be measured (experimentally) and involves stochastic variability

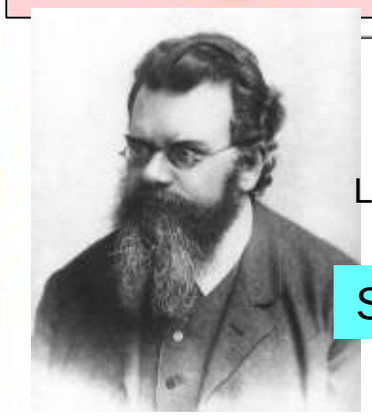
1. Defined as the state or condition of not meeting a requirement, desirable behavior or intended function

Thermodynamics as a Science of Reliability



Why Entropy?

- ✓ Entropy can model multiple competing degradation processes leading to damage
- ✓ Entropy is independent of the path to failure ending at similar total entropy at failure
- ✓ Entropy accounts for complex synergistic effects of interacting degradation processes
- ✓ Entropy is scale independent



Ludwig Boltzmann
1844-1906

Statistical Mechanics Entropy

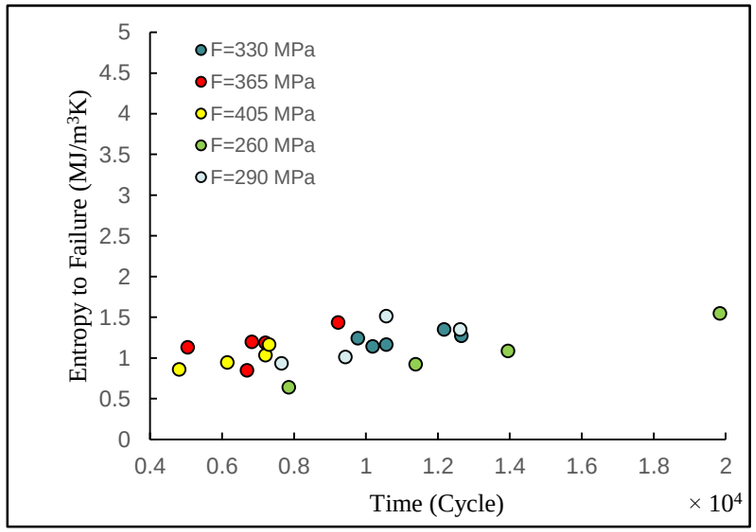
Thermodynamics as a Science of Reliability (Cont.)

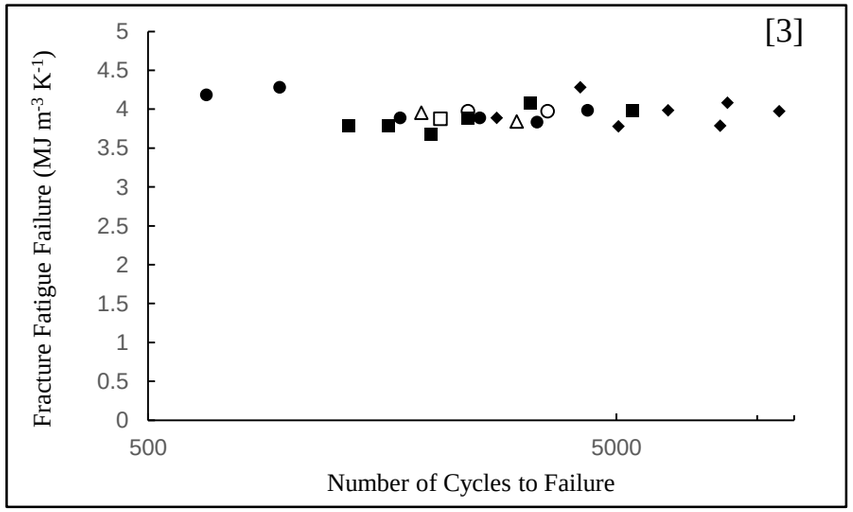
[1]

$$\sigma = \underbrace{\frac{1}{T^2} J_q \cdot \nabla T}_{\text{Thermal}} - \underbrace{\sum_{k=1}^{n} \left(\nabla \frac{\mu_k}{T} \right)}_{\text{Diffusion}} + \underbrace{\frac{1}{T} \tau : \dot{\epsilon}_p}_{\text{Mechanical}} + \underbrace{\frac{1}{T} \sum_{j=1}^{r} v_j A_j}_{\text{Chemical}} + \underbrace{\frac{1}{T} \sum_{m=1}^{h} c_m J_m (-\nabla \psi)}_{\text{External field energy}}$$

$$\sigma = \sum_{i=1}^{m} X_i J_i$$

Product of thermodynamic forces and fluxes





[1] Anahita Imanian and Mohammad Modarres, A Thermodynamic Entropy Approach to Reliability Assessment with Application to Corrosion Fatigue, Entropy 17.10 (2015): 6995-7020
[2] M. Naderi et al., On the Thermodynamic Entropy of Fatigue Fracture, Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 466.2114 (2009): 1-16
[3] M. Naderi et al., Thermodynamic Analysis of Fatigue Failure in a Composite Laminate, Mechanics of Material 46 (2012): 113-122

Conclusions

- Reliability and Risk Analysis Now Forms an Integral Part of Modern Products, Systems and Infrastructures Design and Operation
- Exciting and Abundant Activities in Reliability: Number of Conferences, Educational Programs, Scholarly Journals, Human Resource Demands
- PHM and Integrity Assessment a fast growing area coupled with computational capabilities and big data analytics

Thank you for your attention!