Overview of My Recent Research

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Areas of Recent Focus

- Probabilistic Physics of failure (PHM, ADT, ALT)
  - Fatigue
  - Creep
  - Corrosion
  - Combinations
- PPoF Based Modeling of Structures and Systems
  - Agent-Based Computing
  - Simulations-Based Computing
  - Common Cause Failures
- Probabilistic Risk Assessment and Reliability Analysis
  - More than 20 PRAs of Nuclear Plants
  - PRAs in Transportation (CNGs and Pipelines)
  - PRA of Small Modular Reactors
  - Failure Data Collection and Analysis
  - Modeling complex components (Compressors, pumps, MOVs, etc.)

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

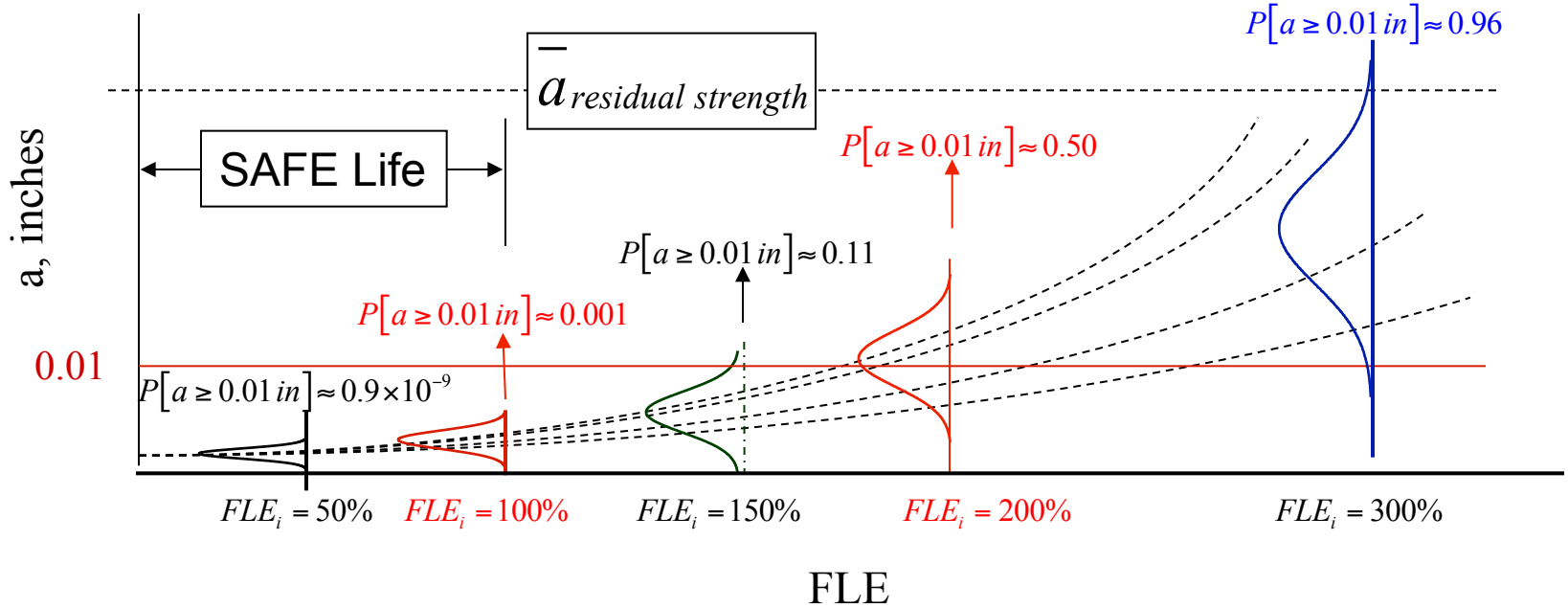
- *Probabilistic corrosion-Fatigue model development in piping*
- *Probabilistic pitting corrosion in pipes*
- *Probabilistic stress corrosion in piping*

Probability-Based Life Tracking

Interpreting FLE in terms of Probability of a > 0.01 inches

Note: 0.01 inches=0.25 mm << $a_{critical}$

$\bar{a}_{\text{Residual Strength}}$ is that crack size at which application of the design limit load (DLL) will cause unstable cracking



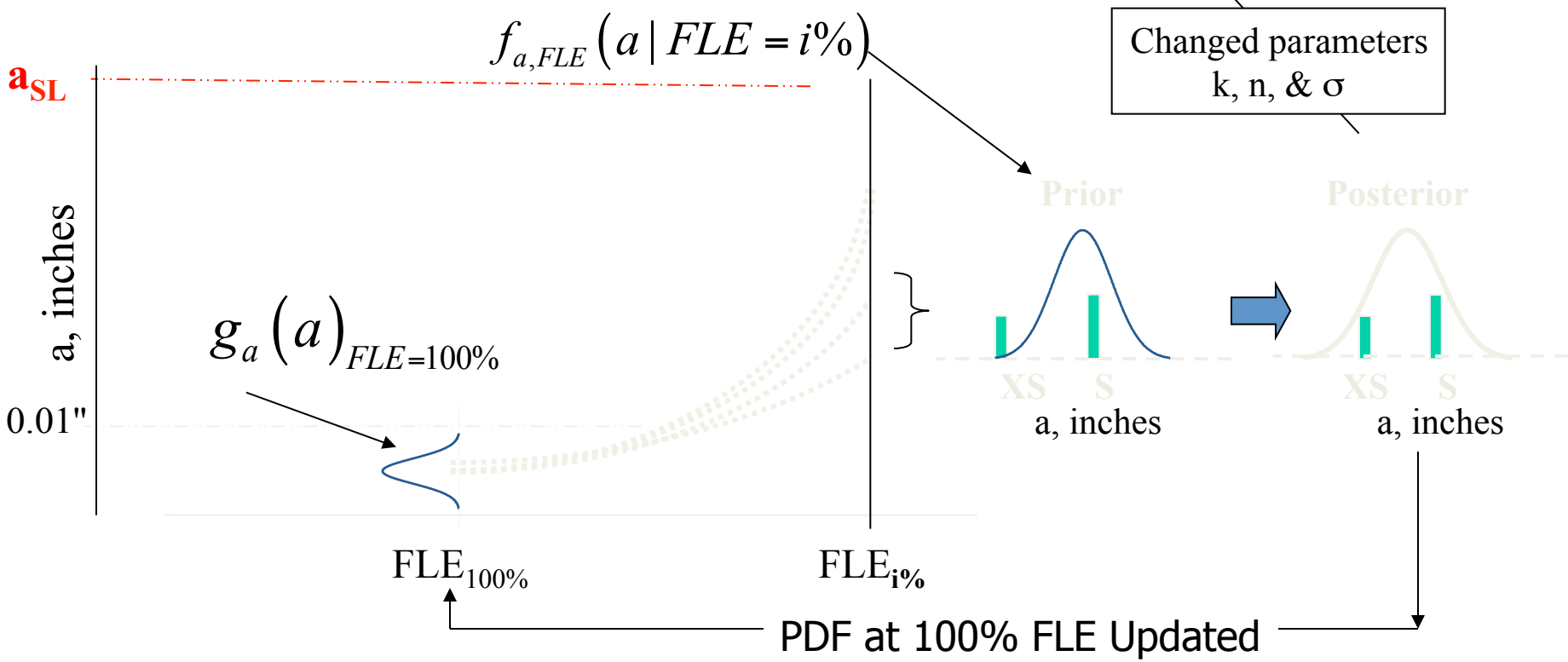
Challenge: Quantify the probability of exceeding residual strength

Probability-Based Life Tracking – Bayesian Approach

For an inspected aircraft at FLE=i%, generate random crack growth with know loads and random material crack growth properties. Fit a joint probability density function.

$$f_{a,FLE}(a, FLE) = \frac{1}{a \cdot \sigma \cdot \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\ln(a)+\ln(k)+n\cdot\ln\left(\frac{1}{FLE}\right)}{\sigma}\right)^2}$$

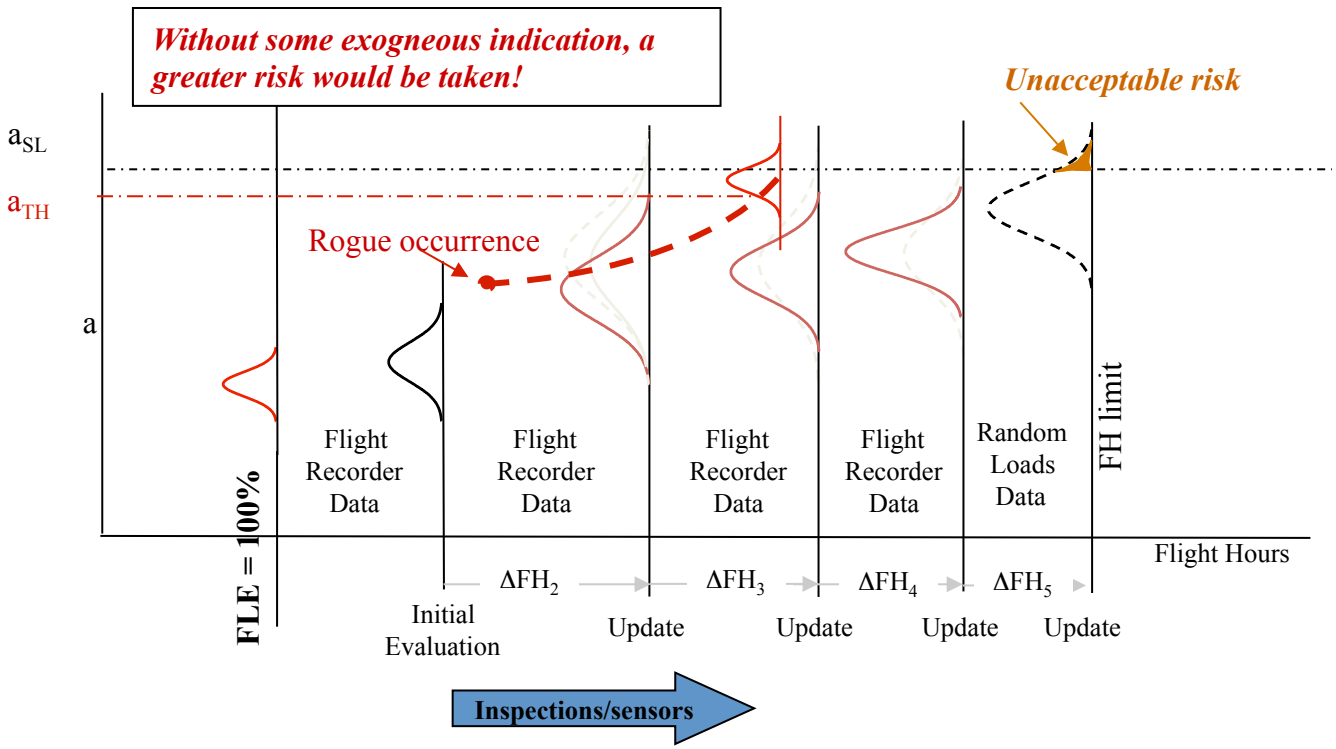
Changed parameters
k, n, & σ



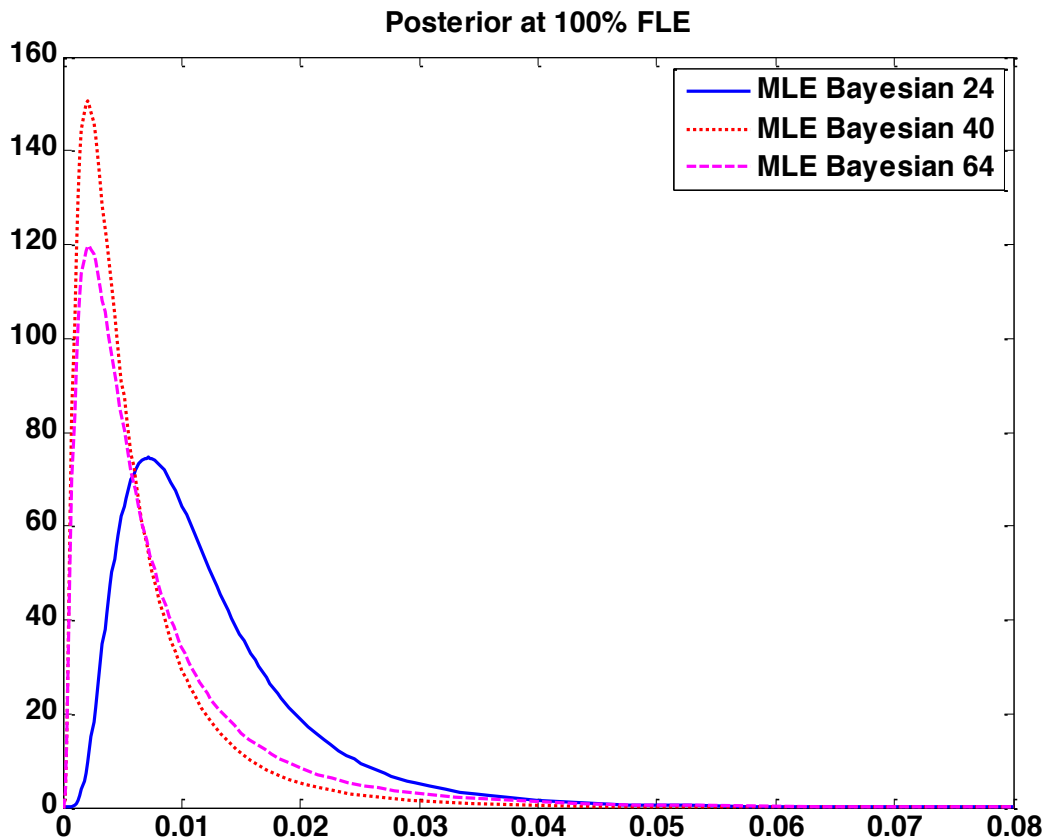
Probability-Based Life Tracking – Bayesian Approach

Model Application (Loads only model!)
The critical problem remaining is the rogue flaw probability

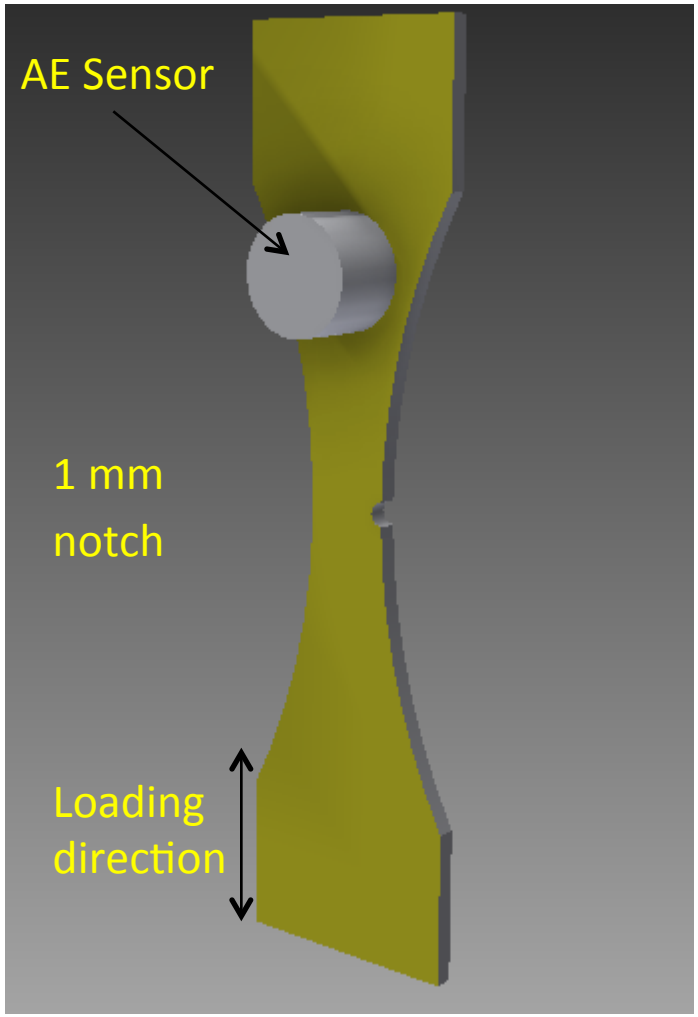
To mitigate the risk of the rogue flaw a sensor suite and/or an inspection schedule would provide the feedback. Ideally a sensor would detect some minimum threshold value with a virtual POD of 100%. Also the threshold must be less than the maximum risk taking crack a_{SL}.

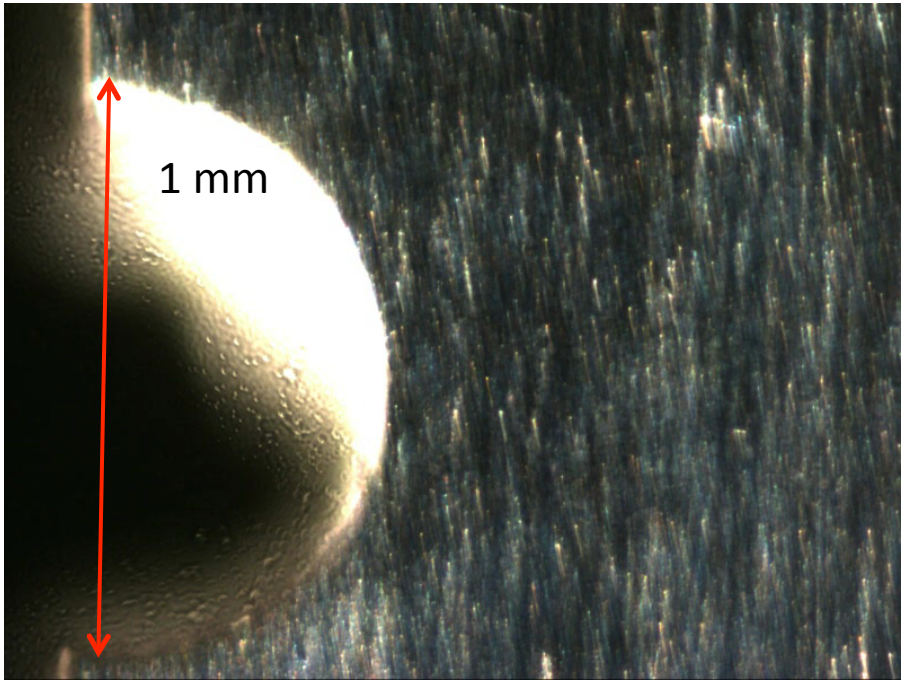


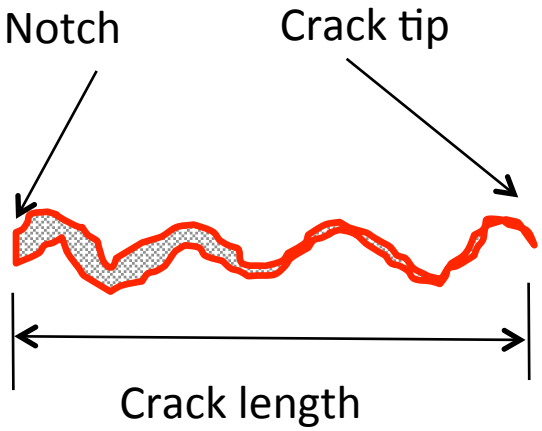
Bayesian Approach Results Based on Example Aircraft Data



Quantifying Crack Size via Information Entropy







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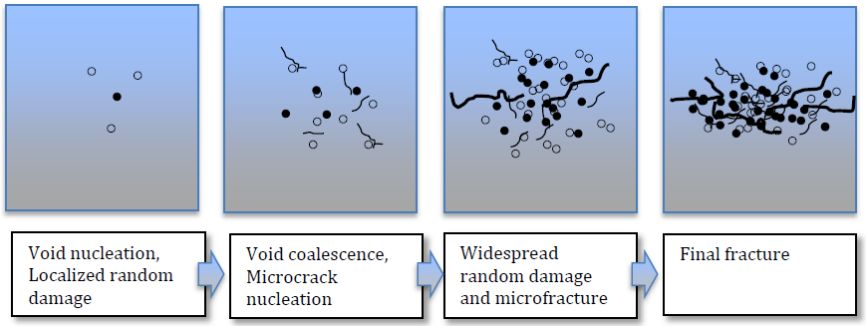
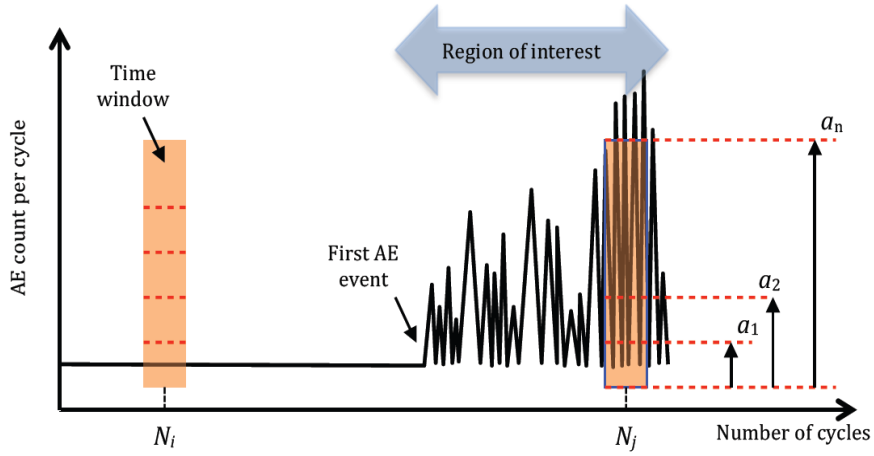
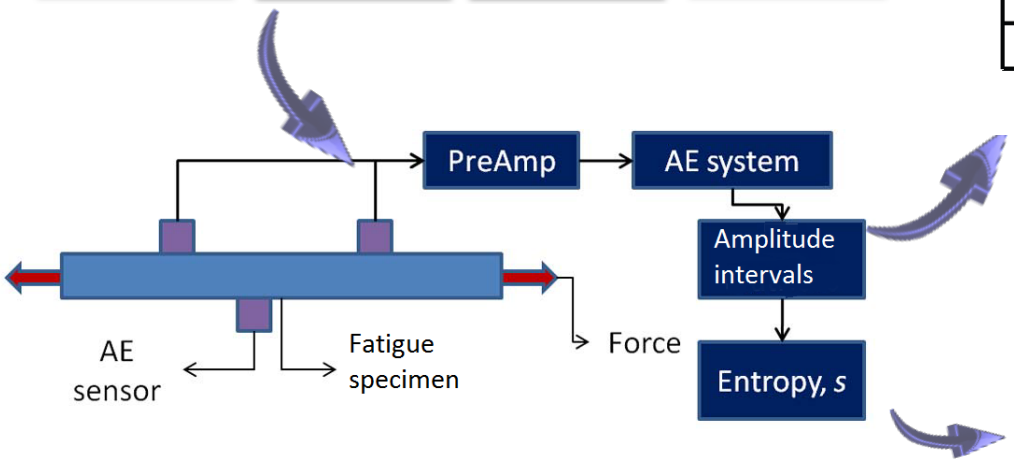






Divide signals into n amplitude intervals:

$a_i \quad i=1,2,\ldots,n$

Define x_i as:

x_i = detected acoustic signals at interval a_i

Probability of detecting signals with amplitude a_i:

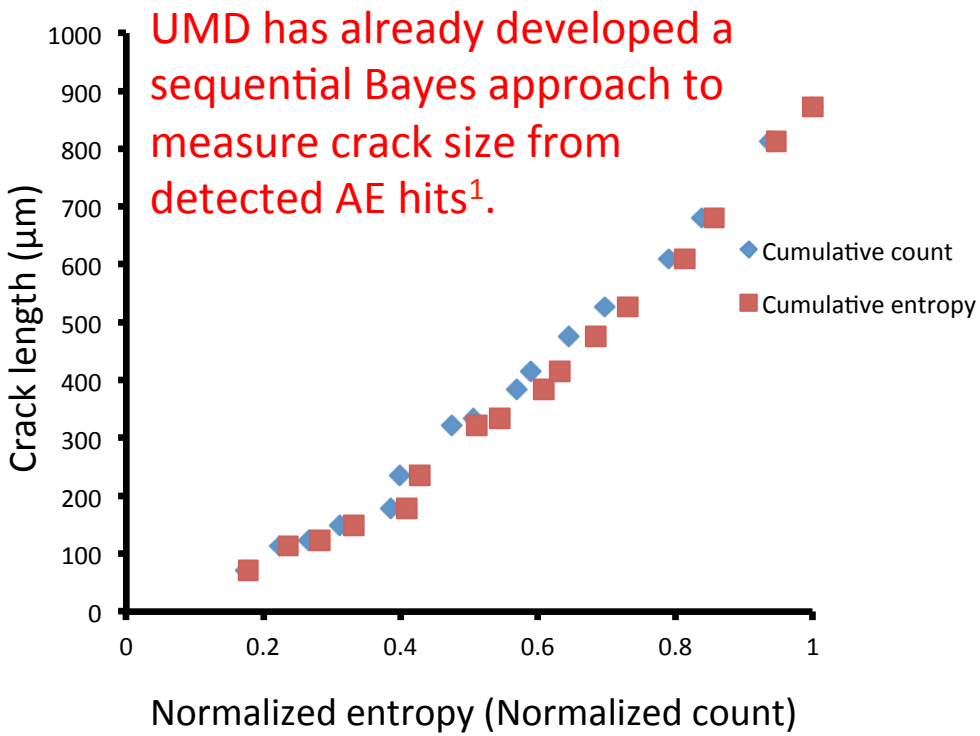
$$p_i = \frac{x_i}{\sum_1^n x_i}$$

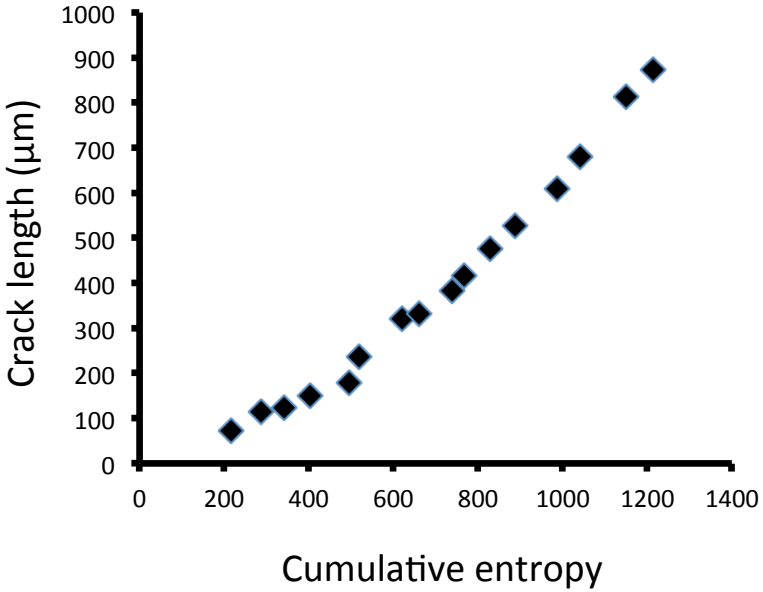
Entropy of the signal, S:

$$S = -\sum_1^n p_i \ln p_i$$

Qi, G., et al., Journal of Materials Science: Materials in Medicine, 23 (2012) 217-228.

Quantifying Crack Size via Information Entropy



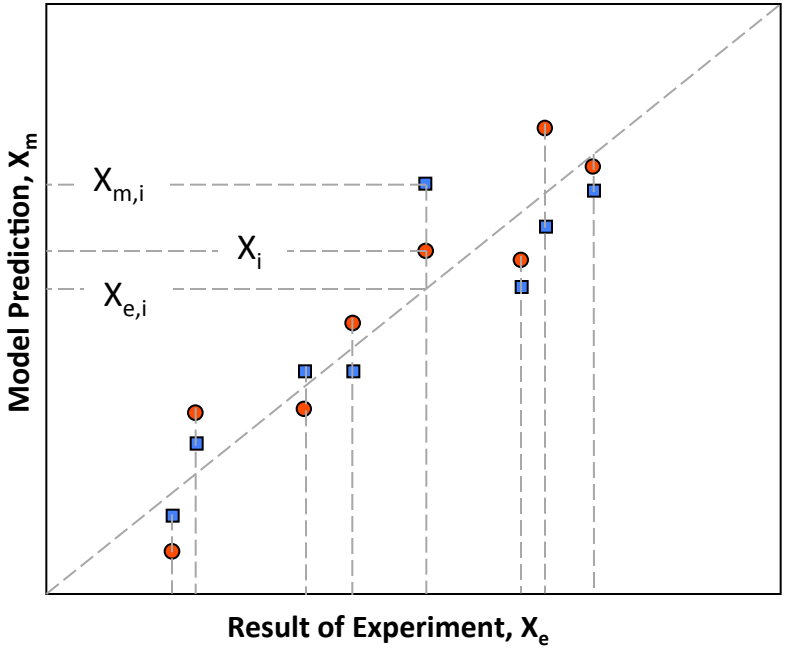


Research questions:

1) What is the advantage of a signal's entropy over the conventional AE hit method for structural health monitoring?
2) Is there a link between info. entropy and the thermo. entropy?

M. Rabiei, M. Modarres, Quantitative methods for structural health management using in situ acoustic emission monitoring", International Journal of Fatigue, Vol. 49, April 2013, pp 81-89.

Multiplicative Error Model



$$\frac{X_i}{X_{e,i}} = F_{e,i} \quad ; \quad F_e \sim LN(b_e, \sigma_e)$$

$$\frac{X_i}{X_{m,i}} = F_{m,i} \quad ; \quad F_m \sim LN(b_m, \sigma_m)$$

where :

X : Real Quantity

X_e : Result of experiment

X_m : Model prediction

F_e : The error factor for experimental data

F_m : The error factor for model predictions

b_e, σ_e : Mean and SD of experimental error factor

b_m, σ_m : Mean and SD of model error factor

$$\left.\begin{array}{l} F_{e,i} X_{e,i} = F_{m,i} X_{m,i} \\ \dfrac{X_{e,i}}{X_{m,i}} = \dfrac{F_{m,i}}{F_{e,i}} = F_{t,i} \\ \text{Independency of } F_m, F_e \end{array}\right\} \Rightarrow F_t \sim LN\left(b_m - b_e, \sqrt{\sigma_m^2 + \sigma_e^2}\right)$$

Multiplicative Error: Bayesian Posterior

$$f(b_m,\sigma_m \mid X_{e,i},X_{m,i},b_e,\sigma_e)=\frac{f_0(b_m,\sigma_m)\times L(X_{e,i},X_{m,i},b_e,\sigma_e \mid b_m,\sigma_m)}{\int_{\sigma_m}\int_{b_m} f_0(b_m,\sigma_m)\times L(X_{e,i},X_{m,i},b_e,\sigma_e \mid b_m,\sigma_m)db_m d\sigma_m} \qquad (3)$$

$where:$

$$L(X_{e,i},X_{m,i},b_e,\sigma_e \mid b_m,\sigma_m)=\prod_{i=1}^{n}\frac{1}{\sqrt{2\pi}\left(\frac{X_{e,i}}{X_{m,i}}\right)\sqrt{\sigma_m^2+\sigma_e^2}}e^{-\frac{1}{2}\times\frac{\left[\ln\left(\frac{X_{e,i}}{X_{m,i}}\right)-(b_m-b_e)\right]^2}{\sigma_m^2+\sigma_e^2}}$$

$f_0(b_m,\sigma_m)$: Prior Joint Distirbution of Parameters

$f(b_m,\sigma_m \mid X_{e,i},X_{m,i},b_e,\sigma_e)$: Posterior Joint Distirbution of Parameters

Given a model prediction such as X_m the distribution of X will be estimated as following:

$$\left.\begin{array}{l} X_m \text{ given as model prediction} \\ F_m \sim LN(b_m,\sigma_m) \\ X=F_m X_m \end{array}\right\} \Rightarrow X \sim LN\left(\ln(X_m)+b_m,\sigma_m\right)$$

Example – FIVE Radiant Heat Flux
Bayesian Approach

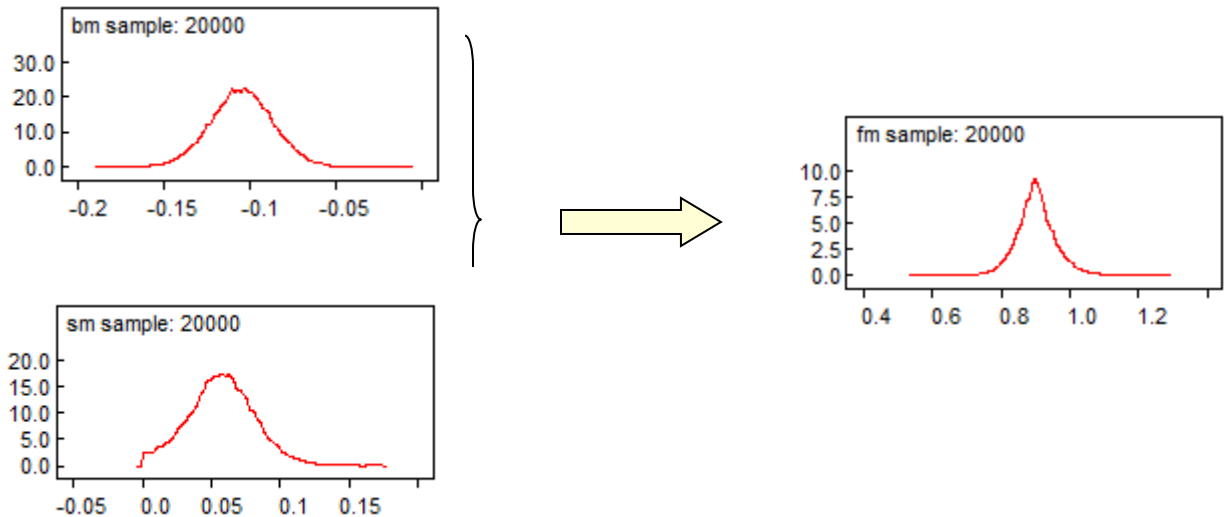
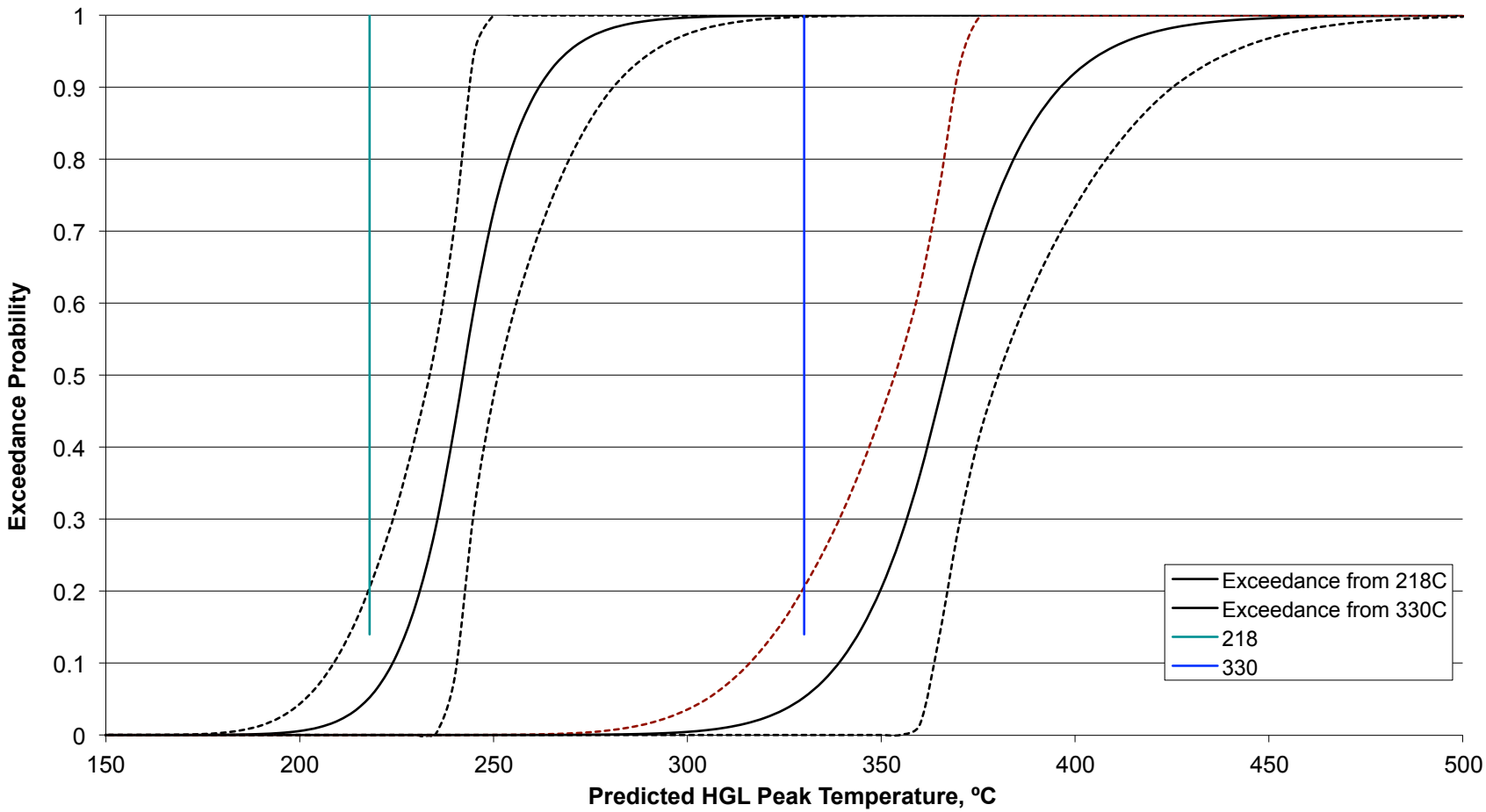


Table I. Summary Statistics of Parameters

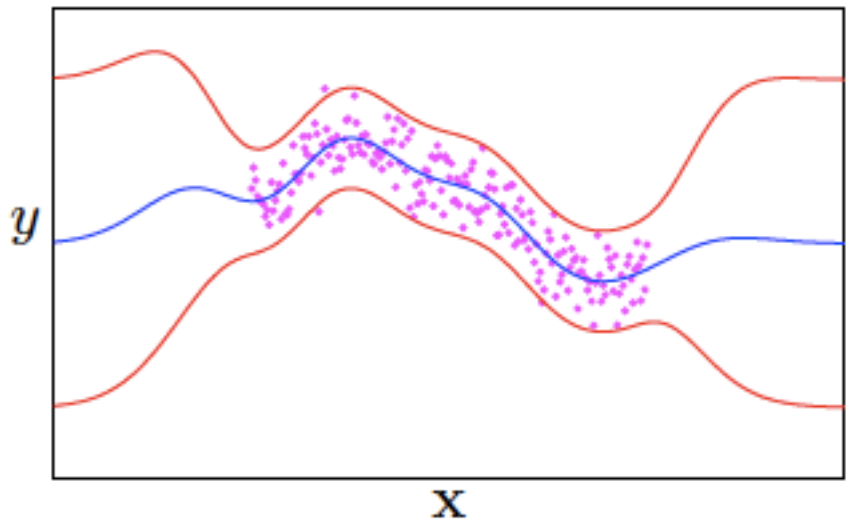
Parameter	Mean	STD	2.5%	97.5%
b_m	-0.1052	1.87E-02	-0.1422	-6.78E-02
s_m	5.72E-02	2.40E-02	8.62E-03	0.1049
F_m	0.902	5.90E-02	0.7885	1.03

Probability of Exceedance: HGL Temperature



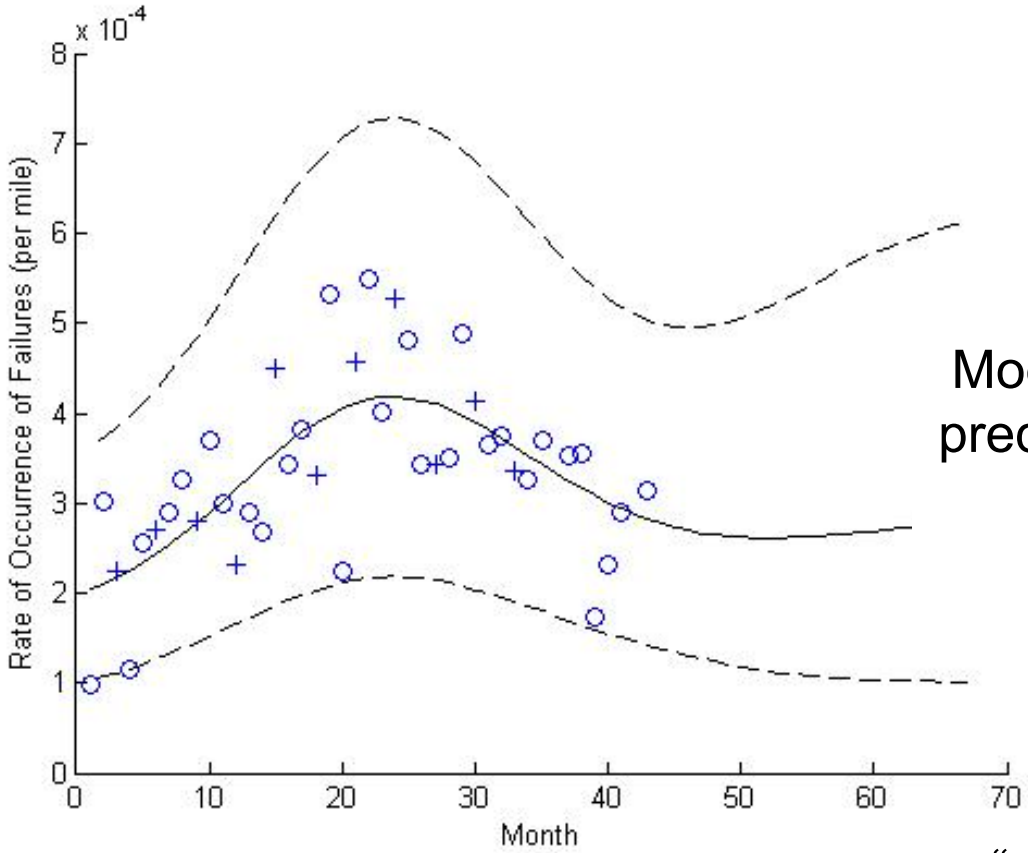
GP Regression

- It is a nonlinear regression when you need to learn a function f with uncertainties from data $D = \{X, y\}$



Ref: Eurandom 2010, Z. Ghahramani

Predicted Result

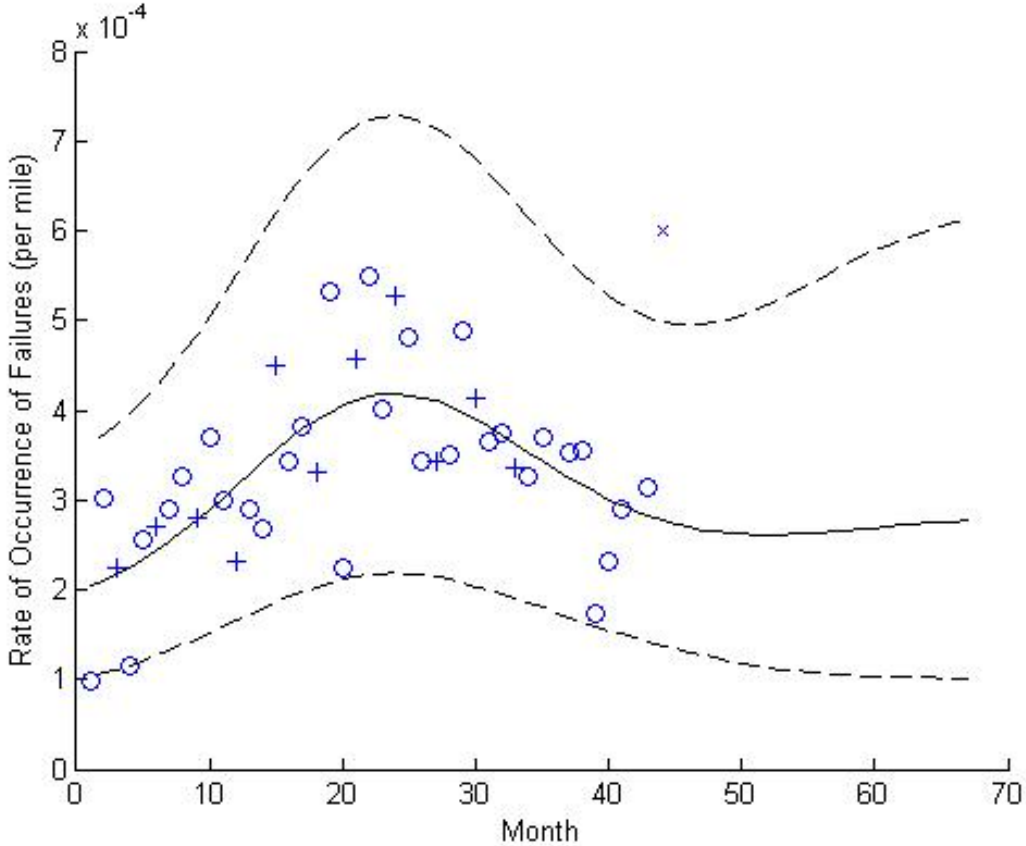


Model provides probabilistic prediction of failures in future months

"+" indicates test data used in goodness-of-fit test

**Dashed lines indicate 95% probability interval

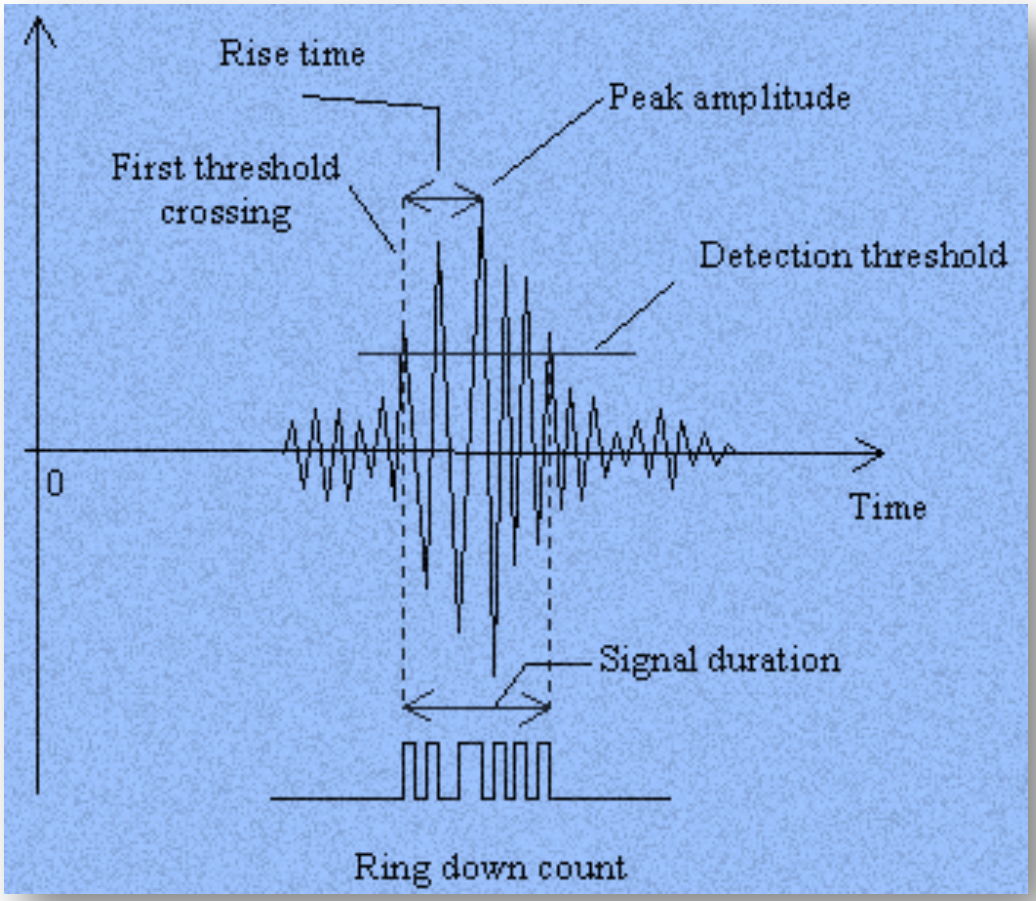
Anomaly Detection Example



**Dashed lines indicate 95% probability interval

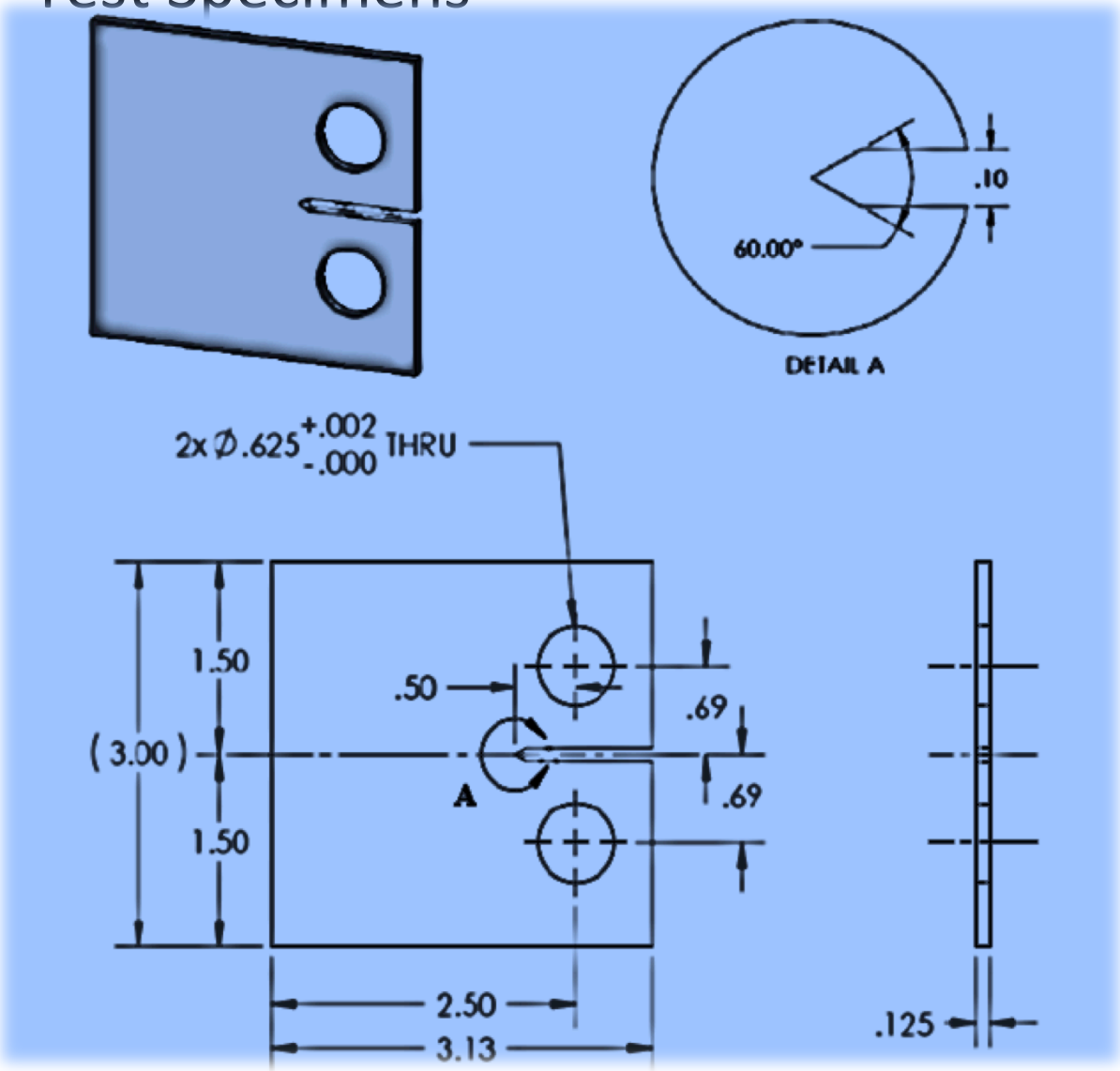
Characteristics of AE Signal

- Counts: the number of times that the AE signal amplitude exceeds a predefined subjective threshold value
- Peak Amplitude: related to the intensity of the source in the material producing AE signal
- Rise Time: the time it takes to reach the peak amplitude of an event



Test Specimens

- Specimen: Compact Tension (CT)
- Material: Al7075-T6 aluminium alloy
- Thickness: 3.175 mm (0.125 in.)



All dimensions are in **inches**.

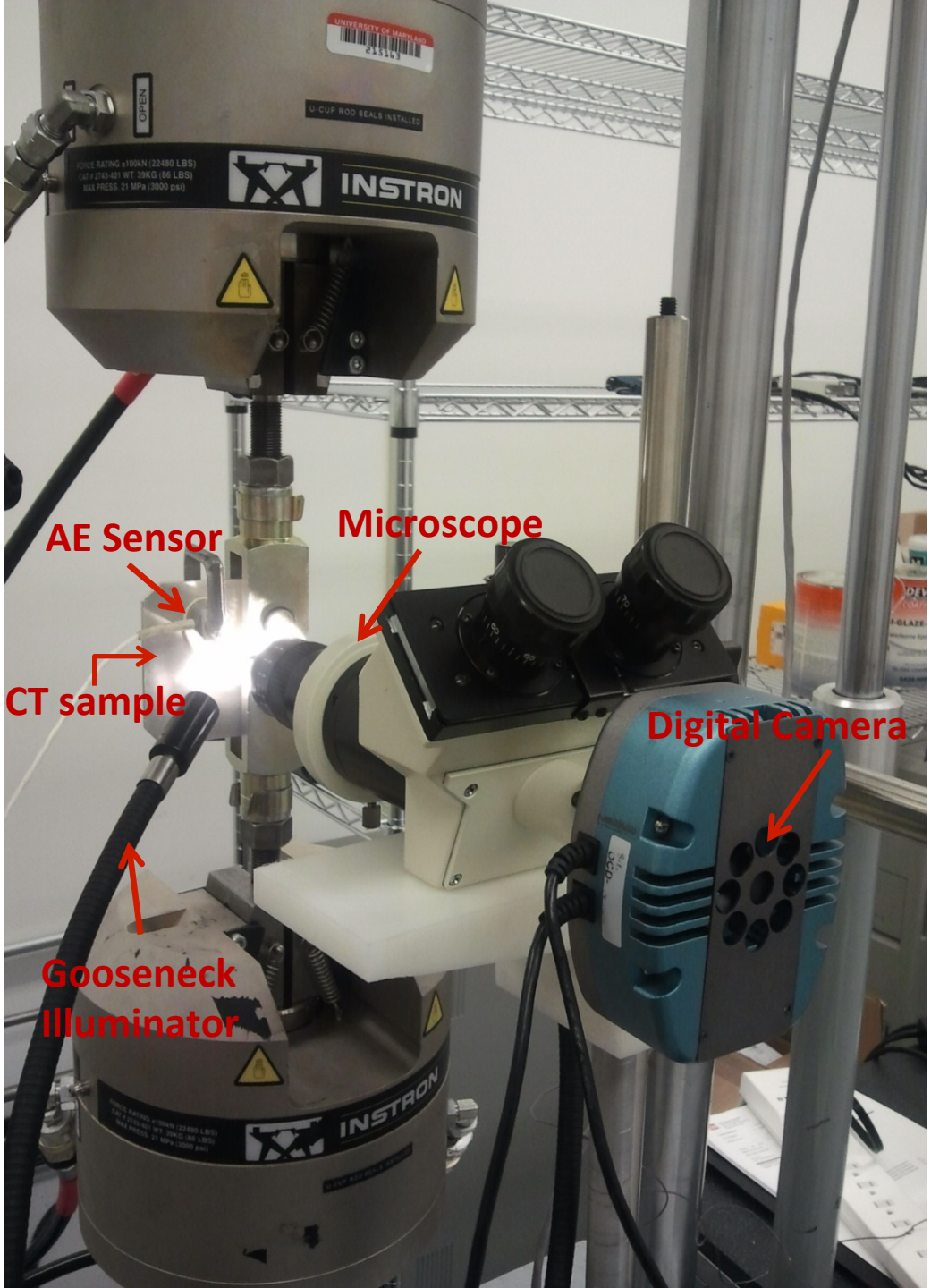
Experimental set up

- Optical microscopy was used as a crack size measurement tool in conjunction with AE sensor

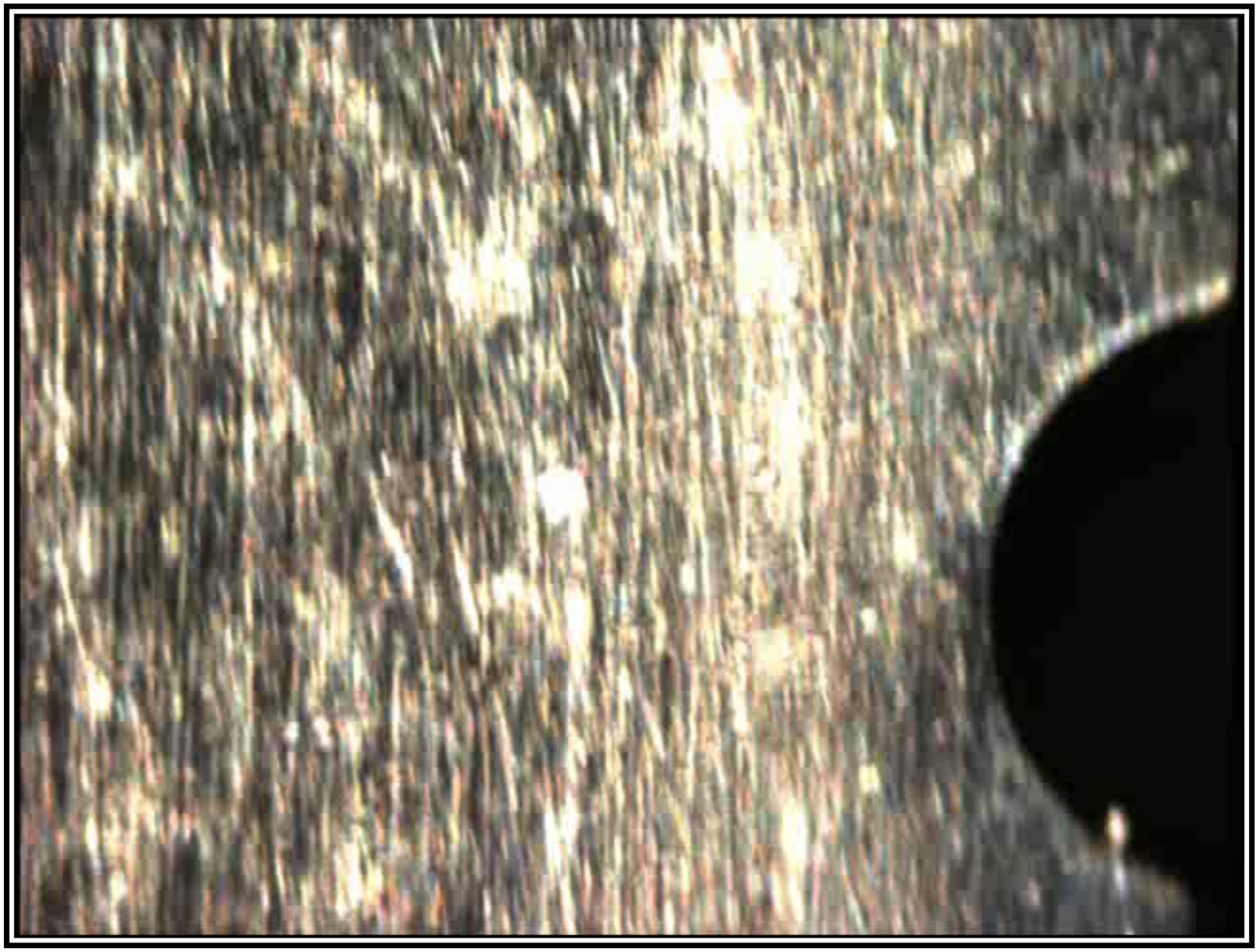
- Time-lapse photography was performed using a digital camera

- Three fatigue tests were performed under uniform cyclic loading :
  (CT1, CT2, CT3)

- minimum load ~ 4.5 kN
- maximum loads ~ 9 kN
- frequency ~ 20 Hz
- loading ratio ~ 0.5.

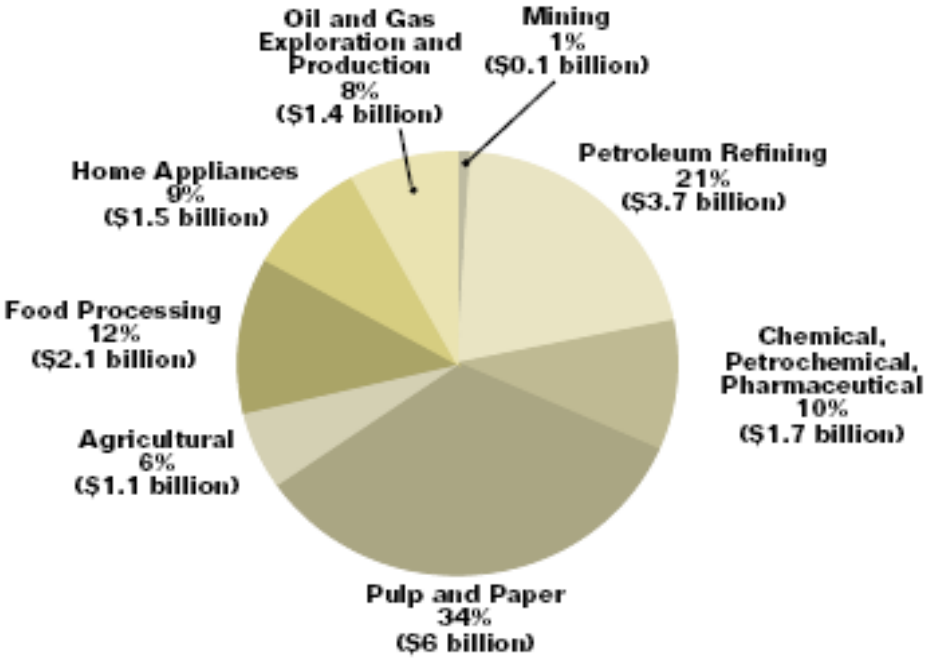


Play the movie



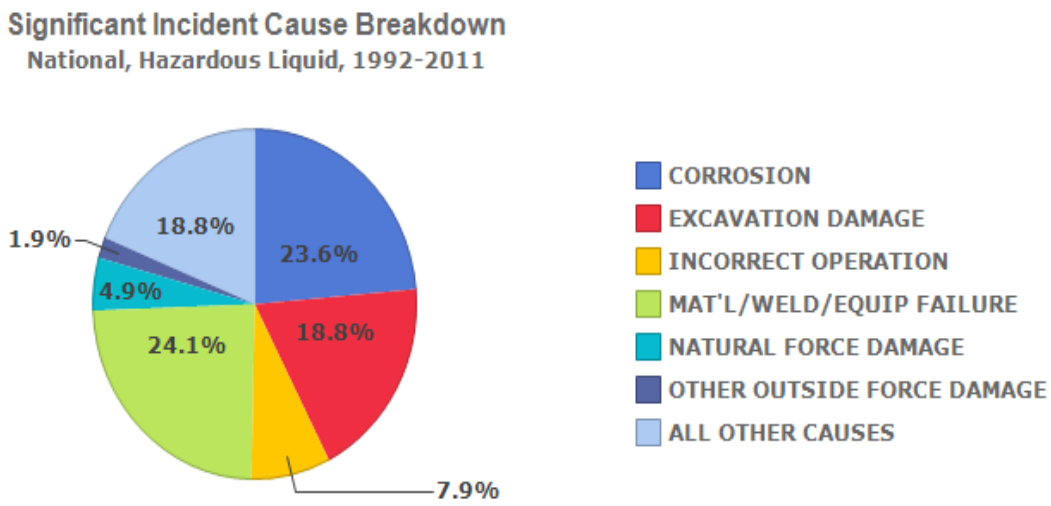
Oil Pipeline PHM

- 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 hars corrosive environments



Oil Pipeline PHM (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)



Source: PHMSA Significant Incidents Files, December 31, 2012

Approach

- Define Conditions:
  - Understand ADNOC needs and interests in the area of pipeline integrity management
  - Define test conditions that matches Abu Dhabi environment and ADNOC fields
- Perform Experiments and Data Generation:
  - Experiments (involving H_2S/CO_2) on representative carbon steel samples
  - Analysis of data and associated uncertainties
  - Develop Lab Facilities at the Petroleum Institute for future ADNOC befits
- Develop Models:
  - Mathematical Model Development
  - Model Validation

Step 1
- Defining the problem
- Defining the test conditions

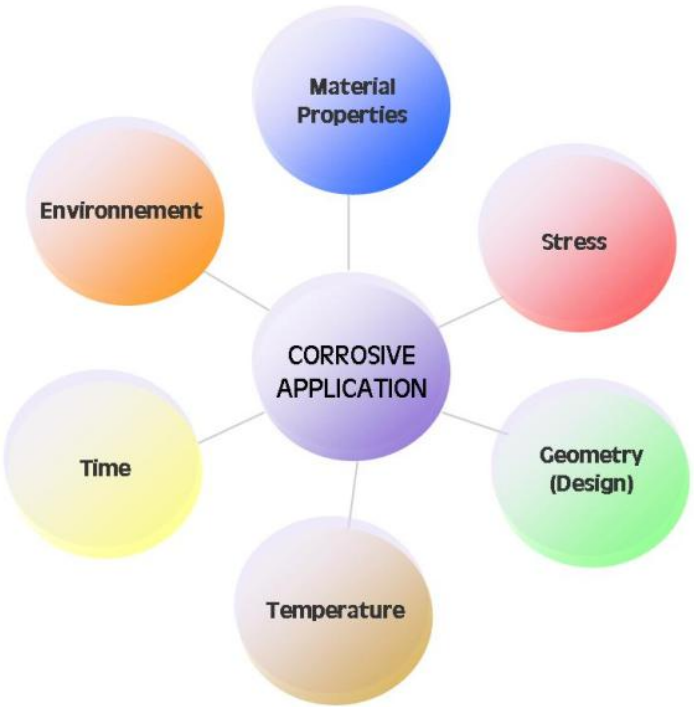
Step 2
- Conducting the experiments
- Data gathering

Step 3
- Model Development and Validation
- Drawing conclusions and recommendations

Steps 1 & 2 Part of Thrust II, Step 3 Part of Thrust 3.

Problem Definition: Step 1

- A discussions with ADCO engineers and management will lead to a better definition of the problem and the required testing conditions.
- Understand:
  - Pipelines H_2S/CO_2 conditions
  - Physical loads, residual stresses, external loads
  - Temperature, pH, stress concentrations, weld flaws

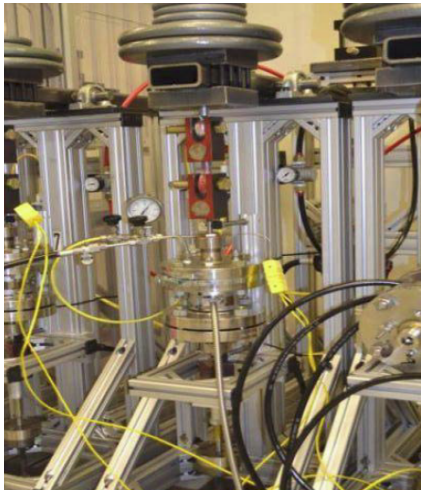


Experimental Work: Step 2

- Dog-Bone samples, API-5L grade B, will be subjected to various cyclic stresses under H_2S/H_2S simulated environments
- Indentations to simulate crack initiation
- study crack propagation and behavior of neighboring cracks on crack growth
- Fractography testing to understand crack growth and coalescence
- Experimental work will be done on 2 phases:
  - Phase 1: a dry test at UMD labs to define the material properties and fatigue characteristics
  - Phase 2: Corrosion testing at Honeywell lab to define the environmental factors effect on material failure

Testing Facilities

- Preliminary Testing:
  - Calibrating tests at UMD labs
- Fundamental Testing:
  - Honeywell Corrosion Lab, Houston, Texas, US
  - The capability allows all different types of testing:
    - Capability to handle 100% H2S and 100% CO2 , no ppm limit.
    - Capability to simulate pressures of up to 10000 psi and temperatures up to 1000 F
  - Leaders in building corrosion research labs
  - Honeywell link allows transfer of corrosion / cracking testing capability under (H_2S/Co_2)
- Petroleum Institute testing:
  - Restart and revive the CORETEST autoclave
  - CO_2 testing



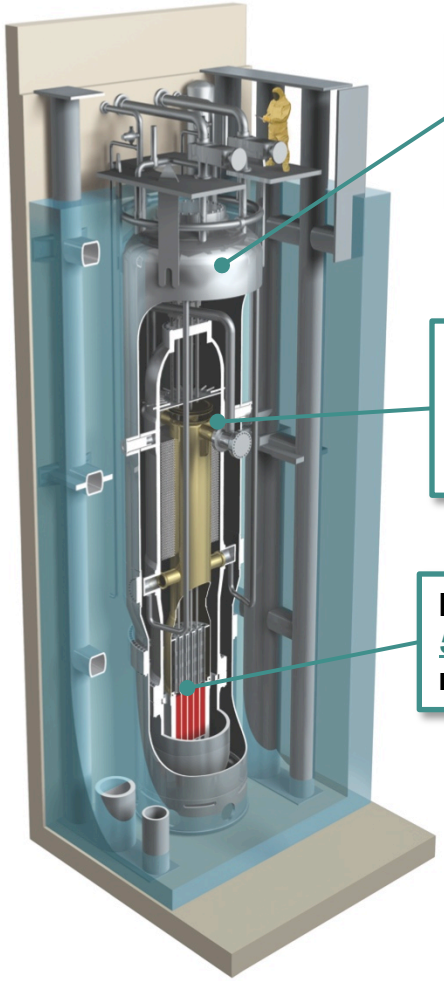
Honeywell

PI

Safety Features on NuScale

- **Natural Convection for Cooling**
  - Inherently safe natural circulation of water over the fuel driven by gravity
  - No pumps, no need for emergency generators
- **Seismically Robust**
  - System is submerged in a pool of water below ground in an earthquake resistant building
  - Reactor pool attenuates ground motion and dissipates energy
- **Simple and Small**
  - Reactor is 1/20th the size of large reactors
  - Integrated reactor design, no large-break loss-of-coolant accidents
- **Defense-in-Depth**
  - Multiple additional barriers to protect against the release of radiation to the environment

45 MWe Reactor Module



High-strength stainless steel containment *10 times stronger* than typical PWR

Water volume to thermal power ratio is *4 times larger resulting in better cooling*

Reactor core has *only 5% of the fuel* of a large reactor

Courtesy of NuScale Power

SMR PRA Modeling Considerations/ Complexities

- Integrated Design
  - Integrated Steam Generator / Health Management
  - Integrated Control Rod Drive Mechanism
  - Integrated RCP
  - New Containment-RCS Interactions
  - Integrated Pressurizer
- Passive systems
  - Operability / conditions of operation
  - Failure modes
  - Thermal/mechanical failure mechanisms (e.g., PTS)
  - Long-term component/structure degradation

SMR PRA Modeling Considerations/ Complexities (Cont.)

- Multi-Module Risk
  - Direct Dependencies
    - Common initiating events / shared SSCs
    - Shared instrumentation, control, fiber optics, other cables, electric divisions
    - Shared systems (e.g., FPS)
    - Capacity of shared equipment (e.g., batteries)

Need for Failure Data

- Lack of data on equipment failure
  - Smaller units, less stress
  - Submerged units
- Initiating event frequencies (are legacy data applicable? What about new initiators?)
  - Internal
  - Integrated components
  - External