Challenges for NDE Reliability Enhancement Using Model Assisted POD

Leonard J. BOND *, Joseph N. GRAY *, Timothy A. GRAY *,
William Q. MEEKER *, Pradeep RAMUHALLI **
* Iowa State University, Center for Nondestructive Evaluation, Ames, IA, USA
** Pacific Northwest National Laboratory, Richland, WA, USA

Abstract

Challenges being faced for in-service inspection (ISI) and monitoring to ensure the enduring safety of civil infrastructure, and at the same time reduce the costs of operation and maintenance. There are some concerns regarding effectiveness of current ISI for detection of early degradation, such as in relation to life extension. With a leak-before-break design philosophy degradation and cracking is highly unlikely to impact safety. However, if more proactive management of material degradation, is to be adopted new methodologies are needed. These challenges have been highlighted with nuclear power industry license extensions to permit operation from 40-60 years, and consideration of the feasibility of a second license extension from 60-80 years. There is a need to avoid surprises when ISI is performed at an outage and a response degradation of reduction in inspection intervals can be expensive. Attention is also being focused on small modular reactors (SMR) that are being considered for deployment with reduced ISI requirements and enhanced on-line monitoring. The situation is further complicated by the improvements in inspection technology that is detecting "indications" that have most probably been in structures since manufacture but are only now being seen. With new technology there is a merging between NDE and that which has been considered structural health monitoring (SHM). Advanced diagnostics, and prognostics, is being used for active components to enable condition based maintenance (CBM), and programs are reducing failures. Attention is now moving to seeking to quantify POD for monitoring early degradation of passive components, for example concrete, cables, pipes, and reactor pressure vessels. This paper will consider model assisted POD in the context of the requirements for NDE and on-line monitoring, diagnostics and prognostics, looking towards legacy nuclear power plants, next generation SMR, and potentially other structures which merge applications of on-line monitoring for both SHM and prognostics. There is a need to move performance metrics beyond methods for macro-defects, such as crack detection and sizing, to address early degradation and prognostics.

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L. J. Bond, J.N. Gray, T.A. Gray, W.Q. Meeker

Iowa State University, Center for NDE &

Pradeep Ramuhalli

Pacific Northwest National Laboratory

CENTER FOR NDE

Outline

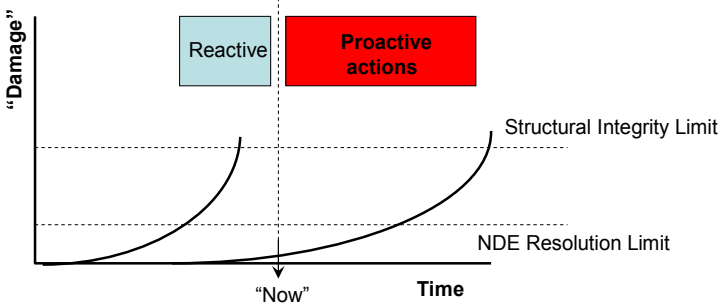
- Introduction and goal
- Damage development – moving beyond “find & fix”
- Grain and FBH – noise and POD
- Damage and degradation
- Measurements and models
- Early damage prognostics (non-linear methods)
- What is missing
- Conclusions
- Acknowledgements

Introduction and goal

- Consider model assisted POD in the context of the requirements for NDE and on-line monitoring, diagnostics and prognostics.
- Apply to legacy nuclear power plants, next generation SMR, and potentially other structures which merge applications of on-line monitoring for both SHM and prognostics.
- Need to move performance metrics beyond methods for macro-defects, such as crack detection and sizing, to address early degradation and prognostics.

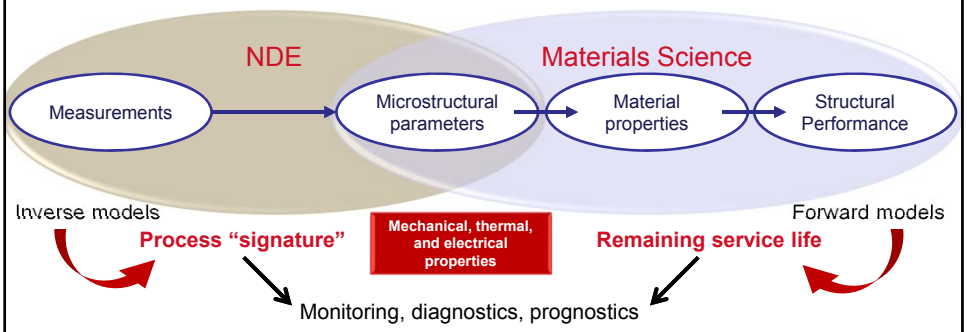
Damage Development with Time: Differentiation Between Reactive and Proactive Actions

Goal is to <u>proactively address potential future degradation</u> in operating plants to avoid failures and to maintain integrity, operability and safety



Move beyond philosophy of "Find and Fix": Finding damage at an outage is expensive – longer outages – more inspection

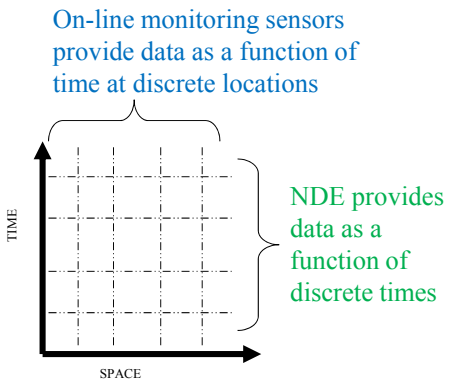
NDE and Materials Science*



*after Ensminger, Bond (2011)

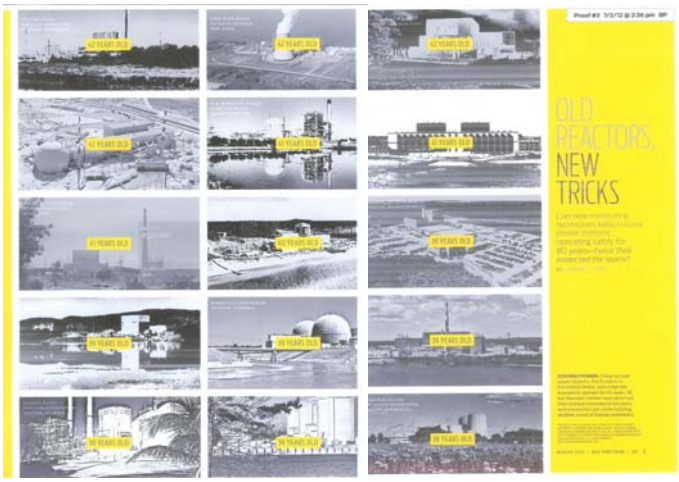
NDE and On-line Monitoring: – Passive Components

- Degradation for infrastructure: mechanisms being identified
- NDE – SHM requirement differences being studied
- Measurements and monitoring gap analysis/needs assessment under development



Fundamental differences in data structure between Nondestructive Evaluation (NDE) and Structural Health Monitoring (SHM))
(After Thompson [2009])

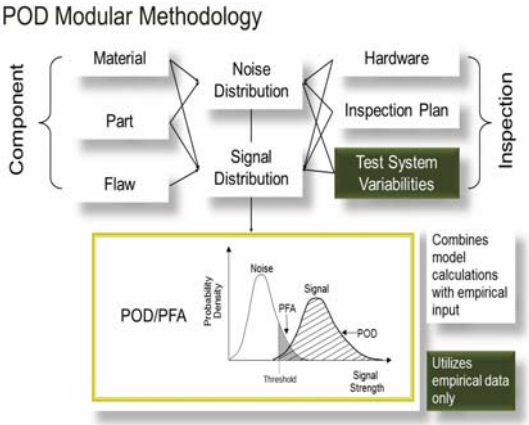
Can smart systems & condition monitoring help keep US nuclear power operating to 80 years?



IEEE Spectrum – August 2012

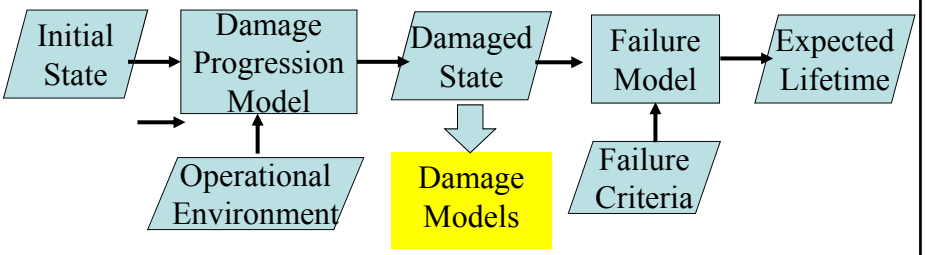
Model-assisted Probability of Detection

Combines knowledge of inspection physics with reliability statistics to arrive at POD results in more timely and cost effective manner compared to traditional empirical approaches



A Utopian View (+)

In principle, we **simply** need to execute the following strategy



This would be a "done deal" if the input data were correct/complete and models were of sufficient accuracy and computationally efficient.

Barriers to Reaching Nirvana*

- **Missing information**
  - Do not currently determine the initial state of individual components/structures/systems with high precision
  - Have not traditionally monitored the operating environment of individual components
  - Damage progression models have traditionally been empirical (e.g., Paris Law)
    - Difficult to incorporate the missing information if it were available
- **Uncertainty**
  - There will always be uncertainty in the input data
- **Variability**
  - Even if we eliminate uncertainty, we would have to take variability into account

*Thompson (2008/9)

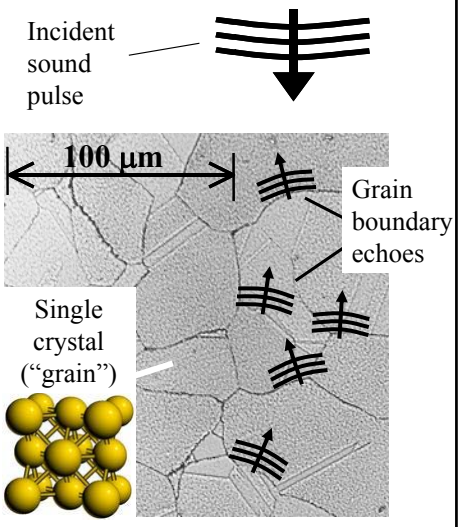
Areas with Research Underway and Gaps

- Operational environment
  - Temperature, strain and chemical sensors under development
- State sensing data
  - Global
    - Structures: strain, displacement, acceleration
    - Propulsion: vibration analysis
  - Local
    - Guided waves to sense structural changes
    - Moisture
    - Ultrasonic, eddy current, … to sense microstructure
- Damage models
  - Under refinement in many programs

(After Thompson)

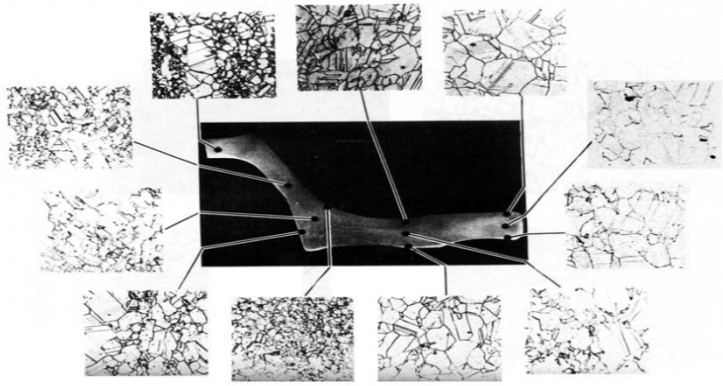
Need for Microstructural Characterization Tools as Well as Flaw Detection Tools

- Need to be able to assess the progression of damage *before* cracks form
  - **Quantification of initial state**
  - **Check of evolution of damage when possible**
- Validation of prognostic calls



Thompson - AFOSR Prognosis Workshop_February 2008

Waspalloy Disk

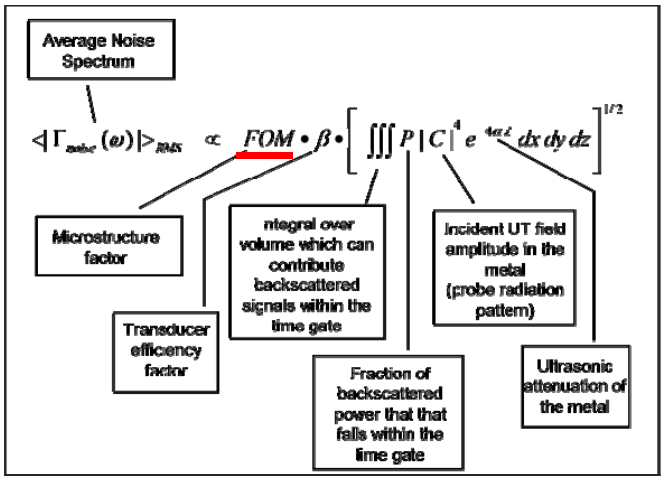


"The scatter in material behavior is attributed to the inhomogeneous microstructure elements with metals."

L. Nasser and R. Tryon, "Prognostic System for Microstuctural-Based Reliability", DARPA Prognostics web site (with reference to work at Cowles, P&W)

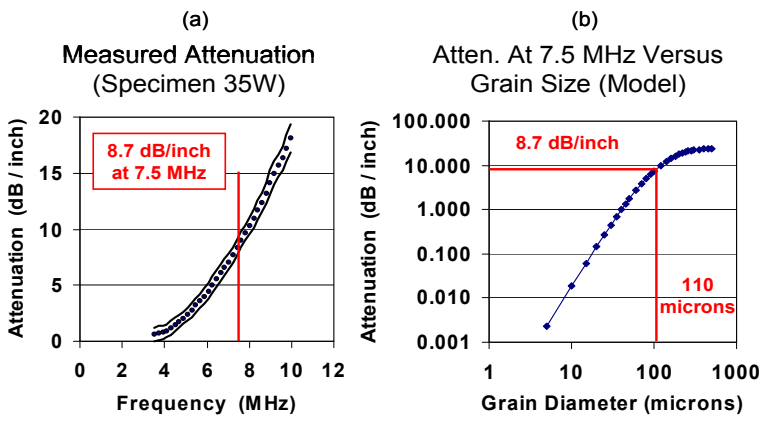
AFOSR Prognosis Workshop_February 2008

Material Grain/Noise Spectrum*



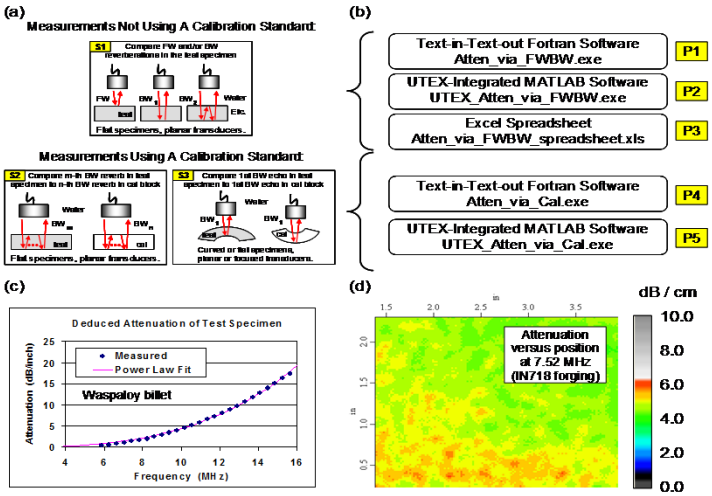
*Margetan (2013)

Measured attenuation-vs-frequency for a hand-forged specimen of the Nickel alloy IN718. (b) Predicted dependence of attenuation (at 7.5 MHz) on grain size, and estimated grain size (110 microns).



Margetan (2013)

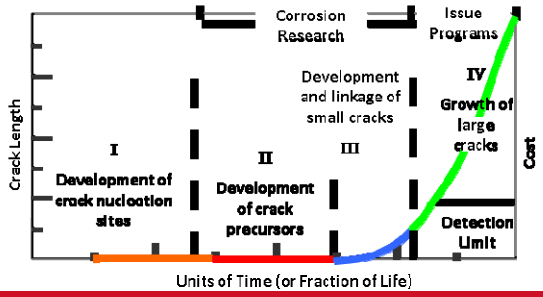
Data collection and analysis options – CNDE short course.



Degradation and aging

- Ultimate lifetime of NPPs limited by material degradation issues
- Present approach to passive component aging management is reactive "find-and-fix", thus ensuring component failure given sufficient operating time

- **Detection of degradation at early stages to enable better aging management of passive components**



New Ingredients

"In many ways, materials damage prognosis is analogous to other damage tolerance approaches, *with the addition of in-situ local damage and global state awareness capability and much improved damage predictive models*"

L. Christodoulou and J. M. Larsen, "Materials Damage Prognosis: A Revolution in Asset Management," Materials Damage Prognosis, J. M. Larsen, L. Christodoulou, J. R. Calcaterra, M. L. Dent, M. M. Derriso, J. W. Jones, ad S. M. Russ, Eds. (TMS, 2005).

Degradation Mechanisms - Classification

- Aging degradation mechanisms are classified into:
  - **Internal**:
    - changes to microstructure or chemical composition
    - change intrinsic properties (thermal aging, creep, irradiation damage, etc.).
  - **Imposed**:
    - physical damage on the component
      - metal loss (corrosion, wear) or cracking or deformation (stress-corrosion, deformation, cracking).
- **Phenomenon of aging degradation are complex**:
  - requires sophisticated, state of science and technology procedures to effectively manage it and ensure safe, reliable operation
  - not only technology is involved,
  - an effective management system is needed in order to correctly implement mitigation or monitoring actions.

IAEA Proceedings Series (2005)

Materials Characterization vs. NDE

- Traditional nondestructive evaluation (NDE)
  - Size and locate flaws
- Materials characterization
  - Characterize microstructure (stress, strain, grain size, moduli, fatigue, fracture toughness)
  - Evaluate/determine material properties PRIOR to and after the formation of flaw.
- Why is materials characterization important to infrastructure reliability and safety?
  - In some cases the first crack can catastrophic, due to zero tearing modulus.
  - To guide focused nondestructive testing to regions with high propensity to fail.
  - For early warning of structural integrity PRIOR to flaw formation.
  - For accurate lifetime prediction

PMMD Program and Information Tool Website was funded by NRC at PNNL

NUREG/CR-6923

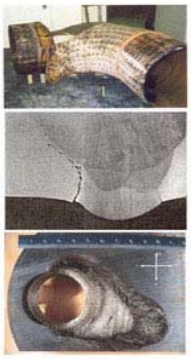
PMMD Proactive Management of Materials Degradation

PMMD Program
- Rationale
- Thrusts
- PMMD Project
- International Forum
- Technical Issues
- Technical Reports
- Technical Meetings
- Contact Us
- Links
- Home

PMMD Information Tool
- Users Guide (1.4Mb)
- Users Guide (Power Point 4Mb)
- NUREG/CR-6923
- Flag View
- Rainbow View
- Parts List View
- Expert View

Welcome to the U.S. Nuclear Regulatory Commission Program on Proactive Management of Materials Degradation (PMMD) for LWRs. The NRC has initiated a new program to promote the understanding and use of PMMD methods and technology in extending the life of LWRs. The program will build national and international collaboration on regulatory research issues. The goal of PMMD activities over the next five years is to place NRC in a position where it has the technical basis to answer some key aging-related degradation questions, including:

- Can licensees safely extend the operating life of existing NPPs to 60-80 years and potentially longer?
- What are the key technical and regulatory issues that require attention to enable license extension?
- What information is needed to position NRC to adequately process and respond to applications for a second (and subsequent) license extension?
- What are the remaining open technical and regulatory issues?



Site at: http://pmmd.pnl.gov

Last Updated: March, 2009
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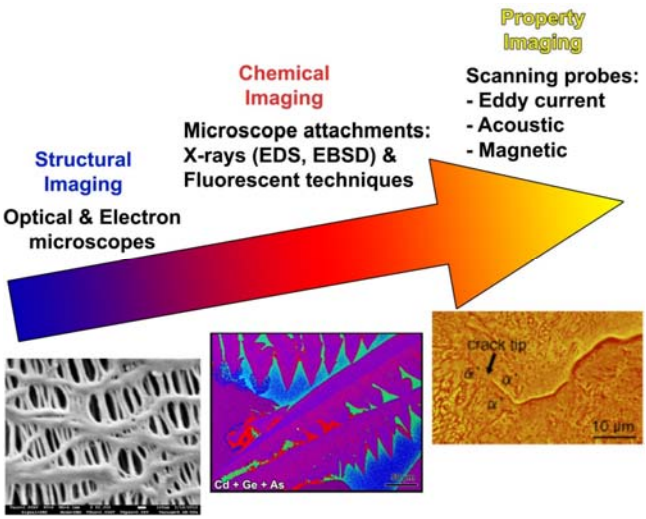
2

Structure: damage scale and measurements*



* PNNL Report 22309 (2013)

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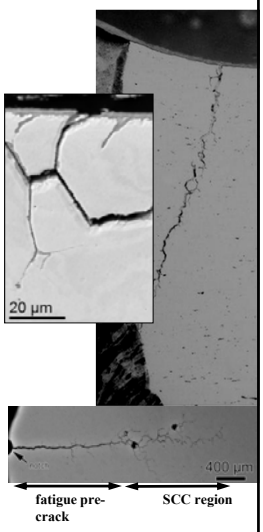
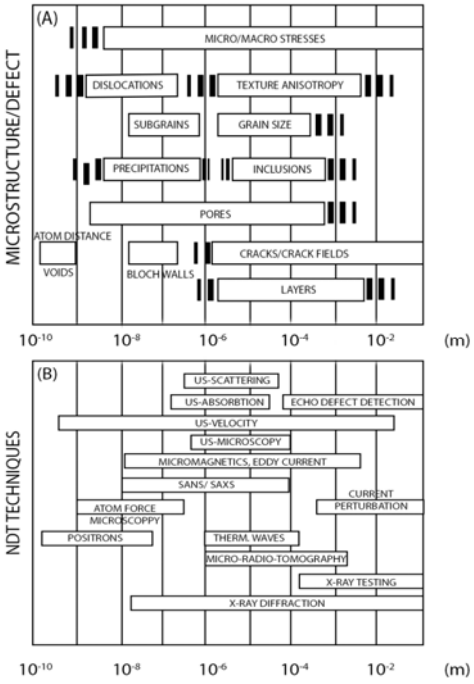
Precursors

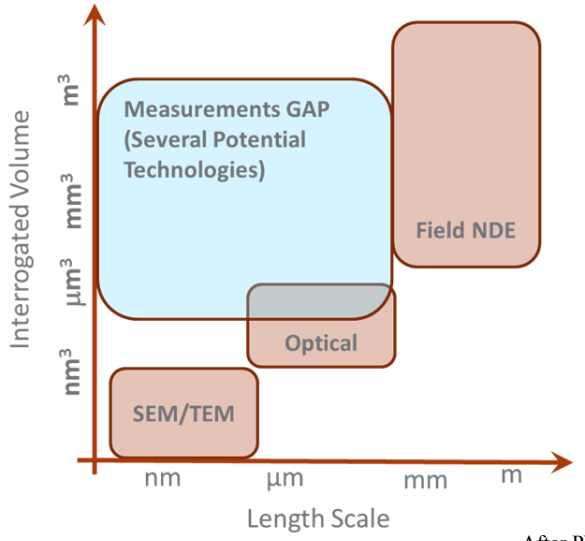
- NDE for materials degradation precursors
  - Nature of precursors depend on material type and degradation mechanism
    - Mechanisms of interest in passive metallic components include fatigue (thermal and mechanical), SCC and embrittlement
  - Local variations in residual stress, grain morphology and material chemistry
    - Local variations in elastic properties, electrical conductivity and magnetic permeability



Microstructural defect length scales and applicable NDE techniques, after (Raj et al. 2003)



Measurement & Modeling gap



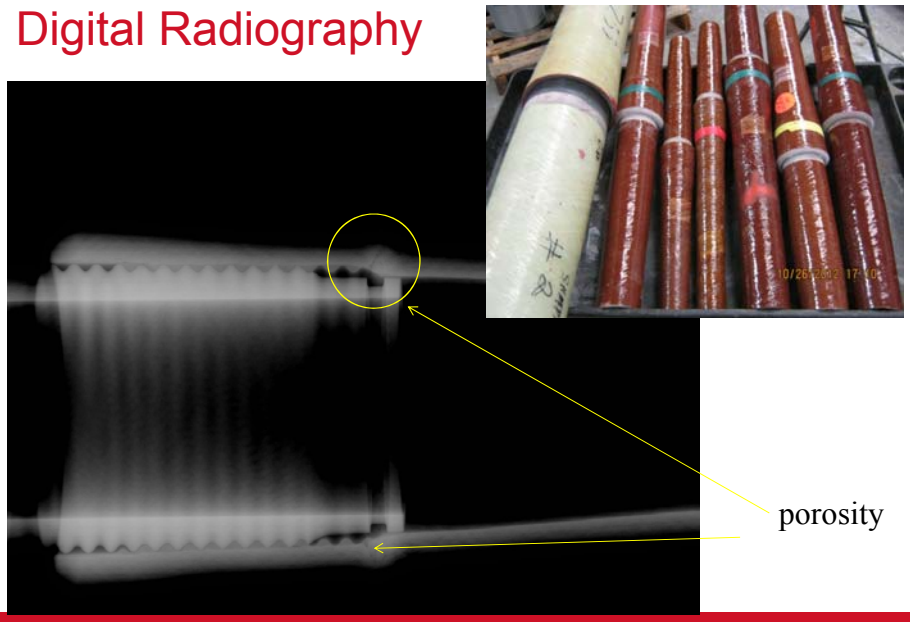
After PNNL Report 22309

Potential degradation characterization metrics

Damage		Brittle	Ductile	Creep	Low cycle fatigue	High cycle fatigue
Micrography	$D=\frac{\partial S_D}{\partial S}$	*	**	**	*	*
Density	$D=\left(1-\frac{\bar{\rho}}{\rho}\right)^{2/3}$		**	*	*	
Elasticity Modulus	$D=1-\frac{\bar{E}}{E}$	**	***	***	***	
Ultrasonic Waves	$D=1-\frac{\bar{V}_L^2}{V_L^2}$	***	**	**	*	*
Cyclic Stress Amplitude	$D=1-\frac{\Delta\sigma}{\Delta\sigma^*}$		*	*	**	*
Tertiary Creep	$D=1-\left(\frac{\bar{\varepsilon}_p^*}{\bar{\varepsilon}_p}\right)^{1/N}$		*	***	*	
Micro-hardness	$D=1-\frac{H}{H^*}$	**	***	**	***	*
Electrical Resistance	$D=1-\frac{V}{\bar{V}}$	*	**	**	*	*

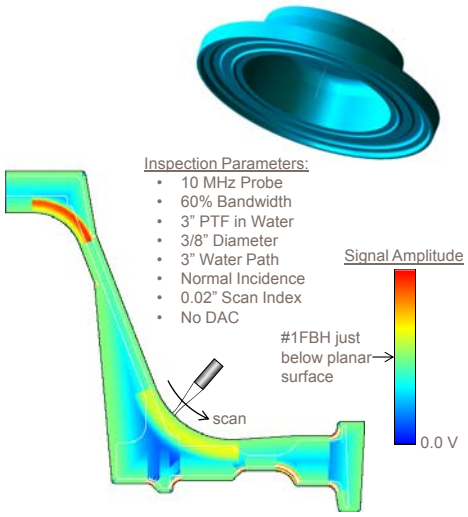
Lemaitre & Lippmann (1996)

Digital Radiography



Model Capabilities – Small Flaw (working codes)

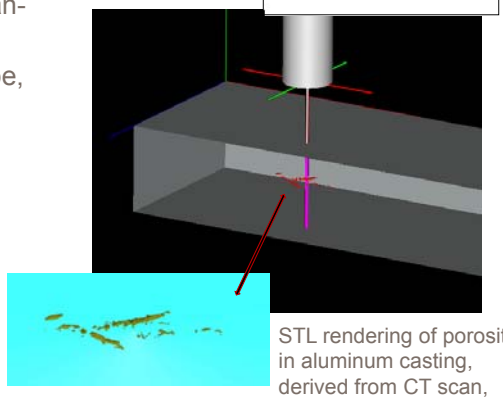
- Thompson-Gray measurement model
- Paraxial beam model (Gaussian-Hermite & multiGaussian)
- Immersion/contact/wedge probe, planar or focused
- Bicylindrical entry surface
- Small internal flaw (<1/3 beam diameter)
  - Kirchhoff approx. for elliptical crack or ellipsoidal void/inclusion
  - Ying & Truell, spherical void/inclusion, L-wave
  - Gubernatis-Domany-Krumhansl, spherical void, S-wave
  - MOOT look-up table, circular crack



Model Capabilities – Large Flaw (working codes)

- Thompson-Gray measurement model
- Paraxial beam model (Gaussian-Hermite & multiGaussian)
- Immersion/contact/wedge probe, planar or focused
- Bicylindrical entry surface
- Large internal flaw
  - Faceted surface
  - STL file format
  - Kirchhoff approximation
  - Independent scattering
  - Side drilled hole (special version)

C-scan image computed using LFM code



STL rendering of porosity in aluminum casting, derived from CT scan, courtesy Joe Gray

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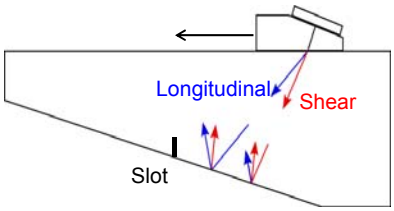
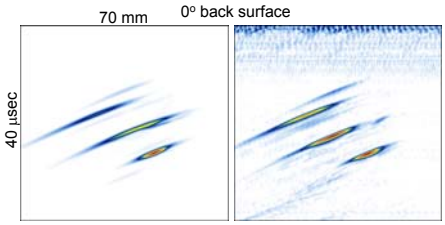
Model Capabilities – Surface Crack (working codes)

- Thompson-Gray measurement model
- Paraxial beam model (Gaussian-Hermite)
- Immersion/contact/wedge probe, planar or focused
- Bicylindrical surface
- Surface-breaking crack
  - Faceted surface
  - Kirchhoff approximation
  - Independent scattering



Sample B-Scan Results
45° L-wave
0° back surface



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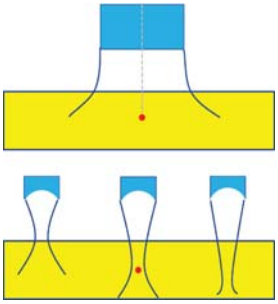
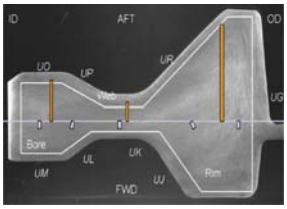
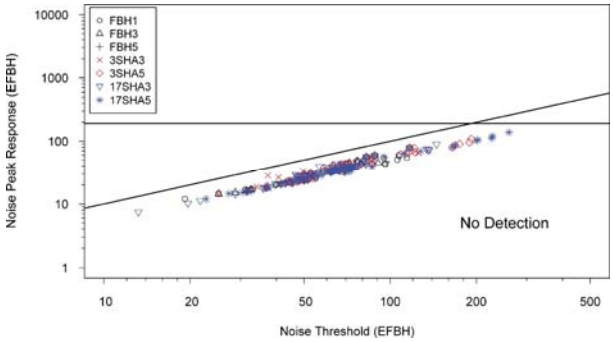
Example modeling FBH – noise limits

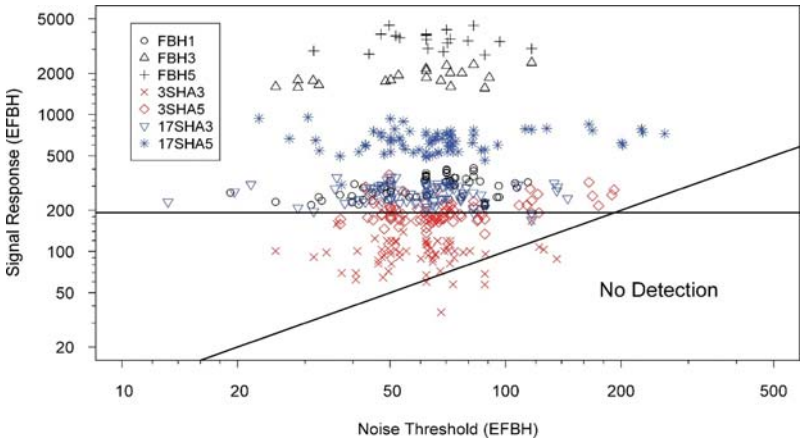




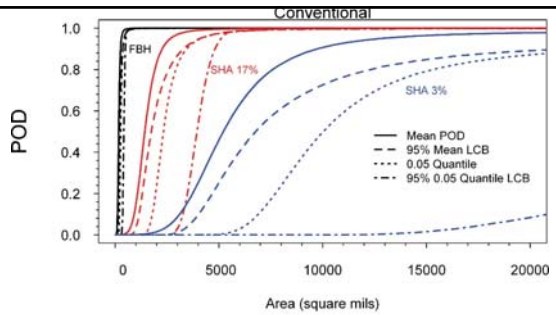


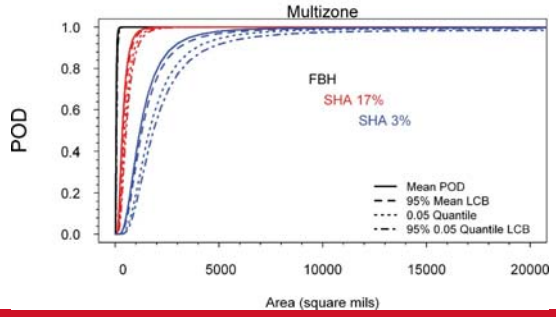
Li et al (2013 in press)

FBH response and noise thresholds



Conventional vs Multi-zone for POD



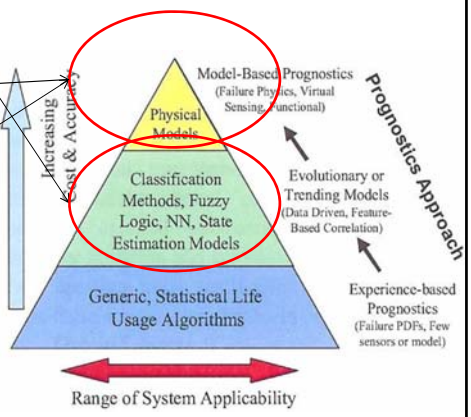


Prognostics

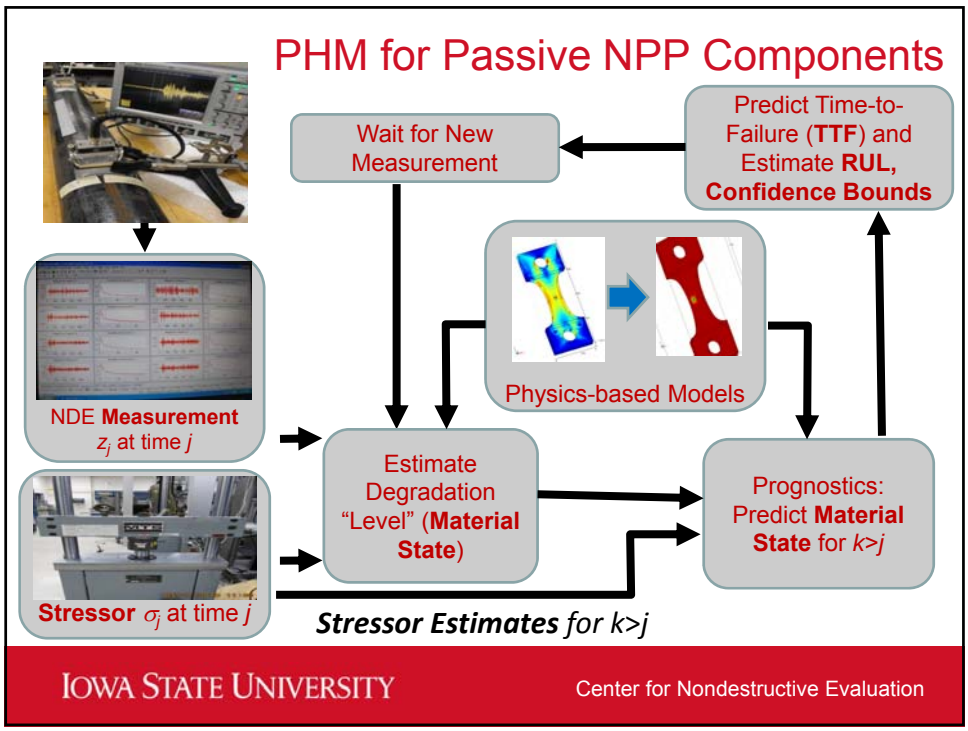
Recurrent Neural Networks

Bayesian Methods

Probabilistic Fracture Mechanics



- Prognostics Algorithms
  - Bayesian algorithms
    - Model-based probabilistic algorithms, capable of providing confidence levels
  - Recurrent Neural Networks (RNN)
    - Generally deterministic – difficult extract confidence levels
  - Probabilistic fracture mechanics
    - Typically focus on large-crack growth


PHM for Passive NPP Components
Wait for New Measurement
Predict Time-to-Failure (TTF) and Estimate RUL, Confidence Bounds
Physics-based Models
NDE Measurement z_j at time j
Estimate Degradation "Level" (Material State)
Prognostics: Predict Material State for $k>j$
Stressor σ_j at time j
Stressor Estimates for $k>j$
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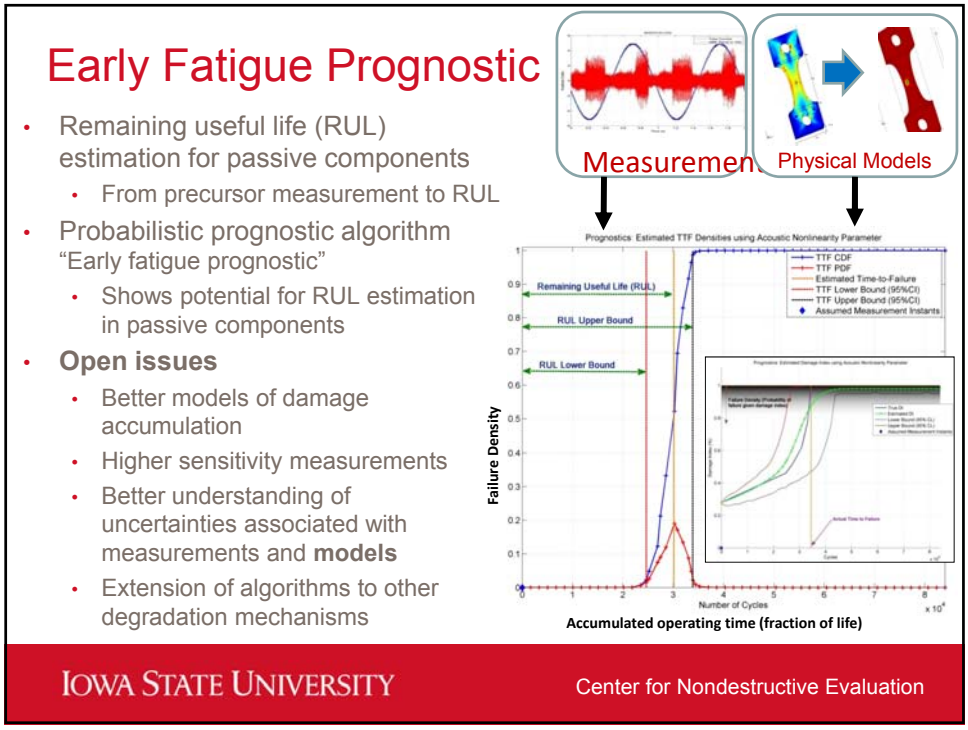
Early Fatigue Prognostic
Remaining useful life (RUL) estimation for passive components
From precursor measurement to RUL
Probabilistic prognostic algorithm "Early fatigue prognostic"
Shows potential for RUL estimation in passive components
Open issues
Better models of damage accumulation
Higher sensitivity measurements
Better understanding of uncertainties associated with measurements and models
Extension of algorithms to other degradation mechanisms
Measurement
Physical Models
Prognostics: Estimated TTF Densities using Acoustic Nonlinearity Parameter
Remaining Useful Life (RUL)
RUL Upper Bound
RUL Lower Bound
Failure Density
Number of Cycles
Accumulated operating time (fraction of life)
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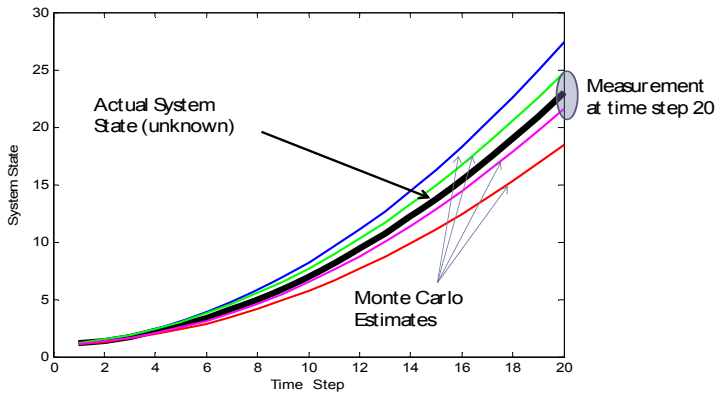
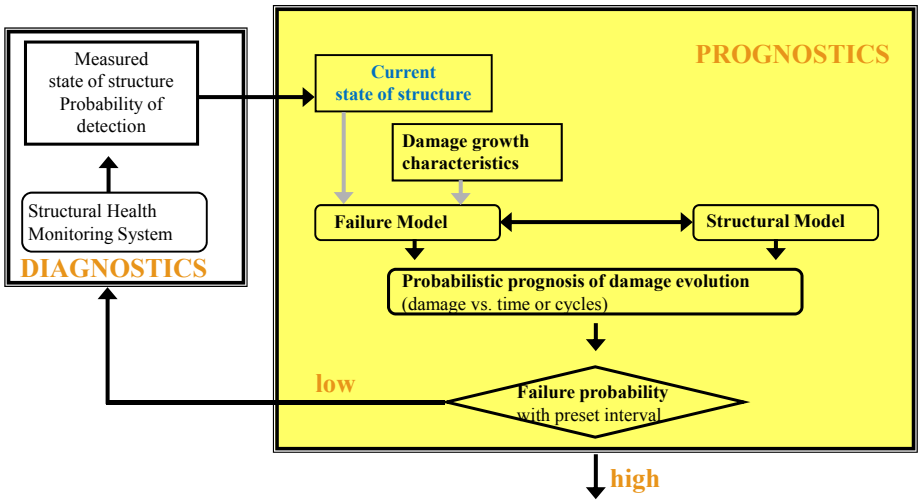
Sample Estimates of the System State Prior to Weighting



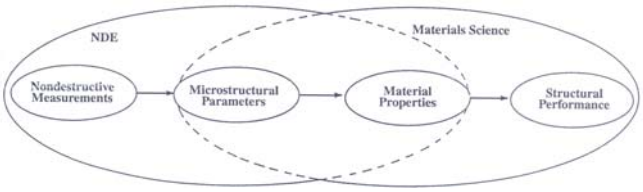
Diagnostics to Prognostics



After J.D. Achenbach – Kriss Lecture (2009)

Detailed Understanding of Microstructure –including damage - must be a Key Ingredient in Development of State Awareness Strategies

- An idealized scenario



- Generally, each link has it challenges
  - Non-uniqueness
  - Inadequate sensitivity to key parameters
  - Limitations of the theory base
- Force a stochastic approach

After AFOSR Prognosis Workshop_February 2008

Conclusions

- Passive components are seen as the key to LTO (60-80 years) for the US nuclear fleet. Increased condition awareness will support better economic assessments of life costs and help to ensure continued safe operation as plants operate longer
- There are models for (i) grain noise, and (ii) discrete flaws –eg FBH that give POD.
- Experimental methods to reliable characterize early damage AT THE RIGHT SCALE
- Models for ultrasound (or other physics) for damage precursors – sensing modality interactions

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