Review of
Current Status/Action Items

R. Bruce Thompson

Status

- Consortium planning meeting in Austin, TX
  - November 18 & 19, 2003
- First MAPOD WG meeting in Albuquerque, NM
  - September 23 & 24, 2004 (ATA NDT Forum)
- Sub-team meeting in Las Vegas, NV
  - November 17, 2004 (ASNT Annual Meeting)
- Second MAPOD WG meeting in Palm Springs, CA
  - February 4, 2005 (Aging Aircraft 2005)
- Third MAPOD WG meeting in Orlando, FL
  - June 9-10, 2005 (AeroMat 2005)
- Fourth MAPOD WG meeting in Orlando, FL
  - September 22-23, 2005 (ATA NDT Forum)

Prospectus

- General Objective:
  - To promote the increased understanding, development and implementation of model-assisted POD methodologies.

Approach

The working group will meet periodically and conduct the following activities:

- Discuss strategies for model-assisted POD determination
- Discuss requirements for models to be used in POD studies
- Identify gaps that need to be addressed between state of the art models and real world problems
- Provide input regarding examples of specific problems that would demonstrate the utility of model-assisted POD activities
- Communicate the results of model-assisted POD demonstrations

Metric

The Model-Assisted POD Working Group will be considered a success if, during its duration, activities under a variety of programs lead to

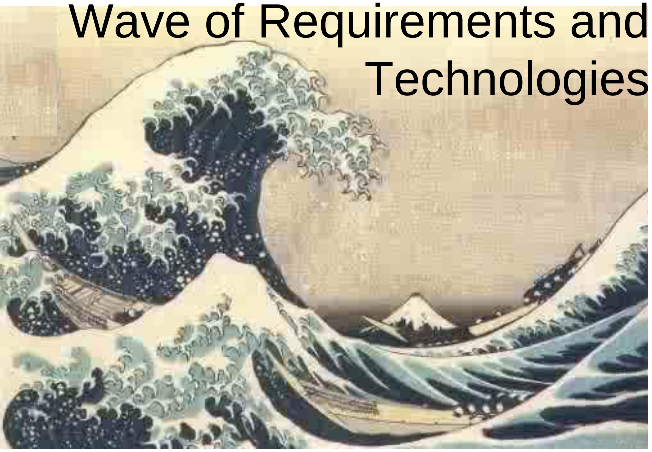
- Draft protocols for model-assisted POD
- Draft requirements for model qualification for use in POD determination
- Model-assisted POD demonstrations

FIRST MAPOD MEETING

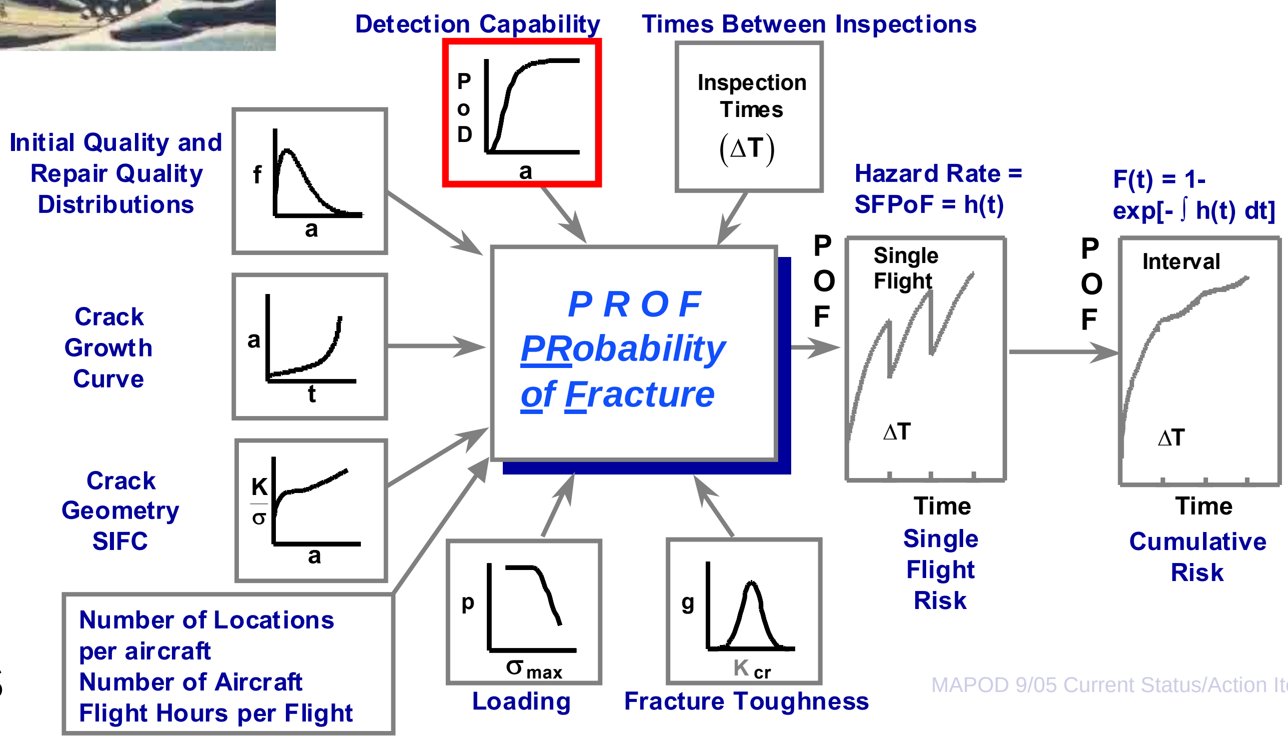
September 23-24, 2004

ATA NDT Forum, Albuquerque, NM

Motivation for Developing More Efficient Ways of Determining POD



- Man-hours for NDE scheduled to increase dramatically!
- Need to insert new technologies into the field, faster and cheaper!
- Implementation of inspections without POD undermines NDE and reliability!
- Damage tolerant risk analysis techniques demand Quantitative NDE! (Gallagher, Babish, and Malas, 2005)

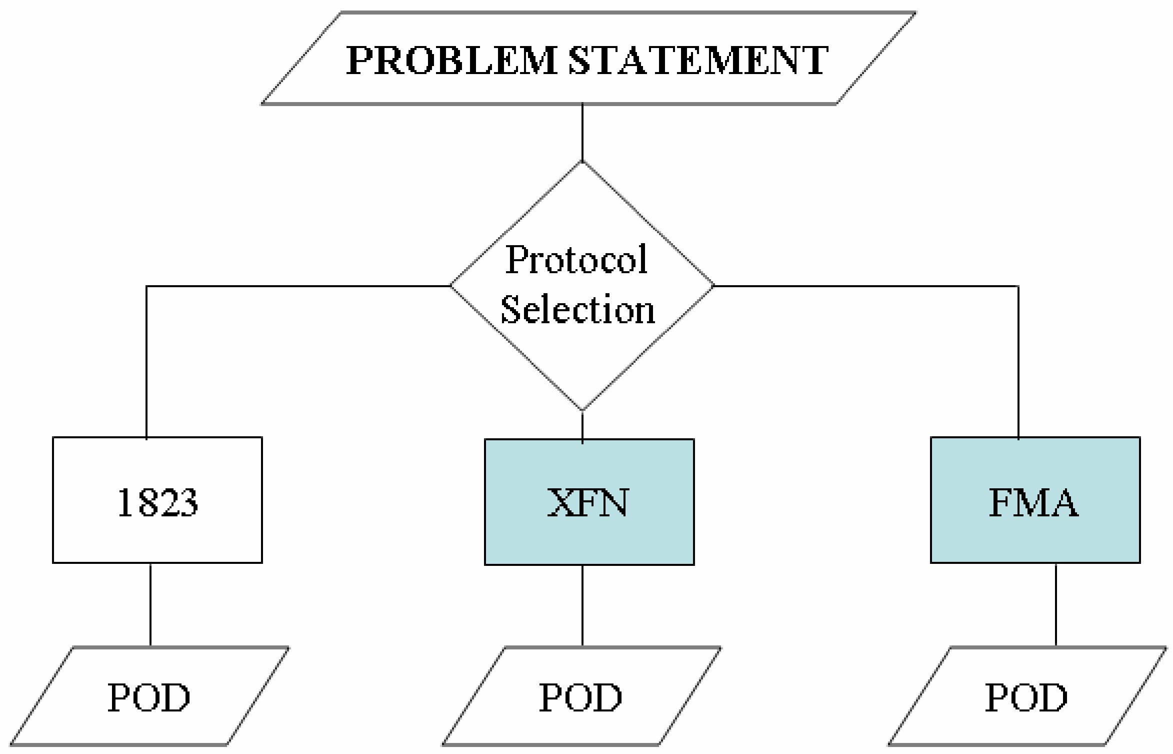


KNOPP/MALAS

Objective

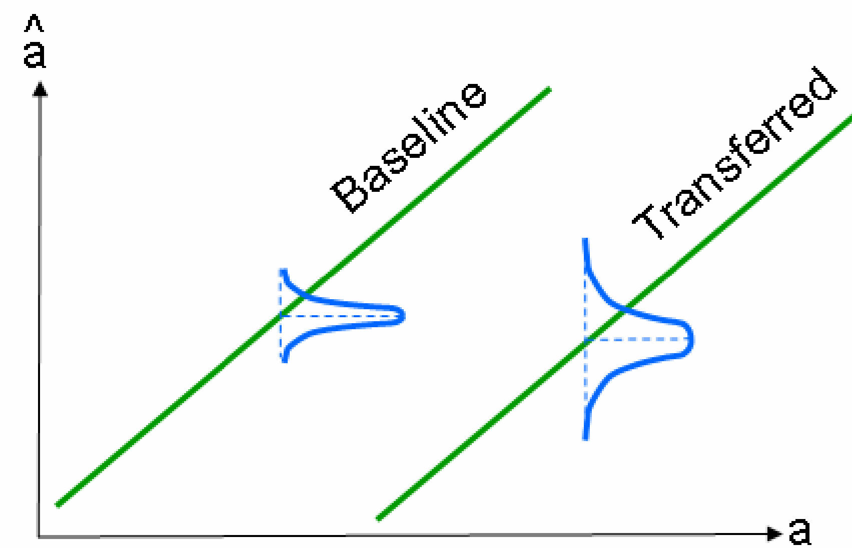
- To codify methods which are less cost/time intensive than 1823

Scope


PROBLEM STATEMENT
Protocol Selection
1823
XFN
FMA
POD
POD
POD

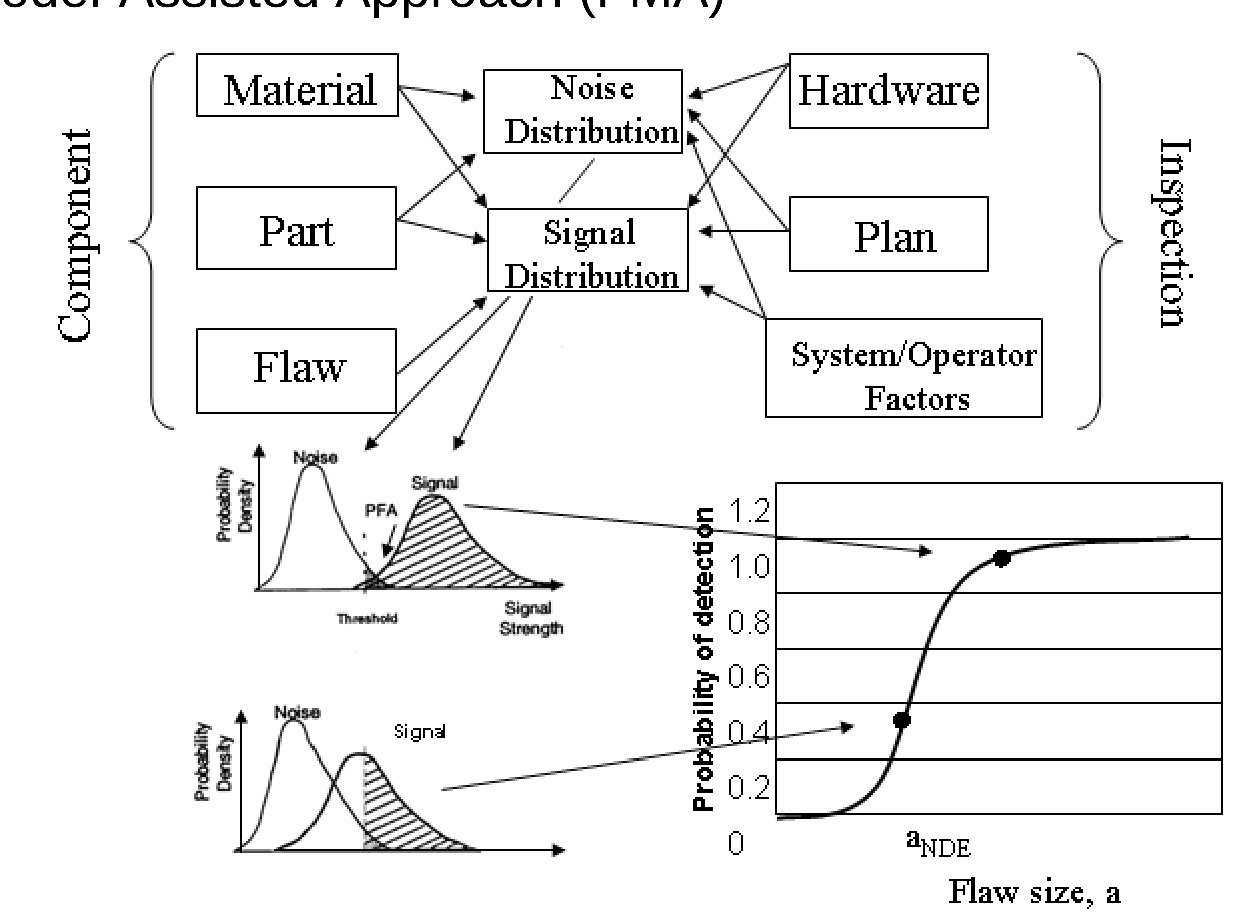
Two Approaches Identified

- Transfer Function Approach (XFN)



Two Approaches Identified

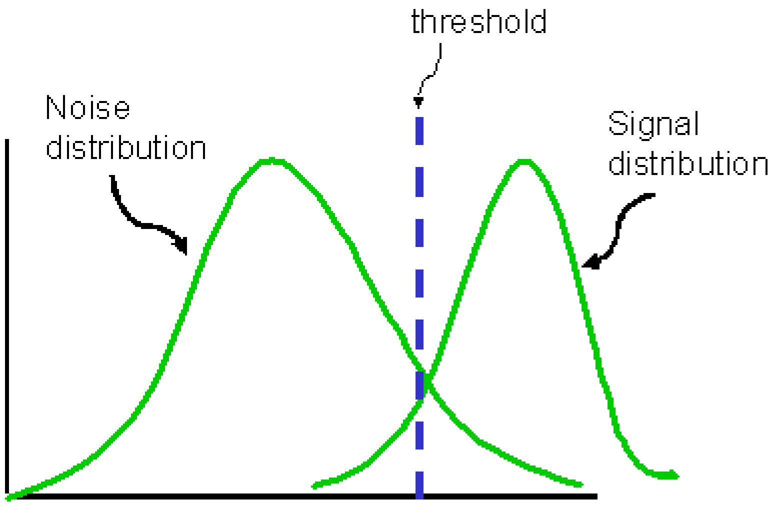
- Full Model-Assisted Approach (FMA)



An Example Given of FMA Approach

Steps to Generate Model-assisted UT POD

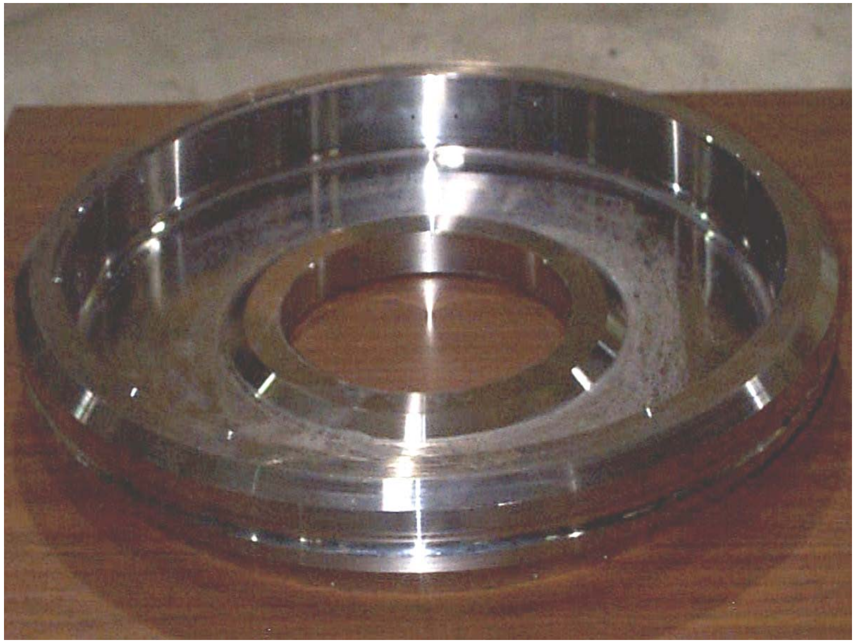
- Determine necessary UT properties
- Establish noise distribution for alloy/system using validated model
  - Material noise
  - Electronic noise
- Calculate signal distribution for inspection parameter set using validated model
  - Transducer
  - Threshold, scan plan
- Apply test system variability factor



UT POD Methodology Validation

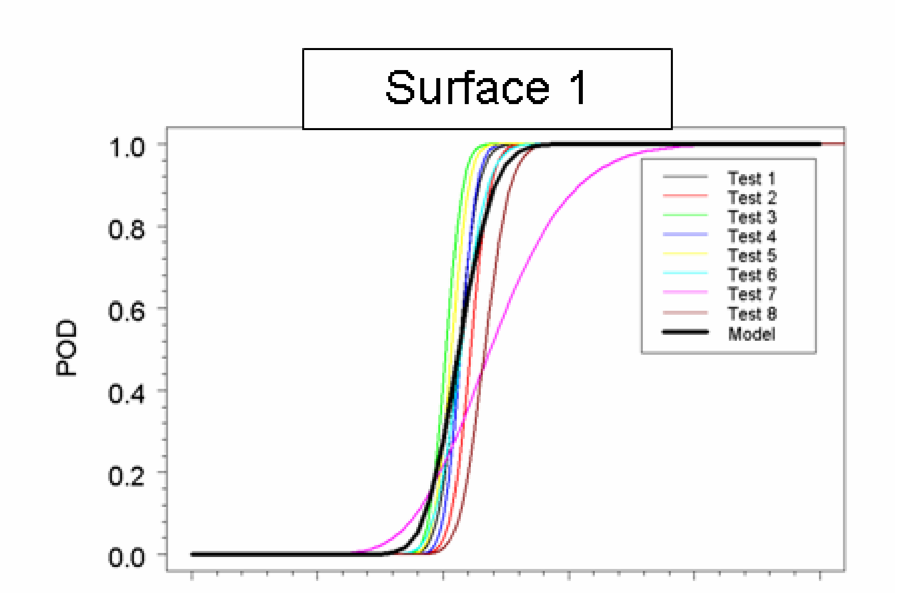
Steps to validation:

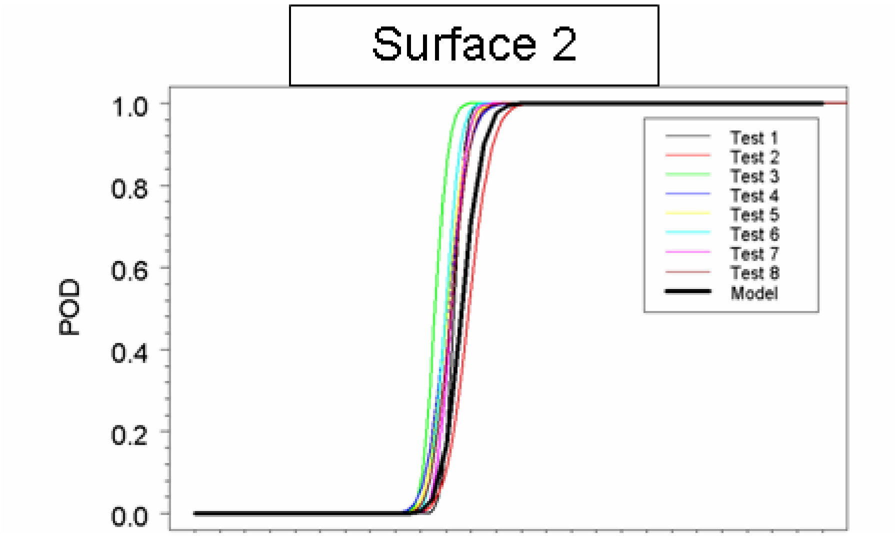
- Design, fabricate and characterize sample
- Generate and analyze system/operator data
- Calculate empirical POD curve
- Calculate model-based POD using validated signal and noise models
- Compare empirical POD to model-based POD



UT POD - System/Operator Data Analysis

- Empirical curves generated for eight system/operator combinations
- Comparison made to model-assisted POD calculation
- Results shown indicate:
  - Model-assisted POD calculations are well within the experimental variability
  - System/operator variability is typical of other empirical POD studies





UT POD Methodology Validation Conclusions

- Empirical data:
  - Used to validate modular methodology through comparison to Mil Std 1823
  - Provides system/operator variability data for use in future calculations
- Final Results:
  - Modular UT POD methodology yields equivalent results to empirical methodology in back to back comparison
  - Modular UT POD enables transducer variability consideration
  - System/operator variability can be applied to other part designs and materials

Conclusions from Prior UT Demonstrations

- Methodology transitioned to
  - other FBH sizes (within validation conditions)
  - other alloys (requires assessment of noise distribution)
  - new systems (requires system/operator characterization)
- Enables inspection to comply with lifing assumptions at least as well as prior methodology
- Allows POD calculations more quickly for other systems
- Accounts for noise and transducer variability
- Results in knowledge of inspection variability
- Includes noise variability more rigorously than before, in addition to the speed advantages
- Established transducer performance characteristics that assured maximum level of variability

Model-assisted POD Applications - Benefits

- Physical models can supplement limited empirical data that would render empirical based POD methods impracticable
- Physical process to be broken into its constituent parts so that cause and effect can be understood
  - Design of improved inspections
  - Evaluation of effects of inspection/process changes
  - Transfer of limited POD data from one geometry to another
  - Quick response to unexpected problems
- Provides POD curves that more accurately represent true capability

Web Site Established

- Model-Assisted POD Working Group
  - Web site is linked from the Center for Nondestructive Evaluation web site at:
  - http://www.cnde.iastate.edu/ under Research

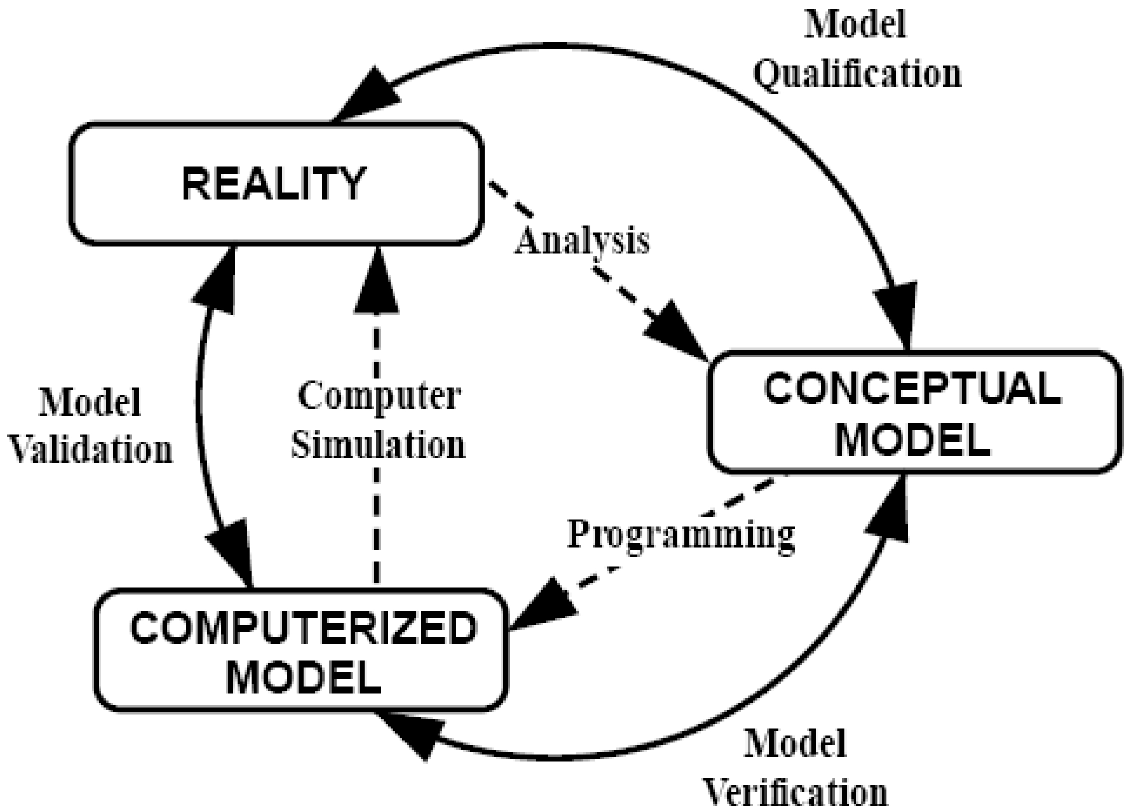
SECOND MAPOD MEETING

February 4, 2005

Aging Aircraft 2005, Palm Springs, CA

Elements to be Included in MAPOD Protocol

View of Modeling and Simulation by the Society for Computer Simulation



© 1979 by Simulation Councils, Inc.

Schlesinger, S., "Terminology for Model Credibility," *Simulation*, Vol. 32, No. 3, 1979, pp. 103-104

An Example of XFN Approach

When are transfer functions used?

Used in situations:

- Where validated physics-based model is not available to provide crack vs. notch relationship
- Where natural defects can not practically be fabricated in the geometry of interest
  - Time
  - Cost
  - Feasibility
    - Controlled cracks in real disk
    - Complex, embedded defects

Transfer Function Example: Summary

Develop an ECI probe

Perform EC measurements on flat panel set with fatigue cracks.

Perform EC measurements on a flat panels EDM notches.

Calculate “ahat vs a” regression lines for both measurements and calculate a “crack vs notch” “knockdown factor”

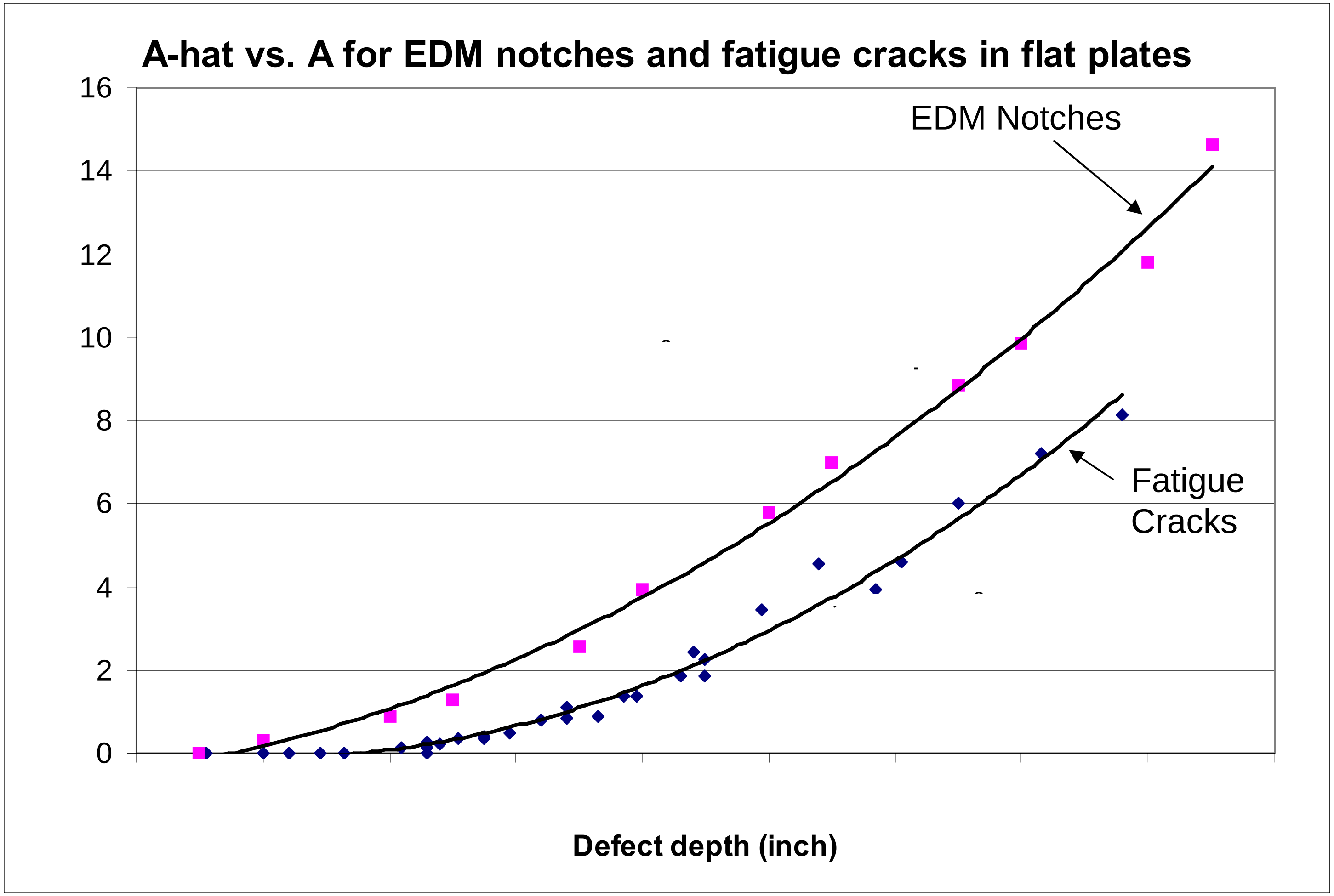
Machine EDM notches in blades distributed throughout the region of interest to establish baseline sensitivity and variability

Reduce the EC amplitude from the EDM measurements in blades using the “knockdown factor” from the crack vs. notch measurements.

Construct “ahat vs. a” regression line and calculate a POD.

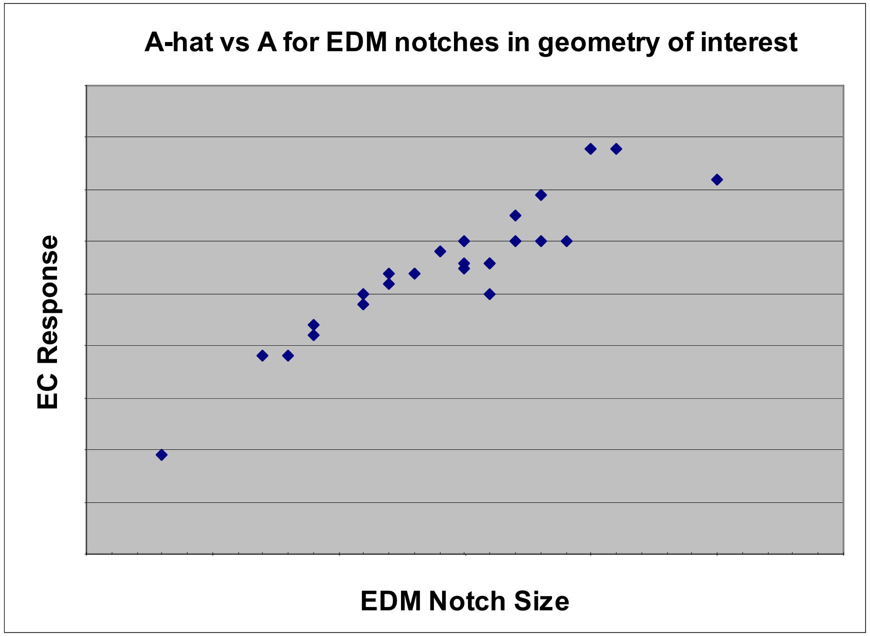
Transfer Function Example

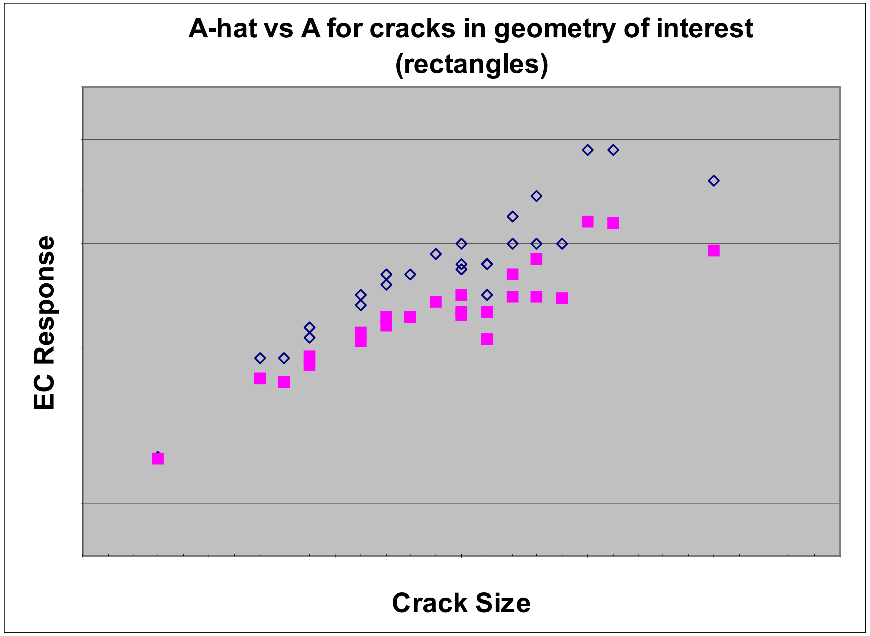
Establish relationship between cracks and EDM notches for flat plate using well-controlled lab studies



Transfer Function Example

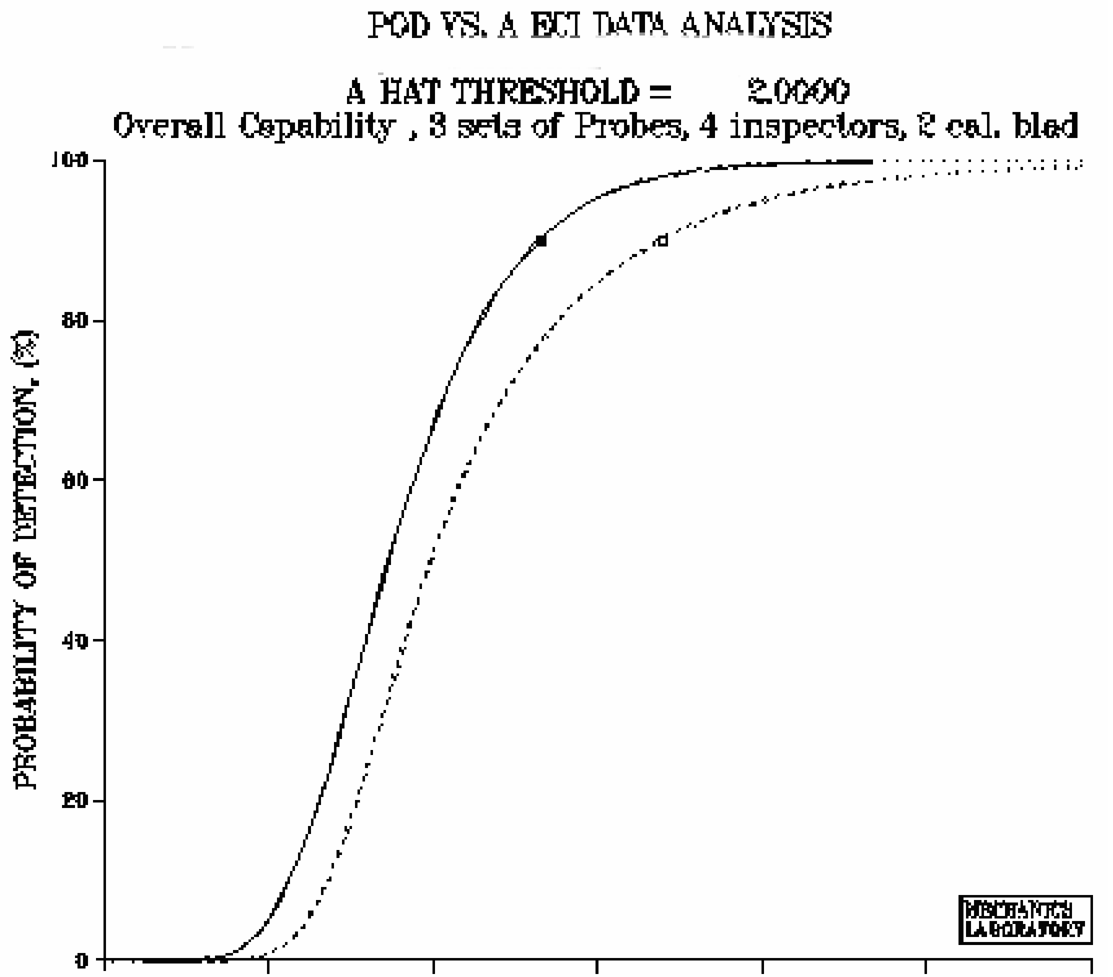
Utilize relationship from flat plates and variability data from notches to generate variability data for cracks in geometry of interest





Transfer Function Example

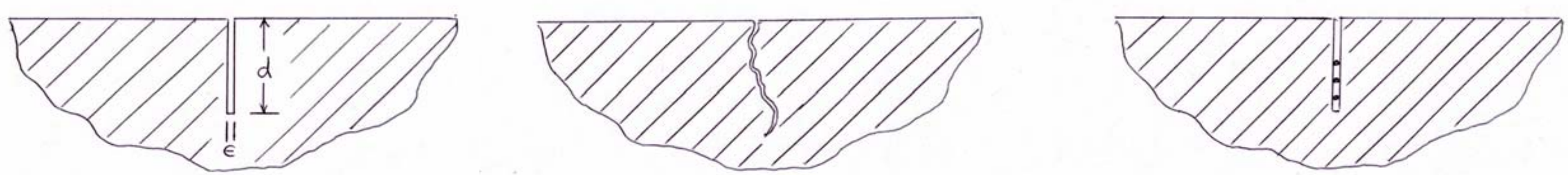
Generate POD vs. crack size curves for the geometry of interest



Role of Physics-Based Models in Comparison of Crack and Notch Response

Cracks

Ideal Mathematical Crack | Morphology Effects | Electrical/Mechanical Contact Effects



Material Mechanisms

- Growth along grain boundaries
- Non-uniform residual stresses

- Oxides and other debris
- Contacting asperities
- Sheared faces

Suggested Strategy

- Use physics-based models to correct notch data for difference between ideal cracks and notches
- Create database of deviations of responses of real cracks from expectations for ideal cracks
  - Include salient materials variables specifying growth factors controlling morphology
    - HCF vs LCF
    - Closure
    - Etc.
- Long term goal
  - Develop “knock down factors” that can be confidentially used in new studies

A Statistical Approach to Model Development

TESI uses global models too:

Signal strength depends on target size, morphology & location, part geometry, probe, scan-plan …

$$\hat{a}_i = \beta_0 + \beta_1 \underbrace{a_i} + \beta_2 \underbrace{\%N} + \beta_3 \underbrace{e^{-\alpha Z_i}} + \varepsilon_i$$

a_i	$\%N$	$exp(Z_i)$
$log(a_i)$	$log(\%N)$	Z_i
$1/a_i$	$1/\%N$	$1/Z_i$

Stochastic component

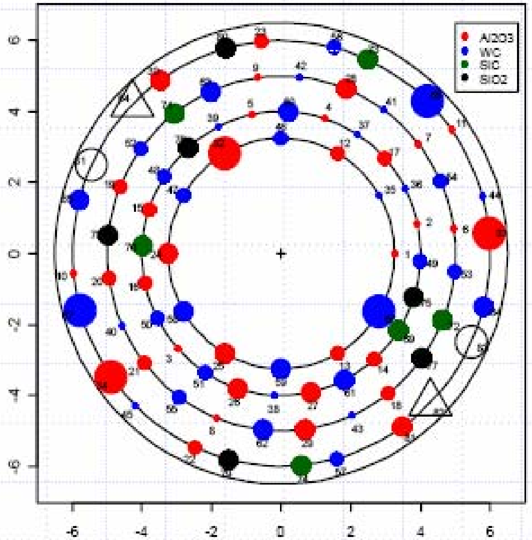
Physical theory can *suggest* the form of the mathematical model.

Charles Annis, P.E.
Statistical Engineering

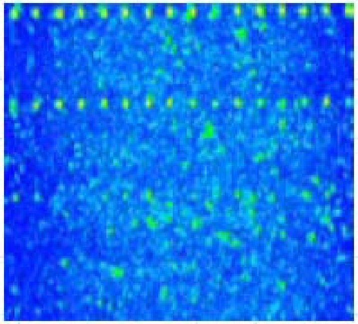
Review:
TESI Specimen to POD Function

1) Design TESI Specimens

2) Build them



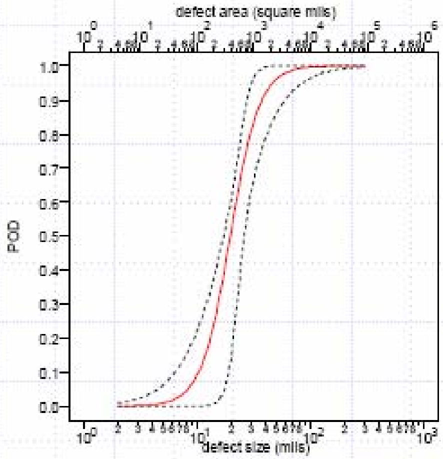
3) Exercise TESI system



4) Do the math and stats

$$\hat{a} = \beta_0 + g\left(\sum_{i=1}^{i=n} \beta_i f_i(x_i)\right)$$

5) Build the POD function



6) Use it to compare systems

Charles Annis, P.E.
Statistical Engineering

"Model-Assisted" means …

… using mathematical models *of appropriate complexity* to augment what can be inferred from the raw data alone.

… recognizing the intermediate goal:

- Using wave mechanics to describe the entire waveform?
- Or describing the maximum amplitude at a location (voxel)?

Charles Annis, P.E.
Statistical Engineering

Summary:

- TESI Goals in Model-Assisted POD are entirely consistent with those of the MAPODWG.

- We are pursuing models more statistical than physical, that nonetheless are firmly founded on physical principles.

Charles Annis, P.E.
Statistical Engineering

THIRD MAPOD MEETING

June 9-10, 2005

AeroMat 2005, Orlando, FL

Repository of MAPOD Protocols
MIL-HDBK 1823 Update Process

- Technical community (combined gov't/industry) develops proposed content
- Draft document distributed for "informal" review and comment cycle
  - Affected/interested contributors
- Comments adjudicated by REO
- Draft document finalized and released for official comment/coordination by ASC/ENOI
  - Adjudication cycle
- Publish

1-2 year cycle – paced by document development

STEPS TO GENERATE FULL MODEL-ASSISTED POD

Draft of 5/31/05

1. Define the intended use of the POD activity.
   a. Identify characteristics of the inspection (i.e., surface connected crack via eddy current, volumetric defect via ultrasonic at normal incidence)
   b. Absolute curves for use in lifing / risk analysis
   c. Relative comparison – if a relative comparison is desired, use only artificial defects in the actual geometry
2. Generate artificial flaws in geometry of interest
   a. Identify artificial flaw type appropriate for the inspection technique and inspection approach considering the geometry and flaw orientation, and inspection physics.
3. Generate artificial flaws in simple geometry
   a. Artificial flaws generated in the simple geometry should be of the same size range and geometry as the artificial flaws in the geometry of interest. For example, if the artificial flaw for an eddy current inspection is an EDM notch installed normal to the surface with a 3:1 aspect ratio, then the artificial flaw in the simple geometry should be an EDM notch installed normal to the surface with a 3:1 aspect ratio.

4. Generate realistic flaws in simple geometry
    a. The same simple geometry should be used for the realistic flaws as was used for the artificial flaws in the previous step.
    b. The realistic flaws should as closely as possible replicate the flaw that the inspection is intended to detect.
5. Collect data on the 3 sample types identified.
    a. Data shall be collected using the same probe type as used in the inspection. Where practical, data shall be collected on all specimens with the same probe. Circumstances may arise where the probe geometry is not conducive to the scanning both the complex geometry and the simple geometry. In this situation, the same sensor design may be used for the simple and complex geometry though in different probe bodies. If two probes are required, both probes should be related to each other through a common artificial defect.
    b. The data should be collected in a manner to minimize variability in a way that is consistent with a laboratory measurement as opposed to an inspection as the intent is to develop an analytical expression to ultimately describe the relationship that will transfer the response of actual defects in to the complex geometry where realistic defects can not be practically generated in quantities sufficient for a purely empirical POD to be generated.

6. Establish relationship between realistic flaws and artificial flaws for simple geometries using data from well-controlled lab studies
    a. Generate regressions to relate realistic defects and artificial defects in the simple geometry.
    b. Generate regressions to relate artificial defects in simple geometry and the complex geometry.
    c. Using the 2 regressions generate above, generate a relationship between the real defects in the simple geometry and the artificial defects in the complex geometry.
7. Determine variability through POD study of artificial defects in geometry of interest.
    a. The POD test matrix should be constructed using the guidelines in MIL-HDBK-1823 or other accepted methodology.
    b. An inspection procedure shall be drafted and the inspectors to be utilized in the POD exercise trained to perform the inspection utilizing specimens not to be used in the POD exercise.
    c. Collect and record the signal response data per the test matrix utilizing trained inspectors and an established inspection procedure.
8. Utilize relationship from samples (step 6) and variability data from artificial defects in complex geometry (step 7) to generate variability data for cracks in geometry of interest
9. Generate POD vs. crack size curves for the geometry of interest utilizing MIL-HDBK-1823 or other accepted methodology.

STEPS TO GENERATE TRANSFER FUNCTION POD

Draft of 5/31/05

Protocol:

1. Identify the scope of the POD study in the context of the intended purpose.
   a. Determine whether one is seeking an absolute POD determination (prediction of reality) for lifing purposes or a relative determination for the purposes of qualifying a replacement inspection technique.
   b. Specify the degree of accuracy desired. The scale of the activity should be adjusted to fit the purpose.
   c. Specify a measure that will indicate when the study will be considered to be complete.
2. Identify those factors that control the signal and noise in the experiment (*Controlling Factors*).
3. Determine whether a *physics-based model* can be used to predict the influence of each controlling factor on flaw signal and noise. For those *controlling factors* for which the answer is yes, go to step 4 and its sequels to treat those aspects of the POD study that can be analyzed by physics-based models. Otherwise, go to step 7 and its sequels to treat those aspects of the problem that should be treated empirically.

4. Acquire *simulation tools* for signal and noise for the factors whose effects can be predicted by a *physics-based model*.
   a. Identify needed *simulation tools*, including the range of *input parameters* for which they will be expected to be used.
   b. Determine if validated *simulation tools* exist. If the answer is yes, acquire the tools and go to step 5. Otherwise,
   c. Develop new *simulation tools*.
      i. Develop appropriate *physics-based models*
      ii. Develop computer software that makes numerical predictions based on those models.
      iii. Incorporate these tools in *simulation tools* that include appropriate user interfaces.
   d. Validate the accuracy of the *simulation tools* in the laboratory through well controlled experiments
      i. Establish the scope of the intended validation, including the range of parameter values to be considered and the level of agreement between experimental measurements and the predicted results that will be considered to be satisfactory
      ii. Include a careful analysis of uncertainties, including consideration of uncertainties in the experimental measurements, uncertainties in the values *of input parameters* to the model, and sensitivity of model predictions to the latter

i. Document the results of the validation experiments in a way that will allow them to be considered in step 4.b of other studies.

5. Acquire input parameters and/or *parameter distributions* appropriate to the measurement situation of interest
   a. Determine whether the *input parameters/parameter distributions* are known. If the answer is yes, go to step 6. If the answer is no,
   b. Determine the *input parameters/parameter distributions* from experiment or expert opinion.
6. Conduct *Flaw Signal Distribution Simulations* and *Noise Distribution Simulations*
   a. Use *simulation tools* to predict mean response and those components of variability of signal and noise described by the *physics-based models*. This defines the marginals associated with each factor whose effects can be treated in terms of *physics-based models*.
   b. Go to step 10.
7. Acquire information about effects of controlling factors that must be treated empirically.
   a. Identify *controlling factors* to be considered, including the range of conditions appropriate to the particular inspection of interest.

b. Determine if the sources of variability controlled by factors that must be treated empirically are statistically independent so that variances add. If the answer is yes, go to step 8 and its sequels. If the answer is no, assess whether independence would be a conservative assumption and if that assumption would lead to acceptable conclusions. If that would be the case, then assume the independence and proceed to step 8. Otherwise, go to step 9 and its sequels. Note that it is often hard to determine independence rigorously. Physical arguments, previous experience, or expert opinion should be used wherever possible to classify sources of variability.

8. Acquire marginal information for independent factors.
   a. Determine if empirical studies for these set of conditions have been previously conducted in a way that defines the needed marginals. If the answer is yes, acquire the marginal information and go to step 10 and its sequels. Otherwise,
   b. Design experiments to assess marginals associated with each controlling factor whose effects are to be treated empirically and have been determined to be independent of those of other controlling factors.
   c. Conduct the needed experiments
   d. Extract the needed marginals.
   e. Go to step 10

9. Acquire covariance information for dependent factors.
    a. Determine if acceptable bounds on the correlation coefficient can be established based on physical arguments, previous experience, or expert opinion. If yes, establish those bounds and proceed to step 9.d. Otherwise,
    b. Design experiments to determine the correlation matrix or other parameters needed to jointly describe multiple sources of variability and thus fully define the noise statistics.
    c. Conduct the needed experiments.
    d. Develop the full covariance description for the dependent factors.
    e. Go to step 10
10. Combine results of steps 6, 8 and 9 into a full description of the distributions of signal and noise
    a. If sources of variability are statistically independent, compute total variance as the sum of the variances derived from models and empirical measurements.
    b. If sources of variability are not statistically independent, compute the generalization of the above
11. Compute POD, PFA, ROC

Description of Sandia/AANC Fatigue Crack Samples

Mike Bode

June 10, 2005

Model Assisted POD Meeting

Orlando, FL

POD Data Accessible at UDRI

UDRI
UNIVERSITY of DAYTON RESEARCH INSTITUTE

RFC/ECIS DATABASE

- 163 sets of â versus a EC data from the ECIS
- 39 specimen sets
  - Between 30 – 80 cracks per specimen set
- At least three inspections of each crack
- At least 2 probes
  - Some repeat inspections with same probe
- ACCESS DB
  - Linked to Excel files containing system setups, â recordings, analysis results, specimen sets, and reports
  - Search on Engine Part, Specimen material, Geometry, Probe Coil Designation, Probe Type, Coil Type, Inspection Frequency

Empirical POD Studies

Status Report for MAPOD-WG
For June 2005 Meeting

Irving Gray,

NDE Technologies, Inc.

Prior Work

- Have Cracks will Travel
- ...

✓***Three Decades of NDI Reliability Assessment**** – Ripudaman Singh

* Provided by Karta Technologies

Literature Review

- Theoretical
- Applications
- Full Studies

- Collected 80+ articles and references
- What is to be done with them?

Review Method

- Location/Group
- Sponsor
- Problem
- Sample Type
- Model
- Simulated Factor
- POD
- PFA / POFC
- Equipment
- IC
- AP
  - Flaw Size
  - Flaw Range
  - Flaw Orientation
- HF
- Cost / Benefit

- Industry
- Material
- Modality
- Study Type
- Validation (Model Validation and POD Validation)
- Flaw Type

- *MAPOD-WG RATING*

Title, Pub Source, Pub Year, Author, sub-Authors, Keywords, Abstract → From Citation (e.g., EndNotes database search

I. GRAY

		Citation							Group	
MAPOD-WG Key Code	Citation Title	Pub Source	Pub Year	Author	Keywords	Abstract Link	Full Text (PDF)	Location / Group	Industry	Sponsor
	EDDY CURRENT ANALYSIS ROUND ROBIN		2002	Kupperman, D.S.	EC Array, POD, F		The link to	Argonne Nat Lab (ANL)	Nuclear	US NRC/ONRI
	PROBABILITY OF DETE	RNE	2004	Zeng, Z., Xuan, L., Sun, L., Udpa, L., Udpa S.				MARG-E&EG ISU	Pipeline	
	INSPECTION OF FASTE	ASIP 2003	2003	Herzog, P.G.	UT Phased Array,	not availab	Portion of /	AF NDI Office Tinker AF	Mil-AF	AF NDI Office

			Modeling Componets			Probability of Detection & False Call			
	Method								
Problem	Method	Study Type	Model	V	Simulated Factor	POD	PFA / POFC	V	Sample Size
crack detection in SG tut	RR	EX&Mod	Argone multiparameter a	good					
parameter study for mag	Parametric Stu	EX&Mod	FEA & parametric functional moc		liftoff		PFA = 5%		
crack detection in Al plates with Phased		EXP	none	n/a	n/a				

		IC				AP			
						Flaw Morphology			
Std Sample	Modality	Equipment	Calibration Method	Noise Distrbution	Material	Flaw Type	Flaw Size	Flaw Range	Flaw Orientation
NRC Steam Ge	EC				Inconel 600				
	MT				Al	A-Mach			
	UT-PA	FastFOCUS R/D T			Al				

	HF				
Recogniyion & Analysis	Training	Mood / Enviro / Fatigue / Mgmt	Cost / Benefit	Notes / Comments	MAPOD-WG Rating
not examined		not examined			

I. GRAY

List of Model-based POD Studies - MAPOD Working Group

Jeremy Knopp, AFRL
John C. Aldrin, Computational Tools

June 4, 2005

Model-Based POD Studies

- **Objective:**
  - **Develop a list of model-based POD studies that have been completed to date**
  - **Develop repository for results of review (with Irving Gray - NDE Technologies)**

Model-Based POD Studies

- **Potential Criteria:**
  1. **Description of NDE Measurement Model**
  2. Model Validation with Experimental Data
  3. **Simulated Studies of Model Parameter Variability on Measures:**
     - **flaw characteristics**
     - material properties, part geometry, measurement noise
  4. **Estimated POD / POFC - Based on Detection Criteria**
     - operator interpretation of signals / images
     - automated classification (threshold, â vs. a, advanced classifier)
  5. Validation of estimated POD / POFC through experimental studies
- **Categories:**
  - ***Limited* study (with potential for POD calculation)**
  - **Model-based POD study**
  - ***Validated* model-based POD study**

KNOPP/ALDRIN

FOURTH MAPOD MEETING

September 22-23, 2005

ATA NDT Forum, Orlando, FL

Model-Assisted POD Working Group
September 22-23, 2005
Crowne Plaza Airport Hotel
Orlando, Florida

THURSDAY, SEPTEMBER 22

1:00 p.m.	Review of Current Status - Bruce Thompson
1:45	Status Update of NRC-CNRC Program as an Example of a Demonstration (Canada) - Butcher
2:05	Status Update of DSTO Program an Example of a Demonstration (Australia) – Thompson for Harding
2:25	Discuss and Revise Next Iteration of XFN Protocol - Smith Leads
3:15	***BREAK***
3:30	Continue Discussion of XFN Protocol
5:00	***ADJOURN***

Model-Assisted POD Working Group
September 22-23, 2005
Crowne Plaza Airport Hotel
Orlando, Florida

FRIDAY, SEPTEMBER 23

8:00 a.m.	Discuss and Revise Next Iteration of FMA Protocol - Thompson Leads
9:30	***BREAK***
9:45	Continue Discussion of FMA Protocol
10:30	Present Further Information on Load and Fatigue Studies at FAA Technical Center as a Candidate for Further Demonstrations - Bode
11:00	Discuss Other Possible Demonstrations/Funding Opportunities - Knopp/Malas
11:30	Review of Action Items
12:00 p.m.	***ADJOURN***

MIL-HNBK-1823

- **NONDESTRUCTIVE EVALUATION SYSTEM RELIABILITY ASSESSMENT**

MIL-HNBK-1823

- 1. SCOPE
  - 1.1 Scope.
  - 1.2 Limitations.
  - 1.3 Classification.
- 2. APPLICABLE DOCUMENTS
  - 2.1 General.
  - 2.2 Government documents.
  - 2.3 Non-Government publications.
  - 2.4 Order of precedence.
- 3. DEFINITIONS

MIL-HNBK-1823

- 4. GENERAL REQUIREMENTS
  - 4.1 General
  - 4.2 System definition and control.
  - 4.3 Demonstration design.
  - 4.4 Demonstration test
  - 4.5 Demonstration analysis
  - 4.6 Presentation of results
  - 4.7 Retesting
  - 4.8 Process control plan

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- 5. DETAILED REQUIREMENTS
  - 5.1 General.
- 6. NOTES
  - 6.1 Intended use.
  - 6.2 Trade-offs between ideal and practical demonstrations.
  - 6.3 Other topics
  - 6.4 Subject Term (Key Word) Listing

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- **APPENDICES**
  - **A. Eddy Current Test Systems**
  - **B. Fluorescent Penetrant Testing Systems**
  - **C. Ultrasonic Testing Systems (UT)**
  - **D. Magnetic Particle Testing**
  - **E. Test Program Guidelines**
  - **F. Fabrication, Documentation & Maintenance**
  - **G. Modeling Probability of Detection**
  - **H. Assessing System Capability**
  - **J. Example Data Reports**