Probabililty of Detection Tutorial Workshop Sessions

1993 ASNT Spring Conference
March 29-April 2

Speaker Hand-Outs

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Probability of Detection
Tutorial Workshop Sessions

Presented in Nashville on Wednesday, March 31

Chairmen:
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Cincinnati, OH
&
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HISTORICAL OVERVIEW OF APPROACHES TO POD

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Tutorial Workshop on Probability of Detection
Spring 1993 ASNT Conference

THINK OF AN NDE PROCESS WITH WHICH YOU ARE FAMILIAR

- o **WHAT SIZE DEFECTS IS IT CAPABLE OF DETECTING?**
  - **HOW DO YOU KNOW THAT?**
- o **WHAT PROPORTION OF THOSE DEFECTS ARE DETECTED?**
  - **HOW DO YOU KNOW THAT?**
- o **TODAY'S PROGRAM WILL HELP ANSWER THOSE QUESTIONS!**

<u>THINK OF TWO NDE PROCESSES</u>

- **WHICH PROCESS FINDS THE SMALLEST DEFECTS?**
  - **HOW DO YOU KNOW THAT?**
- **WHICH PROCESS FINDS THE MOST DEFECTS?**
  - **HOW DO YOU KNOW THAT?**
- **TODAY'S PROGRAM WILL HELP ANSWER THOSE QUESTIONS!**

THINK OF TWO NDE INSPECTORS YOU KNOW

- **DO THEY BOTH PERFORM EQUALLY WELL?**
  - **HOW DO YOU KNOW THAT?**

- **DOES THEIR PERFORMANCE MEET YOUR NEEDS?**
  - **HOW DO YOU KNOW THAT?**

- **TODAY'S PROGRAM WILL HELP ANSWER THOSE QUESTIONS!**

YOUR COMPANY MAKES CYCLICALLY-LOADED PRODUCTS

- **HOW MUCH WILL BETTER INSPECTION IMPROVE PRODUCT LIFE?**
  - **HOW DO YOU KNOW THAT?**
- **WHEN SHOULD YOU SCHEDULE AN IN-SERVICE INSPECTION?**
  - **HOW DO YOU KNOW THAT?**
- **TODAY'S PROGRAM WILL HELP ANSWER THOSE QUESTIONS!**

OUTLINE OF THE TUTORIAL WORKSHOP ON POD

- o **HISTORICAL OVERVIEW OF APPROACHES TO POD (Sturges)**
  - Some basic concepts of capability and reliability
  - An outline of techniques for measuring capability

- o **ELEMENTS OF DETECTION THEORY (Sturges)**
  - Defining "detection"
  - Detection in a signal-to-noise context

- o **ELEMENTARY STATISTICAL CONCEPTS FOR POD ANALYSIS (Annis)**
  - Probability distributions and related topics
  - Sampling concepts and prediction intervals

- o **THE ROC APPROACH TO POD AND PFA (Sturges)**
  - An outline of statistical detection concepts
  - Radar origins, and applications to NDE

OUTLINE OF THE TUTORIAL WORKSHOP ON POD

- **US AIR FORCE APPROACHES TO POD (Annis)**
  - Methods for data acquisition and analysis
  - Advantages and limitations
  - Aerospace applications

- **ROLE OF PHYSICAL MODELLING OF NDE PROCESSES (Thompson)**
  - Modelling the contribution of individual inspection parameters
  - Examples of POD analyses

- **SELECTING AND APPLYING POD METHODS (panel)**

- Charles Annis	United Technologies
- Michael Avioli	Electric Power Research Institute
- Charles Salkowski	National Aeronautics and Space Administration
- Derek Sturges	General Electric Aircraft Engines
- Bruce Thompson	Center for NDE, Iowa State University
- Sharon Vukelich	US Air Force

CONCEPTS OF CAPABILITY AND RELIABILITY

- o **DICTIONARY DEFINITIONS**
  - **CAPABLE: "having capacity or ability; able to do things well; skilled; competent; efficient; able"**
  - **RELIABLE: "can be relied on; dependable; trustworthy"**

- o **INDUSTRIAL QUALITY DEFINITION** (Juran & Gryna, Quality Planning & Analysis)
  - **RELIABILITY: "the probability of a product performing without failure a specified function under given conditions for a specified period of time"**

- o **NDE DEFINITION** (Packman et al., Metals Handbook, 8th edition)
  - **RELIABILITY: "A quantitative measure of the efficiency of (an NDE) procedure in finding flaws of a specific type and size"**

CONCEPTS OF CAPABILITY AND RELIABILITY

- o **CAPABILITY OR RELIABILITY?**
  - **Different concepts - but often used interchangeably!**
  - **Packman's definition works for both**

- o **NDE SYSTEM CAPABILITY/RELIABILITY**
  - **Inspection processes involve numerous factors**
    - **Variations in instrumentation, inspector performance, etc.**
  - **Do these affect Capability and Reliability equally?**

- o **THERE IS NEED FOR A TERMINOLOGY STANDARD**

SUGGESTED DISTINCTIONS IN TERMINOLOGY

- **RELIABILITY:** (Haines, Sturges, Abernethy, Thompson)
  - Composite effect of the following sources of variation
  - CAPABILITY: Defect detectability determined by physics
    - Detection of defects of the same nominal size
  - REPEATABILITY: Changes in performance with time
    - Reinspection by the same inspector or inspection system
  - REPRODUCIBILITY: Differences in nominally identical systems
    - Reinspection after process changes
  - VARIABILITY: Effects of human factors
    - Reinspection by another inspector or inspection system
- **RELIABILITY:** (Avioli)
  - The probability that no flaw exists, given that the inspection process indicates that there is no flaw; (the probability of correct acceptance)

CAPABILITY FROM CALIBRATION

- o **TRUE STATEMENT**
  - **Ultrasonic inspection can reject all indications larger than that from a 0.0008 sq. in. planar void**

- o **THE SUPPORTING EVIDENCE**
  - **Inspection is calibrated from a 3/64" diameter flat-bottomed hole (FBH); indications above 50% of that reference level are rejected**

- o **THE PROBLEM**
  - **No measure of what size defect would be detected or rejected**
  - **Might be misinterpreted as stating all 0.0008 defects rejected**

CAPABILITY FROM PRECEDENT

- **TRUE STATEMENTS**
  - **1 mm long cracks can be detected with Fluorescent Penetrant Inspection**
  - **FPI is capable of detecting 1 mm long cracks**
- **THE SUPPORTING EVIDENCE?**
  - **An indication detected by FPI was caused by a 1 mm crack**
- **THE PROBLEM**
  - **No measure of how many 1 mm long cracks were missed!**
  - **Might be misinterpreted as stating all 1mm cracks detectable**

TYPICAL INDUSTRIAL UNDERSTANDING OF CAPABILITY

- **LIMITED TO SIMPLE STATEMENTS LIKE THE PRECEDING**
  - **Correct and apparently innocuous as stated**
  - **Open to potentially dangerous misinterpretation**
- **WHAT SIZE DEFECT CAN NDE PROCESSES DETECT?**
  - **Honest answer: it has usually not been established!**
- **HOW LONG HAVE WE HAD TO GET THE ANSWER?**
  - **Major NDE processes have been used for 50 to 100 years!**
- **HOW DO WE EXPLAIN THIS APPARENT GAP?**
  - **The question has rarely been asked!**

PROCESS CONTROL APPLICATIONS OF NDE

o **MOST NDE APPLICATIONS IN MOST INDUSTRIES**

- **Emphasis on consistency**
  - **Inspection independent of when or where conducted**
- **Calibrate from artificial defects**
  - **Need reproducible reference targets for each site**

o **NDE USED IN "PACKAGE" OF PROCESS CONTROLS**

- **Typically monitor from raw material through finished product**
  - **Chemical, mechanical, dimensionsal, etc.**
- **Success judged by favorable field-service record**

CAPABILITY FOR REAL DEFECTS?

- **TRUE CAPABILITY NOT ESSENTIAL FOR PROCESS CONTROL**
  - Capability of individual elements in the package not needed

- **MOTIVATORS FOR MEASURING CAPABILITY**
  - Quantitative comparison of various NDE processes
  - Quantitative comparison of various inspectors or systems
  - Need to apply NDE to management of product life

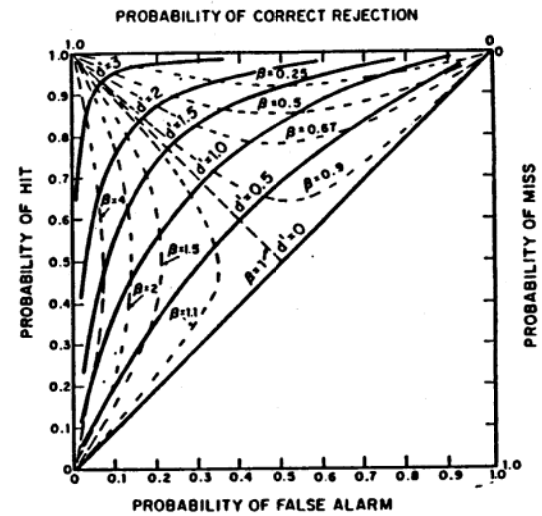
- **FACTORS LIMITING CAPABILITY MEASUREMENT?**
  - Cost, and lack of agreed methodology

CAPABILITY FOR REAL DEFECTS?

- **CAPABILITY EXPRESSED IN PROBABILISTIC TERMS**
  - Inspection processes are too complex to be described deterministically
  - Numerous differences in defect, material, inspection process

- **FOUR OUTCOMES TO EACH INSPECTION (each with a probability)**
  - Detection of a defect that is present
    - Probability of Detection (POD)
  - Non-detection of a defect that is present
    - Probability = (1 - POD)
  - Apparent detection of a defect that is not present
    - Probability of False Alarm (PFA)
  - Non-detection of a defect that is not present
    - Probability = (1 - PFA)

EARLY APPROACHES TO QUANTIFYING DETECTION CAPABILITY



Family of ROC curves based on normal, equal-variance distributions (curves correspond to constant signal-to-noise and threshold)

o DETECTION OF SIGNALS IN NOISE

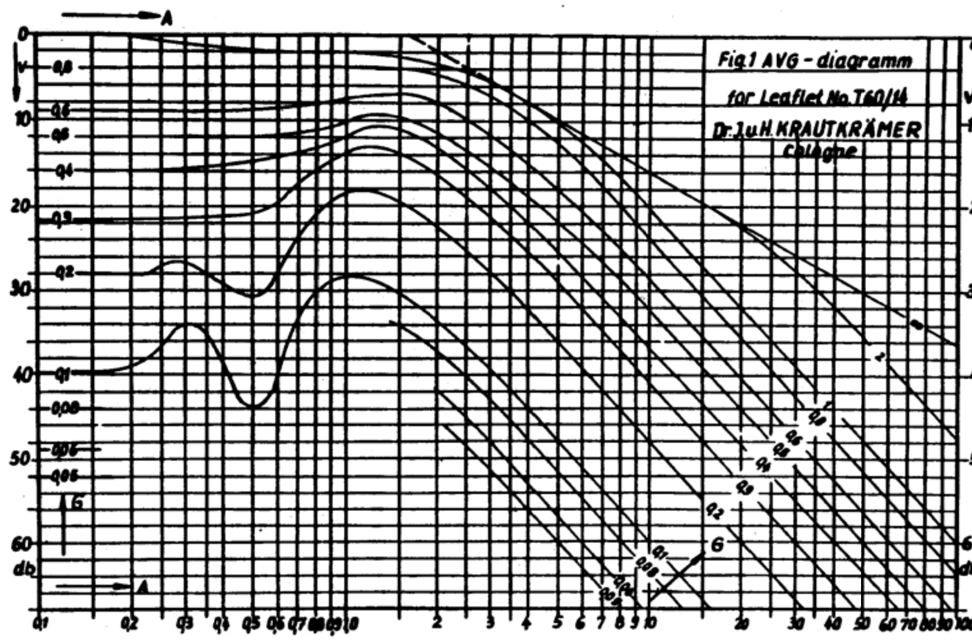
- **Statistical theory of signal detection**
  - **Detection identified with statistical tests for validity of hypotheses**
  - **World War II applications to communications, RADAR and SONAR**
  - **POD and PFA derived from measurements of signal and noise**
- **Later combined with information theory concepts and sensory psychology**
  - **Relative Operating Characteristic formatted by Birdsall (U. Michigan)**
  - **Numerous applications in evaluating detection/decision processes**

EARLY APPROACHES TO QUANTIFYING DETECTION CAPABILITY

- **MATHEMATICAL MODELLING OF ULTRASONICS (1950's)**
  - **Theoretical description of transducer/reflector interaction**
  - **The flat-bottomed hole (FBH) as a defect model**

- **INDUSTRIAL APPLICATION BY THE KRAUTKRAMERS (and others)**
  - **Krautkramer AVG/DGS diagram**
    - **Quantitative relation between backwall and planar disk responses**
    - **Defect size in terms of "Equivalent FBH" (FBH giving same indication)**
  - **Basis for life prediction for steam turbine & generator rotors**
    - **GE (1960's); ASTM Standard A418 (1974)**

THE KRAUTKRAMER DISTANCE-GAIN-SIZE DIAGRAM

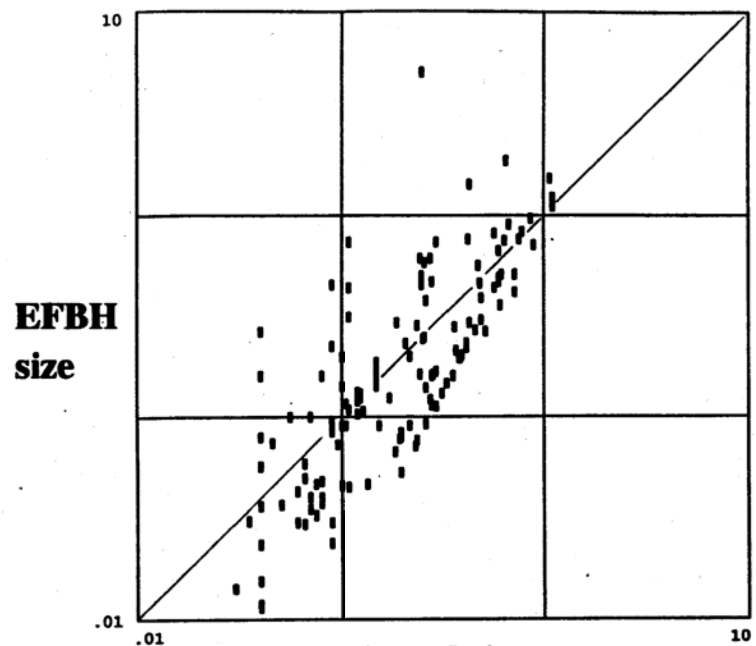


A = Distance (in near-field lengths)

V = Gain (in dB)

G = Size (of a FBH relative to the transducer diameter)

POWER GENERATION INDUSTRY



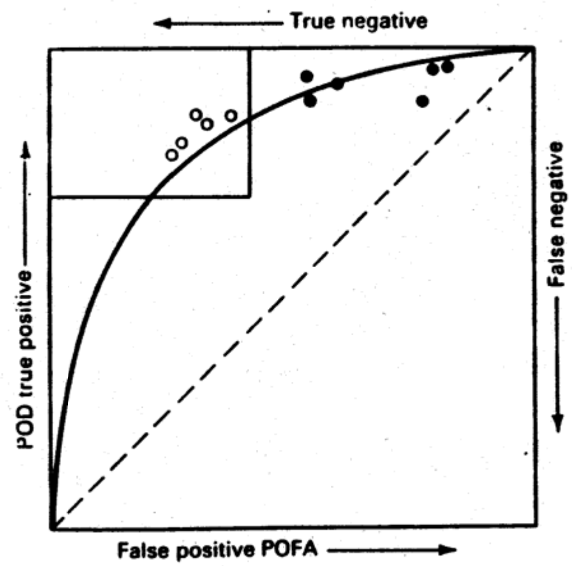
o **COMPARISON OF EFBH AND ACTUAL DEFECT SIZES**

- **Data used to adjust EFBH estimate for individual indications**
- **Modified EFBH size used in predicting rotor life**

POWER GENERATION INDUSTRY

- **POD/RELIABILITY MODELLING APPROACH**
  - **Central Electricity Generating Board (Coffey, 1977 et seq.)**
  - **Theoretical estimates for upper bounds on crack detection and sizing**

- **RELATIVE OPERATING CHARACTERISTIC (ROC) APPROACH**
  - **ROC format adopted for presentation of reactor inspection data**
    - **Used mostly to compare inspector performance**
  - **More on this later ....**



Example of ROC presentation of data

AEROSPACE INDUSTRY

- USAF, NASA, and US AEROSPACE INDUSTRY
  - Work began in the late 1960's
  - Motivated by need for data for fracture-mechanics analysis
    - Needed to counter high cost of maintenance & replacement

- AIRFRAME INDUSTRY PROGRAMS
  - First detailed study published in 1968
  - Fracture-control procedures initiated after loss of F-111 (1969)
  - Several major sponsored programs run in the mid-1970's
    - Lockheed-Georgia evaluated over 500,000 inspection opportunities
    - Reported POD as a function of process, material, inspector, etc.

AEROSPACE INDUSTRY

o **PAST NASA PROGRAMS**

- Awarded contracts for acquisition of quantitative NDE data (1973)
- Produced Shuttle Fracture Control Plan (1974)
  - Defect detectability based on penetrant POD data
  - Distinguished "standard" and "special" NDE capability standards
- Fracture Control applied to Shuttle main engine (1980)
- NASA FLAGRO (fracture analysis program) released (1986)

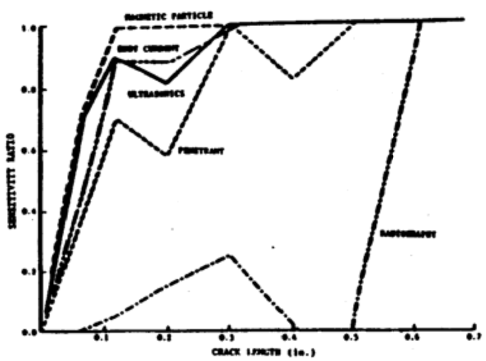
o **FUTURE NASA PROGRAMS**

- Distribution of NASA NDE Reliability Computer Program
- Large-scale effort for fabrication of defect samples

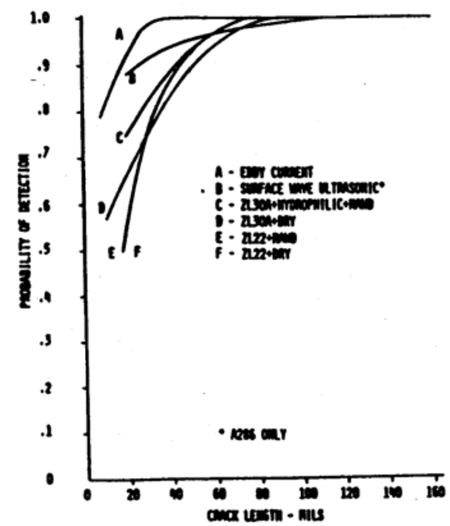
AEROSPACE INDUSTRY

- o US AIR FORCE PROGRAMS
  - AIRCRAFT STRUCTURAL INTEGRITY PROGRAM (ASIP)
    - Requirements defined in MIL-STD-1530A (USAF), issued in 1975
      - First applied rigorously to B-1 bomber
      - ASIP criteria have been applied to over 20 US military planes
  - DURABILITY AND DAMAGE TOLERANCE ASSESSMENT (DADTA)
    - Retrospective review of existing engines (initiated 1978)
  - ENGINE STRUCTURAL INTEGRITY PROGRAM (ENSIP)
    - Requirements defined in MIL-STD-1783 (USAF), issued in 1984

AEROSPACE INDUSTRY



Airframe data (early 1970's)



Engine data (late 1970's)

Typical 1970-period POD data

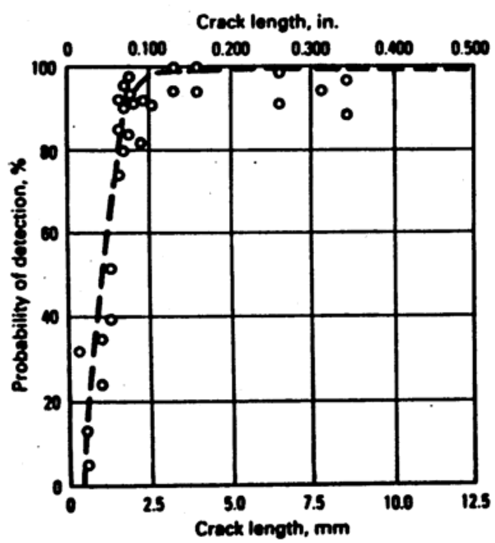
o **INDIVIDUAL MANUFACTURER PROGRAMS**

- **Interest grew in use of POD concepts for other purposes (1970's)**
  - **Comparison of effectiveness of two penetrants**
  - **Comparison of effectiveness of different NDE techniques**

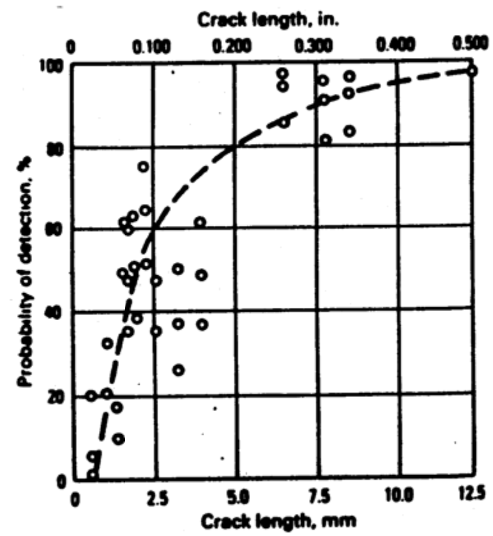
AEROSPACE INDUSTRY

- o **EARLY ANALYTICAL METHODS**
  - Early analyses based on binomial statistics
    - Each defect reported as "hit" or "miss"
    - Arbitrary averaging used to obtain smoothly increasing curves
  - ASNT Standard published in 1982 (now obsolescent)
    - POD for single flaw size and confidence level
      - Find 29 out of 29 defects to get 90% POD with 95% confidence
- o **USAF LED DEVELOPMENT OF NEW STATISTICAL METHODS**
  - Parametric regression techniques make better use of data
  - Incorporated in new MIL-STD for NDE Reliability Assessment (1993?)

AEROSPACE INDUSTRY



Eddy current inspection



X-ray inspection

328 cracks, lengths 0.3 to 18 mm, machined and etched surfaces

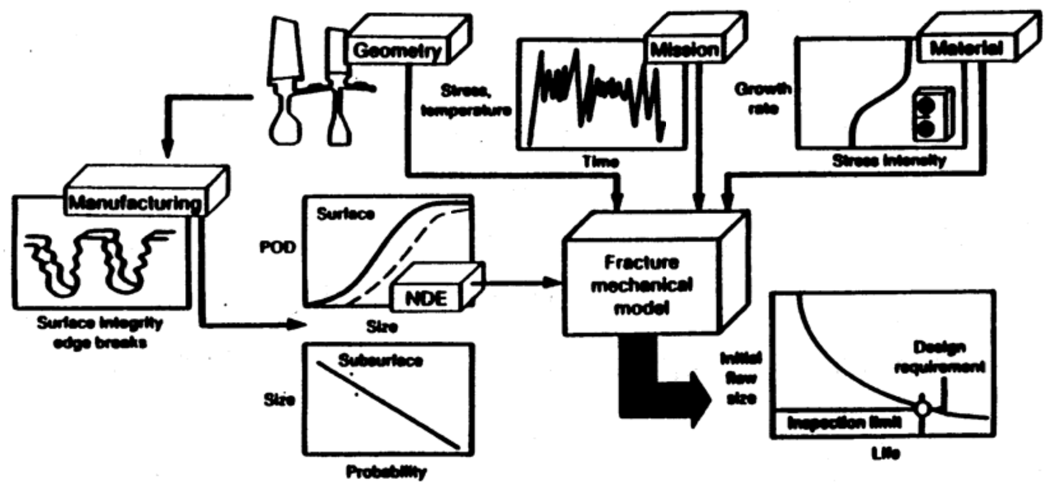
Typical format for current aerospace POD data

AEROSPACE INDUSTRY

- **DESIGN AND LIFING PHILOSOPHIES ARE CHANGING**
  - **"Durability" being replaced by "Damage Tolerance"**

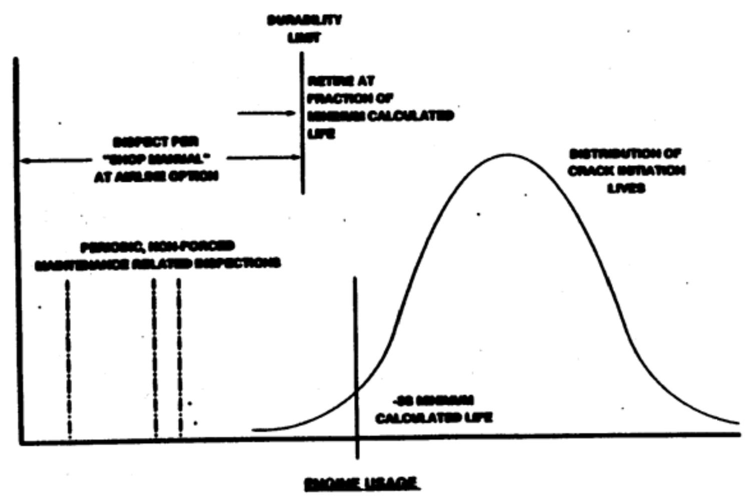
- **DAMAGE TOLERANCE**
  - **Ability of a structure to resist failure due to flaws or other damage for a specified period of unrepaired usage**
  - **Invokes fracture-mechanics and POD**
  - **USAF is encouraging this transition**
  - **FAA has recommended manufacturers to incorporate damage tolerance concepts (1990 Titanium Review Team Recommendations)**

AEROSPACE INDUSTRY



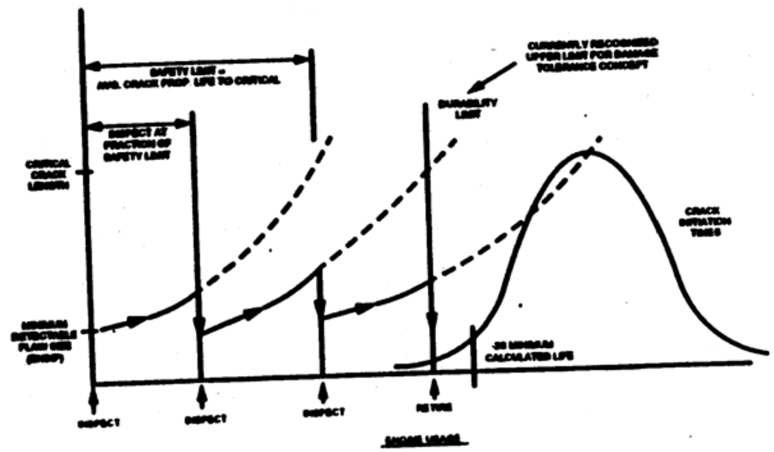
Outline of a fracture-mechanics model for life-management calculations

AEROSPACE INDUSTRY



- o **ROLE OF NDE IN DURABILITY DESIGNS**
  - **Design process does not invoke specific capability of NDE processes**
    - **Production parts are assumed to contain no (detectable) defects**
    - **Assumes no in-service damage (resulting in detectable defects) occurs**
  - **NDE is used during manufacture, as a check on process control**
    - **Capability is less important than repeatability and reproducibility**
  - **In-service "inspections of opportunity" are used as added safeguards**

AEROSPACE INDUSTRY



o **ROLE OF NDE IN DAMAGE TOLERANT DESIGNS**

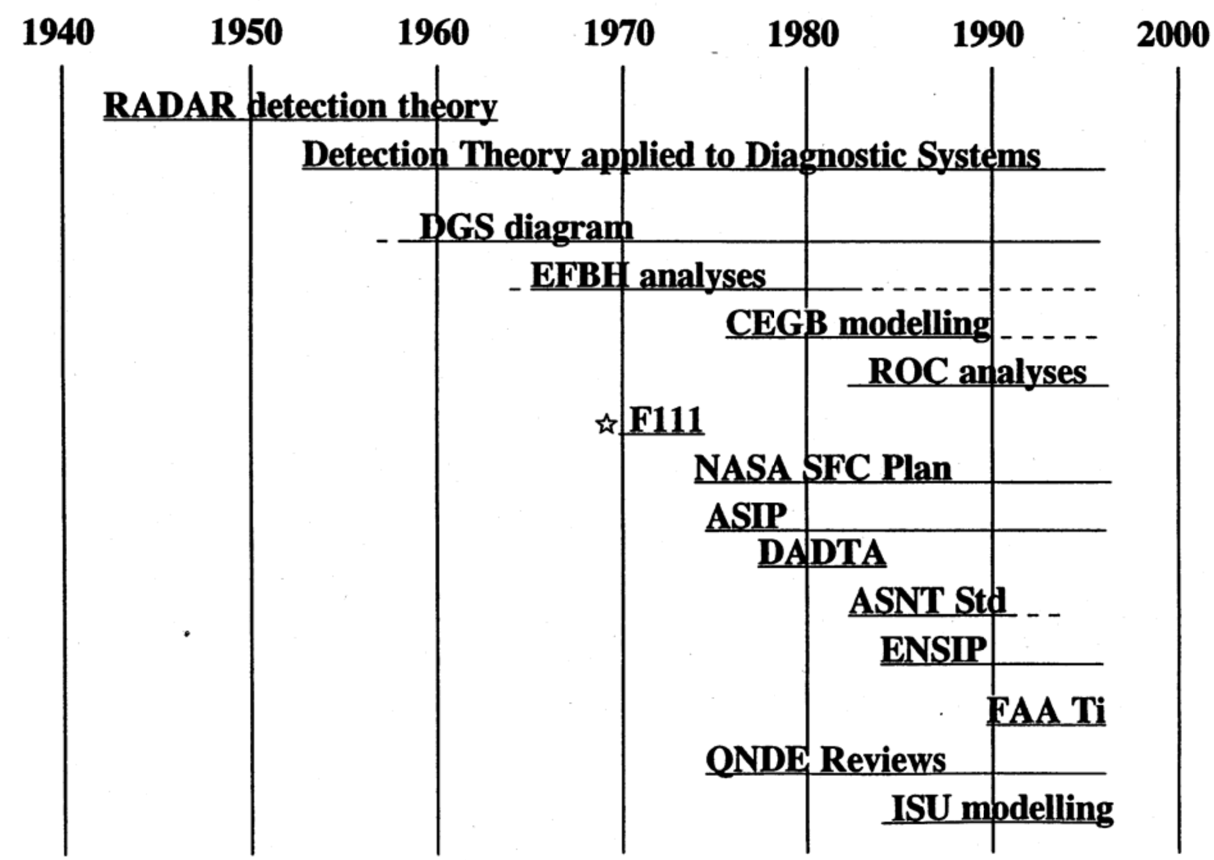
- Design process requires knowledge of capability of NDE processes
  - Inspected parts are assumed to contain defects (below detection limit)
- NDE is used during manufacture as a vital part of life-management process
  - Capability is expressed in terms of Probability of Detection
- In-service inspections are mandated at intervals set (in part) by POD

INTER-INDUSTRY PROGRAMS

- **REVIEW OF PROGRESS IN QUANTITATIVE NDE**
  - Started in 1974 under DARPA/AFWAL sponsorship
  - Currently organized by the ISU Center for NDE and Ames Laboratory
    - Cosponsored by ASNT, DOE, FAA, JHU, NIST, NSF, ONR, USAF
  - Numerous publications relating to Reliability, Capability, POD, etc.

- **POD MODELLING (ISU Center for NDE)**
  - Several studies of POD modelling published (since 1985)
    - Mostly for ultrasonic inspection
    - Work in progress on eddy-current and radiography models
  - Recent studies have also included ROC-type analyses

A PARTIAL CHRONOLOGY



SOME ISSUES TO BE ADDRESSED: STANDARDIZATION

- o **TERMINOLOGY**
  - Agreed definitions of specialized terms are needed
    - Words like Capability and Reliability are used loosely & interchangeably
    - Need to distinguish defect, process and human effects on detection

- o **PROCEDURES**
  - The only existing standard is obsolescent
  - The proposed new standard describes current technology, but ...
    - It concentrates on POD to the almost total exclusion of PFA
    - It is intended for use with simulated defects
    - Problems in relating simulated and natural defects are ignored

- o **GOVERNING ORGANIZATION**
  - ASNT? ... ASTM? ... EPRI? ... FAA? ... ISO? ... NASA? ... USAF?

SOME ISSUES TO BE ADDRESSED: METHODOLOGY

- o RANDOM SAMPLING
  - Samples should be selected randomly from our defect population
    - We are likely to use all the samples we have available!

- o POD ALONE OR WITH PFA?
  - POD-versus-size data ignore PFA
    - PFA is significant to overall life-cycle cost
  - POD-versus-PFA data (usually) ignore defect size
    - Defining detectable defect size is crucial in life-management

- o MEASURE SIGNAL DISTRIBUTIONS OR POD?
  - Basing POD on signal and noise relates NDE to existing detection theory
  - Empirical measurements of POD & PFA may be faster and more direct

SOME ISSUES TO BE ADDRESSED: MEASUREMENTS

- **REAL DEFECTS OR SIMULATED DEFECTS?**
  - Measuring POD with simulated defects gives POD for simulated defects
    - Need to validate simulated-defect data against natural-defect data

- **SUBSURFACE INSPECTIONS**
  - How do we tell if a natural subsurface defect has been missed?
    - An approximate method based only on detected defects has been proposed

- **CAPABILITY OR RELIABILITY?**
  - "Capability" data are often used to represent "Reliability"
  - Which is a better description of the inspection process?
    - One set of samples, one inspector, one set of process conditions
    - Various sample sets, inspectors, and process conditions

SOME ISSUES TO BE ADDRESSED: EXTENDING THE DATA BASE

- o **REDUCE THE COST OF DATA ACQUISITION**
  - **Detection is affected by numerous factors**
  - **POD must be redetermined if any change is made**
    - **Slow and expensive**
  - **Need a method to modify existing data bases**

- o **MODELLING OF INSPECTION PROCESSES**
  - **Modelling provides a basis for modifying POD data**
    - **Model defect properties and inspection process parameters**
  - **Models must be evaluated experimentally**
    - **Data for the modelled defect and the natural defect being modelled**

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