NASA/CP—2002-211682

Fifth Annual Workshop on the Application of Probabilistic Methods for Gas Turbine Engines

October 2002

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NASA/CP—2002-211682

Fifth Annual Workshop on the Application of Probabilistic Methods for Gas Turbine Engines

Proceedings of a conference cosponsored by the
FAA, U.S. Air Force, NASA, and the U.S. Navy
Westlake, Ohio
June 11–13, 2001

National Aeronautics and
Space Administration

Glenn Research Center

October 2002

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5th Annual FAA/Air Force/NASA/Navy Workshop on the Application of Probabilistic Methods for Gas Turbine Engines

NASA

Glenn Research Center

JUNE 11–13, 2001

U.S. AIR FORCE

Preface

We were pleased that you were able to attend the 5th Annual FAA/Air Force/NASA/Navy Workshop on the Probabilistic Methods for Gas Turbine Engines hosted by NASA Glenn Research Center and held at the Holiday Inn Cleveland West.

The history of this series of workshops stems from the recognition that both military and commercial aircraft engines are inevitably subjected to similar design and manufacturing principles. As such, it was eminently logical to combine knowledge bases on how some of these overlapping principles and methodologies are being applied. We have started the process by creating synergy and cooperation between the FAA, Air Force, Navy, and NASA in these workshops.

The recent 3-day workshop was specifically designed to benefit the development of probabilistic methods for gas turbine engines by addressing recent technical accomplishments and forging new ideas. We would like to thank you for your participation in the workshop, because you were the key in accomplishing our goals of minimizing duplication, maximizing the dissemination of information, and improving program planning to all concerned.

This CD Proceeding includes the final agenda, abstracts, presentations, and panel notes, plus the valuable contact information from our presenters and attendees. We hope that this CD Proceeding will be a tool to enhance understanding of the developers and users of probabilistic methods.

The fifth workshop doubled its attendance and had the success of collaboration with the many diverse groups represented including government, industry, academia, and our international partners. So, "Start your engines!" and utilize these proceedings towards creating safer and more reliable gas turbine engines for our commercial and military partners.

Further Inquiries

For additional information concerning the 5th Annual FAA/Air Force/NASA/Navy Workshop on the Application of Probabilistic Methods for Gas Turbine Engines or this electronic document please contact:

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Monday June 11th

7:00 AM—4:00 PM	Registration	Holiday Inn Corridor
7:30 AM—8:00 AM	**Coffee and Breakfast Fare**	**Holiday Inn Corridor**
8:00 AM—8:15 AM	Introduction	Victoria L. Briscoe, SAIC
8:15 AM—8:30 AM	Welcome	Dr. Arun K. Sehra, NASA GRC
8:30 AM—8:50 AM	Air Force Overview	Jeff Brown, Components Branch Wright-Patterson AFB
8:50 AM—9:10 AM	Navy Overview	Paul Zimmerman, Naval Air Systems Command
9:10 AM—9:25 AM	**Break**	**Holiday Inn Corridor**
9:25 AM—9:45 AM	NASA Overview	Jeff Rusick, NASA GRC
9:45 AM—10:05 AM	FAA Overview	Jorge Fernandez, FAA Engine & Propeller Directorate
10:05 AM—10:25 AM	SAE G–11, AIAA, PMC Overview	Suren Singhal, QSS Corporation, ABS
10:25 AM—10:40 AM	**Break**	**Holiday Inn Corridor**
10:40 AM—10:50 AM	Keynote Introduction	Dr. Arun K. Sehra, NASA GRC
10:50AM—11:40 AM	Keynote Address	Dr. A. K. Noor, Old Dominion Univ. BIO
11:40 AM—12:40 PM	**Lunch**	**Available at Hotel or local restaurants**
12:40 PM—1:10 PM	Overview of M.I.T. Gas Turbine Laboratory Robust Aerothermal Design Effort	David L. Darmofal, V. Garzon, V. Sidwell, F. Engelhardt, D. Frey, E. Greitzer, B. Hao, and I.A. Waitz, MIT ABS
1:10 PM—1:40 PM	Probabilistic Study of Fluid Structure Interaction	Dr. Rama S.R. Gorla, Cleveland State University, Dr. Christos C. Chamis and Shantaram S. Pai, NASA GRC ABS
1:40 PM—2:10 PM	Risk-based Probabilistic Approach to Aero-propulsion System Assessment	Mike T. Tong, NASA GRC ABS
2:10 PM—2:25 PM		Question & Answer

Agenda

Monday June 11th (Continued)

2:25 PM—2:55 PM	A Generalized Patched Response Surface Approach for Stochastic Nonlinear Mechanics Problems	Dan M. Ghiocel, STI ABS
2:55 PM—3:25 PM	NESTEM–QRAS: A Tool Estimating Probability of Failure	Dr.Vinod Nagpal, Dr. B.M. Patel, N&R Engineering; Vincent R. Lalli, Jeff Rusick and Dr. Shantaram S. Pai, NASA GRC ABS
3:25 PM—3:35 PM		Question & Answer
3:35 PM—3:45 PM	**Break**	**Holiday Inn Corridor**
3:45 PM—5:45 PM	Issues in Modeling System Reliability	PANEL CHAIR: Dr. Thomas A. Cruse, Consultant. PANELISTS: Mr. Charles Annis, Statistical Engineering, Dr. Jane Booker, Los Alamos Lab., Dr. Dave Robinson, Sandia National Lab., and Robert Sues, Applied Research Assoc., Inc.
5:45 PM—6:15 PM	**Break**	**End of Monday's Session**
6:15 PM—8:30 PM	Reception & Cash Bar	Holiday Inn Foyer—Pool Side

Agenda

Tuesday June 12th

7:00 AM—4:00 AM	Registration	Holiday Inn Corridor
7:30 AM—8:00 AM	**Coffee and Breakfast Fare**	**Holiday Inn Corridor**
8:00 AM—8:05 AM	Welcome Information	Victoria L. Briscoe, SAIC
8:05 AM—8:35 AM	A Probabilistic Approach to Anomalies In High Energy Turbine Discs	Richard S. J. Corran, Rolls-Royce, plc ABS.
8:35 AM—10:05 AM	Update on the FAA Turbine Rotor Material Design Program	Gerald R. Leverant, Craig McClung, Michael Enright, and Harry Millwater, Southwest Research Institute ABS
10:05 AM—10:15 AM	**Break**	**Holiday Inn Corridor**
10:15 AM—10:45 AM	Ceramic Inclusions in Powder Metallurgy Disk Alloys : Characterization & Modeling	Peter Bonacuse, US Army Research Lab, Pete Kantzos, Ohio Aerospace Institute, and Jack Telesman, NASA GRC ABS
7:00 AM—4:00 AM	Registration	Holiday Inn Corridor
7:30 AM—8:00 AM	**Coffee and Breakfast Fare**	**Holiday Inn Corridor**
8:00 AM—8:05 AM	Welcome Information	Victoria L. Briscoe, SAIC
8:05 AM—8:35 AM	A Probabilistic Approach to Anomalies In High Energy Turbine Discs	Richard S. J. Corran, Rolls-Royce, plc ABS.
8:35 AM—10:05 AM	Update on the FAA Turbine Rotor Material Design Program	Gerald R. Leverant, Craig McClung, Michael Enright, and Harry Millwater, Southwest Research Institute ABS
10:05 AM—10:15 AM	**Break**	**Holiday Inn Corridor**
10:15 AM—10:45 AM	Ceramic Inclusions in Powder Metallurgy Disk Alloys : Characterization & Modeling	Peter Bonacuse, US Army Research Lab, Pete Kantzos, Ohio Aerospace Institute, and Jack Telesman, NASA GRC ABS
10:45 AM—11:15 AM	Integrating the Probability of Burst Over a Volume	Richard S. J. Corran, and K. Pacey, Rolls-Royce, plc. ABS
11:15 AM—11:30 AM		Questions & Answer
11:30 AM—12:30 PM	**Lunch**	**Available at Hotel or local restaurants**
12:30 PM—1:00 PM	A Perspective on Reliability: Probability Theory and Beyond	Dr. Nozer D. Singpurwalla, The George Washington University; Dr. Jane Booker, Dr. Thomas R. Bement (posthumously), and Dr. Sallie Keller-McNulty, Los Alamos National Laboratory ABS

Agenda

Tuesday June 12th (Continued)

1:00 PM—1:30 PM	Probabilistic Analysis of Gas Turbine Components Using The New ANSYS Probabilistic Design System	Dr. Stefan Reh, ANSYS Inc. ABS
1:30 PM—2:00 PM	Probabilistic Analysis of a Stator Ladder Using ProFES	Alan C. Pentz, Naval Air Systems Command, and Mark A. Cesare, Applied Research Associates, Inc. ABS
2:00 PM—2:15 PM		Question & Answer
2:15 PM—2:25 PM	**Break**	**Holiday Inn Corridor**
2:25 PM—3:55 PM	Workshop on Probabilistic Design Confidence	PANEL CHAIR: Jeff Brown, Wright-Patterson AFB. PANELISTS: Johnny Adamson, Pratt & Whitney, Thomas Cruse, Consultant, and Paul Roth, G.E. Aircraft Engines
3:55 PM—4:00 PM	**(Head to Bus)**	**End of Tuesday's Session**
4:00 PM—4:30 PM	Travel on Bus	To NASA GRC
4:30 PM—6:00 PM	TOUR	Group breaks into small numbers to view the various technology labs.
6:00 PM—6:30 PM	Travel on Bus	Back to Holiday Inn

Agenda

Wednesday June 13th

7:00 AM—9:00 AM	Registration	Holiday Inn Corridor
7:30 AM—8:00 AM	**Coffee and Breakfast Fare**	**Holiday Inn Corridor**
8:00 AM—8:05 AM	Welcome Information	Victoria L. Briscoe, SAIC
8:05 AM—8:35 AM	Probabilistic Fatigue: Computational Simulation	Dr. Christos C. Chamis, NASA GRC ABS
8:35 AM—9:05 AM	The Prediction of Fatigue Life for Arbitrary Geometries from the Statistical Analysis of Plain Specimen Data	Duncan P. Shepherd, Defense Evaluation and Research Agency ABS
9:05 AM—9:35 AM	Durability and Fatigue of Composite Structures in Acoustic Environment	Levon Minnetyan, Clarkson University, and Qiuzhan Li, AlphaStar Corporation ABS
9:35 AM—10:05 AM	Transient Reliability of Ceramic Structures	Noel N. Nemeth, NASA GRC and Osama Jadaan, University of Wisconsin—Platteville ABS
10:05 AM—10:25 AM		Question & Answer
10:25 AM—10:40 AM	**Break**	**Holiday Inn Corridor**
10:40 AM—11:10 AM	Structural Life and Reliability Metrics-Benchmarking and Verification of Probabilistic Life Prediction Codes	Jonathan S. Litt, Army Research Lab-NASA GRC; Sherry Soditus, United Airlines; Robert C. Hendricks and Erwin V. Zaretsky, NASA GRC. ABS
11:10 AM—11:40 AM	Probabilistic Life and Reliability Analysis of Model Gas Turbine Disk.	Frederic A. Holland, Matthew E. Melis and Erwin V. Zaretsky, NASA GRC ABS
11:40 AM—12:10 PM	NASA-GRC Fatigue Crack Initiation Life Prediction Models	Vinod K. Arya, and Gary H. Halford, NASA GRC ABS
12:10 PM—12:25 PM		Question & Answer
12:25 PM—1:30 PM	**Lunch**	**Available at Hotel or local restaurants**
1:30 PM—2:00 PM	Some Important Math Stats For Results for Applied Probabilistics	Charles Annis, P.E., Statistical Engineering ABS

Agenda

Wednesday June 13th (Continued)

2:00 PM—2:30 PM	The Disparity Between Mechanistic and Empirical Modeling of Variability in Materials Damage Processes	Dr. Gary Harlow and Robert P. Wei, Lehigh University ABS
2:30 PM—2:40 PM		Question & Answer
2:40 PM—2:50 PM	**Break**	**Holiday Inn Corridor**
2:50 PM—3:15 PM	The Use of Probabilistic Methods to Evaluate the Systems Impact of Component Design Improvements on Large Turbofan Engines	Michael H. Packard, SAIC, ABS
3:15 PM—3:45 PM	A Stochastic-Fuzzy Inference System (StoFIS) for In-Flight Jet Engine Performance Diagnostics and Prognostics	Dan M. Ghiocel and Joshua Altmann, STI Technologies ABS
3:45 PM—4:15 PM	Probabilistic Design Methodology and Its Application to the Design of an Umbilical Retract Mechanism	Landon Onyebueke, Ph.D, and Olusesan Ameye, Graduate Student, Tennessee State University ABS
4:15 PM—4:45 PM	Probabilistic Reliability Validation of an Impeller Using DARWIN	Rick Nelson, Dr. Sandeep Muju and Jeff Lentz, Honeywell Aerospace Engines and Systems ABS
4:45 PM—5:05 PM		Question & Answer
5:05 PM—6:00 PM	High Level Panel	Panelists: AIR FORCE (Jeff Brown), ARMY (Pete Bonacuse), FAA (Jorge Fernandez), NASA (Jeff Rusick), and NAVY (Paul Zimmerman)
6:00 PM—ADJOURN!		

NASA Glenn Research Center Overview

June 11, 2001

Arun K. Sehra

Director of Aeronautics(Acting)

GLENN RESEARCH CENTER

at Lewis Field

Organization

Director - D. Campbell
Deputy Director – G. Barna*
Deputy Director for Operations - J. Earls
Assistant Deputy Director for Policy - J. Gaff
Chief Scientist - M. Goldstein

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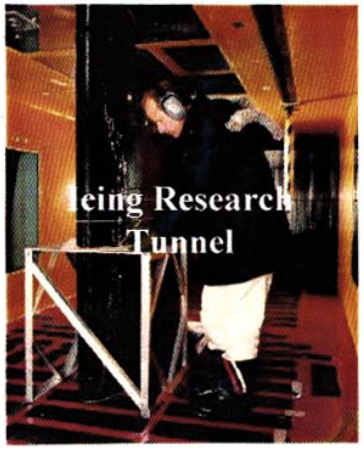
* Acting

GLENN RESEARCH CENTER

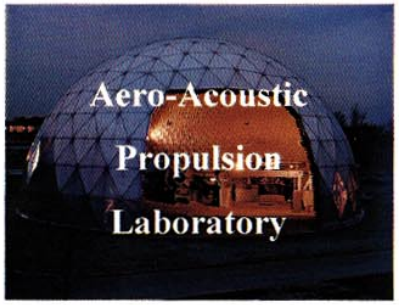
at Lewis Field

GRC Aeronautics Facilities

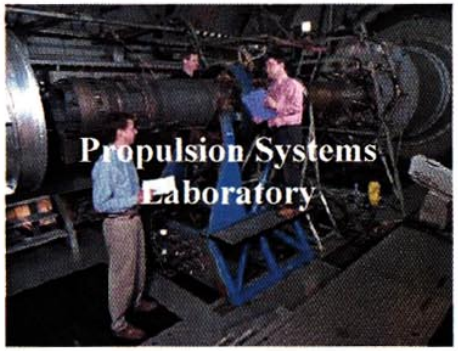
Eminent NASA Propulsion Subsonic, Transonic, Supersonic complex



World's Largest Refrigerated Icing Tunnel

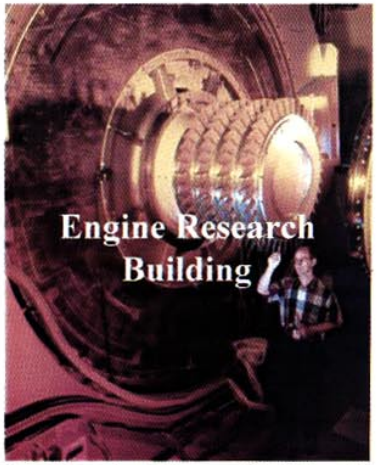


Nozzle Acoustic Test Rig
Powered Lift Rig



NASA's Only Full Scale Engine Altitude Facility

Clean Air Simulated

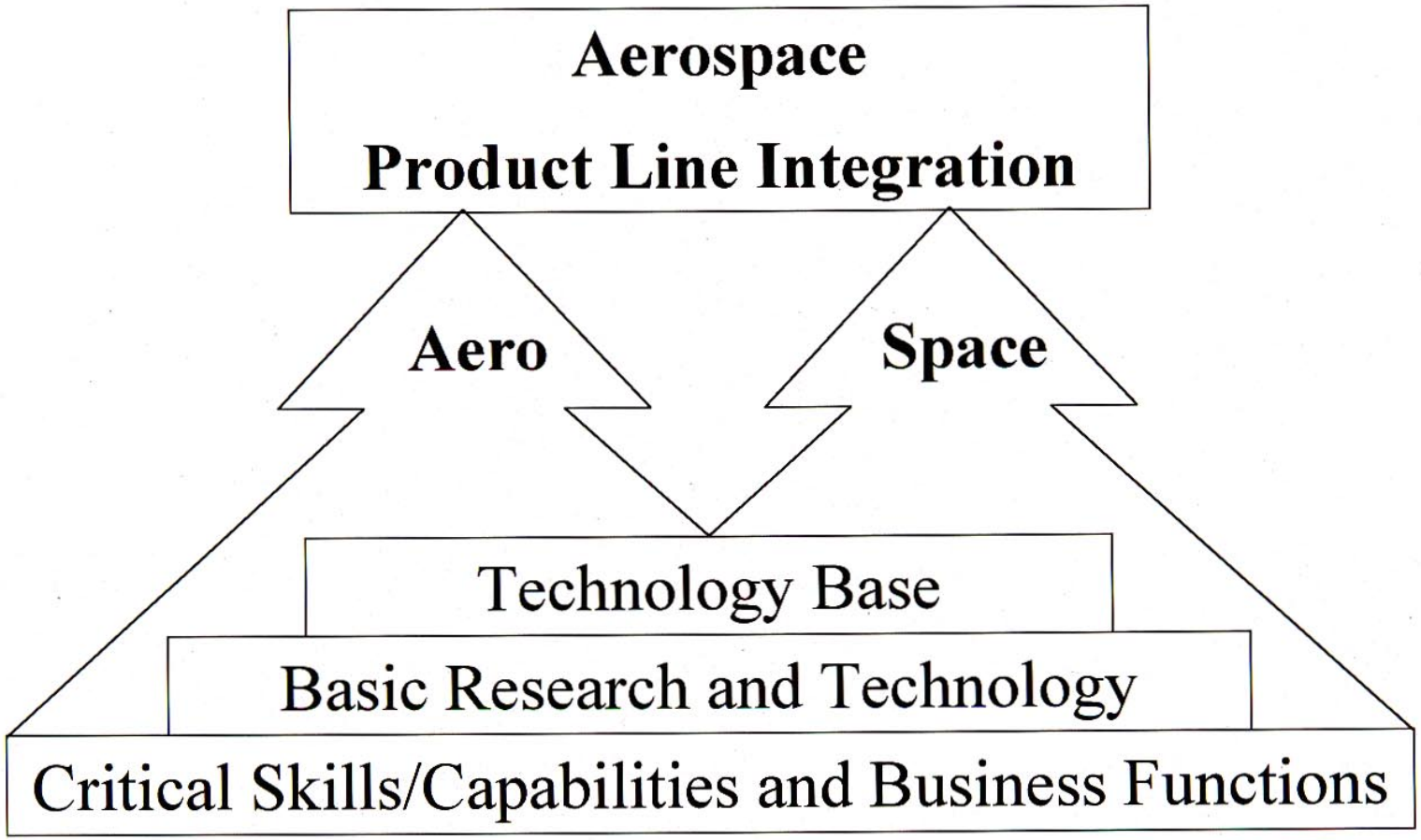


Thirty-six Versatile Engine Component Test Rigs

GLENN RESEARCH CENTER

at Lewis Field

GRC Technology



GLENN RESEARCH CENTER

at Lewis Field

NASA GRC Future Direction
Probabilistic Methods

Primary Thrust

- **Develop high fidelity probabilistic methods for:**
  - **Design (Aero-Thermo-Structural)**
  - **Manufacturing (casting, forging)**
  - **Life Prediction (HCF, LCF, Creep)**
- **Benchmark current and new methods with test data, and experience, working with industry, FAA, and DOD**
- **Advocate use of, and promote a better understanding of probabilistic methods via training, conferences, etc.**

CD-99-79907

NASA GRC Future Direction
Probabilistic Methods

Implementation Challenges

- **Cultural change**
  - A new way of thinking (uncertainty)
  - Design by analysis, validation by test
- **Developing guidelines for application, and extending to full life-cycle process**

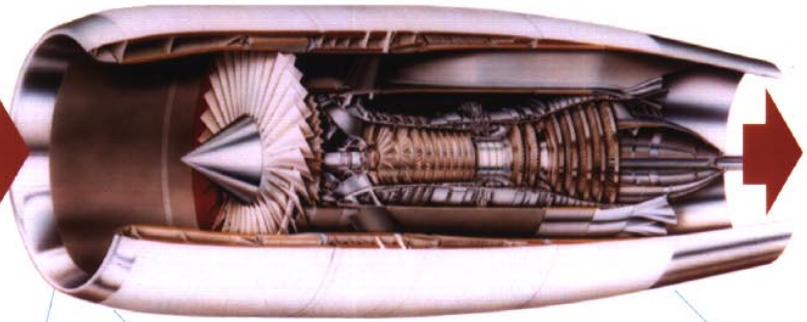
  Design *Life prediction* *Risk management*
- **FAA Certifiability**

CD-99-79910

Numerical Propulsion System Simulation (NPSS)

High Fidelity Validated Models

- Fluid Mechanics
- Heat Transfer
- Combustion
- Structural Mechanics
- Materials
- Controls
- Manufacturing
- Economics



Rapid Affordable Computation of:

- Performance
- Stability
- Cost
- Life
- Certification Req.

NPSS

Integrated Interdisciplinary Analysis and Design of Propulsion Systems

High Performance Computing

- Parallel Processing
- Expert Systems
- Interactive 3-D Graphics
- Networks
- Database Management Systems
- Automated Video Displays

A Numerical Test Cell for Aerospace Propulsion Systems

CD-99-79905

Probabilistic Research at the AFRL Turbine Engine Division

11 June 2001

5th Annual FAA/AIR Force/NASA/Navy Workshop on the Application of Probabilistic Methods to Gas Turbine Engines

Jeffrey M Brown

Lead Structural Analyst

Propulsion Directorate

Air Force Research Laboratory

PRT Probabilistics Vision

Vision

Use probabilistic analysis pragmatically to reduce weight and improve durability of turbine engine components

Process

- Evolve Industry standard work towards probabilistics
- Demonstrate probabilistics on fielded components
- Demonstrate probabilistics design on new designs
- Incorporate probabilistic design into ENSIP

PRT Activities
-Disks-

- Demonstrated successful application of probabilistics on actual designs (Pratt&Whitney & General Electric)
- Developed draft ENSIP Modifications (Pratt&Whitney)
- PRT did not aggressively pursue their transition to ENSIP
- We will aggressively transition them for the 2003 update
- Need to convince non-probabilistitians on validation
- Look to implement probabilistic disk design with IIT

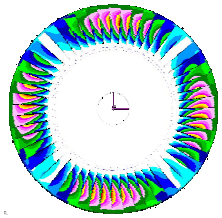
PRT Activities
-Blades-

- Developing Blade HCF design system(PW/GE/Honeywell/AADC/STI)
- Developed draft ENSIP Modifications (Dr. Tom Cruse)
- Modifications accepted into ENSIP for the 2000 update (Probabilistic Frequency Margin)
- Continue Design Process Development and Validation
- Implement probabilistic disk design with IIT

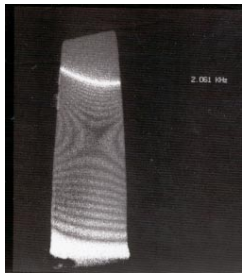
PRT Activities
-Engine Health Monitoring-

- EHM programs funded that use probabilistic to account for sensor data variation and degradation
- On-board life algorithms will be probabilistic
- Initiating Integration of probabilistic design research plans with EHM

Information Information Technology (IIT)



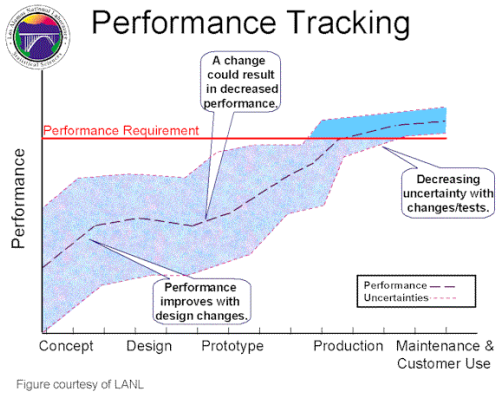
Analysis



Test

Expert Opinion

Integration of data



Updating Process

- IIT is a process for integrated, quantitative assessment of response under uncertainty
- Provides framework for an integrated probabilistic HCF reliability prediction

IIT

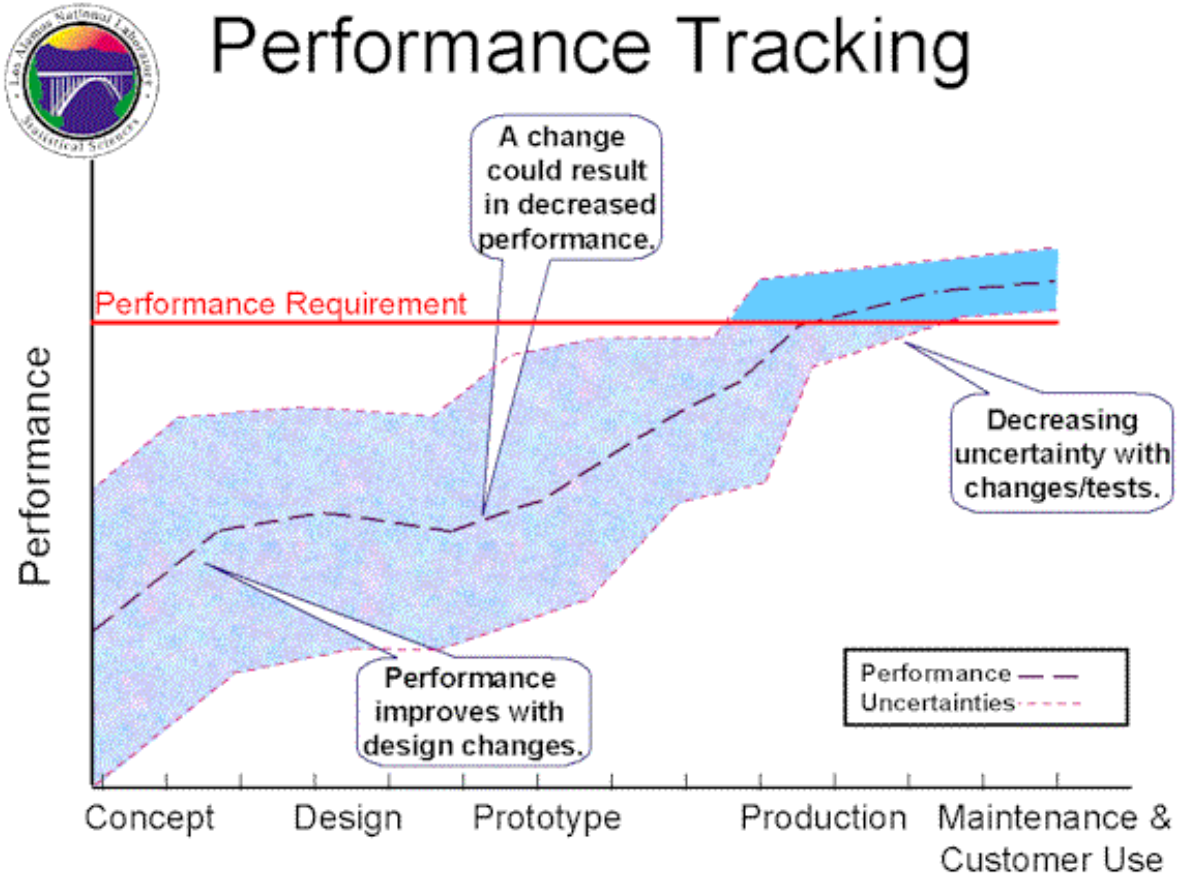


Figure courtesy of LANL

Keys Issues

- Accounting for uncertainty; bounds, intervals & confidence
- Demonstration and testing requirements for validation
- Determining proper application of statistical models and different probabilistic methods on real designs
- Convincing the non-probabilistitian
- Integration with EHM
- Transition to Industry standard work and ENSIP

Naval Air Systems Command Propulsion and Power Systems Probabilistics Overview

Presented to 5th Probabilistic Workshop

Paul Zimmerman

June 11, 2001

18 Months Ago
Jacksonville, FL

- Who we are;
- What we have been doing in the field of probabilistic design;
- Initial definitions for probabilistic terms;
- Our areas of concern for transitioning into Probabilistic Design of Life Limited Components;

Varying levels of progress on the terms and concerns

This Year's Workshop

- Reporting on progress in
  - System risk and reliability;
  - New analytical methods software;
  - Material studies (Composites, Ceramics, Powder);
  - Compressors, impellers, turbines and blades;
  - Burst, HCF, LCF, Anomalies;
  - Validation studies and Case studies;
  - Bridging the gap between the Probabilistic camps;

Observations

- Research of Probabilistic applications to the Rotor disk design has been on-going for nearly 20 years;

- RISC/FAA activities for Hard Alpha Inclusions have gone on for approx. 10 years;

- Development of Probabilistic Blade Design methods began approx. 2 years ago;

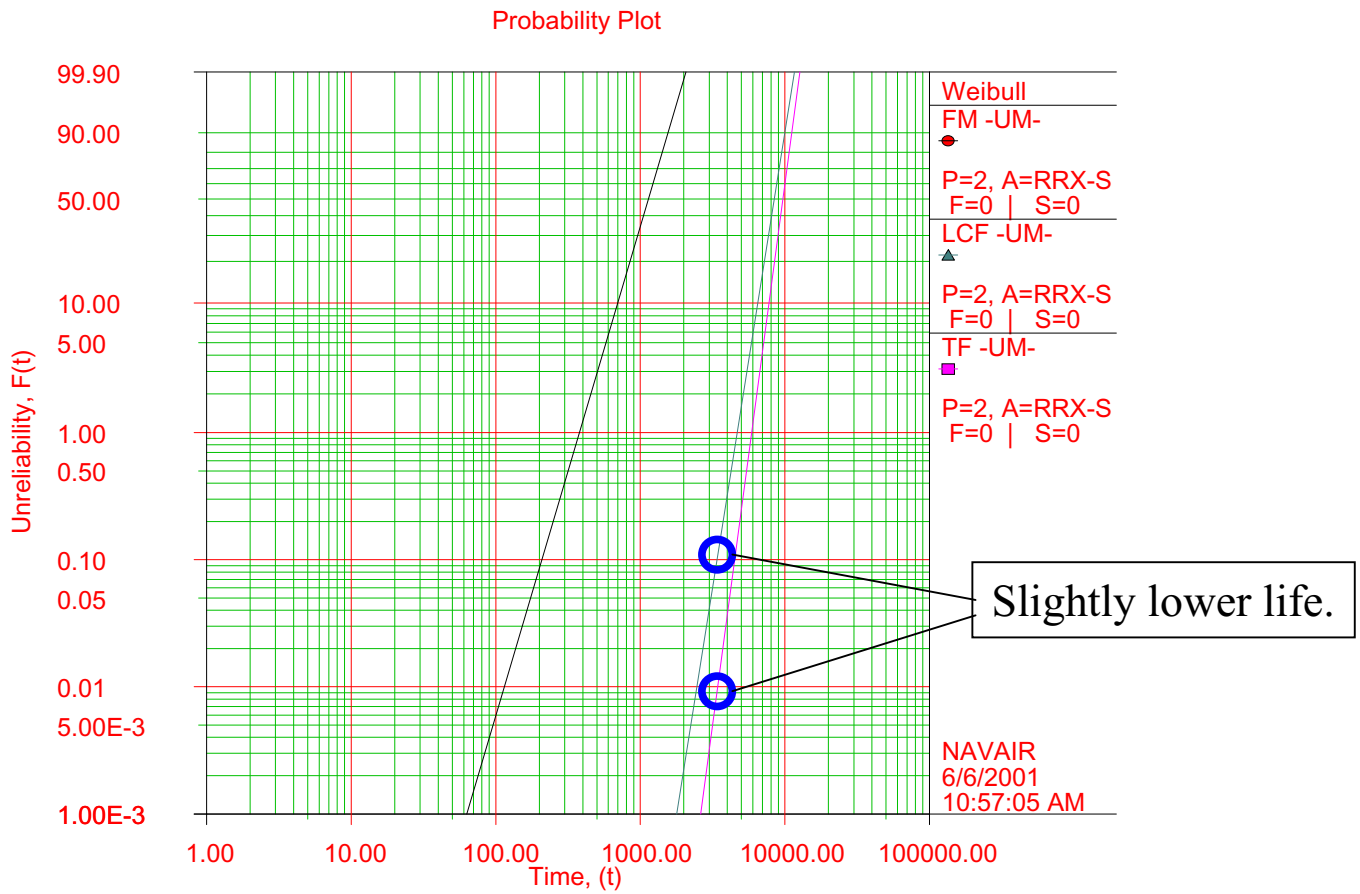
DILEMMA

The DoD is spending $$$ to develop a probabilistic blade design system … and we have not implemented the last probabilistic design system we paid to develop.

How does one justify spending more when we do not transition the technology we have today.

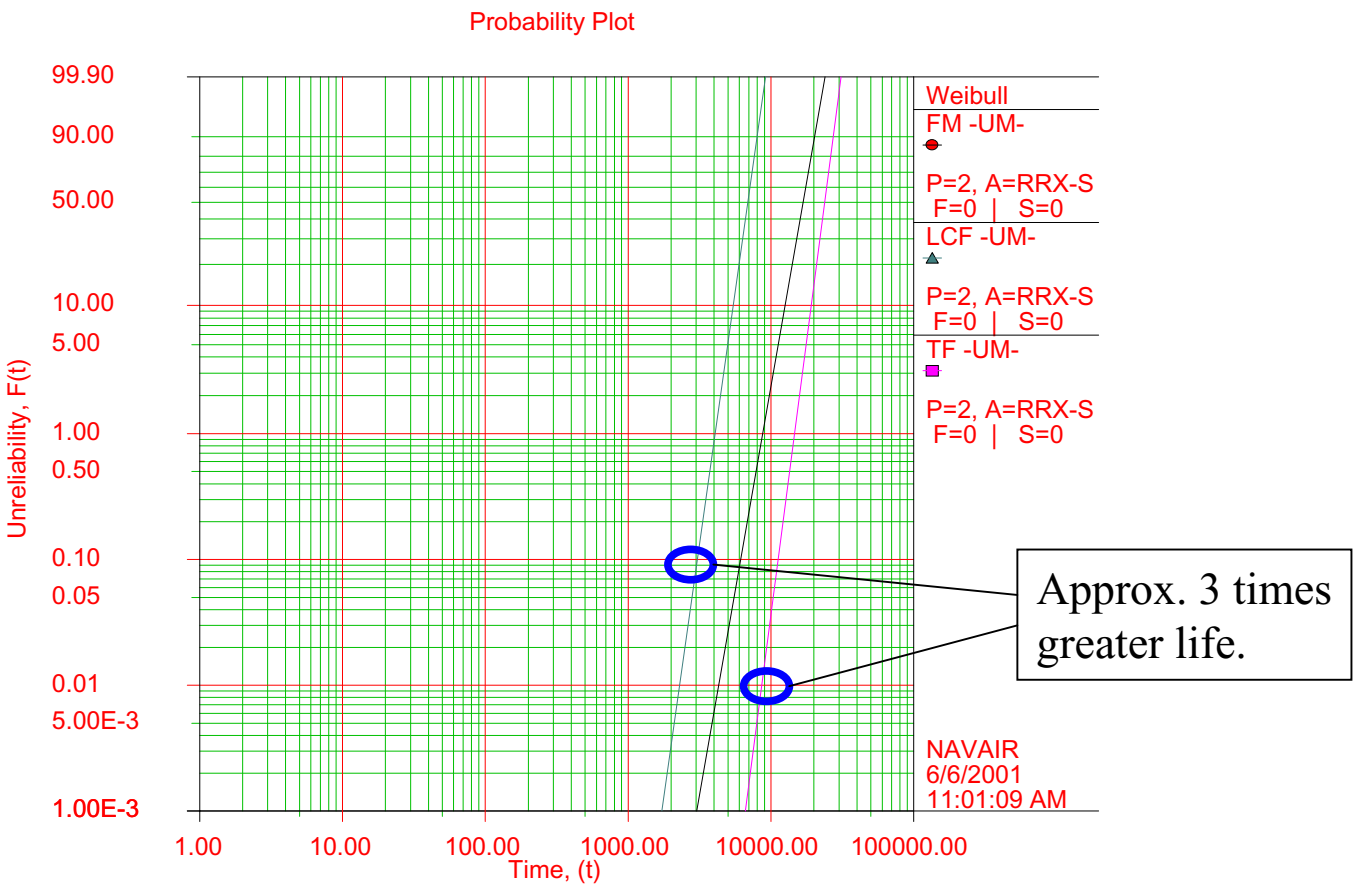
Probabilistics should help us to maintain/improve safety and reduce Total Ownership Costs. These are two of NAVAIR's Strategic Goals.

HOW



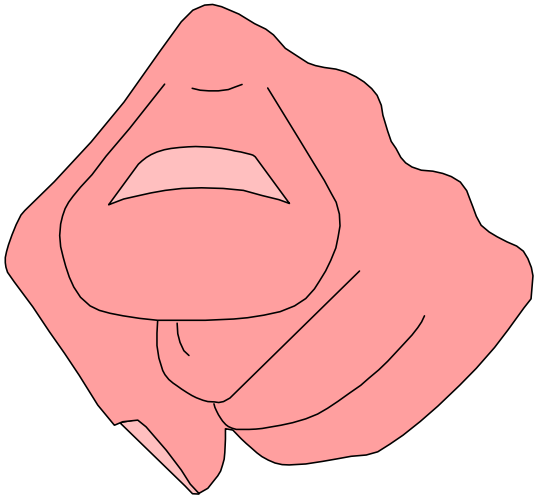
Results: Improved Safety

HOW (Cont.)



Results: Reduced Total Ownership Costs

THE NAVY's CHALLENGE
….. TO YOU!



☛ Update our present LCF life limits for the mature, fielded engines using probabilistic analysis methods;

☛Our field hardware should have sufficient data to validate/correlate your models.

☛ We are prepared to transition this old technology and make room for the new. **ARE YOU?**

NASA OVERVIEW

5th Annual NASA/FAA/Air Force/Navy Workshop
on the
Application of Probabilistics to
Gas Turbine Engines

DEFINITION OF RISK

RISK = LIKELIHOOD * SEVERITY

TYPES OF PROBABILISTIC (RISK) TOOLS

Knowledge-Based Design Synthesis, Similarity, Heritage

RAPTOR, RELEX

Probabilistic Risk Assessment (PRA)

QRAS, SAPHIRE

Probabilistic Design

NESTEM (FPI), PROB_ANSYS, PROFESS, UNIPASS, GENOA

Operations Risk Simulation / Visualization

ARENA / WORLD TOOLKIT

Risk Management / Structured Analysis

ORACLE / PREDICT

CURRENT NASA AEROSPACE TECHNOLOGY PROGRAM SUPPORT

Ultra Efficient Engine Technology/GRC/Joe Shaw $40 MIL

- **Michael Packard/SAIC, Use of probabilistic Methods to Evaluate the Systems Impact of Component Design Improvements on Large Turbofan Engines**
- Dr. Vinod Nagpal/N&R, Probabilistic Combustor Liner Structural Analysis
- Dr. Rama Gorla/CSU, Probabilistic CFD Combustor Liner Analysis

CURRENT NASA AEROSPACE TECHNOLOGY PROGRAM SUPPORT

BASE Propulsion and Power/GRC/Peter McCallum $94 MIL

- **Dr. David L. Darmofal/MIT, Overview of MIT Gas Turbine Laboratory Robust Aerothermal Design Effort**

- **Mike T. Tong/GRC, Risk-Based Probabilistic Approach to Aero-propulsion System Assessment**

- **Johnathan S. Litt/ARL, Structural Life and Reliability Metrics-Benchmarking and Verification of probabilistic Life Prediction Codes**

CURRENT NASA AEROSPACE TECHNOLOGY PROGRAM SUPPORT

Safety and Mission Assurance/GRC/Bill Wessel $47 MIL

- **Dr. Vinod Nagpal/N&R, NESTEM-QRAS: A Tool for Estimating Probability of Failure**

- **Vinod K Arya/GRC, NASA-GRC Fatigue Crack Initiation Life Prediction**

- Dr. Vinod Nagpal/N&R, Probabilistic GEAE Rotor Analysis
- Dr. Vinod Nagpal/N&R, Probabilistic RR Fan Blade
- Dr. Vinod Nagpal/N&R, Probabilistic Honeywell Blade Analysis

CURRENT NASA AEROSPACE TECHNOLOGY PROGRAM SUPPORT

Aviation Safety/LARC/GRC/Jaiwon Shin/Doug Rohn $70 MIL

- Dr. Shantaram Pai/GRC, Probabilistic Manufacturing, Casting and Forging

CURRENT NASA AEROSPACE TECHNOLOGY PROGRAM SUPPORT

Intelligent Synthesis Environment/LARC/ GRC (CANCELLED)

- **Dr. Jane Booker/LANL, PREDICT Modeling**
- **Dr. Rama S Gorla/CSU, Probabilistic Study of fluid Structure Interaction**
- Dr. Christos C Chamis/GRC, Probabilistic Equivalence Modeling

CURRENT NASA AEROSPACE TECHNOLOGY PROGRAM SUPPORT

Intelligent Synthesis Environment/LARC/GRC (CANCELLED)

- Jane Malin/JSC/EPOCH, Automated Functional FMEA
- Bob Shishko/JPL, Probabilistic Mars Rover and ISS Monte Carlo Simulations
- ARC, Futron, PRA of ISS
- LARC, Dynamic FTA Software
- John Olds/Georgia Tech, ROSETTA Monte Carlo RLV System Modeling
- Tracy Fredrickson/KSC, Visualization of Shuttle Ground Operations
- Tracy Fredrickson/KSC, ARENA Simulation OF Shuttle Ground Operations
- Tracy Fredrickson/KSC, PRA for Shuttle Ground Operations

FUTURE NASA AEROSPACE TECHNOLOGY PROGRAM SUPPORT

2nd Generation Reusable Launch Vehicle (RLV)/MSFC $475 MIL

"will substantially reduce technical, programmatic and business risks associated with developing a safe, reliable, and affordable RLV architecture"

"dramatically improve safety while significantly reducing the cost of launch services"

FUTURE NASA AEROSPACE TECHNOLOGY PROGRAM SUPPORT

Computing, Information, & Communication Technology (CICT)/ Design For Safety (DFS)/ARC $195 MIL

"dramatic change in how systems engineering and operations will be performed, placing risk estimation and risk countermeasures for overall mission and human safety on a more rigorous, explicit, and quantifiable basis. This would allow design trades to be evaluated based on risk factors…"

FUTURE PROBABILISTIC TOOLS AND APPLICATIONS

PAST

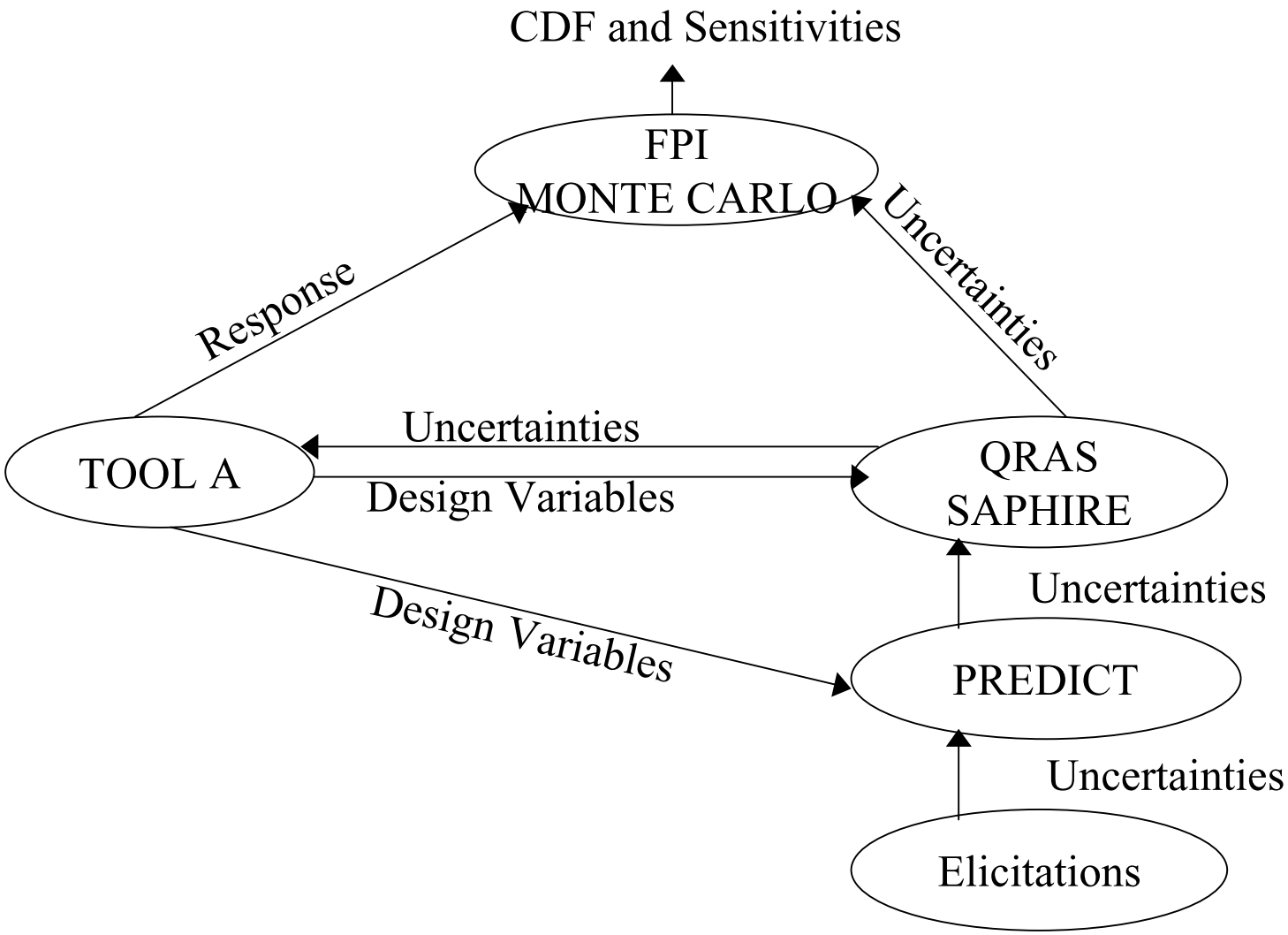
STAND-ALONE COMPUTER CODES / DETAILED DESIGN ANALYSIS
STRUCTURES / MATERIALS / LIFING

FUTURE EMPHASIS

INTEGRATED SOFTWARE ENVIRONMENT / CONCEPTUAL DESIGN
PROBABILISTIC PERFORMANCE
PROBABILISTIC MANUFACTURING
PROBABILISTIC CFD
PRA / SAFETY / REQUIREMENTS ANALYSIS
PRA / RELIABILITY

PROBABILISTIC TOOLS

PROPOSED APPROACH



EMPHASIS ON COMPLETE LIFE CYCLE PROCESS

- REQUIREMENTS PHASE
- CONCEPTUAL DESIGN
- PRELIMINARY DESIGN
- DETAILED DESIGN
- MANUFACTURING
- OPERATIONS

CULTURAL CHANGES REQUIRED FOR SUCCESS

•SAFETY AND RELIABILITY PROCESSES INTEGRATED WITH THE EARLY DESIGN PROCESSES

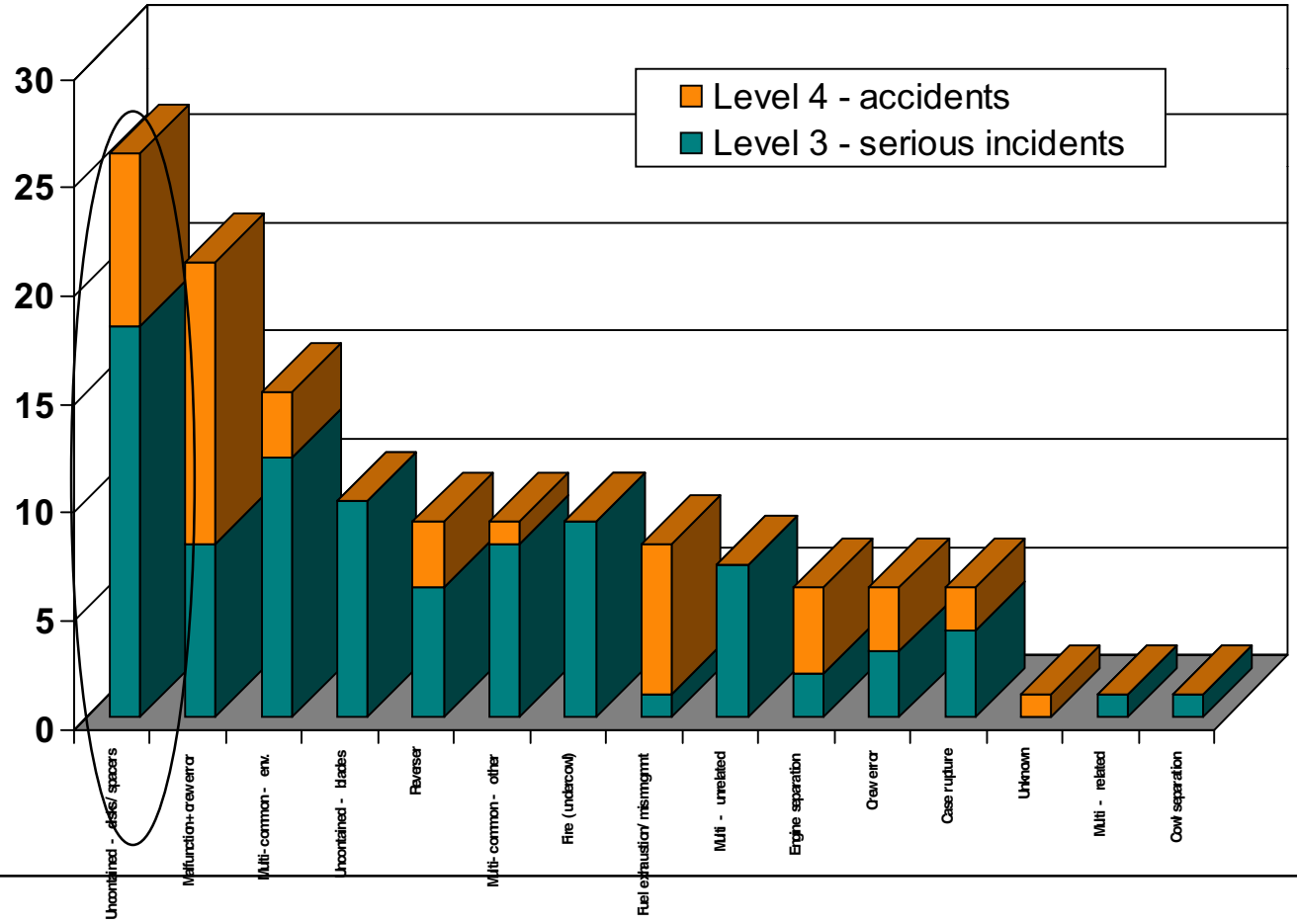
•UNCERTAINTIES QUANTIFIED AND ASSESSED OVER ALL THE LIFE CYCLE PHASES

•INTEGRATED SOFTWARE ENVIRONMENTS WHICH INCLUDE PROBABILISTIC CAPABILITIES

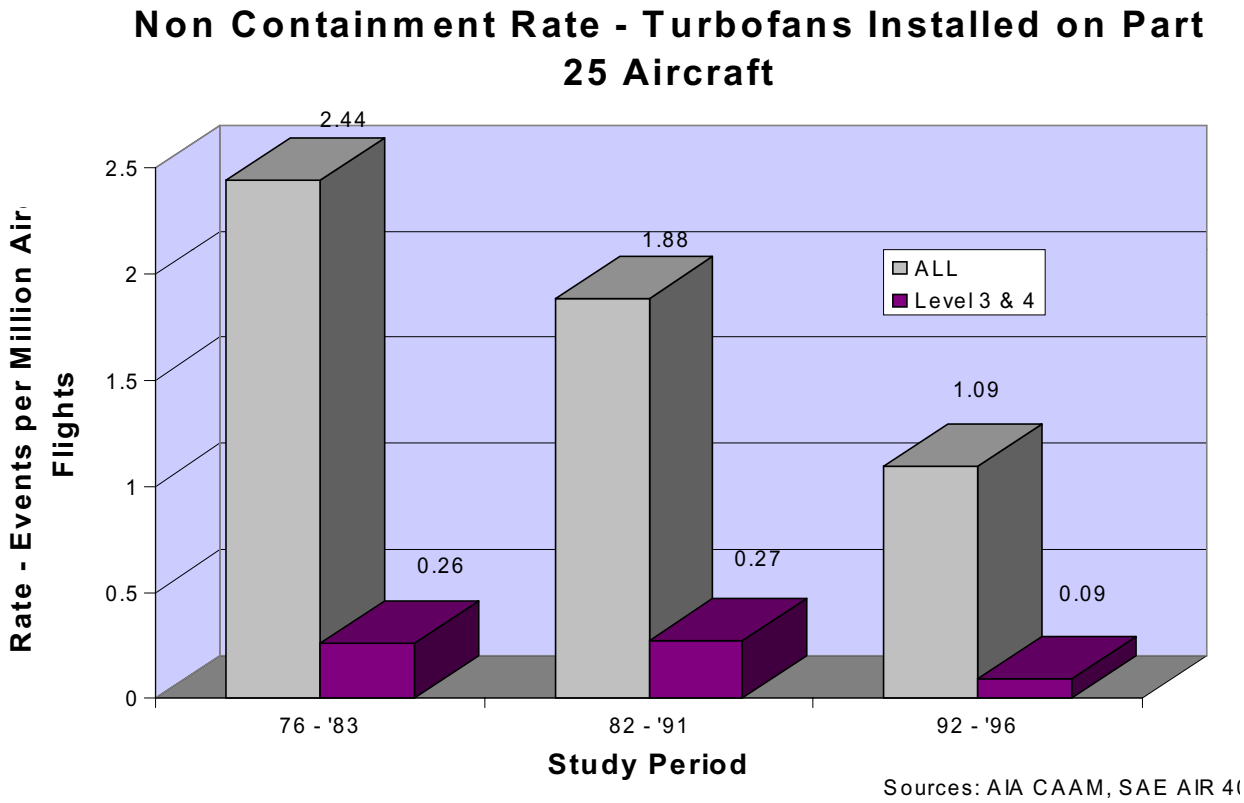
FAA/USAF/NASA/NAVY Workshop on the Application of Probabilistic Methods to Gas Turbine Engines

Jorge Fernandez
ANE-102
781-238-7748

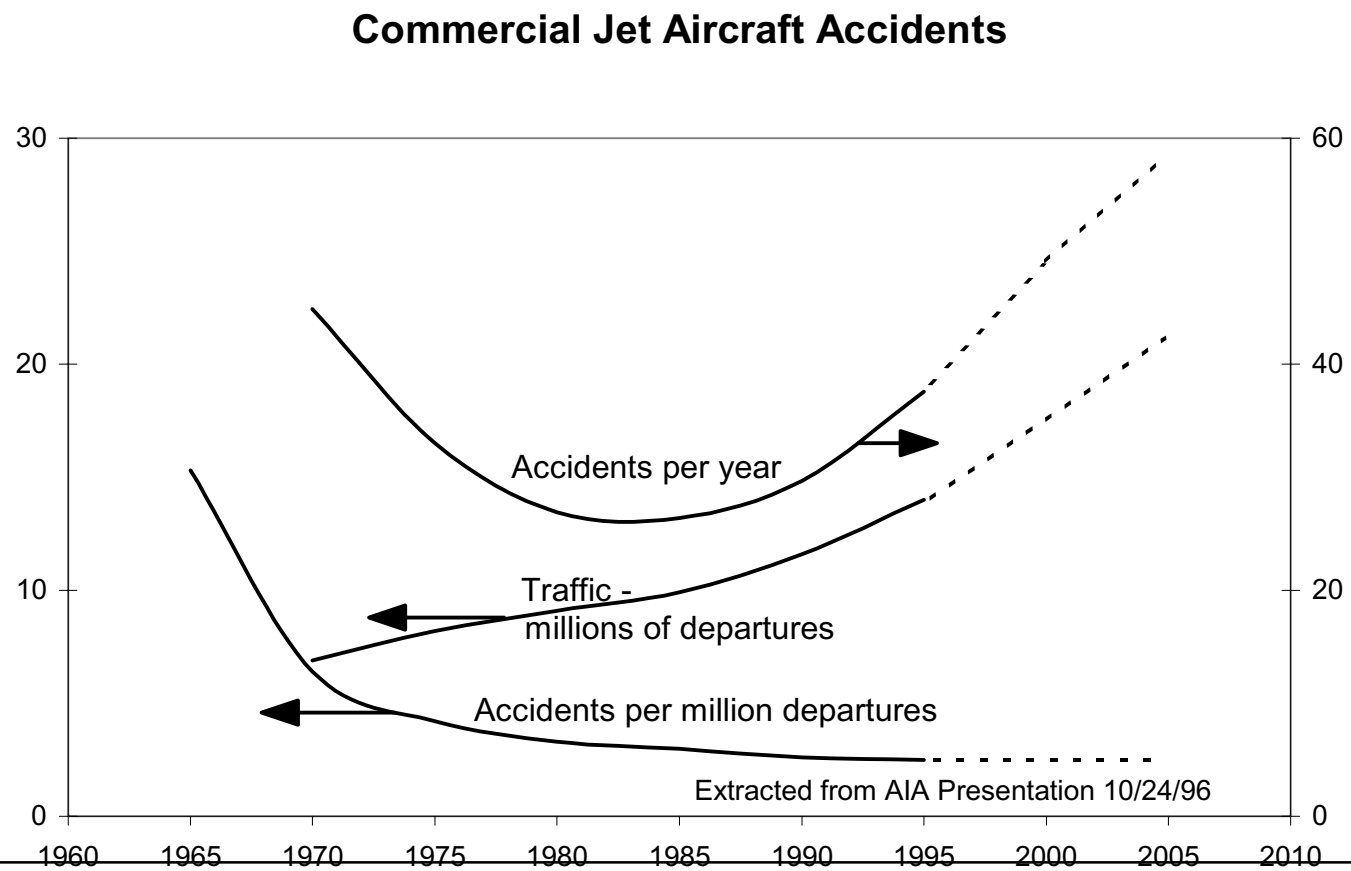
Turbofans Installed on Part 25 Aircraft



Non Containment History



Usage Drives Safety Requirements



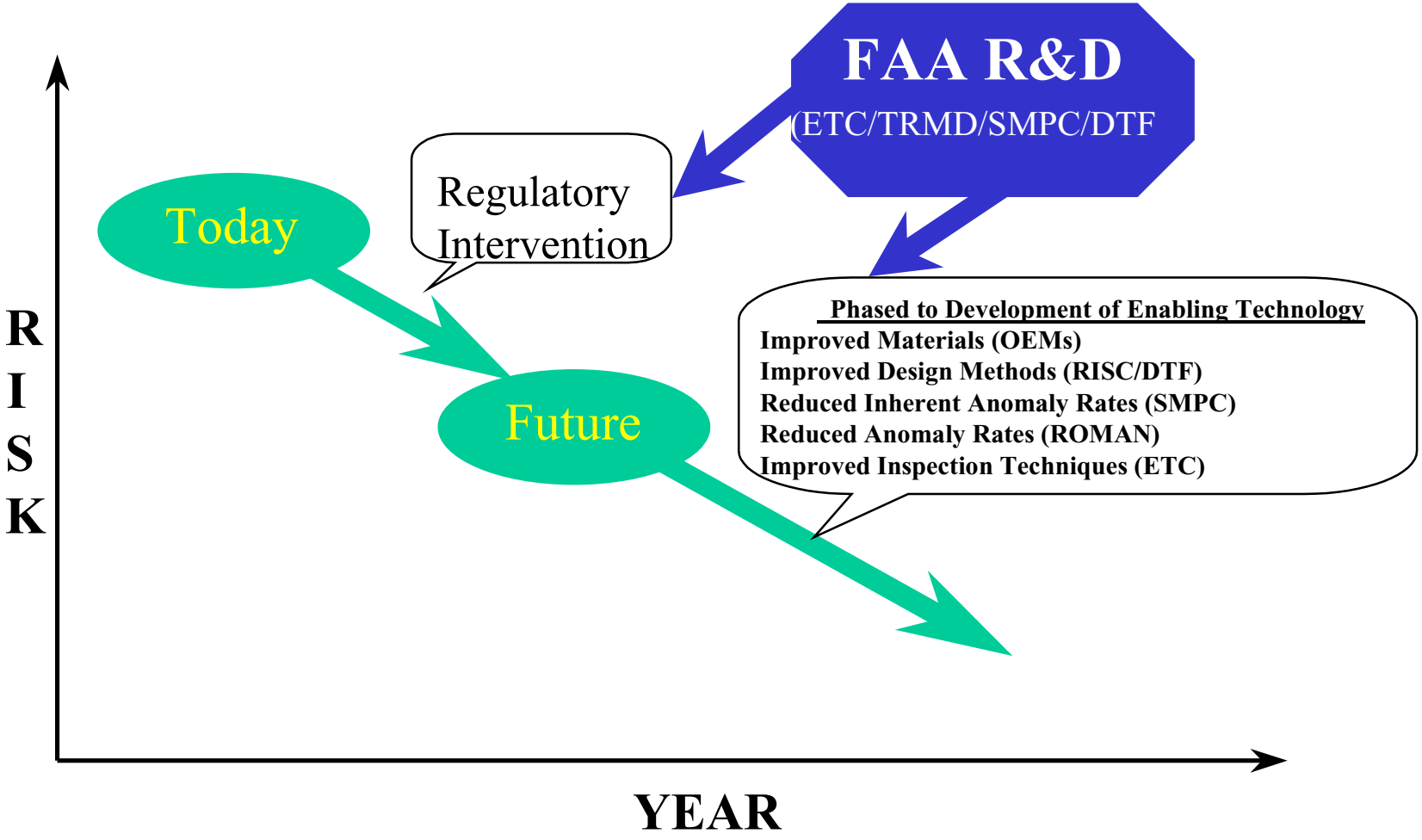
FAA CHALLENGE

- Current uncontained failure rate, that can significantly hazard the aircraft, is 1 event per 10 million flights.
- Uncontained failure rate, although decreasing, needs further improvement due to increased aircraft population growth.
- Causal factors encompass design, manufacturing, and operation.

FAA/Industry Initiatives

- FAA&Engine Manufacturers recognize the need to address the potential for unanticipated anomalies, and to adopt a Damage Tolerance (DT) philosophy.
- AIA Rotor Integrity Subcommittee (RISC) assist FAA in developing and implementing the DT philosophy.
- Turbine Rotor Material design (TRMD) R&D program is developing the DT design code (DARWIN).

FAA Objectives - Linkage to R&D



Conclusion

- Further reduction in critical rotating part failures is needed
- FAA / Industry sponsored initiatives and R,E&D provide the foundations for improving integrity and durability of engine critical rotating components.
- FAA/DOD/NASA Partnerships can leverage resources to meet ultimate mutual goals

SAE G-11, AIAA, PMC OVERVIEW

Suren Singhal
QSS Group, Inc.
Cleveland, Ohio 44135
Phone: 216–977–1433
Email: ssinghal@grc.nasa.gov

Suren Singhal will focus on (1) the need, implementation issues, challenges, and order-of-magnitude cost & time saving benefits of implementing nontraditional approach in our industries and government agencies, (2) the need for training in academic institutions as well as within the industry and government agencies, and (3) the systems perspective for enabling mission-reliable, risk-averse, and safe yet economically-viable and internationally-competitive engineering practice in routine as well as highly complex strategic systems. Examples of already accrued benefits by using probabilistic approaches will be presented. The discussion will be linked with the role of professional societies. The discussion will include the genesis, progress, status, and future plans of the SAE G-11 Reliability, Maintainability, Supportability, and Logistics (RMSL) Division and especially the Probabilistic Methods Committee (PMC). The PMC comprises more than one hundred industry, government, and academia engineers, scientists, managers, and professors. Some of the best professionals known nationally and internationally are actively involved in the PMC. They are working on documents including: (1) state-of-the-art probabilistic methods and software tools, (2) applications such as those for airworthiness, design, and manufacturing, (3) barriers to implementation of probabilistic methods, (4) legal issues in real-life applications, etc. The discussion will include the role and activities of the PMC co-group, the PM Leadership Council comprising of senior executives from industry, government, and academia. The AIAA activities in the area of non-deterministic approaches will also be presented. The discussion will conclude with recommendations for a national agenda to fully realize the potential of nontraditional approaches in engineering and non-engineering economies.

SAE G-11, AIAA, PMC Overview

by Suren Singhal on behalf of all G-11 Members

Presented at The 5th Annual FAA/Air Force/NASA/Navy
Workshop on the Application of Probabilistic Methods
for Gas Turbine Engines
Westlake, OH; June 11, 2001

The Engineering Society for Advancing Mobility
LAND – SEA – AIR - SPACE

Reach for the Full Potential

Outline

- Introduction
- SAE Activities
- AIAA Activities
- Other Professional Activities
- Conclusions & Recommendations

Introduction

- Issue, Proven Solution, Challenges
- Examples
- Systems Perspectives
- Role of Professional Societies

Professional Societies Serving the Community Needs

Issue

Global competition and the state of U.S. national budget mandate the need for new innovative ways of increasing efficiency with **real and measurable cost reduction.**

Proven Solution

Some form of probabilistic engineering is currently being used by some U.S. corporations, resulting in billions of dollars of **real and measured savings.**

A sample use of probabilistic engineering by U.S. Air Force has demonstrated savings of millions of dollars.

THE TIME IS RIGHT FOR PROBABILISTIC ENGINEERING

Challenges

- Today's Safety Factor Approach
- Show me the proof
- Training, tools, certification
- Barriers, legal issues

Paradigm shift is easier said than adopted

EXAMPLES OF PROBABILISTIC ENGINEERING WITH DEMONSTRATED COST SAVINGS

- Fighter wing --- REDUCED WEIGHT BY 15% (Northrop-Grumman)
- Bird strike on aircraft engine ---SAVED LIVES (Lockheed-Martin)
- Aircraft cooling duct fabrication --- SAVED $500K (P&W)
- Space Shuttle docking module --- REDUCED TESTING COST FROM $500K TO $50K (Boeing-Rockwell)
- PE-based Design for Six Sigma --- MOTOROLA SAVED $11B and GE ON THE WAY TO SAVE $8B

Probabilistic engineering is for real with proven order of magnitude savings. Expect > 1 to 10 cost to benefit payoff!!

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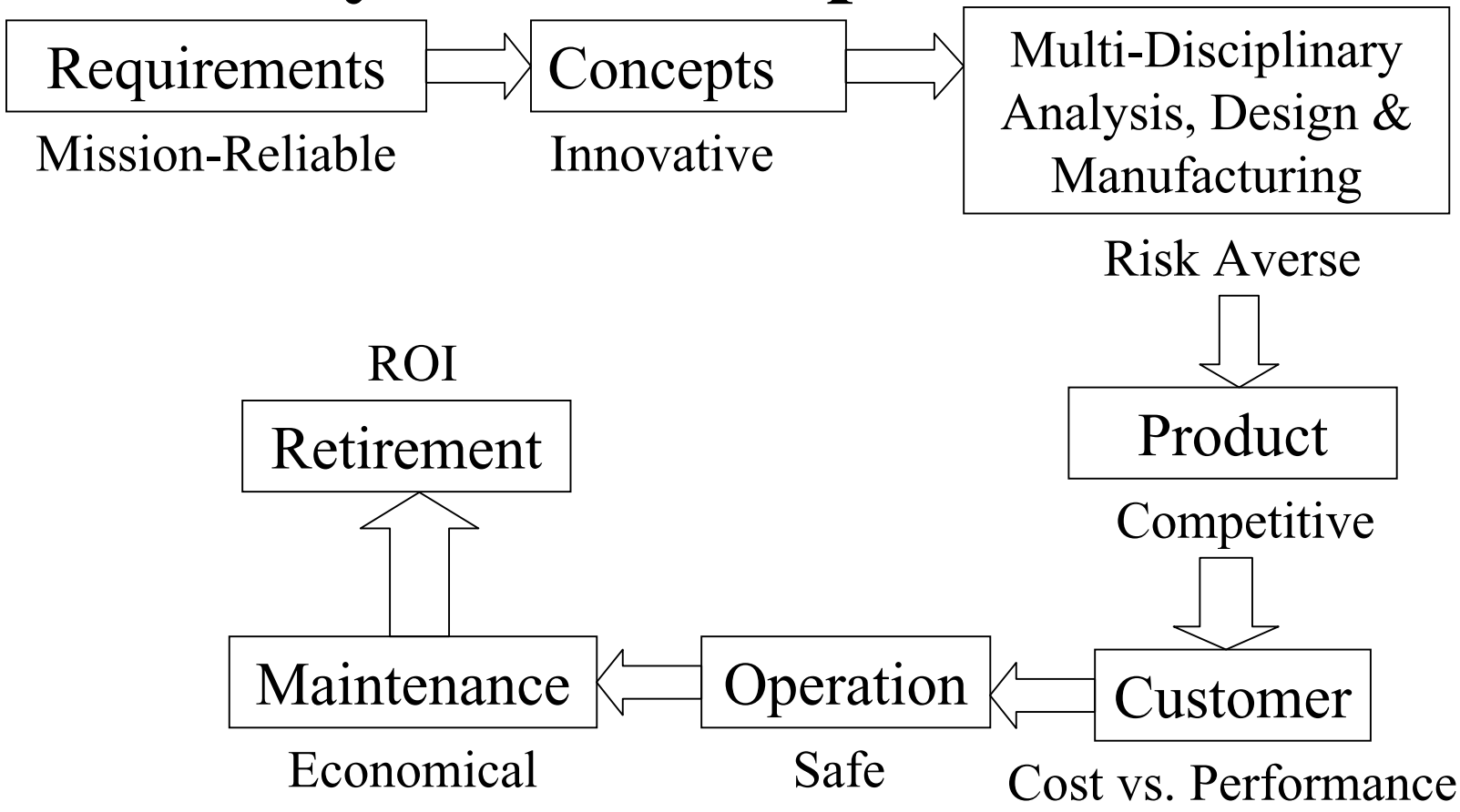
Systems Perspective



Uncertainties are inherent in every step

backup

Role of Professional Societies

- **Awareness**
- **Understanding**
- **Resources**
  - ***Tools**
  - ***Training**
  - ***Experts**
- **Implementation**

Professional societies can be the catalyst in bringing people & new ideas together

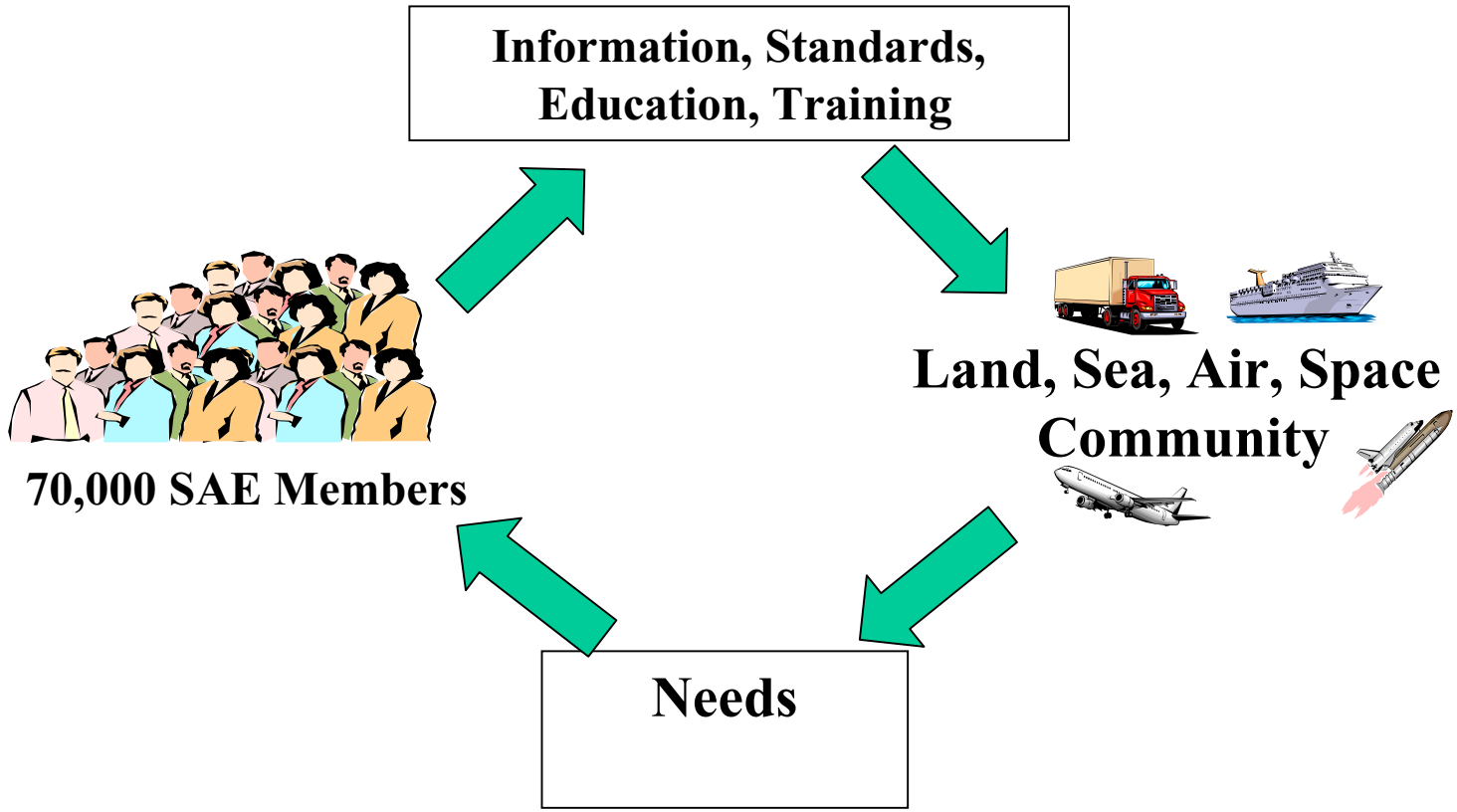
SAE G-11 Activities

- RMSL Division
- Probabilistic Methods (PM) Committee
- PM Leadership Council

SAE G-11 Web site:
http://forums.sae.org/access/dispatch.cgi/TEAG11PM_pf

RMSL
Division

Why Are We Here?

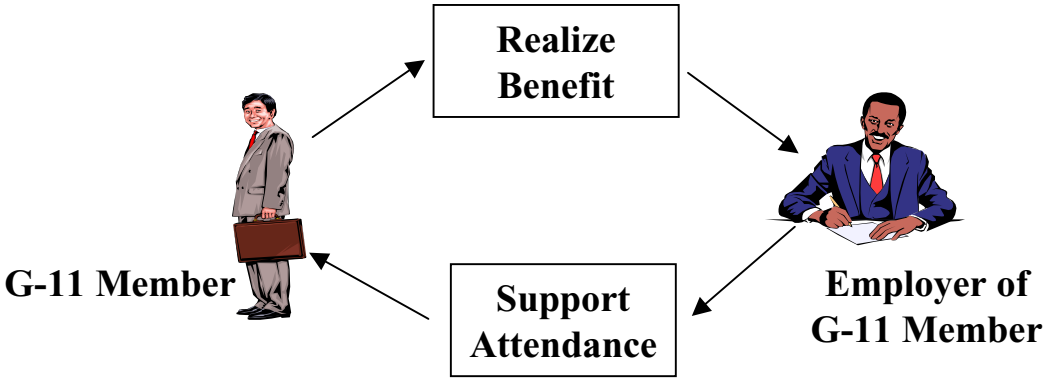


Serving the Engineering Community

RMSL
Division

Why Are We Here?

- Industry, govt., academia face-to-face
- How does your organization compare?
- What are the best practices?
- Technology interchange and networking
- Access to information and resources
- Partnership with some of the best in the business



RMSL
Division

How do We Work?

Deliver results to individual organizations

Develop projects and partnership teams

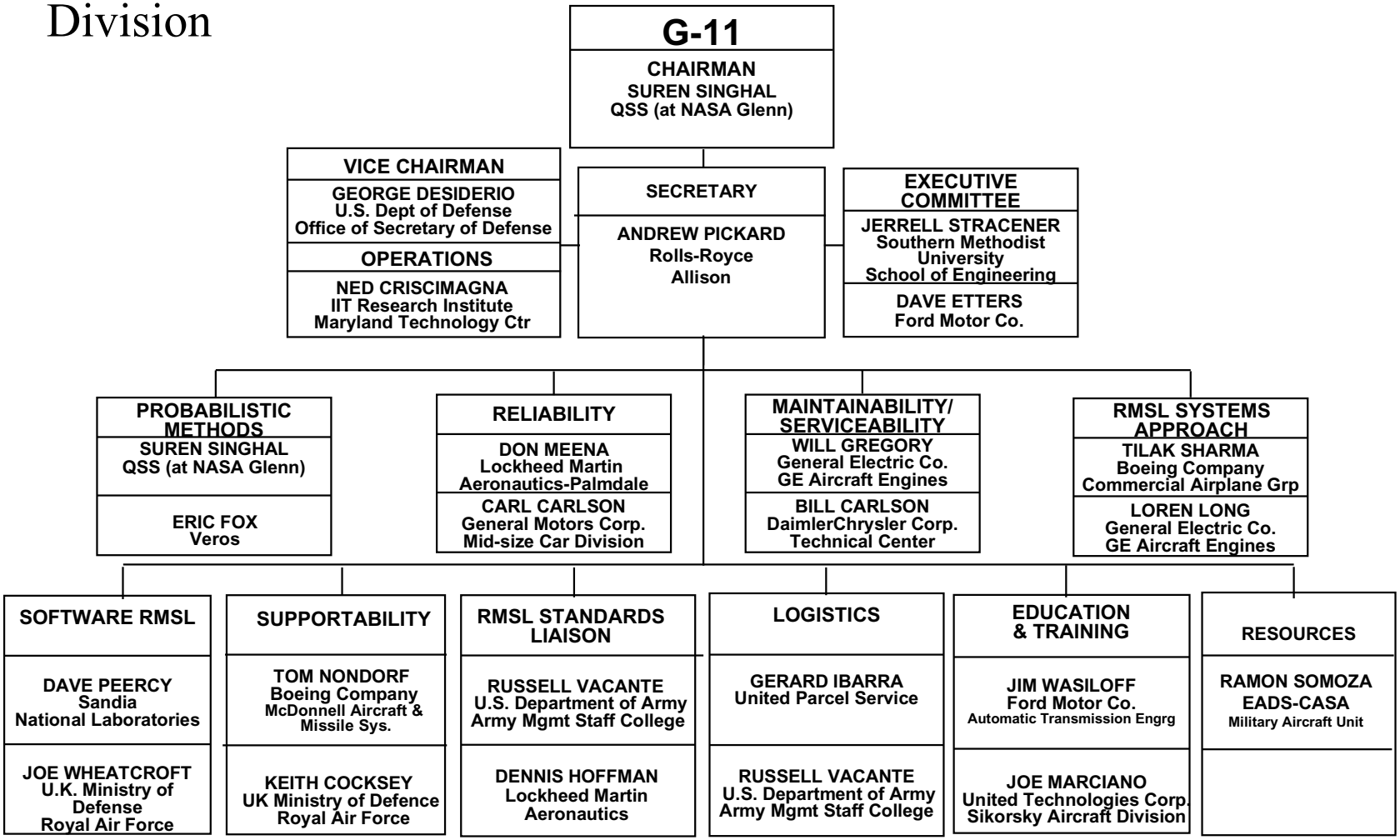
Understand needs of Industry and individual organizations

- Division meets twice a year
- Committee/Project Leaders conduct telecons

Delivering to the Engineering Community

RMSL Division

ORGANIZATION



Dynamic Organization Based on Members & Projects

backup

RMSL
Division

What Have We Done So Far?

- Published resource documents, information reports, standards and guidelines on RMSL & PM
- Conducted Workshops
- Facilitated significant industry, government and academia interaction
- ----------

The G-11 Members Keep Making a Difference

RMSL Division

Preliminary List of Publications Issued (Available from SAE – 724-776-4841)

	Title	Publ.	Product Code	Sponsor
1	"Evaluation Criteria for Reliability Centered Maintenance (RCM) Processes"	8/99	JA1011_199908	TEAG11SL (Chair: D. Netherton)
2	"Software Support Concept"	6/99	JA1006_199906	TEAG11 (Chair: D. Peercy)
3	"Reliability Program Standard Implementation Guide"	3/99	JA1000/1-199903	TEAG11R (Chair: D. Elters)
4	"Perceptions and Limitations Inhibiting the Application of Probabilistic Methods"	12/98	AIR5086	TEAG11PM (Chair: C. Pomfret)
5	"Software Reliability Program Standard"	7/98	JA1002_199807	TEAG11SW (Chair: D. Peercy)
6	"Software Supportability Program Implementation Guide"	7/98	JA1004_199807	TEAG11SW (Chair: D. Peercy)
7	"Reliability Program Standard"	6/98	JA1000-199806	TEAG11R (Chair: D. Elters)
8	Probabilistic methods, A Joint Industry/Government/Academia Assessment of Needs and Goals"	10/97	ARD050047	TEAG11PM (Chair: S. Singhal)
9	"Software Supportability – An Overview"	1/97	AIR5121	TEAG11SW
10	"Integration of Probabilistic Methods into the Design Process"	1/97	AIR5080	TEAG11PM (Chair: E. Fox)
11	"Reliability and Safety Process Integration"	7/96	AIR5022	TEAG11
12	"Solid Rocket Booster Reliability Guidebook-Vol. II Probabilistic Design & Analysis Methods for Solid Rocket Boosters"	6/96	AIR5006/2	TEAG11
13	"Liquid Rocket Engine Reliability Certification"	4/96	ARP4900	TEAG11
14	Recommended RMS Terms and Parameters"	12/95	AIR4896	TEAG11R
15	"RMS Information Sourcebook"	11/93	ARD50046	TEAG11
16	"The FMECA Process in the Concurrent Engineering (CE) Environment"	6/93	AIR4845	TEAG11
17	"Solid Rocket Booster Reliability Guidebook"	2/91	ARD50013	TEAG11
18	"Survey Results: Computerization of Reliability, Maintainability & Supportability (RM&S) in Design"	1/90	AIR4276	TEAG11

backup

RMSL Division

Preliminary List of Publications in Progress (Drafts May Be Available From Chairperson)

	Title	Publ.	Product Code	Sponsor
1	"Maintainability Program Standard		JA1010	TEAG11M (Chair: W. Gregory)
2	"Basic Concepts, Models and Approximate Methods for Probabilistic Engineering Analysis"		AIR5083	TEAG11PM (Chair: D. Ghiocel)
3	"Applications of Probabilistic Methods"		AIR109	TEAG11PM (Chair: T. Torng)
4	"Legal Issues Associated with the Use of Probabilistic Design Methods"		AIR5113	TEAG11PM (Chair: A. Pickard)
5	"Reliability Testing Standard"		JA1009	TEAG11R (Chair: W. Grimes)
6	"Failure Modes, Effects, and Criticality Analysis Procedures"		J2336	TEAG11S (Chair: H. Hetrick)
7	"Supportability Process Standard"		J2336	TEAG11S (Chair: H. Hetrick)
8	"Guide to the Reliability Centered Maintenance (RCM) Standard		JA1012	TEAG11SL (Chair: D. Netherton)
9	"Software Supportability Program Implementation Guide"		JA1005	TEAG11SW (Chair: D. Peercy)
10	"Software Reliability – An Overview"		J2443	TEAG11SW (Chair: D. Peercy)
11	"Software Reliability Program Standard"		J2444	TEAG11SW (Chair: D. Peercy)
12	"Software Reliability Implementation Guide"		J2445	TEAG11SW (Chair: D. Peercy)
13	"Software Supportability Program Standard"		J2446	TEAG11SW (Chair: D. Peercy)
14	"Software Supportability Implementation Guide"		J2447	TEAG11SW (Chair: D. Peercy)
15	"Software Support Concept"		J2448	TEAG11SW (Chair: D. Peercy)

backup

RMSL Division

Where Are We Headed?

- RMSL should remain the focus unless otherwise so indicated by our customers.

- Need to revitalize and reinvigorate all G-11 activities and participants based on customer needs.

- Transition to an electronically-linked network to rapidly respond to individual and organizational needs, but continue face-to-face semi-annual meetings.

- Elevate G-11 to Systems Engineering Council

Just do what's relevant & will be useful

backup

RMSL Division

Revitalization of G-11

Vision: Be the authoritative source of RMSL information, education, and standards that the national and international leaders turn to!

Goals:

(1) Re-establish projects based on customer need only. (Initial buy-in, continuous interest, of direct use and benefit.)

(2) Link projects to participants with overlap in their day job.

(3) Communicate with senior management on what we do in conjunction with what will attract their attention.

backup

RMSL Division

Revitalization of G-11 (Continued)

Goals:

(4) Establish liaisons with relevant groups. (NATO, U.K., Ministry of Defense, ISO, IEEE, NAE, -------)

(5) Broadcast relevant standards already developed by G-11.

(6) Meet at locations most likely to attract participants.

(7) Need to listen to and hold hands of new participants.

(8) Integrate RMSL workshops with RAMS

backup

G-11 Probabilistic Methods Committee (PMC)

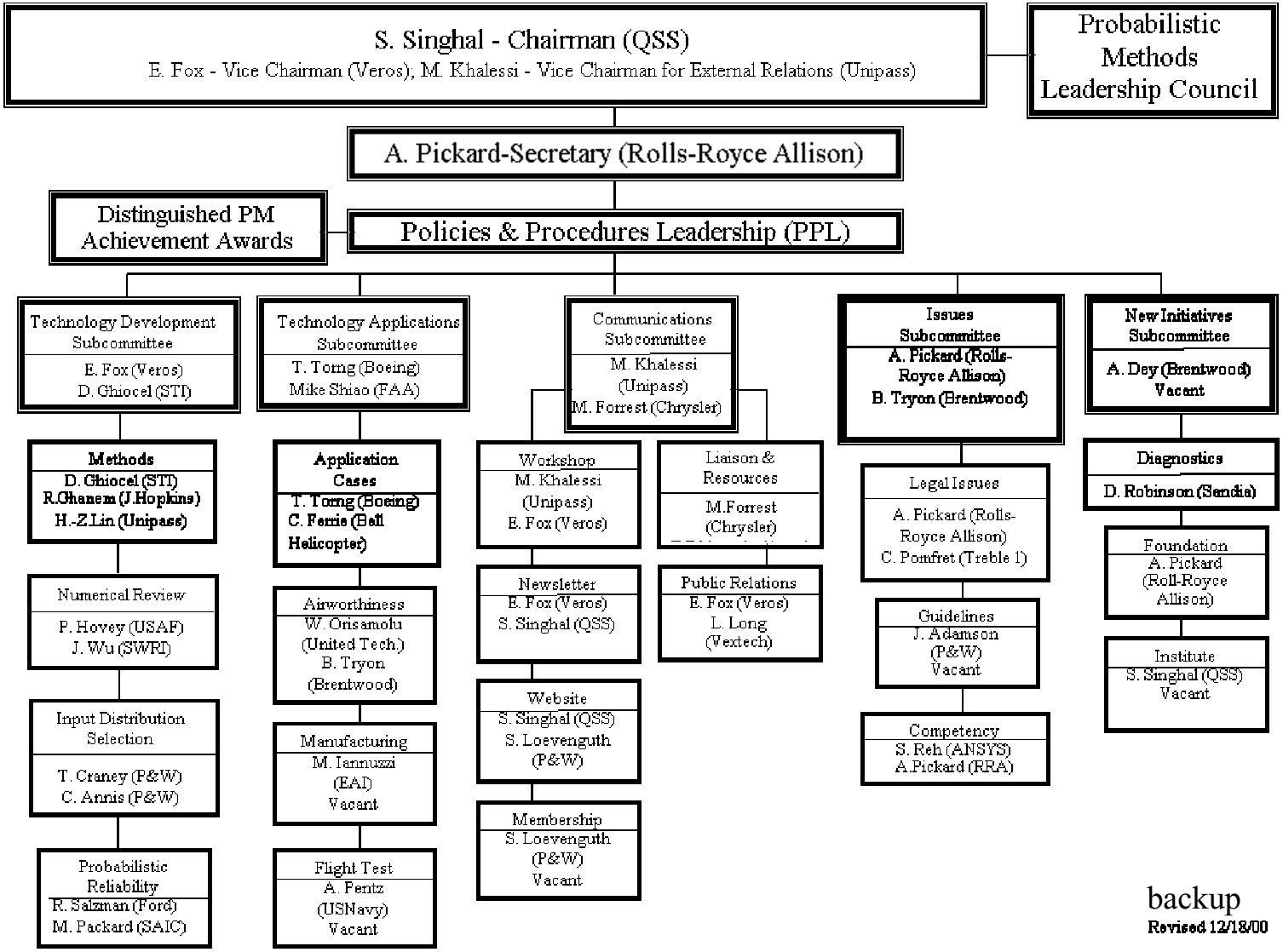
Vision

To serve as the **premier** Probabilistic Methods group with **balanced**, **broad** representation in industry, government, and academia that carries with it **authoritative insight** and the ability to envision, initiate, and implement a holistic agenda for probabilistic methods that **benefits all people**.

Brainstorm, initiate & implement probabilistic projects for the benefit of all, especially member organizations

G-11 PMC

People



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Revised 12/18/00

G-11 PMC

Products

- Technology Development & Applications – Compile Information
- Documents (AIR/ARD)
- Education & Training
- Recommendations to industry, government, and academia
- Standards

G-11 produces information, documents, education, training, recommendations, and standards

G-11 PMC

G –11 DIVISION
PROJECT INFORMATION
UPDATED AT MARCH 26-28, 2001 MEETING
MIAMI, FLORIDA

NAME OF PROJECT	
LIST OF PARTICIPANTS: **(please include e-mail address)** **This list will be published on the web page for this project. It will also serve as a special access list for the Team's Private Area located in SAE's Private Forum. This will be where draft documents reside for this project and allow easier communication among team participants.** **NOTE: INDICATE PRIMARY (P) OR SECONDARY (S)**	
AIR/ARD NUMBER AND TITLE:	
SCOPE/PURPOSE/END RESULT:	**Scope:** - - **Purpose:** - - **End Result:** ___

Please return this form to Suren Singhal or Eric Fox before leaving Meeting

backup

G-11 PMC

G –11 DIVISION
PROJECT INFORMATION
UPDATED AT OCTOBER 23-26, 2000 MEETING
RENO, NEVADA

TABLE OF CONTENTS: **(If a draft is available, it will be placed on the web page for the project.)**	
RELEVANCE TO INDUSTRY/GOV'T: **(who is going to benefit)**	
PROJECTED COMPLETION DATE:	

Please return this form to Suren Singhal or Eric Fox before leaving Meeting

backup

G-11 PMC

G –11 DIVISION
PROJECT INFORMATION
UPDATED AT OCTOBER 23-26, 2000 MEETING
RENO, NEVADA

MEETING ACCOMPLISHMENTS:	
FUTURE PLANS: **(Action Items/Including Dates)**	

Please return this form to Suren Singhal or Eric Fox before leaving Meeting

backup

G-11 PMC

MISSION STATEMENTS FOR OUR PM COMMITTEE WEBSITE

Subcommittee: **Technology**

Mission: To develop and disseminate technical information about probabilistic Methods which can be used easily by industry, government, and academia.

1. Project: Integration of probabilistic Methods in Design

Mission: To develop an approach which will integrate probabilistic methodologies with design practices, procedures, and software codes currently being used.

2. Project: Computational Probabilistic Methods

Mission: To create a state-of the-art, nationally recognized resource document on Probabilistic methods for use by industries for advanced engineering applications and probabilistic designs.

3. Project: Applications of Probabilistic Methods

Mission: To capture previous experience and lessons learned in the application of probabilistic methods, and to provide examples and points-of –contact for initiating new applications.

4. Project: Probabilistic methods Case Studies

Mission: To provide guidelines by which probabilistic methods should be used in different types of problems.

5. Project: Integration of probabilistic methods in Manufacturing

Mission: To identify and describe the engineering challenges, requirements, and methods employed in manufacturing and quality control.

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Mission

To identify the industry need and means of rapid communication and transfer of the probabilistic technology to the industry and facilitate the adaptation of the requisite technology by the industry.

Projects

1. **Needs/Goals**
   To identify industry, government, and academia needs and goals and to ensure SAE G-11 PM Committee addresses these needs and goals. To promote PM usage in industry and government through (a) increased awareness by providing pre-eminent source of information on all aspects of PM, and (b) induced synergism by establishing communications between organizations/parties interested in PM.

2. **Workshop**
   To develop and present a workshop demonstrating practical applications of PM.

3. **Newsletter**
   To communicate G-11 and other national/international PM activities via a semi-annual newsletter.

4. **Membership**
   To expand participation of scientists, engineers, and managers in G-11 PM activities.

5. **Publications**
   To make people aware of PM technology and its potential benefits by publishing articles in engineering and non-engineering magazines.

6. **Awards**
   To recognize significant industry, government, academia PM contributions exemplifying time and cost savings, support, training, and dedication.

7. **Website**
   To create and update a website location to inform the public of G-11 PM technology and its potential benefits via an electronic environment.

8. **G-11 Liaison**

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G-11 PMC

Subcommittee: **Issues**

Mission: To address the controversies, reluctances, litigation aspects and standards associated with the introduction of PM into design, manufacturing, certification, operation, maintenance, and retirement.

1. Project: Barriers to probabilistic Methods

Mission: To address the barriers which impede the acceptance of PM in the design, manufacturing, and user communities and examine the benefits and limitations of PM so that their use can be properly understood and practiced.

2. Project: Probabilistic Methods Legal Issues

Mission: To address the barriers which impede the acceptance of PM in the design, manufacturing, and user communities and examine the benefits and limitations of PM so that their use can be properly understood and practiced.

3. Project: Probabilistic Methods Legal Issues

Mission: To examine the legal aspects of utilizing PM, most notably the quantification of risk/safety and the attendant ramifications.

Subcommittee: **New Initiatives**

Mission: To initiate new projects with significant potential impact on use and communication of PM technology.

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G-11 PMC

Accomplishments

•In 1992, we began with 6 members with a goal of 50 in 5 years.
Nine years later today, we stand at > 100 (including non-attending ones)!

•In 1993, we began with 5 generalized long term goals.
Eight years later today, we stand at 20 (15 active) projects!

•In 1994, we began working on 1 SAE document.
Seven years later today, we have published 3, are about to publish 3 more, and are pursuing 4 more.

•In 1995, we began with the idea of PM Leadership Council.
Six years later today, we have > 30 Council members!

•In 1996, we began with an idea of a PM newsletter.
Five years later today, we have published 9 issues!

backup

G-11 PMC

Accomplishments

•In 1997, we introduced 4 PM achievement awards.
Four years later today, we are preparing for the 5th award ceremony!

•In 1997, PMLC recommended we conduct PM Workshops.
We presented PM Workshops in 1997 & 1998!

•In 1999 and 2000, we focused on & demonstrated stable growth in the PM attendees & enhanced our linkage with industries.

•In 2001, we are beginning with more bold ideas!!

We are influencing our organizations' competitiveness!

With your dedication, anything is possible!!

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G-11 PMC

Status of Documents

Category	Title	%Complete	Estimated Completion Date	SAE Report #
Technology	Probabilistic Engineering Methods, Volume I	99%	10/1	AIR 5083
	Probabilistic Engineering Methods, Volume II	75%	1st draft by 10/01	Not Yet Assigned
	Numerical Review	75%	1st draft by 10/01	AIR 5110
	Input Distribution Selection	5%	Outline by 10/01	Not Yet Assigned
	Probabilistic Reliability	20%	1st draft by 10/01	Not Yet Assigned
Applications	Application Cases	80% (Volume 1)	Final by 10/01	AIR 5109
	Airworthieness	70%	1st draft by 10/01	Not Yet Assigned
	Manufacturing	40%	In Progress 3/03	Not Yet Assigned
Issues	Legal Issues	99%	Approved	AIR 5113
	Guidelines		Discussion Phase 10/02	AIR 5115
	Minimum Competency	40%	10/1	Not Yet Assigned
	Diagnostics		Just Beginning 10/03	Not Yet Assigned
	Flight Test Cost Reduction	5%	Outline by 10/01	Not Yet Assigned

G-11 PMC

Future Plans

G-11 PMC as an internationally recognized premier source for:

- PM Information
- PM Experts
- PM Applications
- PM Training

Keep working until PM becomes a routine practice!

Probabilistic Methods Leadership Council

- Charter – High-Level Advisory Group
- Members – Senior Executives
- Current Focus – Risk Assessment & Probabilistic Design Practice
- On-Going Projects – Recommend minimum PM competency to engineering accreditation board

Leadership Council has made a difference in accomplishing the G-11 PMC vision.

AIAA Activities

- Technical Subcommittee on Service Life Design & Reliability Assessment & the NDA Forum
- Working Technical Group – Nondeterministic Approaches (NDA)

AIAA Structures TC web site:

http://jafar.ncsa.uiuc.edu/aiaa/organization/TechSub/reliability.html

AIAA

Technical Subcommittee on Service Life Design & Reliability Assessment

- Initiated as Probabilistic Methods (PM) Subcommittee of the Structures TC in 1993
- Initiated & successfully implemented focused sessions on PM papers at the annual SDM Conference
- Initiated & have organized a panel discussion at the annual SDM Conference.
- Approved by AIAA as NDA Forum

The aerospace professional engineering community has pulled together to make AIAA activities a success

AIAA

Working Technical Group – Nondeterministic Approaches (NDA)

- An electronic committee dedicated to furthering the implementation of nondererministic approaches in the engineering community
- Conducted a joint industry/government/academia workshop for nation-wide recommendations on the use of nondeterministic approaches.

A dedicated group of members continue to encourage the use of nondeterministic approach

Other Non-Profit Professional Activities

A web-based professional community & resource for non-traditional approaches:

WWW.NTACENTER.COM

- Web site under construction
- First segment with focus on PM & NDA accessible in August, 2001

A central one-step web-based resource for non-traditional approaches for America tomorrow!

Conclusions

•Payoff from interdisciplinary probabilistic engineering will be orders of magnitude of investment.

•SAE G-11 PMC provides a forum:

- to learn from each other
- to compile & disseminate relevant information

SAE is fulfilling the current PM need

Recommendations

- Sensitize & Educate yourself
- Find the right tools
- Start with applying PM to the right prototype
- Realize full potential of PM

PM – A ROUTINE PRACTICE!

Your Action Pack

(1) **Get involved in G-11 -** Announcement for the next G-11 PMC meeting

(2) **Propose your project** – New Project executive Summary Form

(3) **Submit a PM application for publication** – PM Application Summary Sheet

(4) **Inform your colleagues -** Suggestion for potential new members

Manage Uncertainties OR

Risk Being Managed by Them!

Action (1) Get Involved in G-11
Announcement for the next G-11 PMC Meeting

The Fall 2001 Meeting of the SAE G-11 Probabilistic Methods Committee will be held in Monterey, California during October 1-3, 2001.

The three-day meeting will be focused on technical discussions among your peers from industry, government, and academia.

The topics to be discussed include:

(1) **Probabilistic Engineering Methods** – What are the various probabilistic methods, how are they alike and/or different, where are they applicable, and how can you use them in real-life?

Relevance to Industry & Government – Details and references on various probabilistic methods and recommendations on which methods can be used for what real-life problem.

(2) **Numerical Review**- Several typical engineering problems are being solved using different probabilistic simulation codes. The discussion includes: what problems, what results by different methods, and how can industry use which code for what problem.

Relevance to Industry & Government – Case studies of typical problems encountering uncertainties, results of solutions to these problems run by different codes, and recommendations on which code is applicable where.

(3) **Input Distribution Selection** – What distribution to select when there is little or no data?

Relevance to Industry & Government – Too often, we get bogged down thinking we need a lot of data before we can quantify uncertainties. Not True. There are ways to do credible probabilistic analysis with little data.

(4) **Application Cases** – We are compiling the applications of probabilistic analysis demonstrating time & cost savings by various organizations.

Relevance to Industry & Government – Too often, we say, "Show Me the Proof of the Pudding". With help from many contributors, we hope to produce such a document. Problem is – not too many people are coming forward due to proprietary nature. So, we are asking to document only minimum information including problem description, what method used, did it result in any savings, and how much?

(5) **Airworthiness** – How to use probabilistic methods for airworthiness – a project proposed by a PMLC Member.

Relevance to Industry & Government – Airworthiness is a key issue for the aerospace community. There are uncertainties associated with it. By learning how to assess the effects of these uncertainties, we hope to be able to help industry produce airworthy vehicles which are more efficient and cost effective at the same time.

(6) **Manufacturing** – This project started with plans for integrating probabilistic methods in the manufacturing process but is currently focused on dimensional tolerancing during the manufacturing process.
Relevance to Industry & Government – Tolerancing during the manufacturing process is a key issue that governs warranty, cost, failure rate, etc. With this project, we hope to provide guidance on tolerancing.

(7) **Legal Issues** – We are looking at legal precedence and what issues may arise when you use probabilistic methods.
Relevance to Industry & Government – There is the widespread belief that when things are designed using deterministic approach, they are designed correctly. And that if you use probabilistic approach, you designed it to fail (one in so many times). Sure, it invites public scrutiny. The fact is, it is the probabilistic approach that accounts for real-life uncertainties allowing us to design correctly.

A paper was published in an AIAA Conference with an eye-opening conclusion – if an organization does not use probabilistic methods, tools for which are now available, then that organization could be find negligent for not using such tools.

(8) **Standards** – What standards need to be set by whom, when, etc.?
Relevance to Industry & Government – Much discussion is taking place in consultation with FAA, industry, and others on how to go by start setting a pilot standard for certification by probabilistic methods, eventually leading to full standards for analysis, design, manufacturing, testing, certifications, maintenance, operations, and retirement.

(9) **Competency** – What is the minimum competency in probabilistic methods that our engineers should have before graduating from college? This project was proposed by SAE PMLC.
Relevance to Industry & Government – We have initiated contact with ABET and are brainstorming as to what should our engineering colleges teach, both on the undergraduate and the graduate level so that our industry and government don't have to spend a lot of money training engineers in how to quantify uncertainties.

(10) **Diagnostics** – How to incorporate probabilistic methods into diagnostics?
Relevance to Industry & Government – Knowing how to account for uncertainties in diagnostics, can lead to significant cost savings and can result in reducing failures.

(11) **Probabilistic Reliability** – How to compute reliability by quantifying uncertainties?
Relevance to Industry & Government – Correct reliability computations both at the component and system level are needed so one can design an item based on its expected usage and life span.

(12) **Flight Test Cost Reduction** – How can one reduce the high cost and time of flight testing? We will look at the whole picture including analysis, ground testing, and in-flight testing? This project was inspired by the Boeing President for Phantom Works, Mr. Swain.
Relevance to Industry & Government – cost savings and faster time to market!!

There are other ongoing operational projects. If you can make a good case, we will consider a new project that can help our industry and government. For further information, contact:

Meeting Details: Kerry Tielsch (ktielsch@sae.org)
Technical: Suren Singhal (ssinghal@grc.nasa.gov)

Action (2) – Propose your project
New Project Executive Summary Form

Title:_____

Submission Date:_____ **Revision:** _____

Project Leader:_____ **Alternate:** _____

(Address) _____

(Phone/Fax) _____

(E-mail) _____

Background: _____

Objective(s): _____

Scope: _____

Benefit to Industry/
Government/Academia:_____

Relation to Other AIR's:_____

Target Dates: Outline - _____
First Draft - _____
Expected Completion Date - _____

When completed, please submit to your committee chairperson.

Action (3) – Submit a PM application for publication

Probabilistic Methods Application Summary Sheet

1. **Application No:** (Do not answer this question)

2. **Type of Industry:**

3. **Project Title:**

4. **Reason for Using Probabilistic Approach:**

5. **Probabilistic Method Used:**

6. **Rationale for Selection of the Type of Probabilistic Analysis Used for This Application:**

7. **Probabilistic Analysis Results Summary and Benefits:**

8. **Describe Whether or Not the Results Were Verified (Analytically, or by Test):**

9. **Potential Application of This Analysis to Other Industries:**

10. **Cost Versus Benefits Analysis:**

11. **Referenced Technical Report or Paper:**

Please submit to Suren Singhal at:
ssinghal@qssgess.com

Action (4) – Inform your colleagues Suggestions for Potential New Members – Please Print	
Name:	Last: First:
Company:	
Email:	
Phone Number:	
Fax#:	
Address:	
Name:	Last First:
Company:	
Email:	
Phone Number:	
Fax#:	
Address:	
Name:	Last: First:
Company:	
Email:	
Phone Number:	
Fax#:	
Address:	

SUBMITTED BY:_____

Phone#:_____

Email:_____

Keynote Speaker

Ahmed K. Noor is Eminent Scholar and Professor of Aerospace Engineering, Old Dominion University, Norfolk, VA. He is also the Director of the Old Dominion University's Center for Advanced Engineering Environments at NASA Langley Research Center, Hampton, Virginia. He is also the Florida Space Research Institute Distinguished Scholar of Advanced Learning Systems. From 1990-2000, he was the Ferman W. Perry Professor of Aerospace Structures and Applied Mechanics Chair, and the Director of the University of Virginia's Center for Advanced Computational Technology at NASA Langley Research Center, Hampton, Virginia. Dr. Noor received his B.S. degree with honors from Cairo University (Egypt), and his M.S. and Ph.D. from the University of Illinois at Urbana-Champaign, respectively.

He taught at Stanford University, Cairo University (Egypt), University of Baghdad (Iraq), the University of New South Wales (Australia), George Washington University and the University of Virginia before joining Old Dominion University. He has edited 30 books and authored over 350 papers in the fields of advanced design and synthesis environment, advanced learning technology, aerospace structures, structural mechanics, computational mechanics, and new computing systems. Currently, he is the Editor-in-Chief of Advances in Engineering Software published by Elsevier, the Associate Editor of Applied Mechanics Reviews published by ASME, and serves on the Editorial Board of several international journals.

He is a Fellow of five professional societies: the American Institute of Aeronautics and Astronautics, American Society of Mechanical Engineers, American Society of Civil Engineers, the American Academy of Mechanics, and the U.S. Association for Computational Mechanics. He is a Founding Member of both the International and U.S. Associations of Computational Mechanics, and is a Past President of USACM. He served on a number of committees of the National Research Council/National Academy of Engineering including Large Space Systems, Computational Mechanics, and Aeronautical Technology in the Year 2000. He served on the NSF High Performance Computing Panel.

He has been active in AIAA, ASME and ASCE for many years and served as the Chairman of the Committee on Computing in Applied Mechanics, ASME, and Structures Technical Committee. He received a number of awards including the 1989 ASCE Structures and Materials Award for exceptional contributions to the advancement of aerospace technology in civil engineering, the Technical Achievement Award from the National Academy of Engineering in 1995, and the Distinguished Probabilistic Methods Educator Award of SAE International in 2000.

An Overview of the M.I.T. Gas Turbine Laboratory Robust Jet Engines Project

D. Darmofal, V. Garzon, V. Sidwell, F. Engelhardt,
D. Frey, E. Greitzer, B. Hao, I.A. Waitz
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
Phone: 617–258–0743, Fax: 617–258–5143
Email: darmofal@mit.edu

In this presentation, we will overview the M.I.T. Gas Turbine Laboratory Robust Aerothermal Design effort. Initiated in the fall of 1999, the five-year goals of this program are:

G1 Identification and quantification of key drivers for engine-to-engine variability in aerothermal quality including validation against data.

G2 Definition of criteria for the design of engines with a commercially-significant reduction in sensitivity to variability including analysis of cost trade-offs.

G3 Development of improved processes for monitoring and controlling the effects of variability on aerothermal quality.

G4 Implementation of one or more of the above elements in an industrial setting.

The effort currently involves four faculty members, four graduate research students, interactions with engine manufacturers including Pratt & Whitney and SNECMA, and support from NASA Glenn Research Center. On-going projects within the group are:

- Quantification and modeling of geometric variations for compressor blades due to manufacturing,
- Probabilistic, robust design of compressor blades with geometric variability,
- Impact of secondary flow system variability and modeling uncertainty on bearing load and turbine durability,Identification of key drivers for variability in combustor stability.

Our talk will include both an overview of the program goals and a status report of the on-going research projects.

An Overview of the M.I.T. Gas Turbine Laboratory Robust Jet Engines Project

Fredrik Engelhardt, Victor Garzon,

Beilene Hao,Vince Sidwell

David Darmofal, Dan Frey,

Ed Greitzer, Ian Waitz

Massachusetts Institute of Technology

Team Members

Participating Organizations

M.I.T.

NASA Glenn

Pratt & Whitney

SNECMA

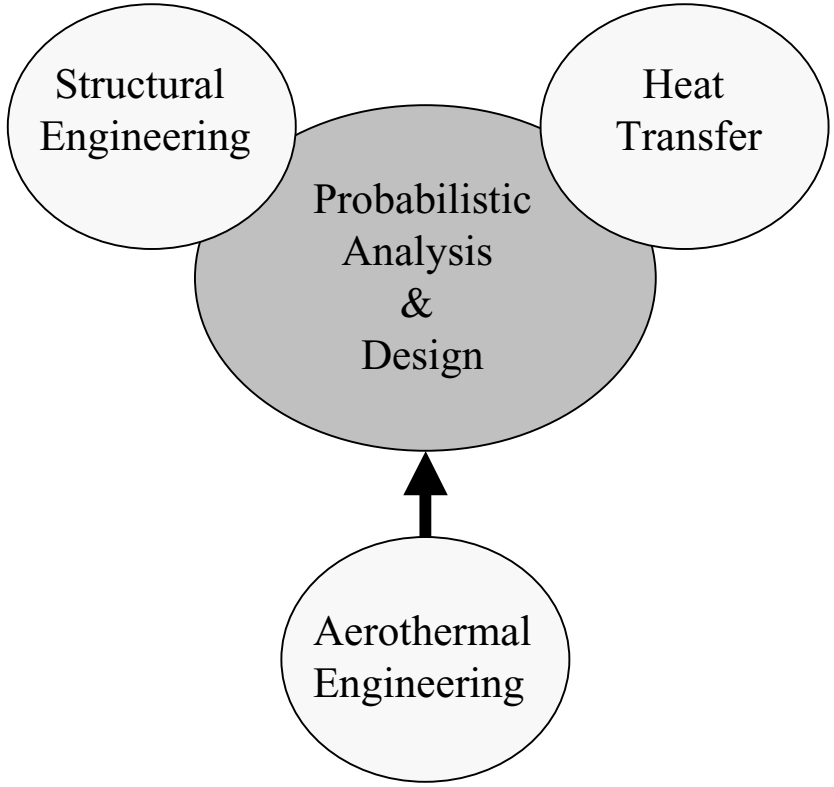
Hamilton Sundstrand

Senior Personnel

Prof. David Darmofal, Prof. Daniel Frey

Prof. Ed Greitzer, Prof. Ian Waitz

The Need for Probabilistic Aerothermal Design



5 Year Success Goals

G1 Identification and quantification of key drivers for uncertainty and engine-to-engine variability in aerothermal quality including validation against data.

G2 Definition of criteria for the design of engines with a commercially-significant reduction in sensitivity to variability and uncertainty including analysis of cost trade-offs.

G3 Development of improved processes for monitoring and controlling the effects of variability on aerothermal quality.

G4 Implementation of one or more of the above elements in an industrial setting.

Research Topics: System Level

S1 Acquisition and analysis of in-service performance and repair data (from maintenance logs, part lists, FADEC, etc) to help identify key drivers in engine variability.

S2 Identification of key drivers for uncertainty and variability in aerothermal quality using appropriate models for system level engine performance and component input uncertainty and variability.

S3 Estimation of variability in engine-related costs (including development, production, and operating costs) due to uncertainty and variability in aerothermal quality.

System Level (Cont'd)

S4 Validation of modeling methodologies against manufacturing and operational data.

S5 Application of robust design to engine system model to reduce uncertainty and variability in aerothermal quality including cost trade-offs and validation against data.

S6 Development of real-time processes for monitoring and controlling variability effects at the system level.

Research Topics: Component Level

C1 Quantification and modeling of input variability at the component level.

C2 Assessment of input variability effects on component aerothermal quality.

C3 Estimation of variability in engine-related costs (including development, production, and operating costs) due to component uncertainty and variability in aerothermal quality.

Applied to:

compressor, combustor & turbine

Component Level (Cont'd)

C4 Experimental validation of methods for assessing component variability effects on in aerothermal quality.

C5 Application of robust design to reduce variability in component aerothermal quality including experimental validation.

C6 Development of improved processes for monitoring & controlling the effects of variability on component aerothermal quality.

Applied to:

compressor, combustor & turbine

Current Research Projects

- System level probabilistic analysis and design using a non-ideal cycle analysis
- Quantification and modeling of geometric variability in compressor blade manufacturing
- Probabilistic design of compressor blades under geometric uncertainty
- Identification of robustness driver in combustor using reactor networks
- Impact of secondary flow uncertainty on turbine blade life

System Level Robust Aerothermal Design

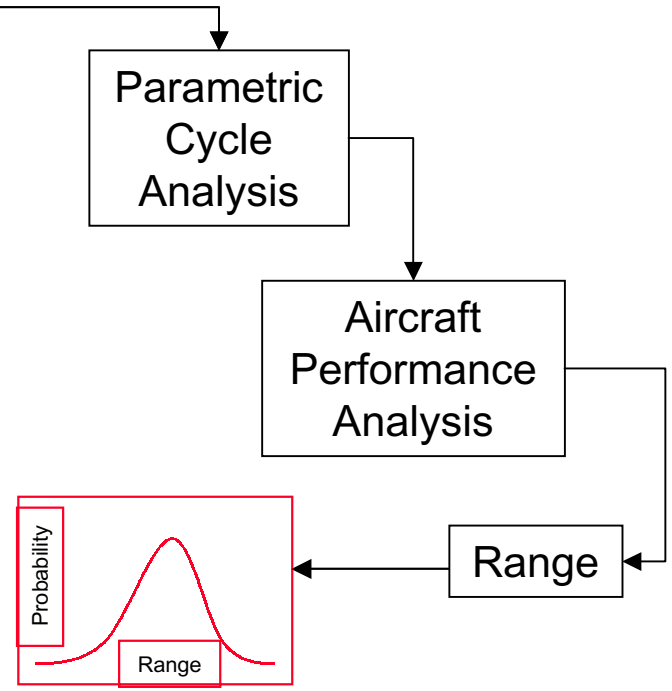
Probabilistic Engine Cycle Analysis and Design: Sidwell & Darmofal

Control Parameters:

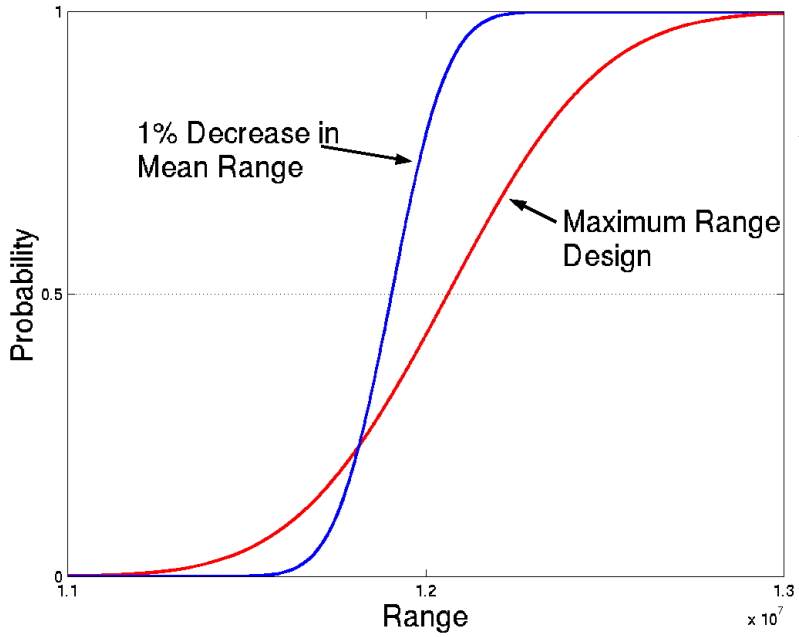
- Efficiencies for compressor, fan, and turbine (η_c=.90-.93, η_f=.91-.95, η_t=.90-.94)
- Turbine inlet temperature (T_{T4}=1600K-1800K)
- Overall pressure ratio (π_c=35-45)
- Fan pressure ratio (π_f=1.3-1.7)
- Bypass ratio (α=5-11)

Noise Parameters:

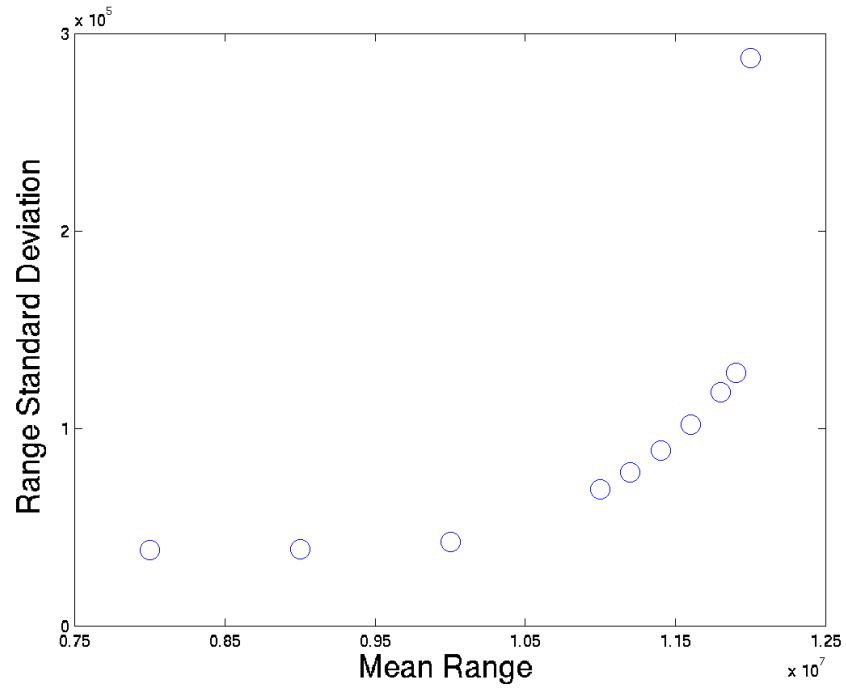
- Variability to establish distributions for compressor, fan, and turbine efficiencies ($\sigma_{\eta c}$=±.0025, $\sigma_{\eta f}$=±.0025, $\sigma_{\eta t}$=±.0025)



Robust Cycle Analysis



1% Decrease in mean range allows a 63% decrease in standard deviation.



Probabilistic Simulation Techniques for Compressor Blade Design

Victor Garzon, Prof. David Darmofal

Motivations:

– Aircraft engine compressors must operate reliably over a wide range of conditions and hence be insensitive to geometric variability.

– Deterministic CFD and optimization tools can be supplemented by *probabilistic* techniques to produce fast and reliable estimates of performance variability caused by random geometric perturbations.

– *Robust Design* methods can be combined with CFD tools and probabilistic techniques to explore design spaces in search of *robust* blade designs.

Objectives:

– To identify geometric modes of variability present in compressor blades (due to manufacturing imperfections and wear). These modes can then be used to generate statistical populations in probabilistic simulations.

– To develop and implement robust methodologies and software tools for the design of robust compressor cascades.

NASA/CP—2002-211682

Current Research Status

- Collaboration with Pratt & Whitney
  - Acquisition of coordinate measurement machine (CMM) data from manufactured compressor blades.
  - Use of P&W's proprietary software for CMM data post-processing and airfoil geometry manipulation (cold-to-hot and vice versa).
- Implementation of various probabilistic techniques and robust design methods
  - Principal components analysis on P&W's compressor blade data.
  - Estimation of first and second moments via response surfaces, Monte Carlo and probabilistic quadrature methods.
  - Application of response surface, Taguchi methods, and gradient-based optimization in exploring the design space for robustness.

Principal Component Analysis

- PCA is a statistical technique for reducing a set of correlated variables to a smaller uncorrelated set. The uncorrelated vectors are called the *principal components* of the sample.
- One way to obtain the principal components of a set of vectors is to look at the eigenvectors of their covariance matrix.
- First define an appropriate error vector, e.g., assuming correspondence between *nominal* and *measured* points,

$$\mathbf{e} = \begin{bmatrix} \mathbf{x}^{\text{nom}} - \mathbf{x}^{\text{meas}} \\ \mathbf{y}^{\text{nom}} - \mathbf{y}^{\text{meas}} \end{bmatrix}$$

- The covariance matrix of the error vector is given by

$$\mathbf{\Sigma} = E\left[(\mathbf{e} - E[\mathbf{e}])(\mathbf{e} - E[\mathbf{e}])^{\mathrm{T}}\right]$$

Principal Component Analysis (Contd.)

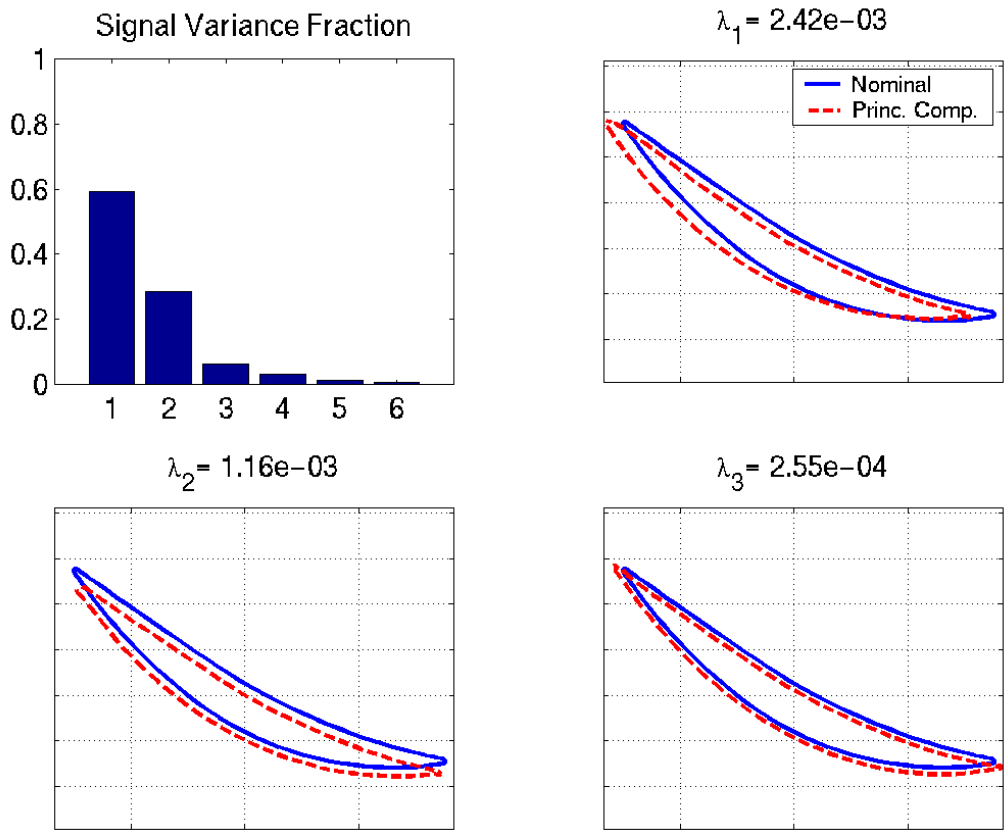
- The eigenvalue decomposition of the covariance matrix is

$$\mathbf{\Sigma} = \mathbf{V}\mathbf{D}\mathbf{V}^{-1}$$

where the columns of $\mathbf{V}$ are the eigenvectors of $\mathbf{\Sigma}$ and $\mathbf{D} = \mathrm{diag}(\lambda_1, \lambda_1, \cdots, \lambda_n)$.

- The eigenvector corresponding to the largest eigenvalue, λ_1, gives the direction of the first principal component.
- In this case the principal components represent the perturbation modes present in the blade measurements.
- The eigenvalues of $\mathbf{\Sigma}$ correspond to the variance of the distribution with which the modes appears in the data.

Principal Components Analysis of Compressor Blade Measurements



x displacement and twist

y displacement

chord length

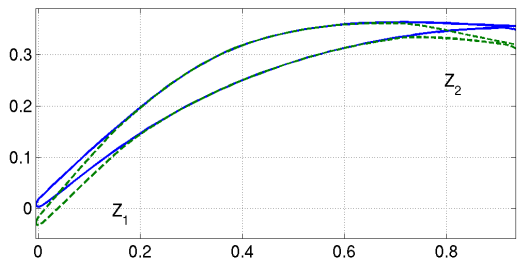
Probabilistic Blade Design

Design parameters (chord)

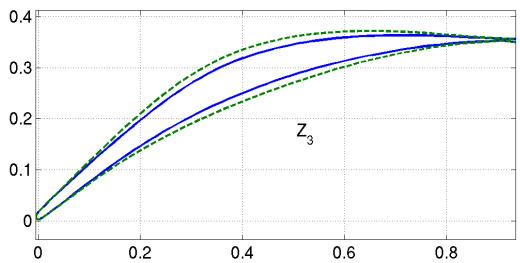
LE droop	TE droop	Thckns.
+0.008	+0.008	-0.013

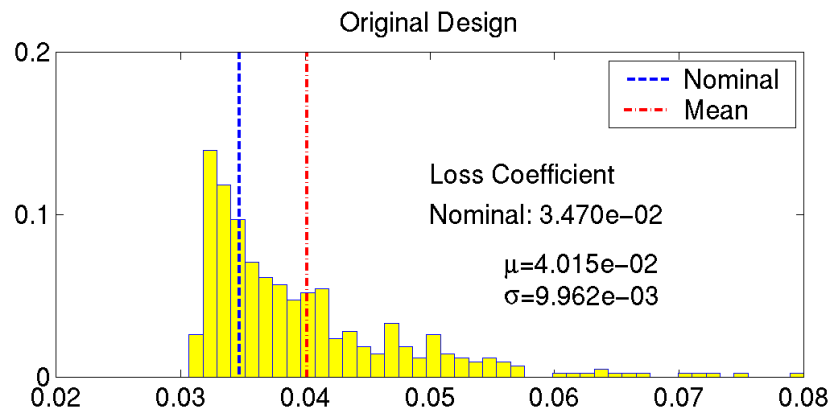
15% reduction in mean loss coeff.

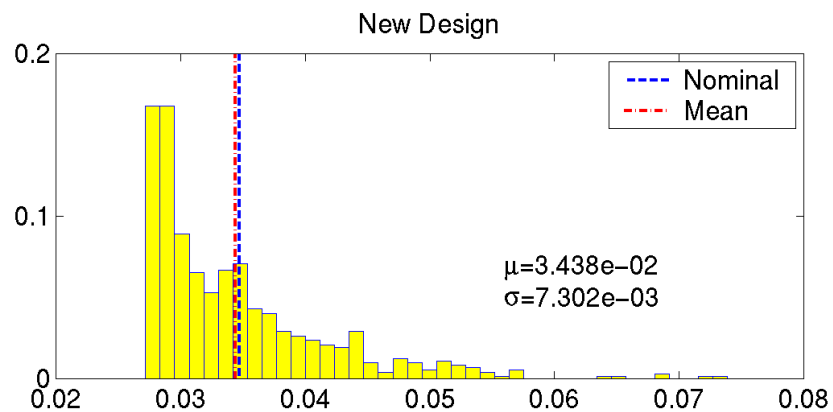
LE/TE Droop



Thickness







Gas Turbine Combustors

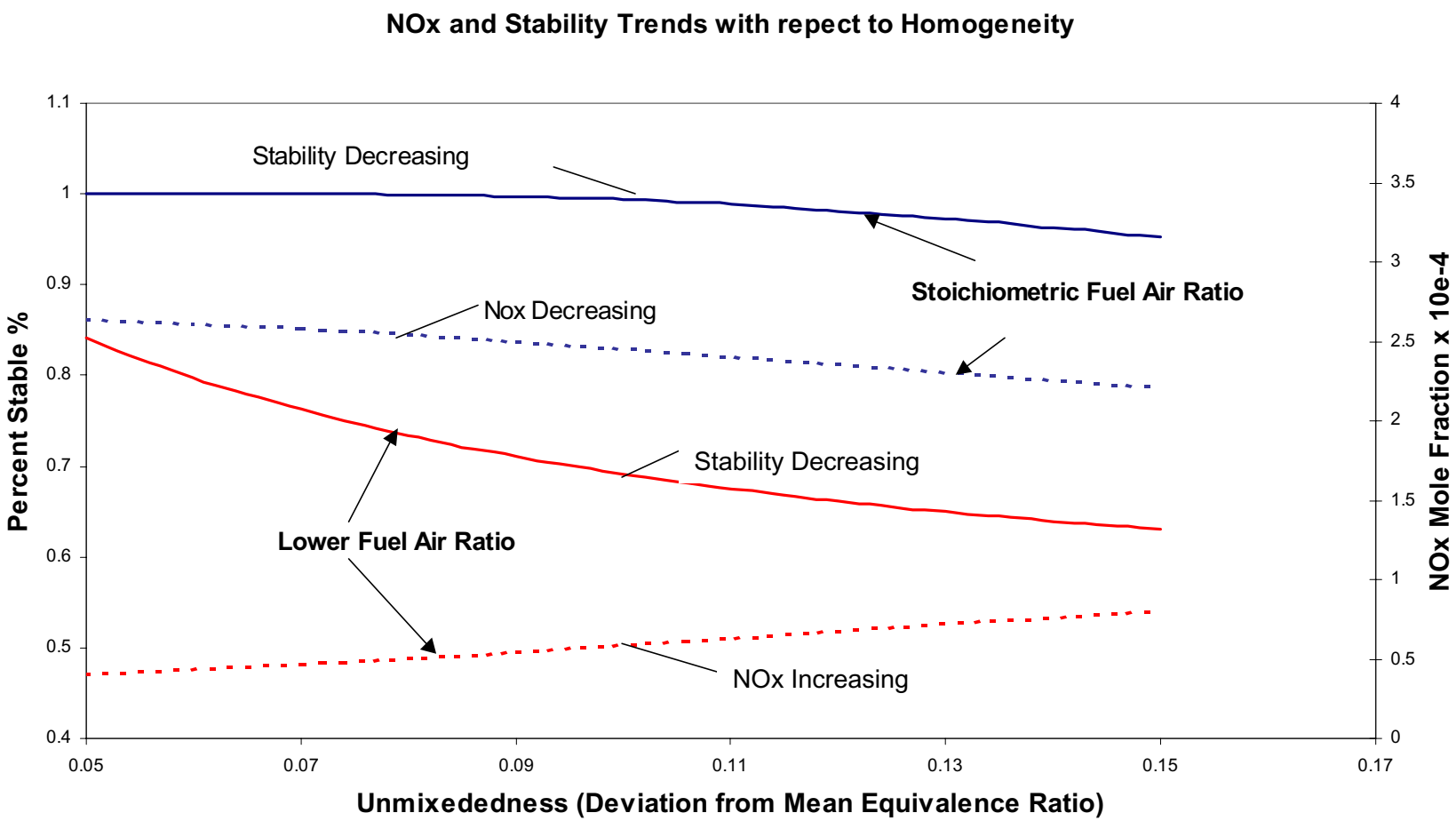
Beilene Hao, Prof. Ian Waitz

- Non-linear systems that have been seen to be highly sensitive to operational and manufacturing variations.
- Some resulting problems include:
  - Lower overall combustor performance
  - Unpredicted combustor flame-outs
  - Decreased combustor and turbine component life
- Trade-off studies & design optimization balancing all combustor functional requirements are difficult to achieve using current combustor design methods.

Robust Combustion: Goals

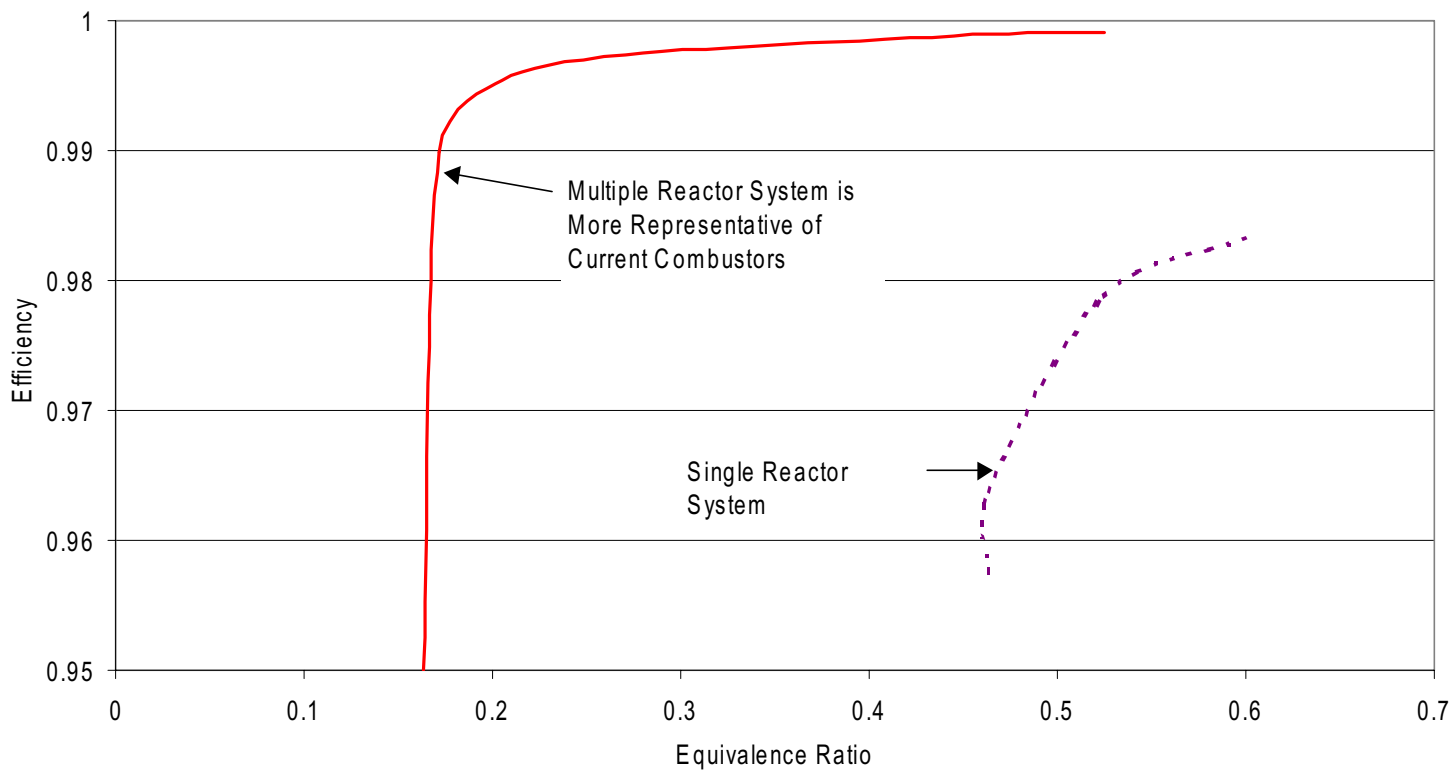
- Using a reactor network, identify key drivers of functional variability - performance, stability, emissions, noise, durability, etc.
- Gather existing data on variability and verify numerical results.
- Assess methods for reducing sensitivity to operational and manufacturing variation and optimizing functional trade-offs

Initial Trade-Off Studies: Single Reactor



ROBUST JET ENGINES

Three Reactor Model Initial Results



Summary

- Significant opportunities exist in probabilistic aerothermal design of jet engines and their components
- Significant barriers exist to achieving probabilistic aerothermal design
- Developed critical partnerships with industry
- Several on-going projects both at system and component levels
- Critical need to better understand the cost implications of variability

Probabilistic Study of Fluid Structure Interaction

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ABSTRACT

Probabilistic CFD design is needed because we are asked to do more with less. To cost effectively accomplish the design task, we need to formally quantify the effect of uncertainties (variables) in the design. Probabilistic design is one effective method to formally quantify the effect of uncertainties. Our objective is to establish a revolutionary new early design process, by developing non-deterministic physics-based probabilistic design tools, which will include all the life cycle processes. Breakthroughs will be sought in speed, accuracy, intelligence, and usability of the system.

This paper is concerned with the usefulness of parametric optimization method coupled with a Navier-Stokes analysis code for the aero-thermodynamic design of turbomachinery combustor liner. The interconnection between the CFD code and NESSUS codes facilitated the coupling between the thermal profiles and structural design. We have developed new concepts for reducing the computational cost of unsteady, three-dimensional, compressible aerodynamic analyses for multistage turbomachinery flows. The flow was modeled by the three-dimensional Favre-Reynolds-averaged Navier-Stokes equations using the k-ε turbulence closure, which was integrated using an implicit third-order upwind solver. The methodology developed in this paper is expected to lead to the design optimization of turbomachinery blades.

NASA/CP—2002-211682

PROBABILISTIC STUDY OF FLUID-STRUCTURE INTERACTION

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5th Annual FAA/Air Force/NASA/Navy Workshop
On The Application of Probabilistic Methods for Gas Turbine Engines
June 11-13, 2001- Holiday Inn, Westlake, OH

PRESENTATION OUTLINE:

- Background
- Need
- Objective
- Approach
- Concluding Remarks

BACKGROUND:

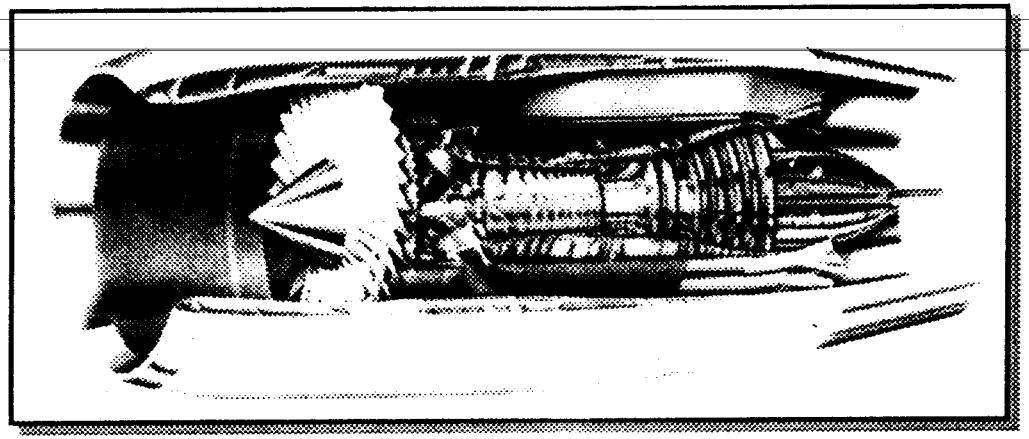
- Future advanced military aircraft gas turbine propulsion systems will be characterized by and designed for improved performance and reduced cost as compared to current capability.

- To cost effectively accomplish that design task; we need to formally quantify the effect of CFD uncertainties (variables) in the design.

- Probabilistic design is one effective method to formally quantify the effect of uncertainties.

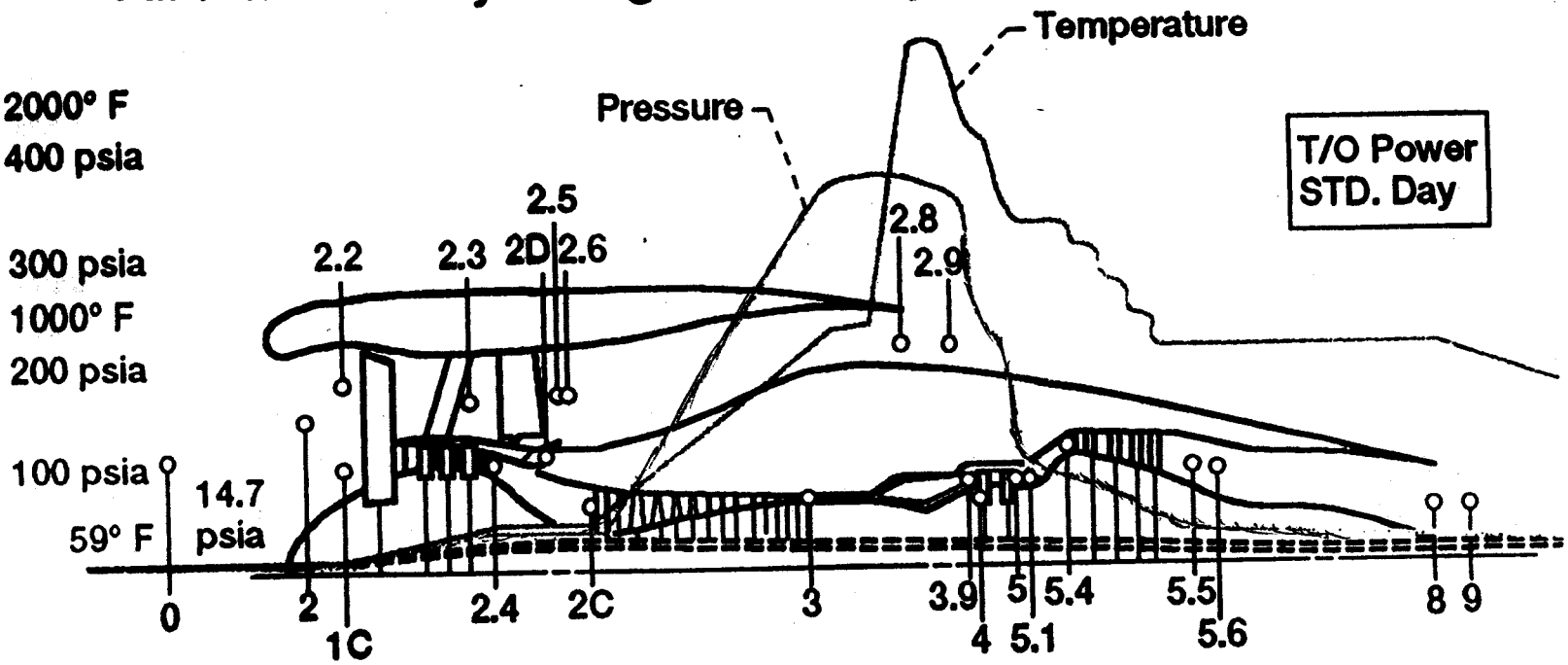
- NASA wants to strengthen the structural probabilistic analysis capability to include aerodynamic and heat transfer uncertainties.

Engine Components Under Service-Environment Loadings



The structure is the natural multi-discipline integrator.

Aircraft Turbojet Engine Aerodynamic Environment



Legend:

0	Ambient
2	Engine inlet
2.2	Fan tip (bypass) stream inlet
1C	Fan hub (LP compressor) stream inlet
2.3	Fan discharge
2.4	LP compressor discharge
2D	LP compressor discharge bleed port exit
2.5	Bypass stream mixing plane
2.6	Bypass duct inlet (after mixing)
2.8	Bypass duct jet nozzle throat
2.9	Bypass duct jet nozzle exit (complete expansion)
	Temperature ———
2C	HP compressor inlet
3	HP compressor discharge
3.9	HP turbine 1st-stage nozzle inlet (w/o cooling flow)
4	HP turbine rotor inlet (w/cooling flow)
5	HP turbine discharge (w/o cooling flow)
5.1	HP turbine discharge (w/cooling flow)
5.4	LP turbine inlet (w/cooling flow
5.5	LP turbine discharge (w/o cooling flow)
5.6	LP turbine discharge (w/cooling flow)
8	Primary jet nozzle throat
9	Primary jet nozzle exit (complete expansion)
	Pressure ———

CD-92-59961

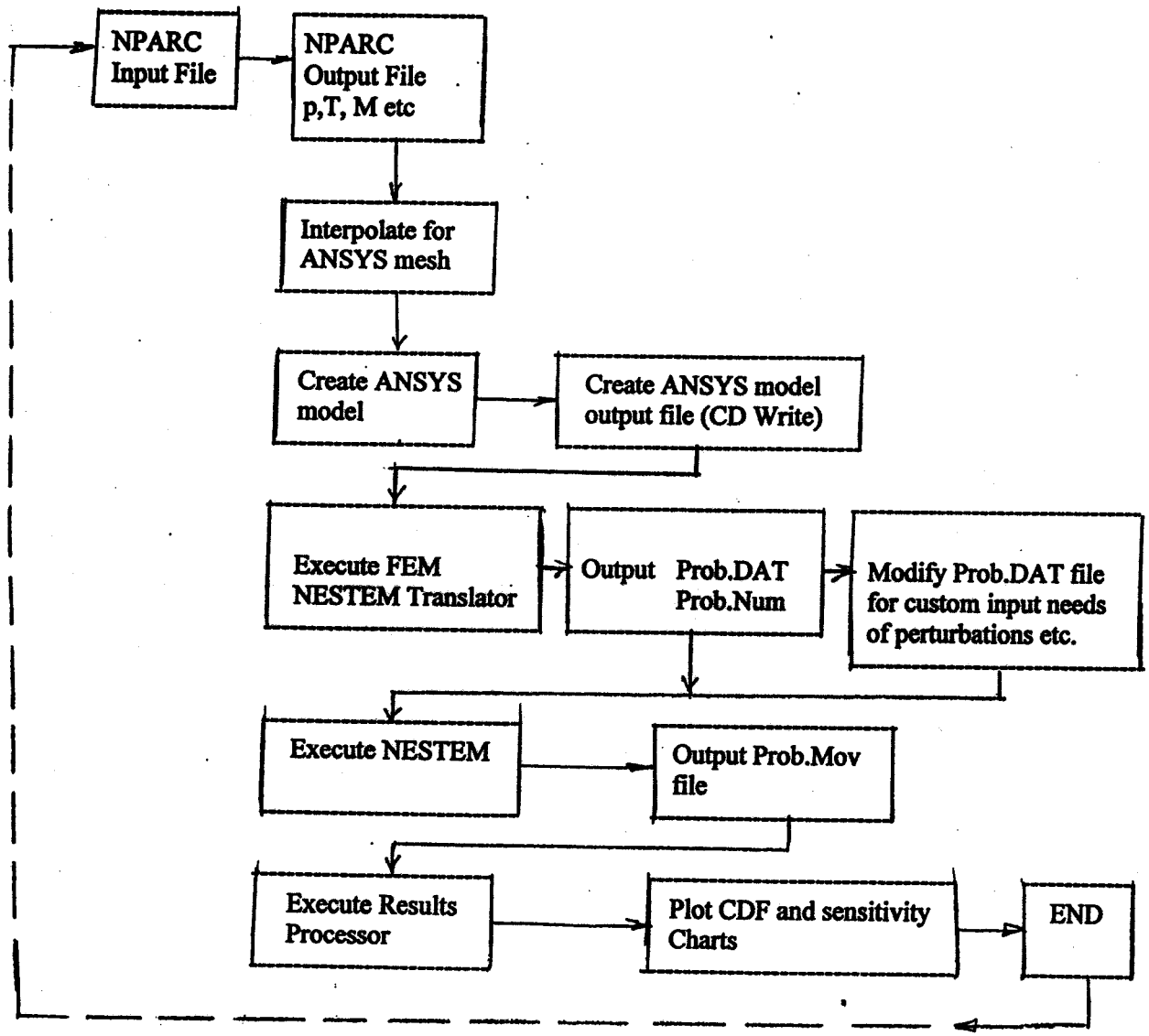
NEED/OBJECTIVE/APPROACH

- NEED: Probabilistic CFD design is needed because we are asked to more accurately describe the flow effects on structures.

- OBJECTIVE: Develop Technology for establishing a revolutionary new early design process, by means of non-deterministic physics-based probabilistic design tools, which will include all the life cycle stages.

- APPROACH: Investigate the application of probabilistic design methods coupled directly with a CFD Navier-Stokes analysis code for the aero-thermodynamic and structural design of turbomachinery components.

COMPUTATIONAL APPROACH by the Coupling of NPARC and NESTEM



The Navier-Stokes Solver

- The computational code NPARC version 3.1 was selected for the aerodynamic analysis of the present research.

- NPARC solves the Euler or Navier-Stokes equations in conservation law form on a multi block body fitted grid system.

- The flow can be assumed to be laminar, turbulent or inviscid. A variety of turbulence models, including the k-ε model can be selected.

NPARC Variables:

Mach number

Inlet Total Pressure

Inlet Total Temperature

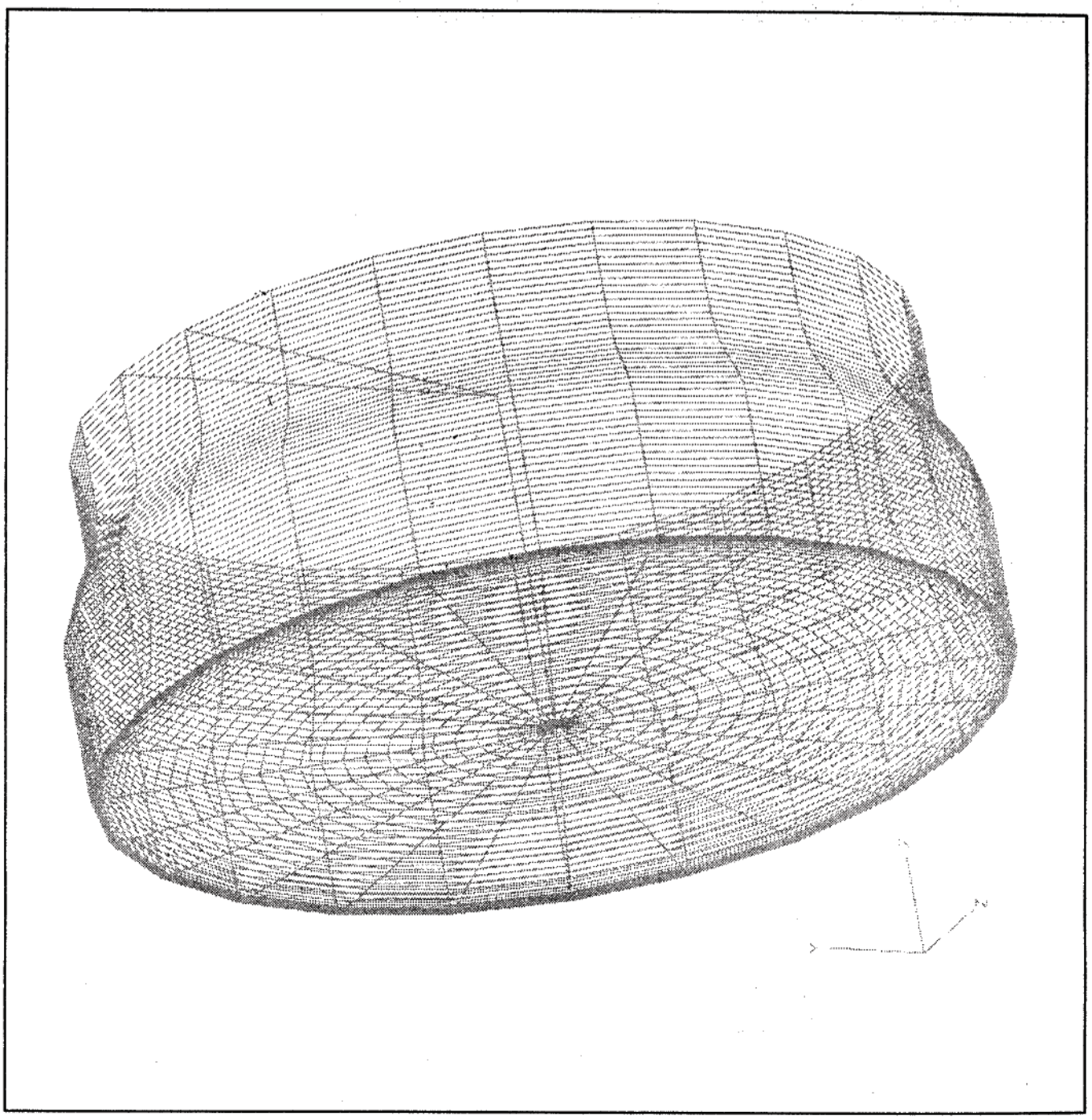
Exit Temperature

NESTEM Probabilistic Structural Analysis Code

- NESTEM is an enhanced version of NESSUS (Numerical Evaluation of Stochastic Structures Under Stress)
- NESTEM maintains all NESSUS capabilities including structural analysis using a finite element approach and adds three significant features (heat transfer analysis, geometry generation and ceramic material property generation)

RANDOM VARIABLES:

Coefficient of thermal expansion
Pressure load on outside
Stiffness coefficients matrix from material properties
Convection fluid temperature inside
Convection fluid temperature outside
Film cooling flow inside
Convection film coefficients outside
Radiation temperatures on inside
Radiation temperatures on outside
Emissivity of surface
Gas Emissivity inside
Gas Emissivity outside
Gas absorptivity inside
Gas absorptivity outside
Conductivity axial
Conductivity tangential
Conductivity through thickness



EXAMPLE PROBLEM: Combustor Liner

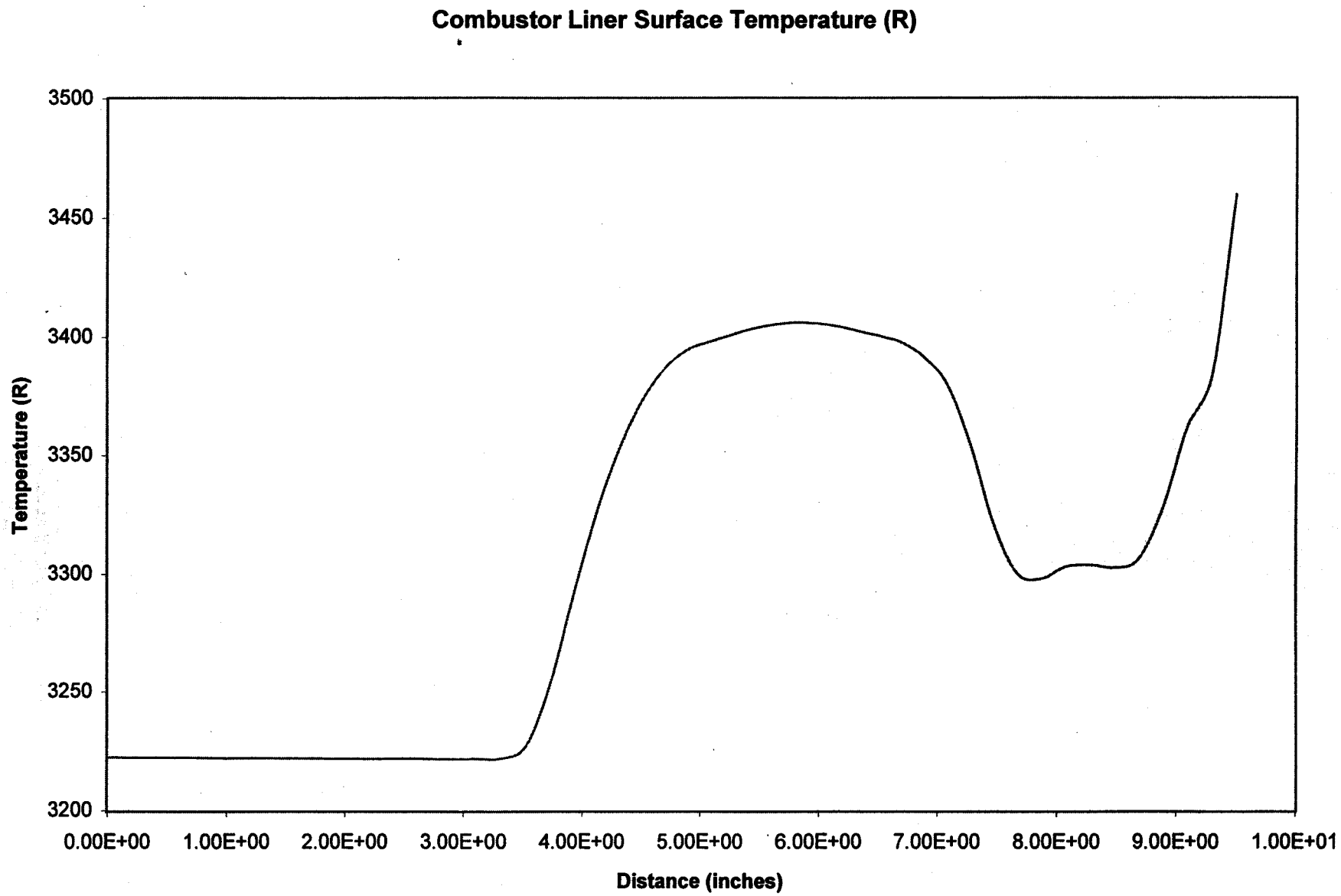
Radius at ID 25.00”

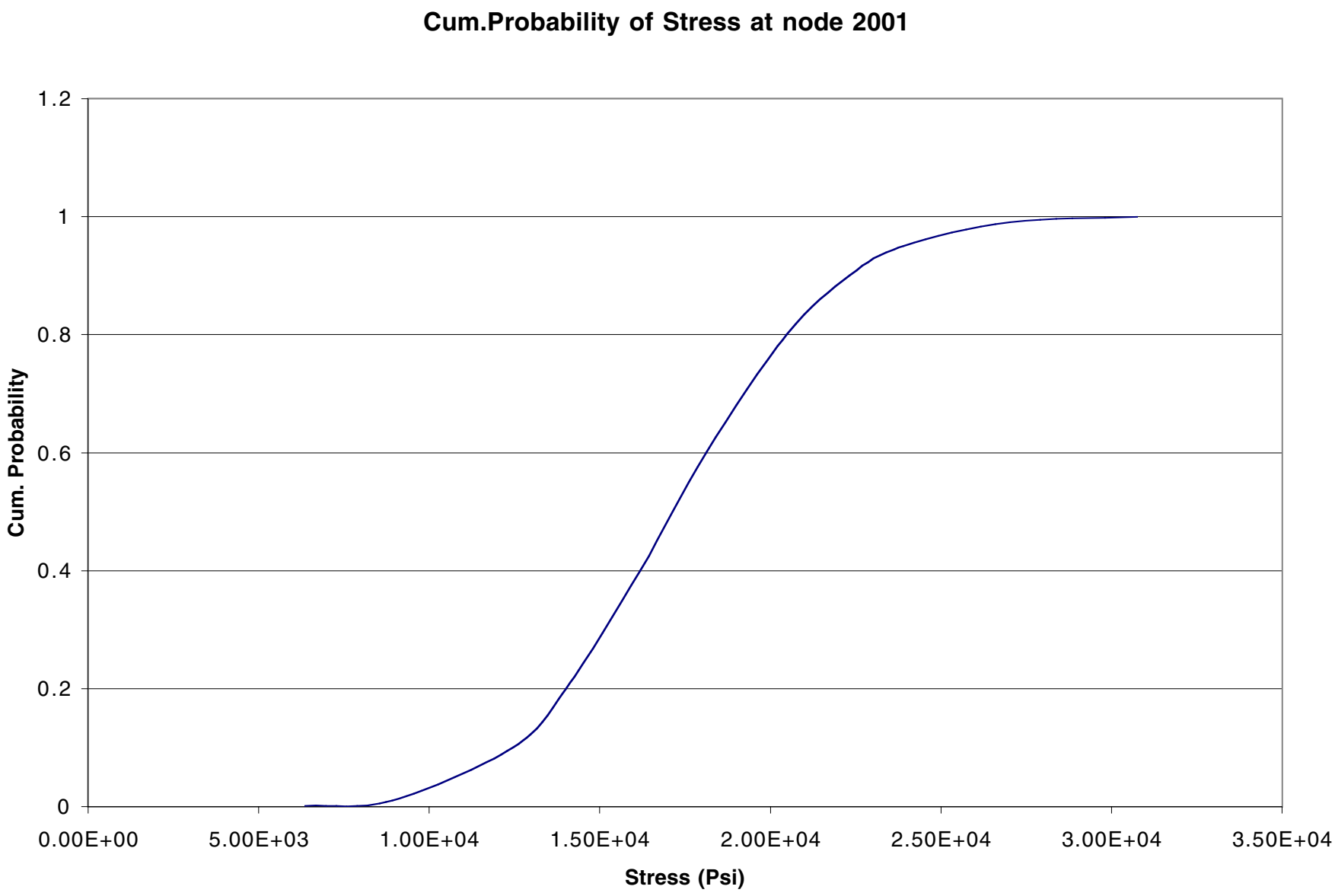
Length 9.5”

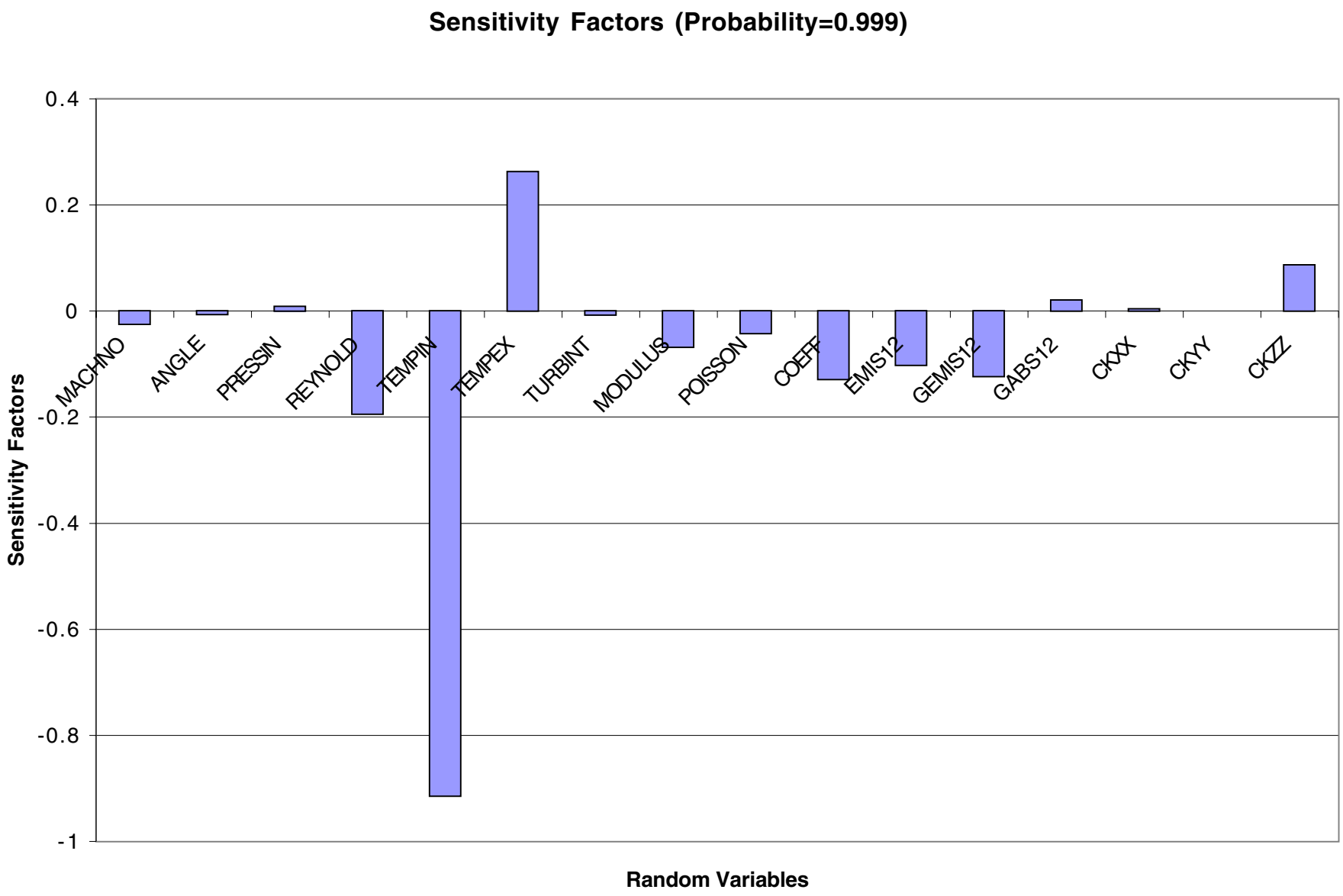
Thickness 0.1”

Number of Elements 1400
(8 node Brick)

Number of Nodes 2400


Combustor Liner Surface Temperature (R)
Temperature (R)
3500
3450
3400
3350
3300
3250
3200
0.00E+00
1.00E+00
2.00E+00
3.00E+00
4.00E+00
5.00E+00
6.00E+00
7.00E+00
8.00E+00
9.00E+00
1.00E+01
Distance (inches)


Cum.Probability of Stress at node 2001
Cum. Probability
1.2
1
0.8
0.6
0.4
0.2
0
0.00E+00
5.00E+03
1.00E+04
1.50E+04
2.00E+04
2.50E+04
3.00E+04
3.50E+04
Stress (Psi)


Sensitivity Factors (Probability=0.999)
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Sensitivity Factors
MACHNO
ANGLE
PRESSIN
REYNOLD
TEMPIN
TEMPEX
TURBINT
MODULUS
POISSON
COEFF
EMIS12
GEMIS12
GABS12
CKXX
CKYY
CKZZ
Random Variables

CONCLUDING REMARKS

- Probabilistic method was described by coupling NPARC and NESTEM codes to investigate the effects of aerothermodynamic variables on structural design of turbomachinery components.

- Probability analysis for nodal temperatures can be performed by perturbing the aerodynamic and heat transfer variables.

- The material properties and the radiative heat transfer have significant effect on the component life.

- NPARC and NESTEM can be effectively used to study the influence of aerodynamic and heat transfer variables on the life of components such as the combustor liner.

- This methodology is proposed to be extended to study the probabilistic design of turbomachinery blades.

Risk-Based Probabilistic Approach to Aeropropulsion System Assessment

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In an era of shrinking development budgets and resources, where there is also an emphasis on reducing the product development cycle, the role of system assessment, performed in the early stages of an engine development program, becomes very critical to the successful development of new aeropropulsion systems. A reliable system assessment not only helps to identify the best propulsion system concept among several candidates, it can also identify which technologies are worth pursuing. This is particularly important for advanced aeropropulsion technology development programs, which require an enormous amount of resources. In the current practice of deterministic, or point-design, approaches, the uncertainties of design variables are either unaccounted for or accounted for by safety factors. This could often result in an assessment with unknown and unquantifiable reliability. Consequently, it would fail to provide additional insight into the risks associated with the new technologies, which are often needed by decision makers to determine the feasibility and return-on-investment of a new aircraft engine.

In this work, an alternative approach based on the probabilistic method was described for a comprehensive assessment of an aeropropulsion system. The statistical approach quantifies the design uncertainties inherent in a new aeropropulsion system and their influences on engine performance. Because of this, it enhances the reliability of a system assessment. A technical assessment of a wave-rotor-enhanced gas turbine engine was performed to demonstrate the methodology. The assessment used probability distributions to account for the uncertainties that occur in component efficiencies and flows and in mechanical design variables. The approach taken in this effort was to integrate the thermodynamic cycle analysis embedded in the computer code NEPP (NASA Engine Performance Program) and the engine weight analysis embedded in the computer code WATE (Weight Analysis of Turbine Engines) with the fast probability integration technique (FPI). FPI was developed by Southwest Research Institute under contract with the NASA Glenn Research Center.

The results were plotted in the form of cumulative distribution functions and sensitivity analyses and were compared with results from the traditional deterministic approach. The comparison showed that the probabilistic approach provides a more realistic and systematic way to assess an aeropropulsion system. In summary, the probabilistic methodology has the following advantages:

1. It provides decision-makers with a tool that allows them to assign priorities to needed technological developments and thus increase the likelihood that R&D investments will have high payoffs.
2. It provides insight into the risks associated with new technologies, which makes it easier for the decision-makers to determine the benefit and return-on-investment of a new aircraft engine.

3. It allows the decision-makers to detect problems early before they become critical. Because of this, risks can be mitigated accordingly and resources (time, R&D funding, etc.) can be used more wisely.

4. It quantifies the reliability of a new aircraft engine. As a result, risks can be mitigated early and catastrophic engine failure will be minimized.

5. The results from probabilistic assessment are more credible and reliable, because it incorporates the 'past lessons learned' (i.e., expert opinions, historical data, etc.) to quantify the risks. As a result, the likelihood of repeating past mistakes will be minimized.

The current work addressed the application of the probabilistic approach to assess specific fuel consumption, engine thrust, and weight. Similarly, the approach can be used to assess other aspects of aeropropulsion system performance, such as cost, acoustic noise, and emissions.

NASA/CP—2002-211682

Risk-Based Probabilistic Approach to Aeropropulsion System Assessment

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Cleveland, Ohio
U.S.A.

Presentation Outline

- Background
- Methodology
- Numerical example
- Summary & Concluding Remarks
- Future Works

Objective

- To demonstrate the application of probabilistic approach and its feasibility for aeropropulsion system assessment.

Keys to a Successful Engine Development Program

- Develop reliable and cost-effective technologies.
- Rapid turn around time.
- Make critical decisions in the early stages of engine development - more design freedom and lower cost.

The Role of Aeropropulsion System Assessment in NASA

- Quantify the benefit of new propulsion technologies.

- Identify the best propulsion system concept amongst several candidates.

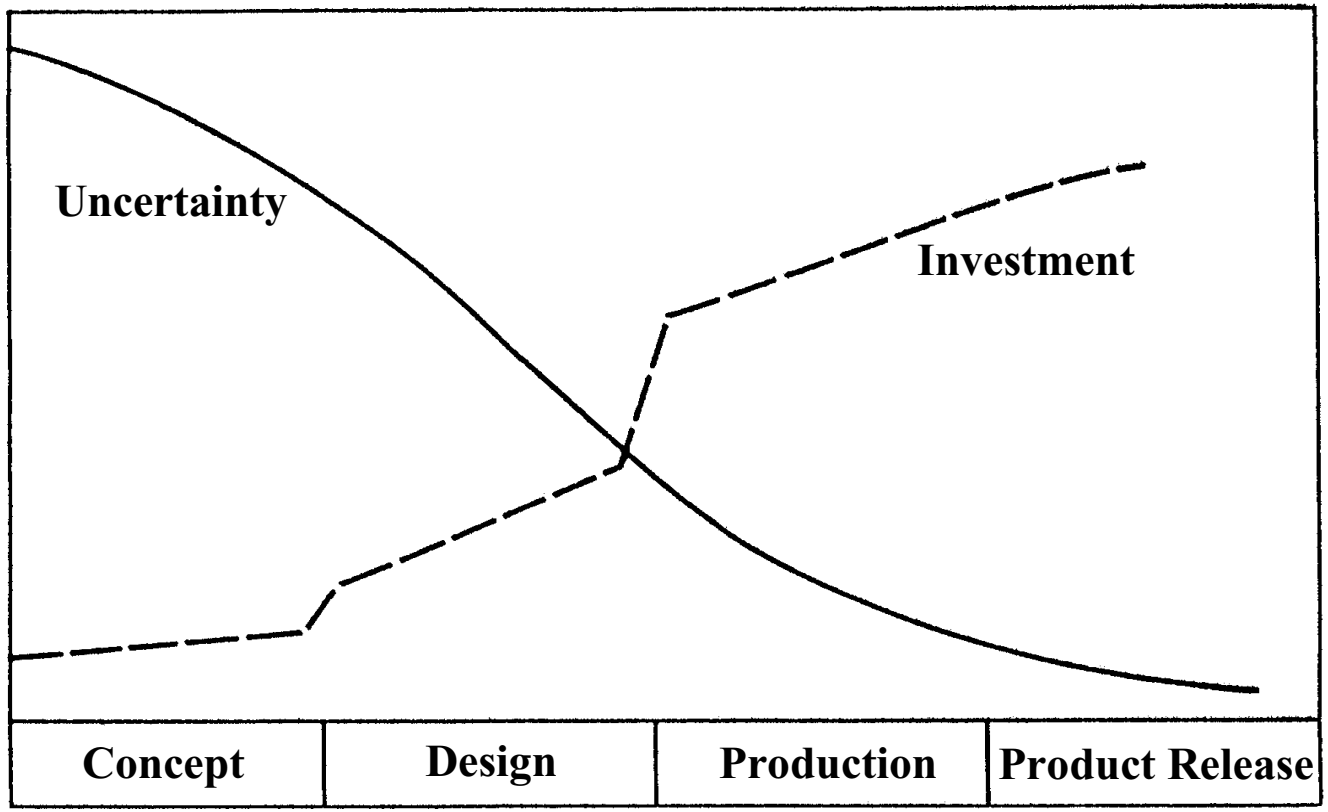
- Identify high payoff technologies worthy of pursuit to decision makers.

<u>via conceptual analyses</u>:

- thermodynamic analysis – cycle performance
- flowpath analysis – engine sizing & weight
- mission analysis – fuel burn, emissions
- economic analysis - cost

Why Probabilistic Approach at the Conceptual Stage?

High uncertainty & Relatively low investment



Propulsion System Life Cycle

Aeropropulsion System Design Uncertainties - Examples

- Uncertainty due to technology infusion.
- Uncertainty in the various engine component performance.
- Uncertainty in mission requirements.
- Uncertainty in cost.
- …….etc.

Probabilistic Approach
Step-by-Step Procedures

- Identify basic design variables and their uncertainties.
- Quantify the uncertainties with distributions, means, and scatters, based on expert opinion elicitation, historical data, etc.
- Identify the response variables - SFC, thrust, weight, etc.
- Establish functional relationships between the design variables and the response variables
  - analytical expressions, numerical evaluation thru computer codes (such as NEPP*, WATE*).

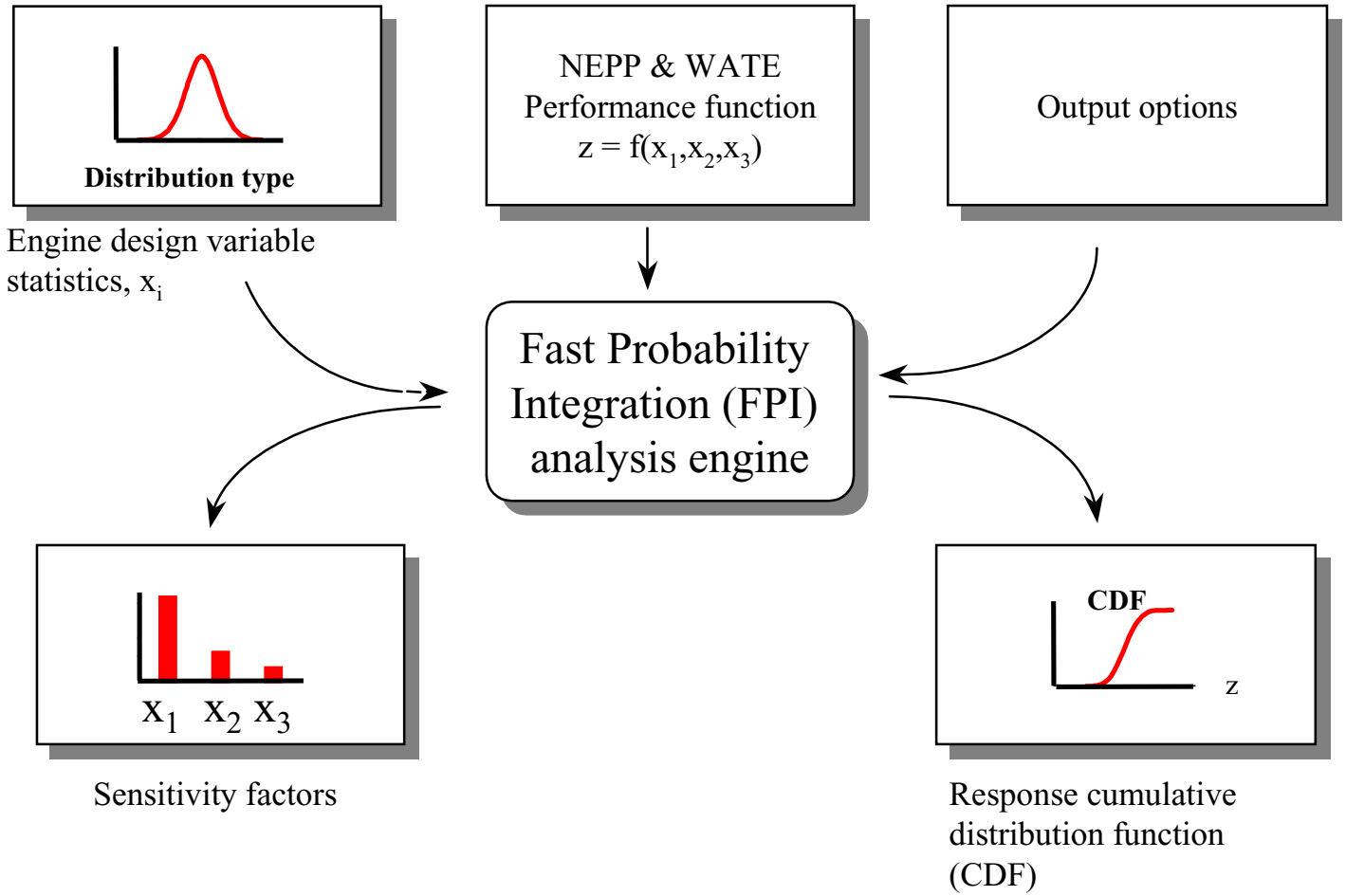
**NEPP - NASA Engine Performance Program*
**WATE - Weight Analysis of Turbine Engines*

Probabilistic Approach
Step-by-Step Procedures (cont'd)

- Perform perturbation for the selected set of design variables (mean & standard deviation) to generate response variables.
- Perform probabilistic analysis (FORM, SORM, Monte-Carlo, etc.)
  - to compute cumulative distribution functions of the response variables.
  - to compute the sensitivity factors of the response variables.

**FORM – First Order Reliability Method*
SORM – Second Order Reliability Method

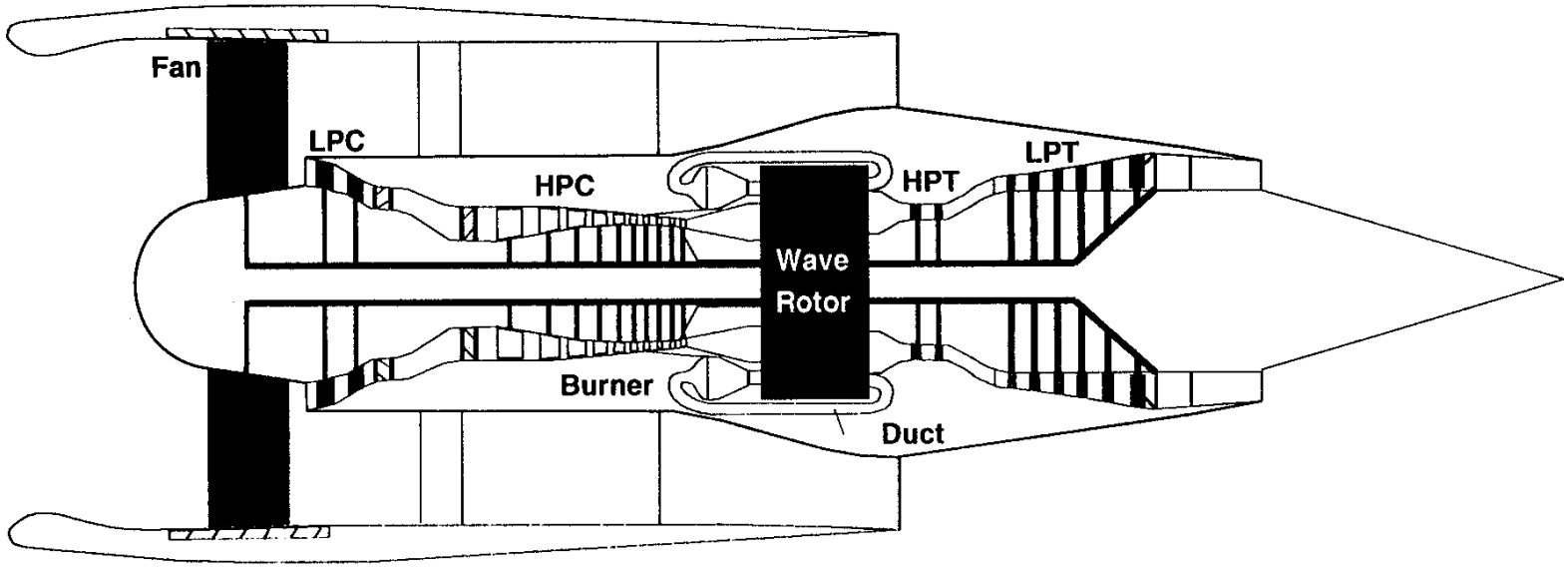
Probabilistic Approach - Schematic



Numerical Example

A Wave Rotor-Enhanced Turbofan Engine

Sea-Level Static Thrust ≈ 90,000 lbs



Wave Rotor–Enhanced Turbofan Engine

Probabilistic assessment of engine SFC, thrust, and weight.

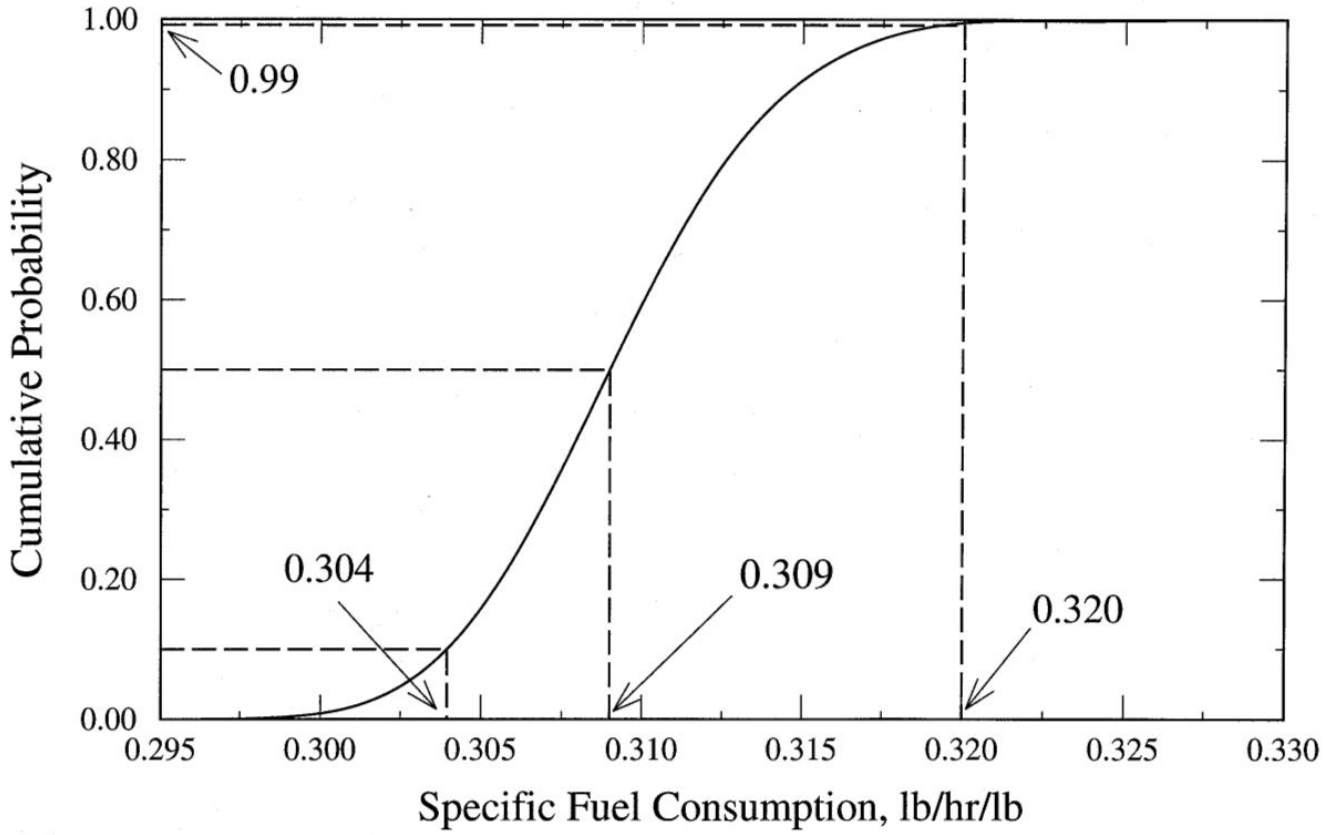
Design Variables with Uncertainties

Design Variable	Deterministic Approach (From Ref 1)	Probabilistic Approach		
		Mean	Standard Deviation	Distribution Type
Fan efficiency	0.91	0.91	±0.01	Normal
LPC efficiency	0.88	0.87	±0.01	Normal
HPC efficiency	0.85	0.87	±0.01	Normal
Wave rotor pressure ratio	1.15	1.13	±0.01	Normal
HPT efficiency	0.89	0.88	±0.01	Normal
HPT inlet temp	3200 R	3200 R	±50 R	Normal
LPT efficiency	0.93	0.91	±0.01	Normal
Bleed flow, %	19.5	19.0	±0.5	Normal
Turbine disk material ultimate strength	100 ksi (690 Mpa)	100 ksi (690 Mpa)	±5 ksi (±40 Mpa)	Weibull

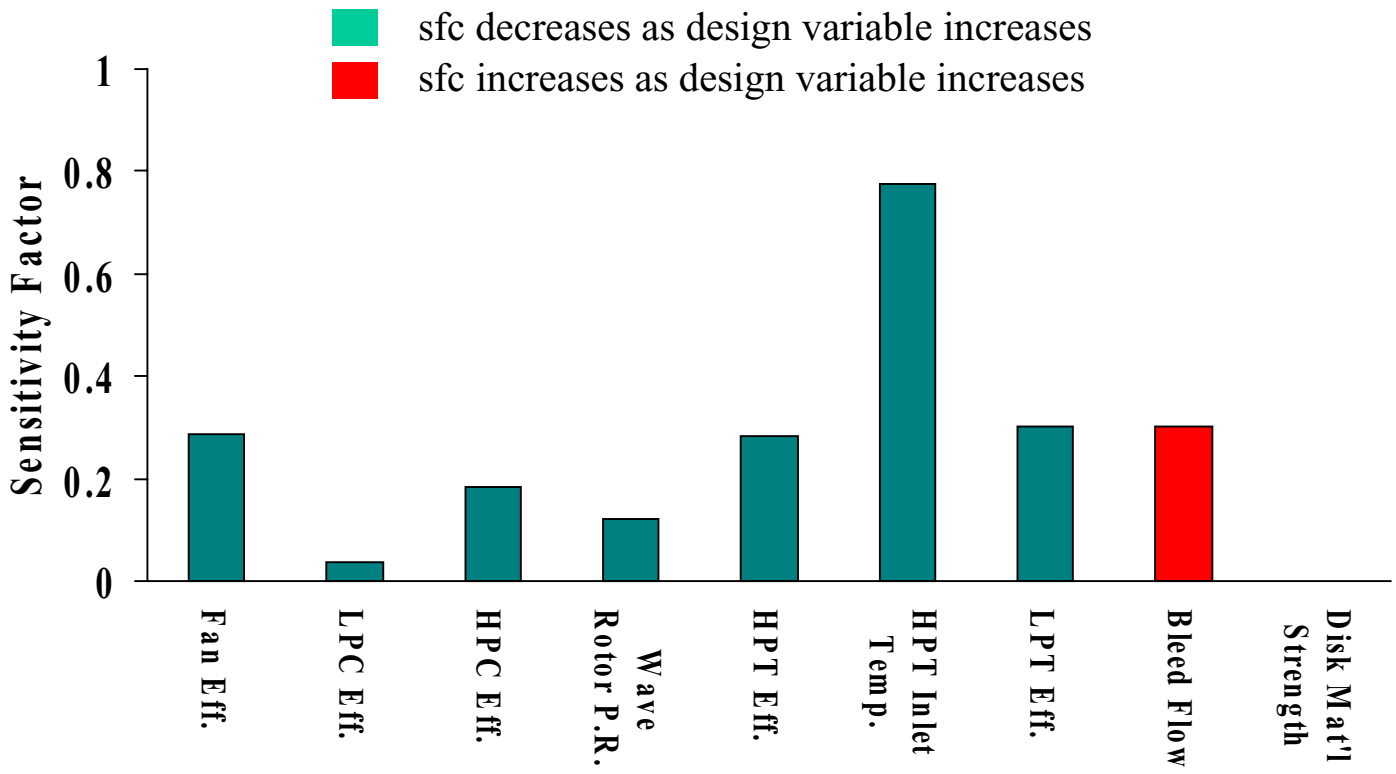
Other Design Variables

Design Variable	Deterministic Approach	Probabilistic Approach
Inlet flow	2800 lb/s	
Inlet recovery	1.00	
Inlet temperature	545.7 R	
Fan pressure ratio	1.59	
Fan corrected flow	2875 lb/s	
LPC pressure ratio	1.55	
HPC pressure ratio	15.8	
Wave rotor temp. ratio	1.91	

Probabilistic Approach Quantifies the System Performance Uncertainty

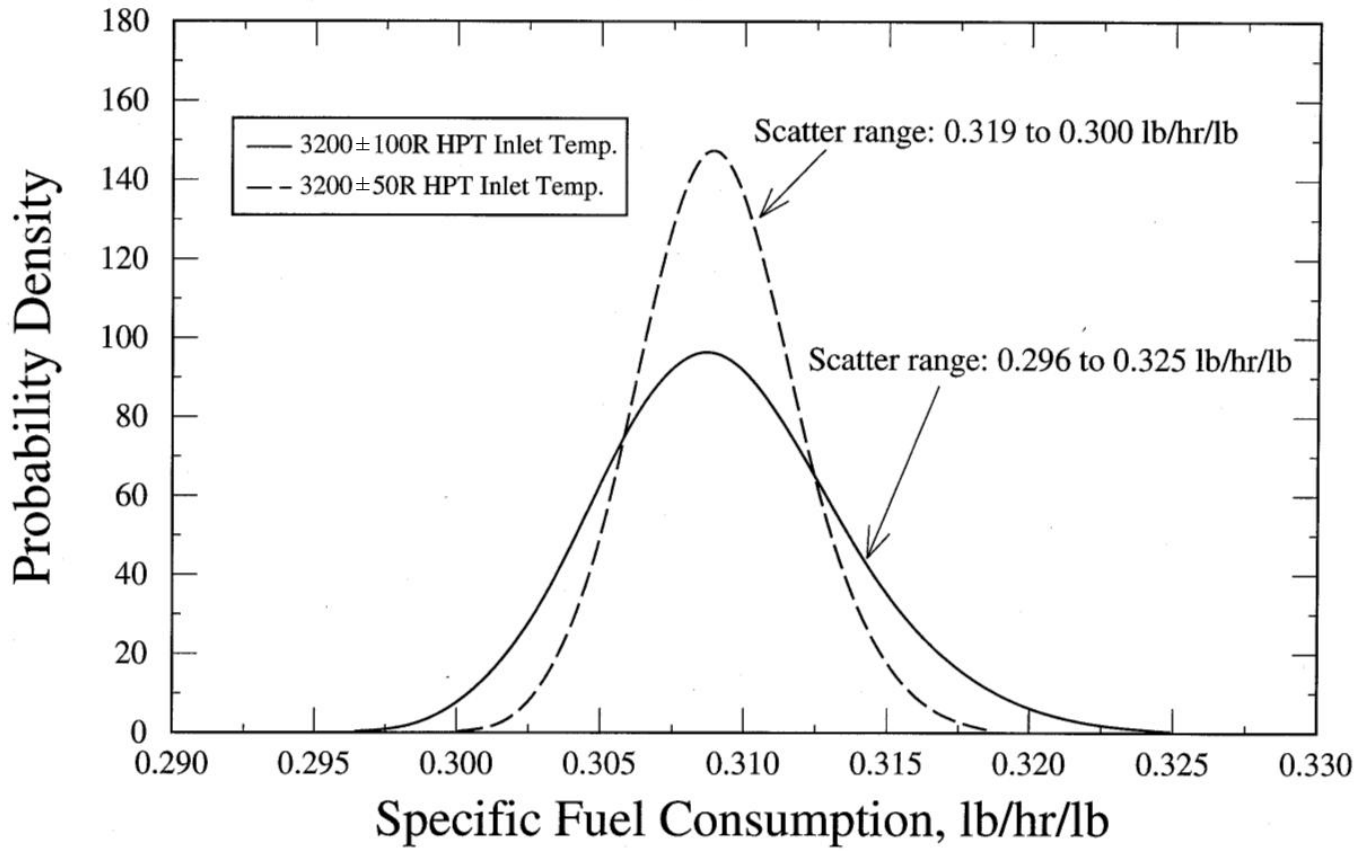


Sensitivity of Specific Fuel Consumption 99% Probability Level



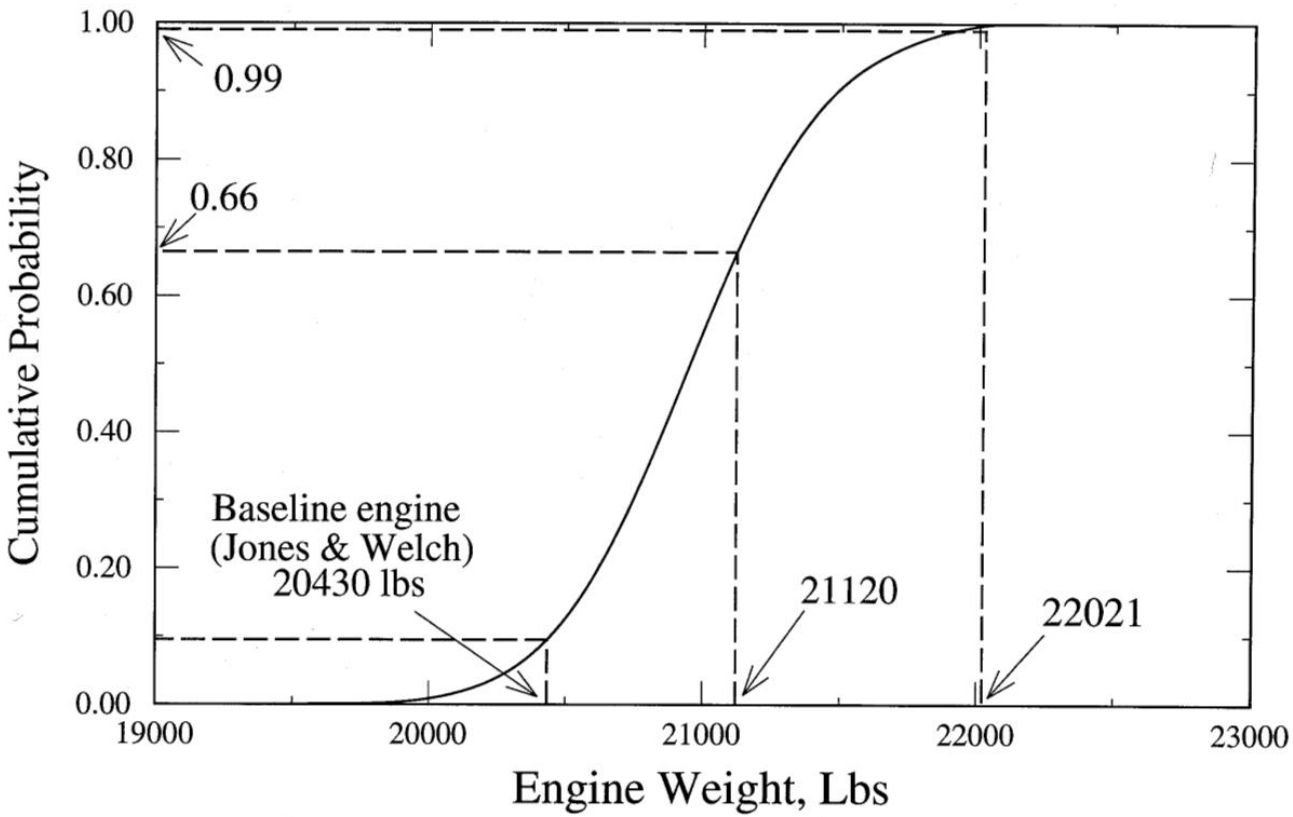
Higher sensitivity factors identify dominant variables to control that would result in biggest payoff.

Probabilistic Approach Enables Better Risk Guarantee to the Customers

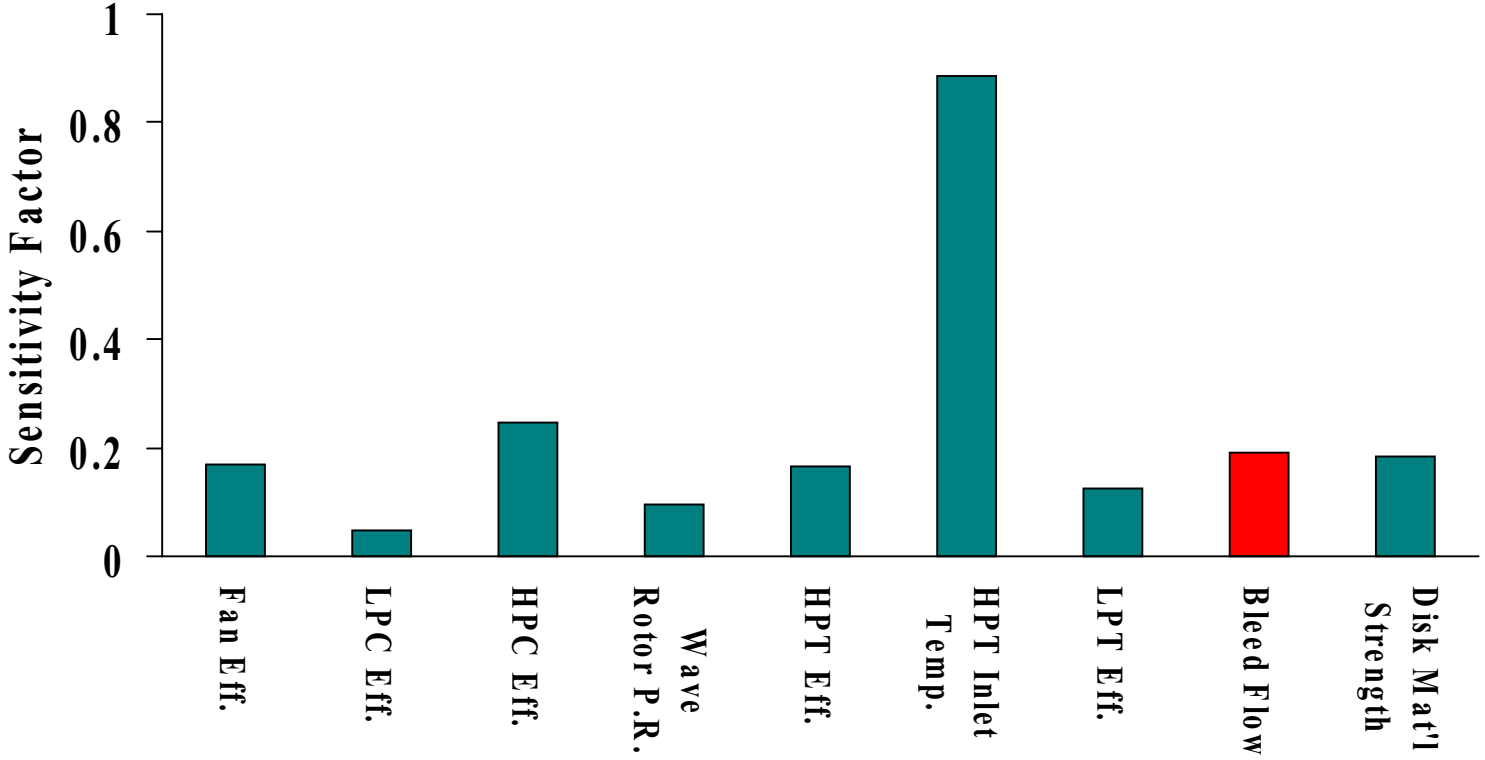


It reduces SFC scatter by about 35%!!!

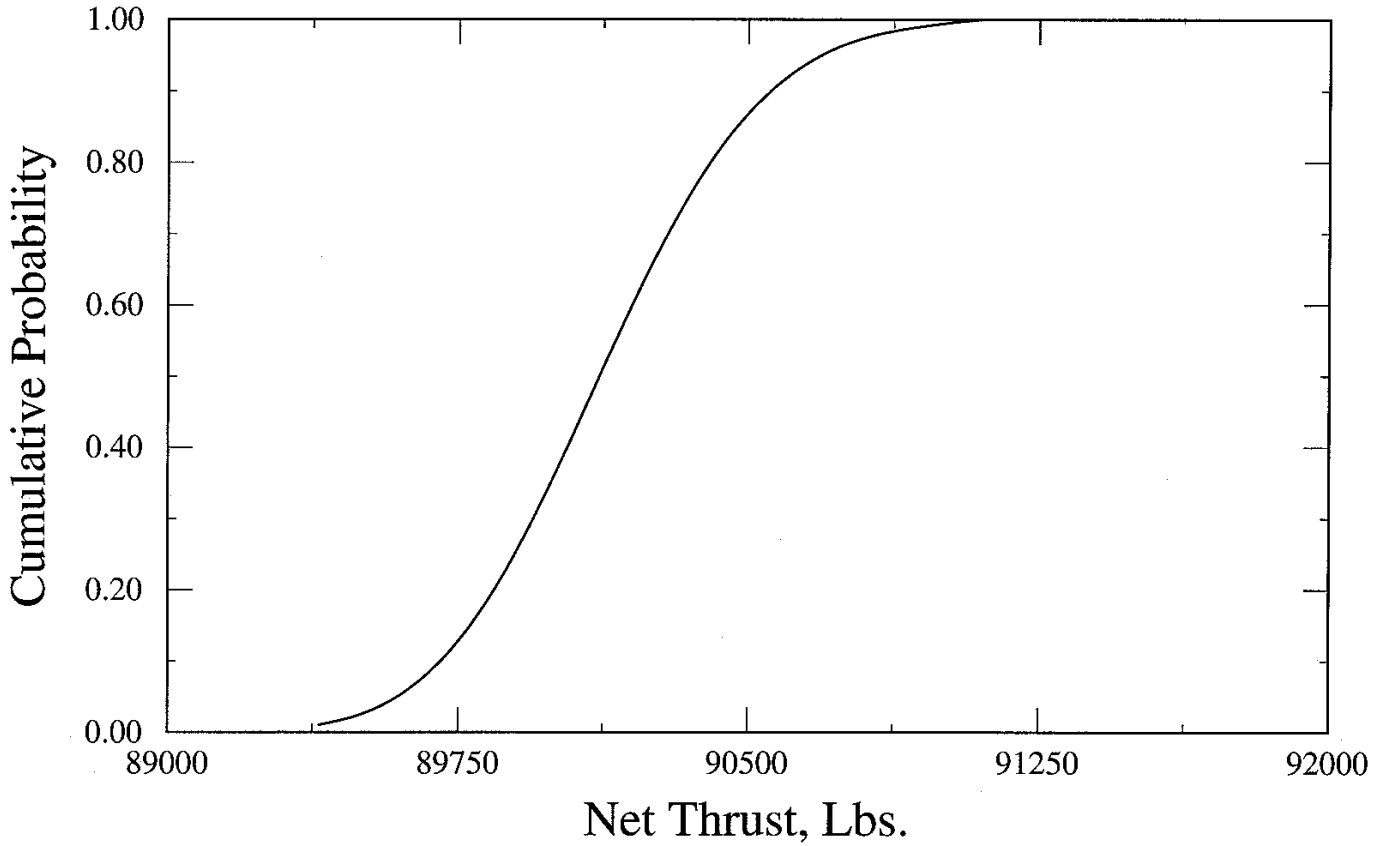
CDF of Wave Rotor-Enhanced Turbofan Engine Weight



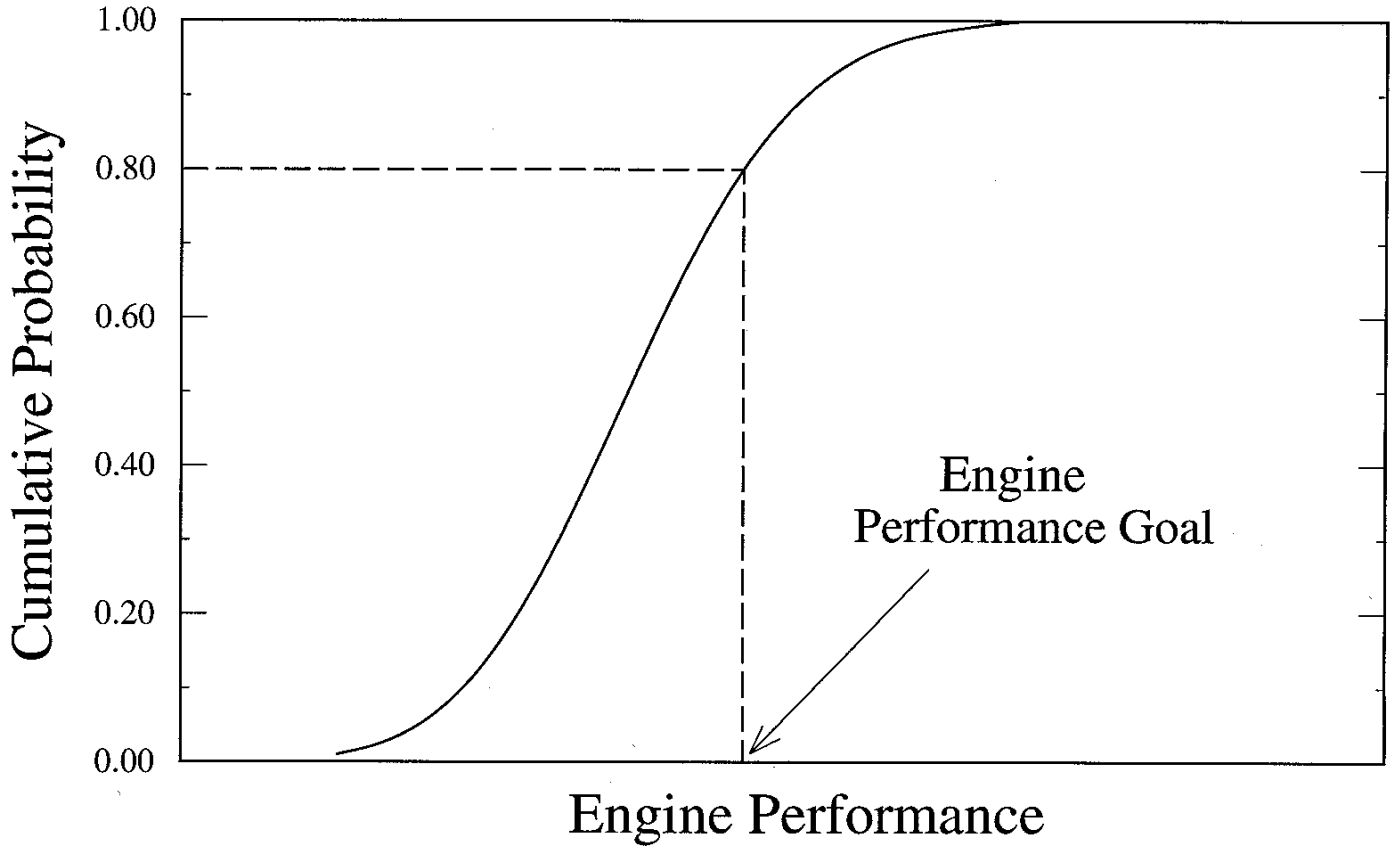
Sensitivity of Engine Weight
99% Probability Level



CDF of Wave Rotor-Enhanced Turbofan Engine Net Thrust



Probabilistic Approach Enables More Realistic System Assessment



Summary of Probabilistic Approach

- **Quantifies the uncertainties**
  - more realistic and systematic way to develop new technologies.

- **Incorporates the 'lessons learned' to quantify the development risks**
  - more credible and reliable results.
  - minimize the likelihood of repeating past mistakes.

- **Provides information on risk sensitivity**
  - aid decision-makers in assigning priorities to needed technological developments.
  - increase the likelihood that R&D investments will have high payoffs.

Summary of Probabilistic Approach (cont'd)

- **Detects problems early before they become critical**
  - development risks can be mitigated early and resources (time, funding, manpower, etc.) can be used more wisely.

- **Provides additional insight into the risks associated with new technologies**
  - makes it easier for decision-makers to determine the benefit and return-on-investment of a new technology.

Concluding Remarks

- Probabilistic approach is a feasible and rational approach for developing aeropropulsion technologies.

- Effective communication (cooperation) between the technologists and analysts is critical for performing meaningful probabilistic analysis.

The biggest risk of all is ignoring risk!!!

Future Works

- Probabilistic tradeoff analyses –
  - performance – thrust, fuel burn, weight, noise, CO_2 & NO_x emissions
  - durability
  - cost

- Integrate probabilistic system assessment with decision tree analysis to aid decision making

Engine performance, durability, and cost are tradeoffs.

In-Flight Engine Diagnostics and Prognostics Using a Stochastic-Neuro-Fuzzy Inference System

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Email: dghiocel@sti-tech.com

ABSTRACT

The paper will present the concept of a generalized physics-based approach to stochastic nonlinear mechanics problems. The generalized approach that is based on a multiple local-averaging of stochastic response. The "patches" are the local-averaging subdomains in stochastic parameter space. The proposed approach is practical and highly applicable to complex physics problems, such as the HCF prediction and large nonlinear systems behavior. The proposed approach can accurately incorporate complex nonlinear statistical dependencies within uncertainty propagation in large systems.

Using the proposed approach a Patched-Based Monte Carlo (PBMC) simulation technique is developed. The proposed PBMC simulation technique assumes that the nonlinear system response surfaces are non-stationary physics-based stochastic fields defined by a set of nonlinearly correlated stochastic variables. The PBMC simulation technique can be applied to partition large-size stochastic systems in cascaded subsystems, being capable of transmitting accurately the all the key physics-based uncertainties and their complex statistical dependencies. In contrast to the standard Response Surface Monte Carlo (RSMC), PBMC assumes no functional form for the approximation of stochastic response and its correlation structure. PBMC is much more efficient for high-dimensional highly-nonlinear problems than the standard RSMC. Also, it provides more insights in the stochastic system behavior.

In-Flight Engine Diagnostics and Prognostics Using A Stochastic-Neuro-Fuzzy Inference System

Dr. Dan M. Ghiocel

Dr. J. Altmann

STI Technologies

A PCB Group Company

5th FAA/Air Force/NASA/Probabilistic Methods for Gas Turbine Engine workshop

June, 2001

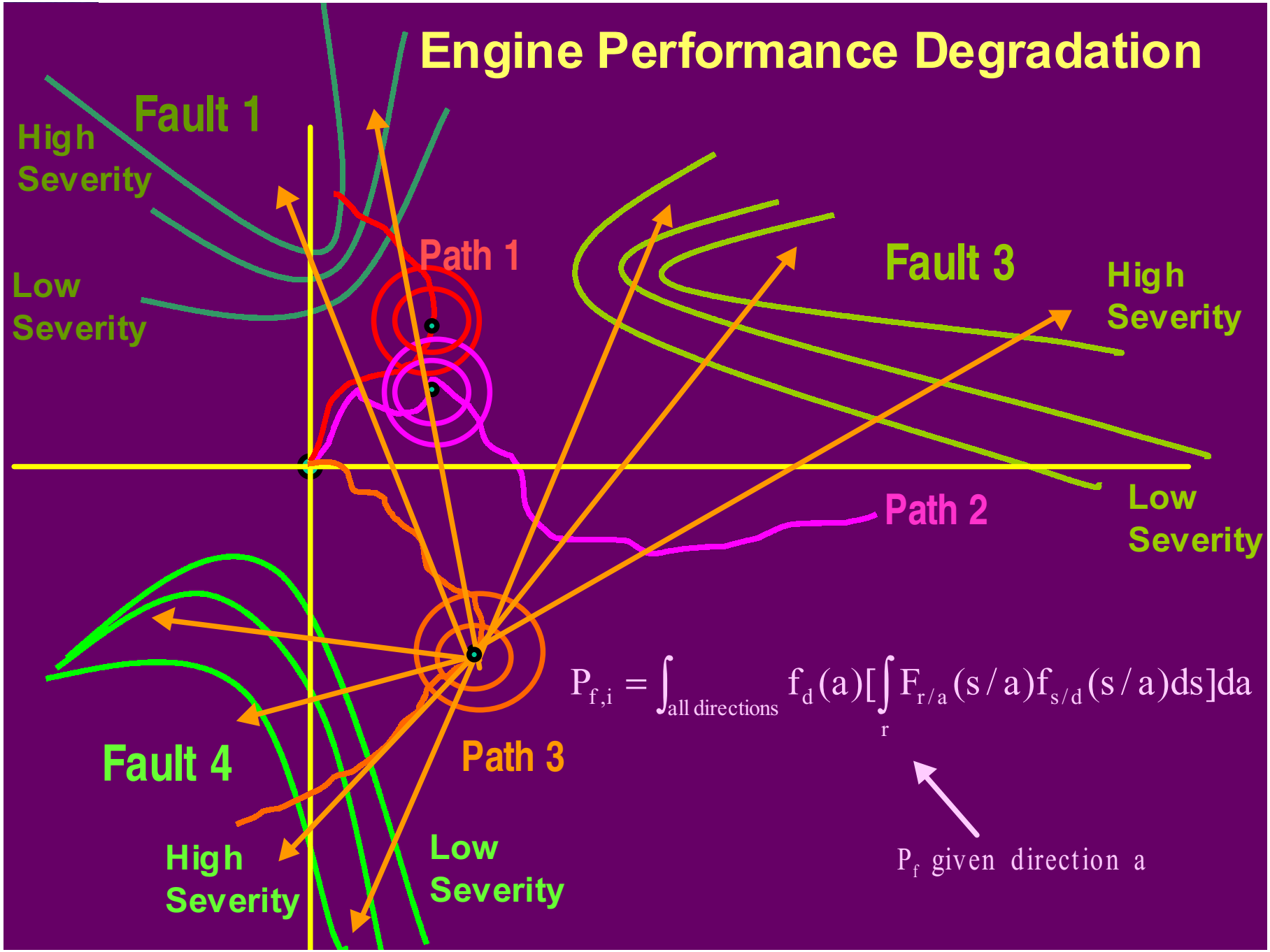
Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

Presentation Content:

Engine Performance-Based Diagnostics
Description of Probabilistic Fault Diagnostic/Prognostic Procedure
- **Ground-Test Data and In-Flight Data**
- **Interpretations of Results**
- **Concluding Remarks**

Engine Vibration-Based Diagnostics
- **Using Ground-Test Data**
- **Spectral Analysis, Track-Orders, Projected Profiles**
- **Feature Extraction Issues**

Concluding Remarks


Engine Performance Degradation
Fault 1
High Severity
Low Severity
Path 1
Fault 3
High Severity
Low Severity
Path 2
Fault 4
Path 3
High Severity
Low Severity
$P_{f,i} = \int_{\text{all directions}} f_d(a)[\int_r F_{r/a}(s/a) f_{s/d}(s/a) ds] da$
P_f given direction a

Probabilistic Fault Diagnosis Analysis

Fault Diagnostic Probability = Failure Probability

$$p_f = \int \ldots \int f_X(x_1, x_2, \ldots, x_n) dx_1, dx_2 \ldots dx_n$$

Fault Diagnostic Index = Reliability Index

$$p_f \approx \Phi(-\beta)$$

Performance (Reliability) Degradation Indices:

- **Cumulative Index**

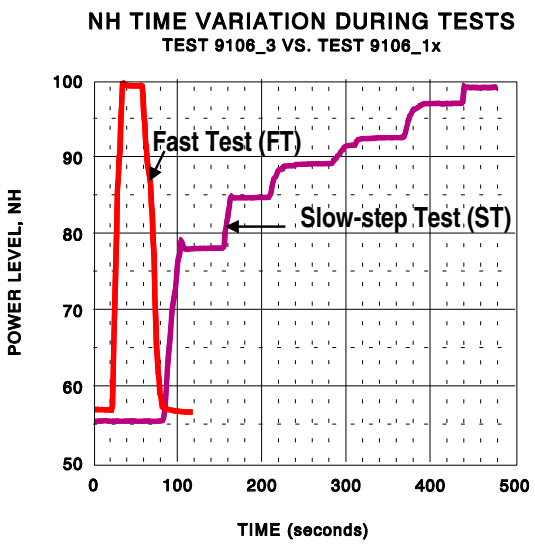
$$C_{0,t} = -\frac{\beta_t - \beta_0}{\beta_0} = -\frac{\Delta\beta_{ot}}{\beta_0}$$

- **Evolutionary Index**

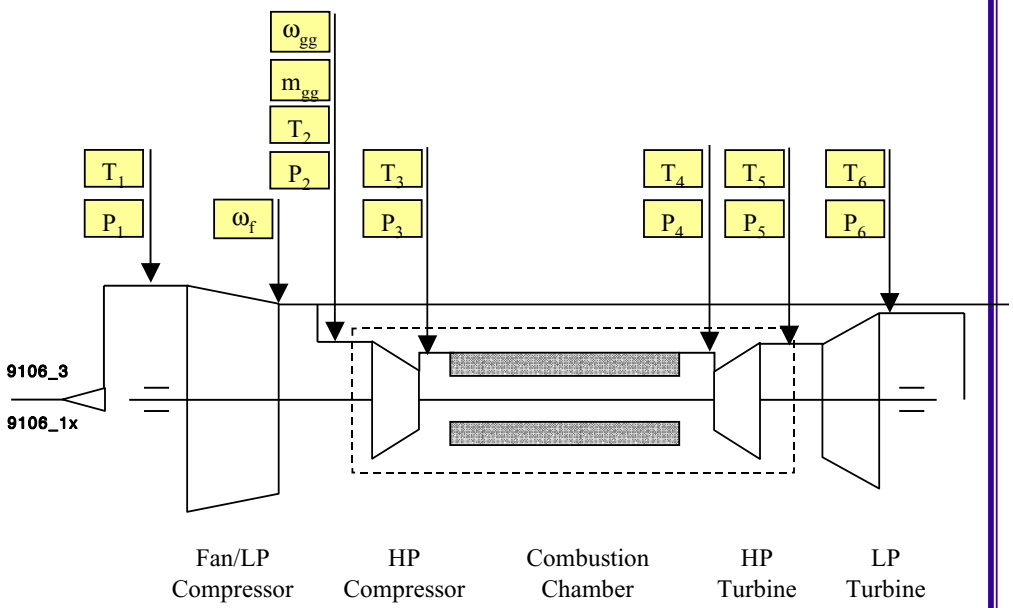
$$E_{ti,ti+1} = -\frac{\beta_{ti+1} - \beta_{ti}}{\beta_{ti}} = -\frac{\Delta\beta_{ti,ti+1}}{\beta_{ti}}$$

Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

Using Ground-Test Data



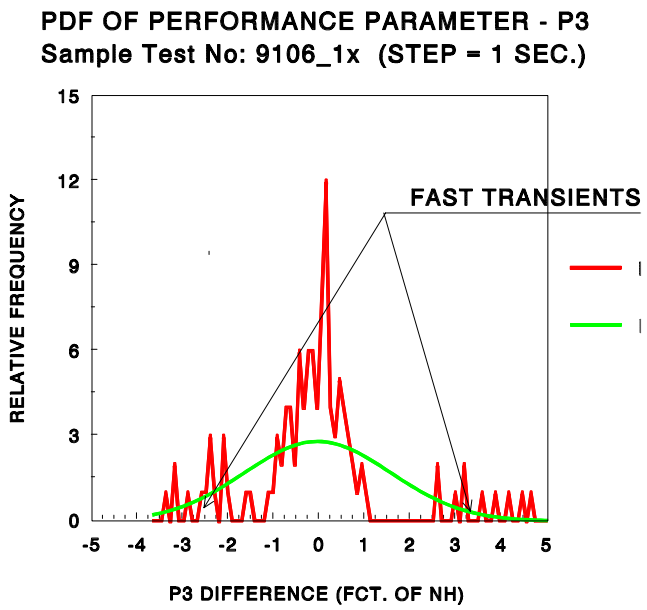
Test Measurements



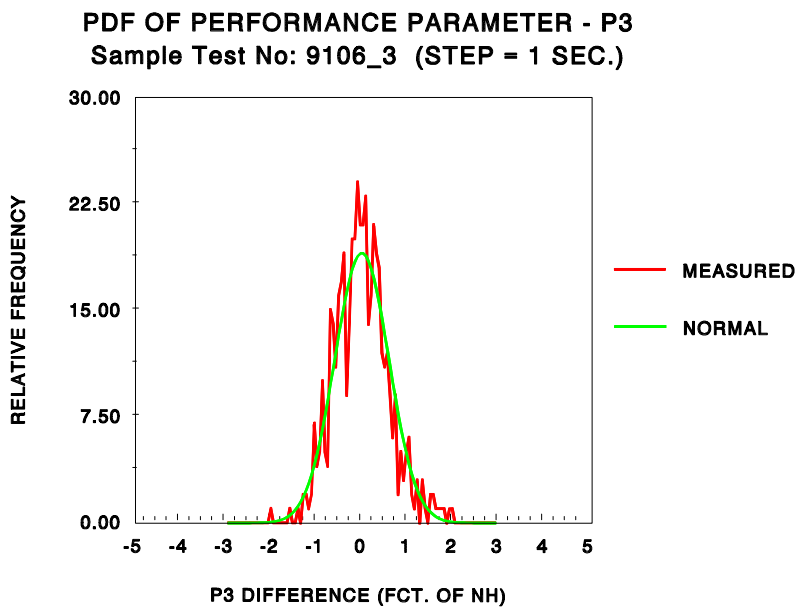
Calibrated GPA Model

Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

Probability Density of dP3



Fast Test

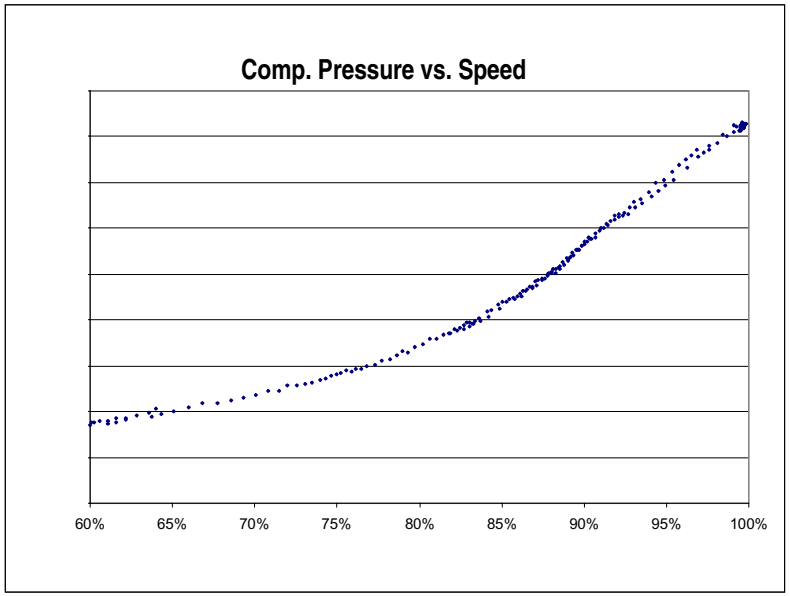


Slow Test

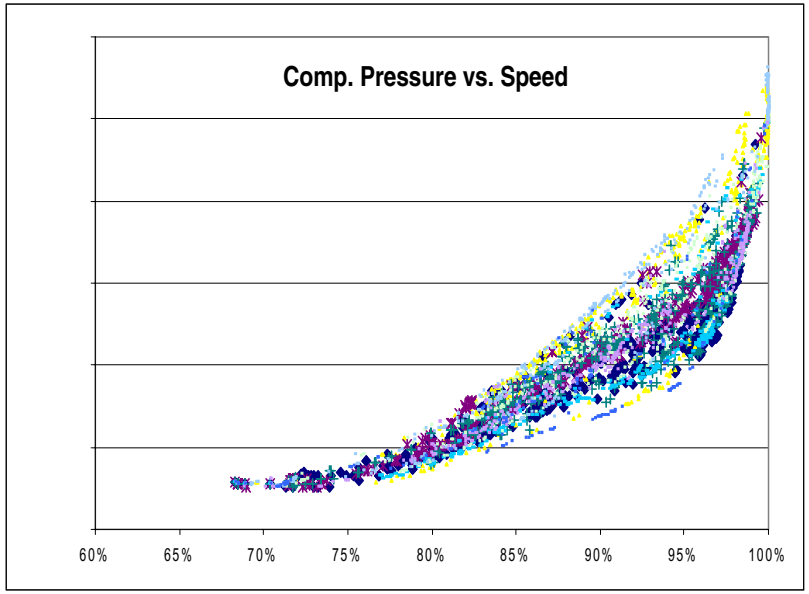
Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

In-Flight vs. Ground Test Data

Ground-test data



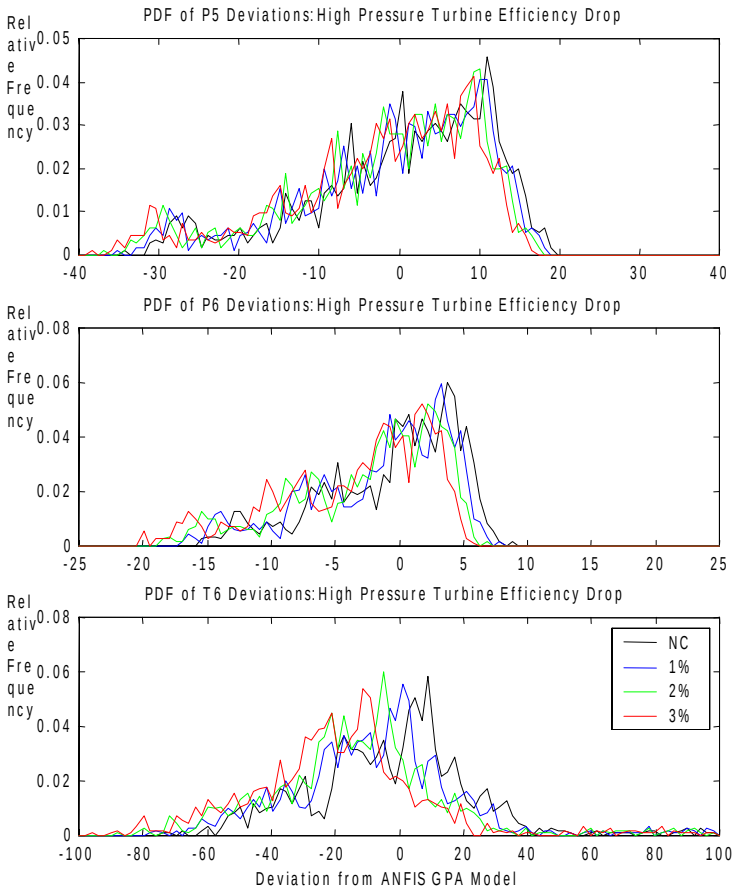
In-flight data



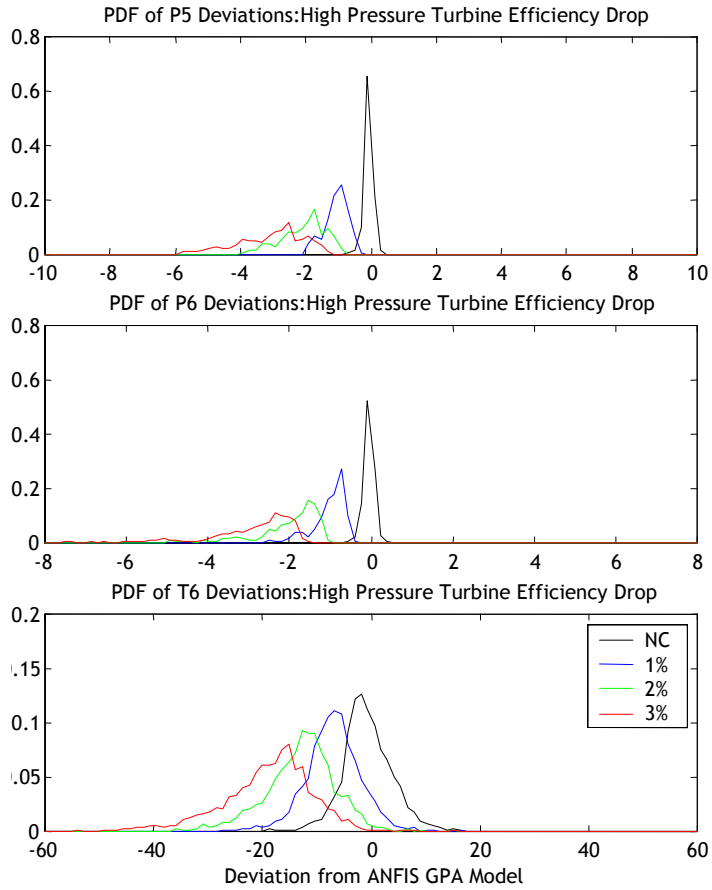
Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

Engine Performance Parameters

Function of 1 variable

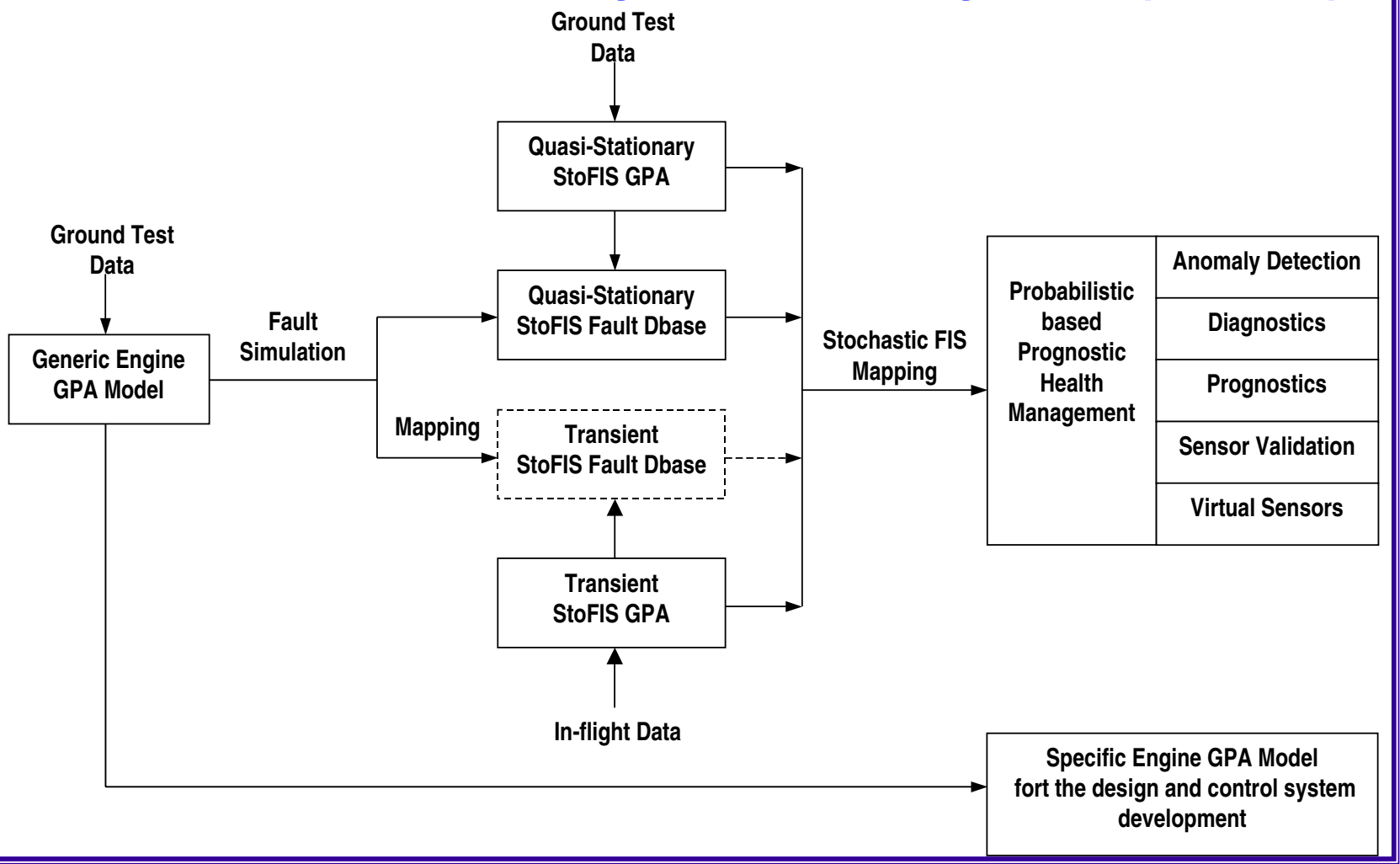


Function of 5 variables



Engine Health Risk Management Using A Hybrid Stochastic-Fuzzy Inference System

Stochastic-Neuro-Fuzzy Inference System (StoFIS)



Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

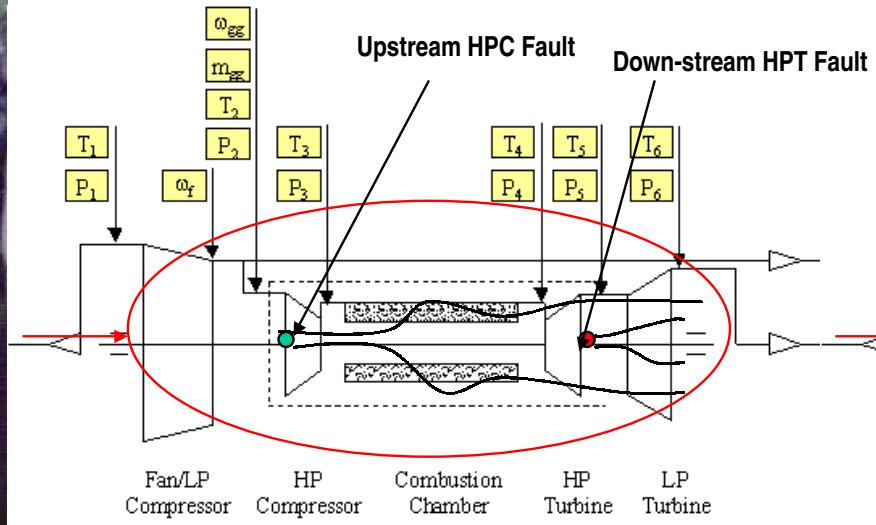
In-Flight Engine Models (for Single/Multiple Faults)

Transient Engine Models:

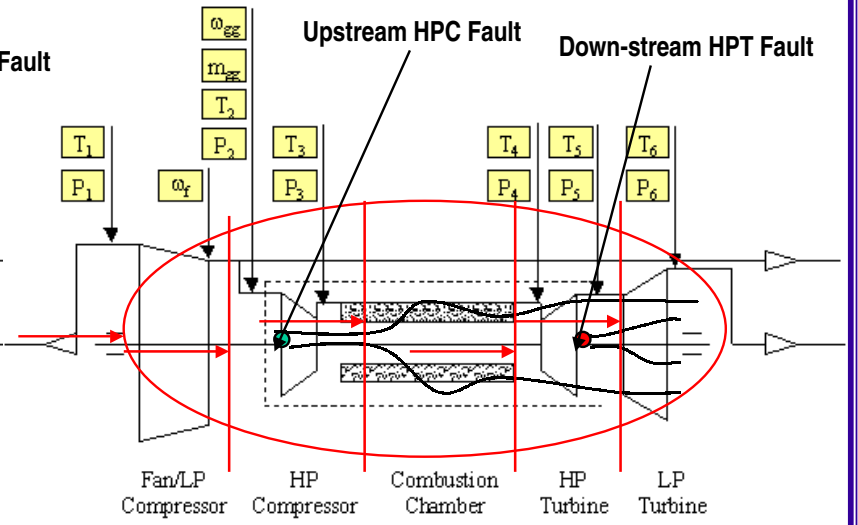
$$P_n, T_n = fn(P_1, T_1, \dot{m}_{gg}, \omega_f, \omega_{gg}) \qquad P_n, T_n = fn(P_{n-1}, T_{n-1}, \dot{m}_{gg}, \omega_f, \omega_{gg})$$

Quasi-Stationary Engine Models:

$$P_n, T_n, \dot{m}_{gg}, \omega_f = fn(P_1, T_1, \omega_{gg}) \qquad P_n, T_n, = fn(P_{n-1}, T_{n-1}, \omega_{gg})$$



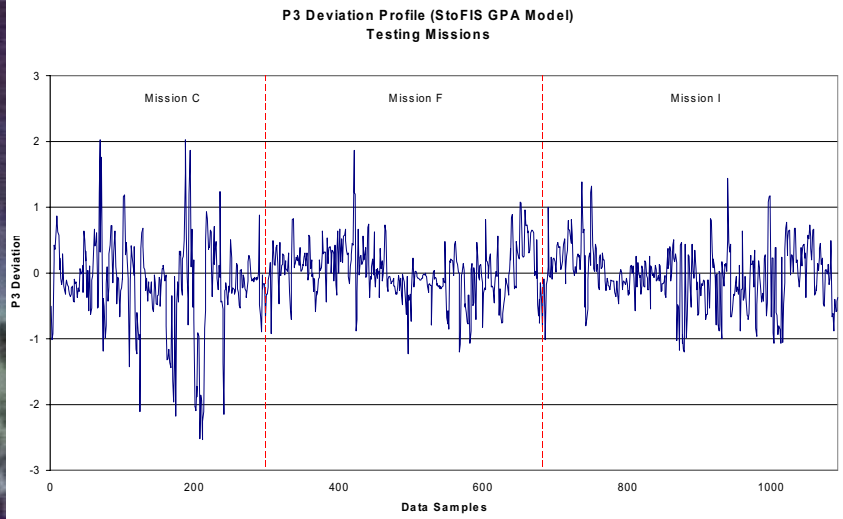
Overall StoFIS GPA Model

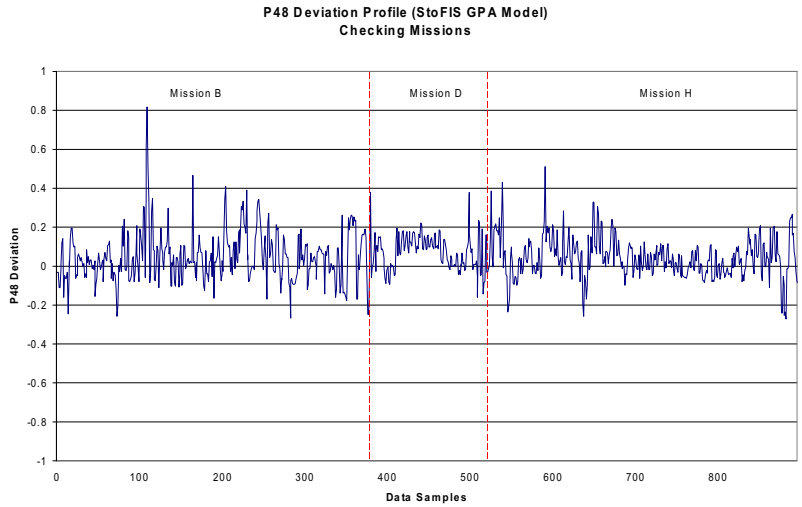


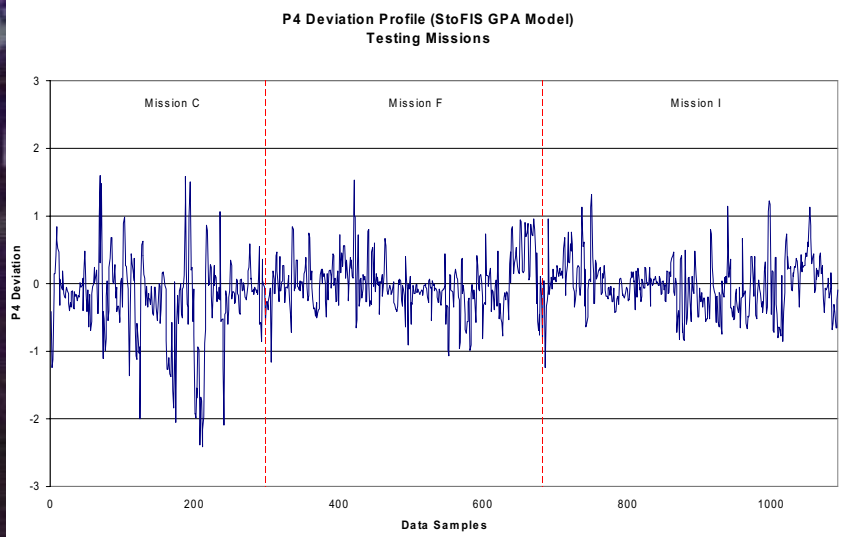
Compartmentalized StoFIS GPA Model

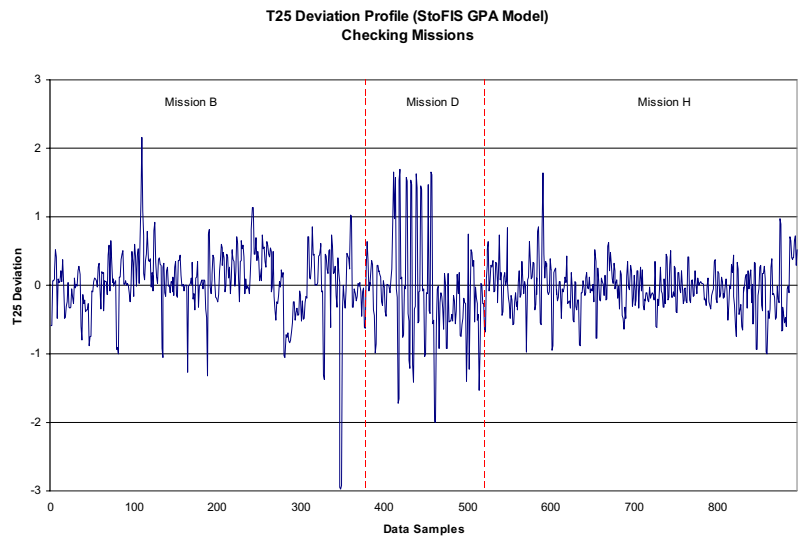
Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

Stochastic Parameter Deviations









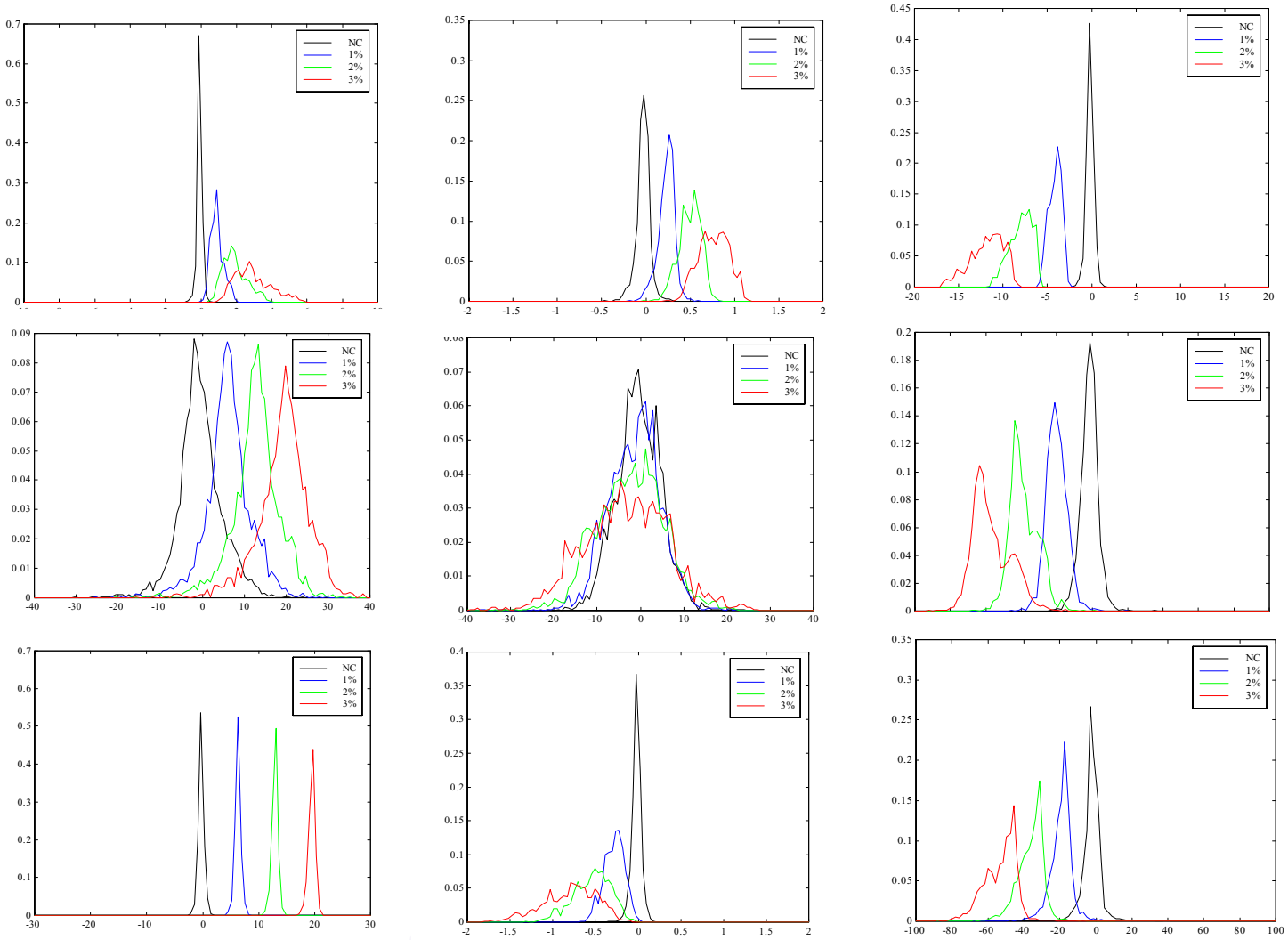
Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

PDFs for Parameter Deviations

Fault #4: Drop in High Pressure Turbine Capacity

Fault #2: Drop in Low Pressure Turbine Capacity

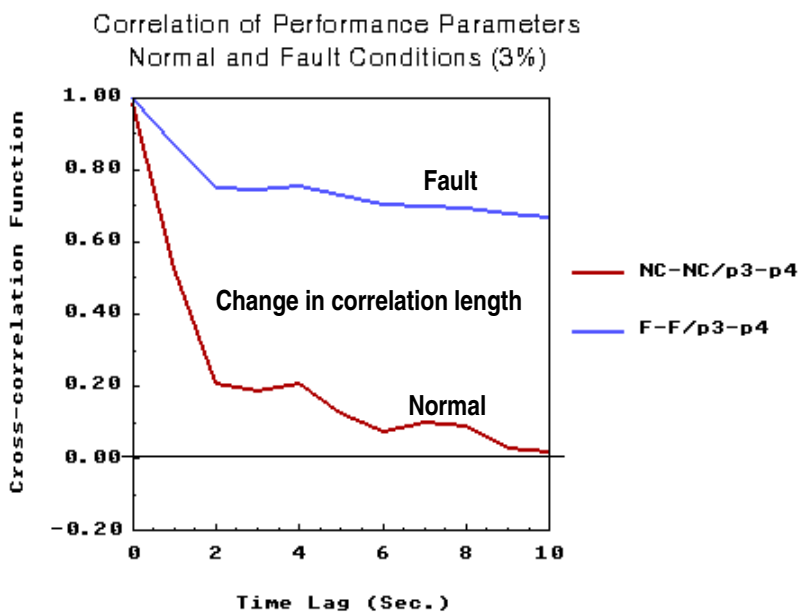
Fault #7: Drop in High Pressure Compressor Efficiency



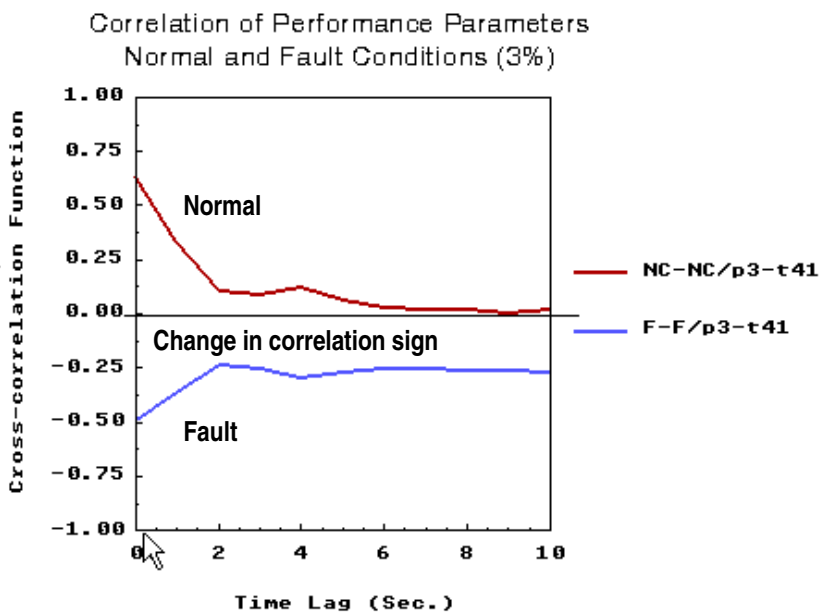
Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

Parameter Correlations for Normal and Fault Conditions

Pressures P3 and P4

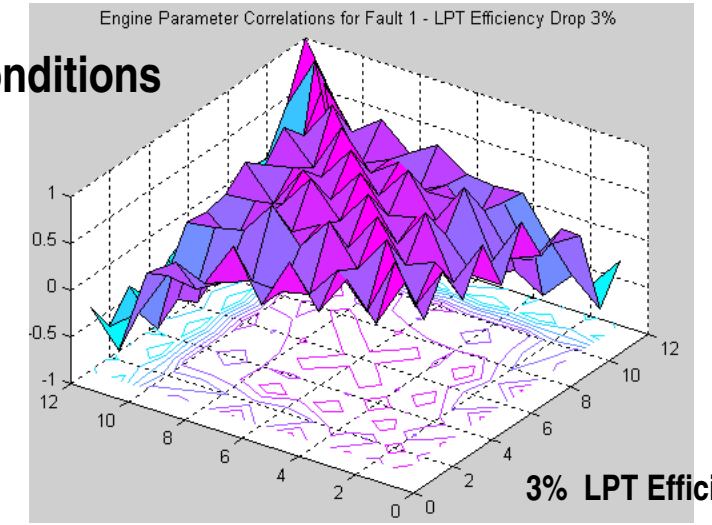


Pressure P3 and Temperature T41



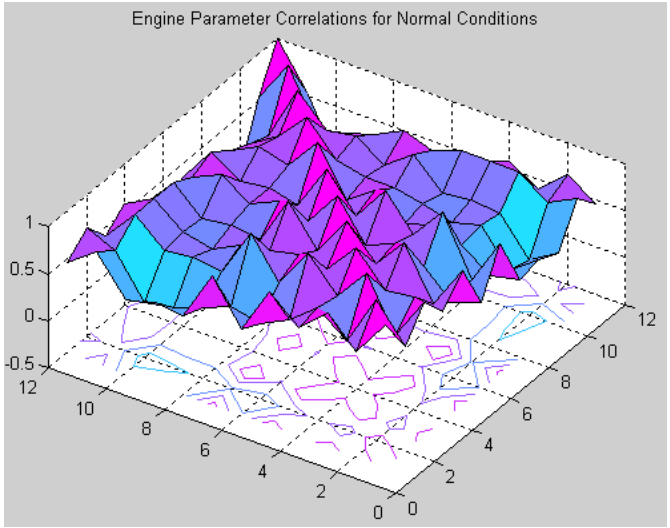
Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

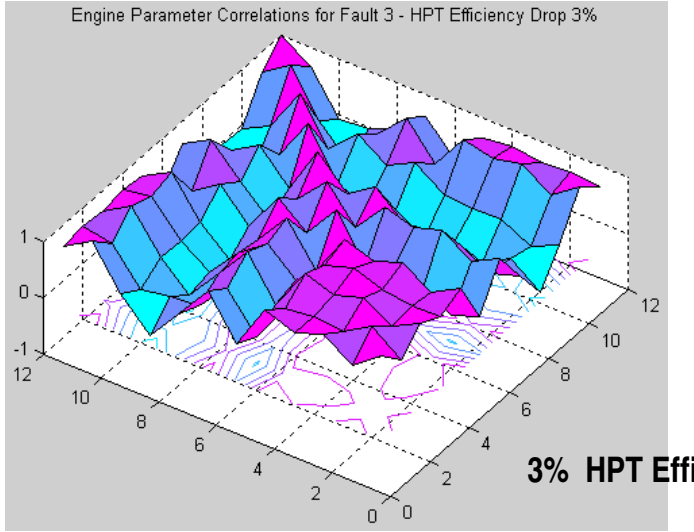
Fault Conditions



3% LPT Efficiency Drop

Normal Conditions

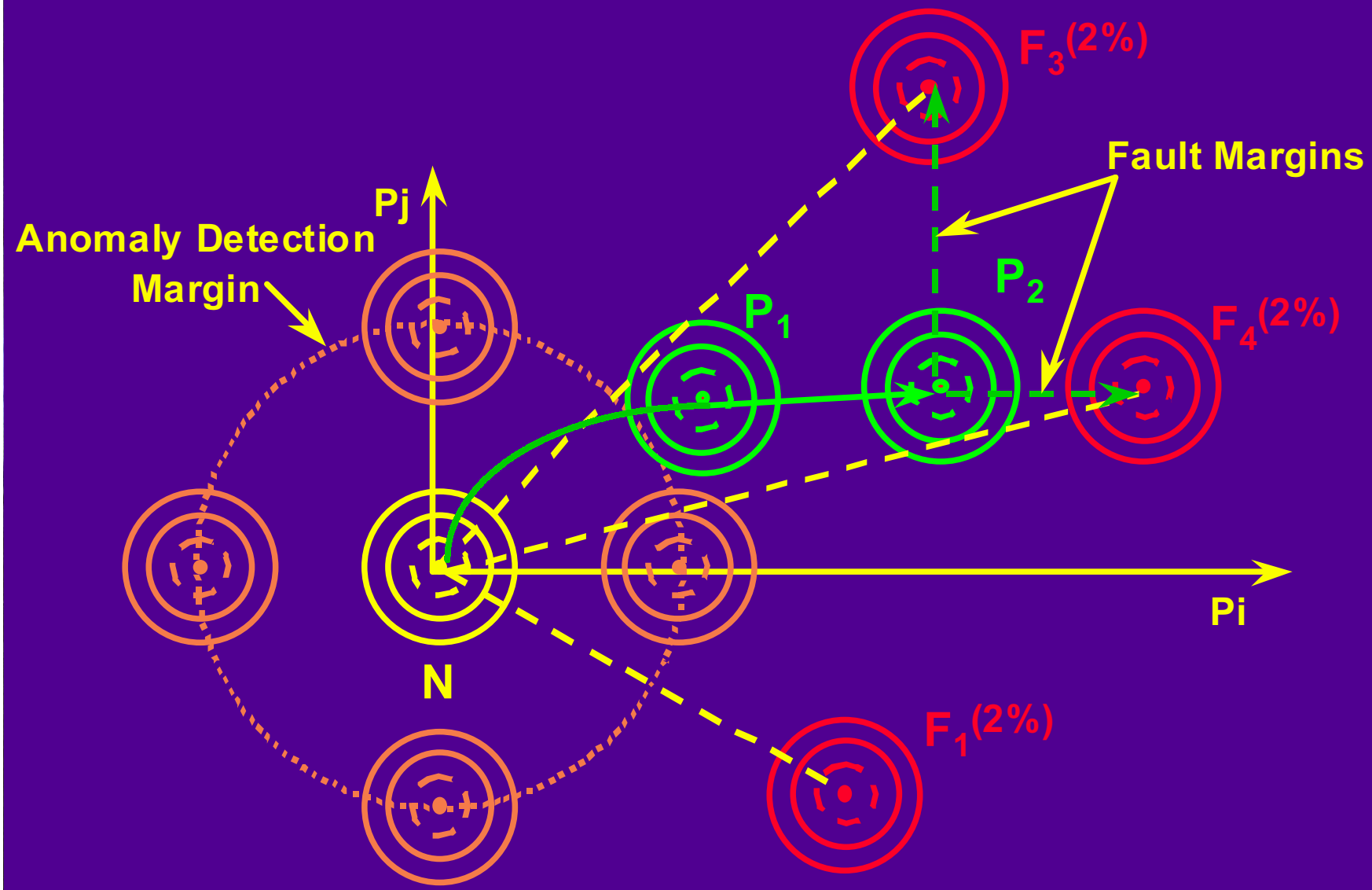




3% HPT Efficiency Drop

Note: Changes in the correlation structure are fault dependent

Probabilistic Fault Diagnostic/Prognostic Procedure

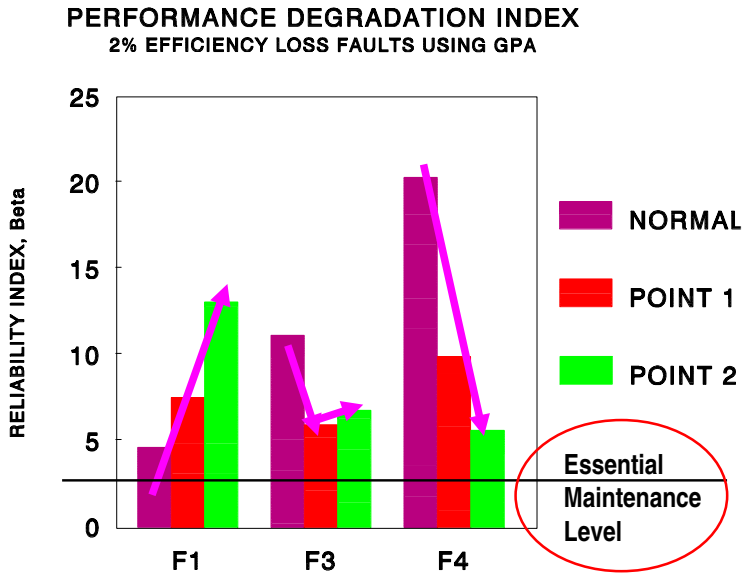


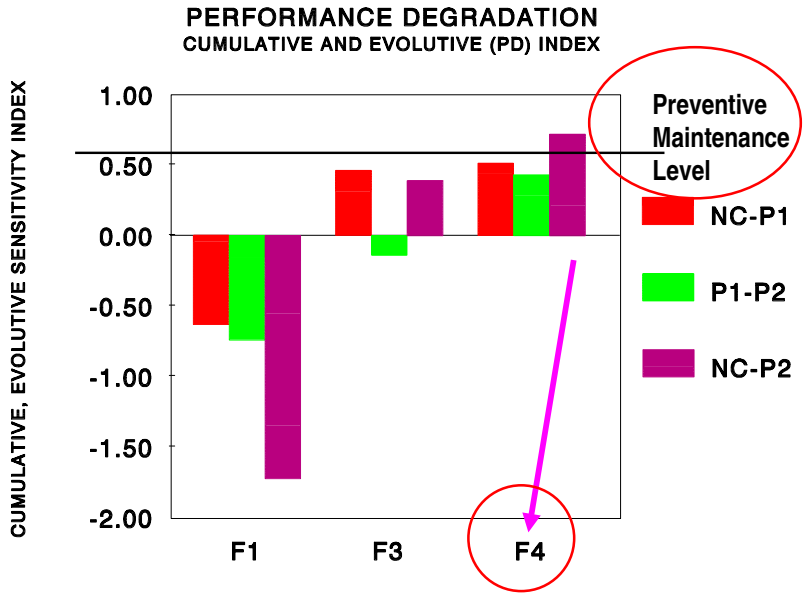
Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

Use of Reliability Index for Diagnostics and Prognostics

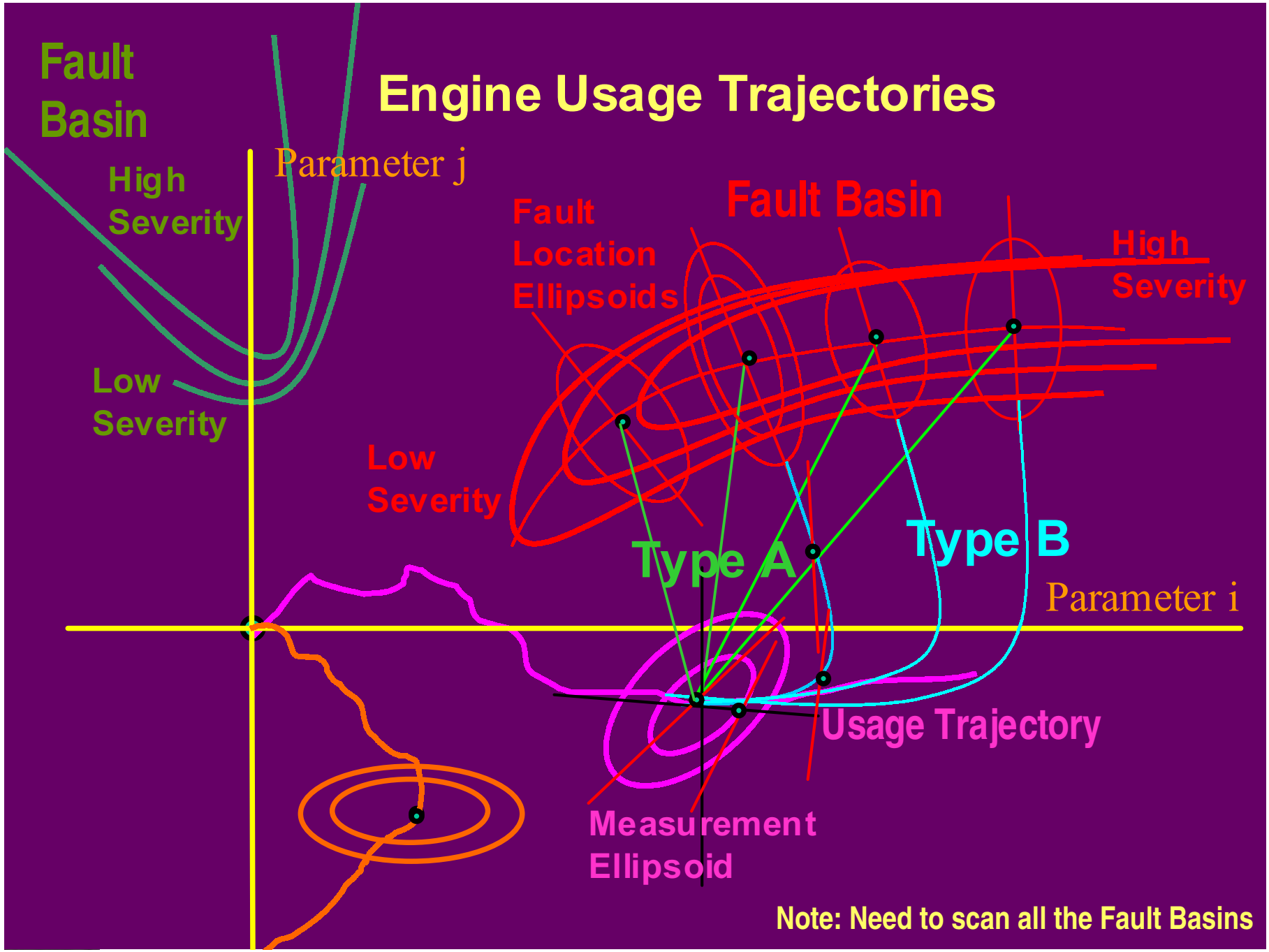
Diagnostics:
Reliability Index

Prognostics:
Reliability Sensitivity Index





Prognostics: If there are 1000 FH between P1 and P2 measurement time, using the computed Beta1-2 = 4.25 (9.92-5.67), it results a predicted remaining life of 130 FH = 1000/4.25(4.25-3.70) FH for maintaining the target safety level, Target Beta = 3.70 (Pf=10E-04).
NOTE: For rapidly evolutive faults needs to compute reliability degradation at small time increments


Engine Usage Trajectories
Fault Basin
High Severity
Low Severity
Parameter j
Fault Location Ellipsoids
Fault Basin
High Severity
Low Severity
Type A
Type B
Parameter i
Usage Trajectory
Measurement Ellipsoid
Note: Need to scan all the Fault Basins

Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

Comparative Results

Quasi-Stationary Engine Model:

$P_n, T_n, \dot{m}_{gg}, \omega_f = fn(P_1, T_1, \omega_{gg})$

8 Engine Faults - 1%, 2%, 3%:

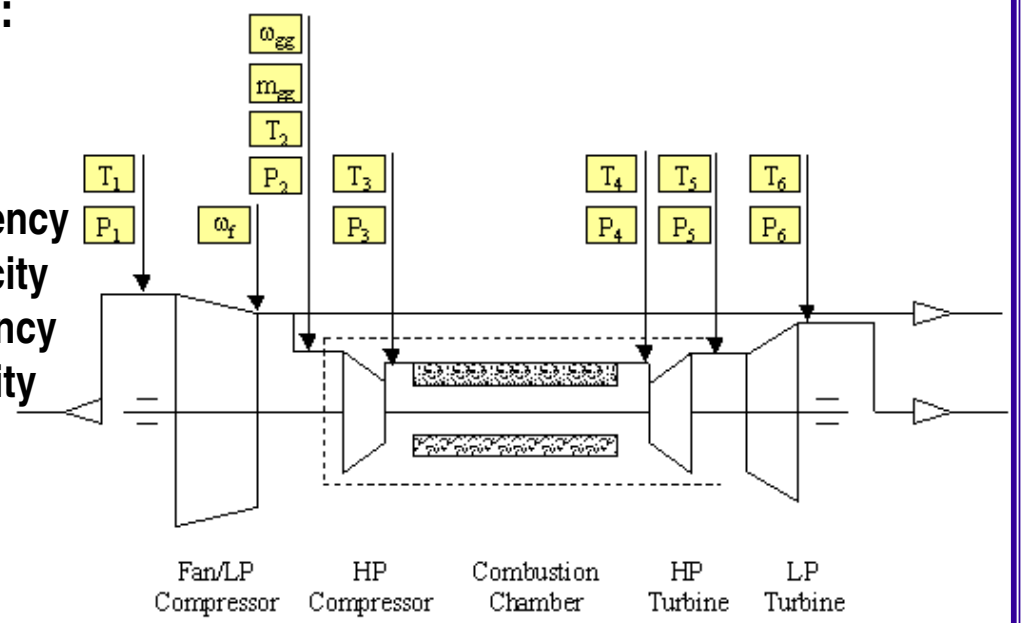
1 LPT Efficiency	5 HPC Efficiency
2 LPT Capacity	6 HPC Capacity
3 HPT Efficiency	7 Fan Efficiency
4 HPT Capacity	8 Fan Capacity

Transient Engine Model:

$P_n, T_n = fn(P_1, T_1, \dot{m}_{gg}, \omega_f, \omega_{gg})$

7 Faults - 1%, 2%, 3%:

1 LPT Efficiency	4 HPC Efficiency
2 LPT Capacity	5 HPC Capacity
3 HPT Efficiency	6 Fan Efficiency
	7 Fan Capacity

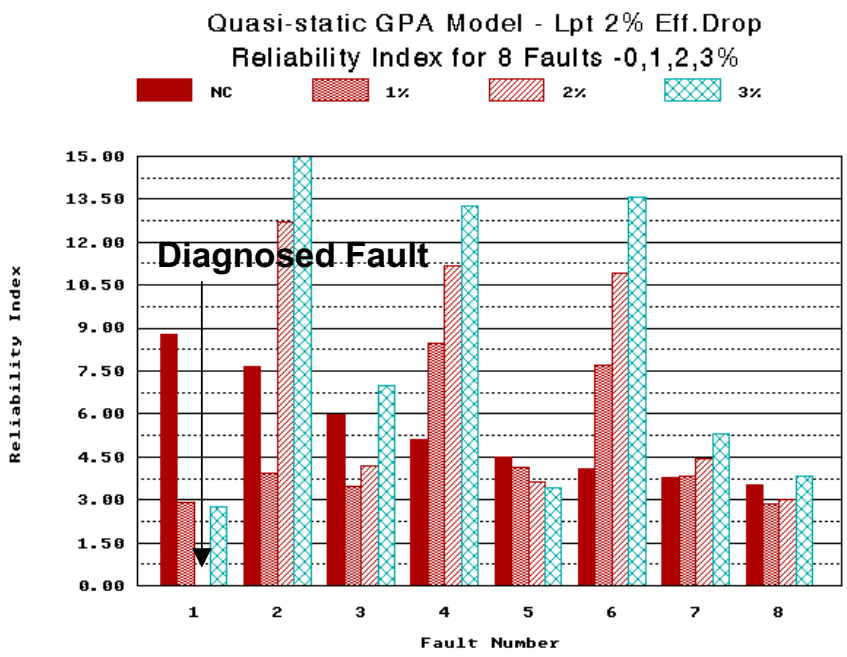


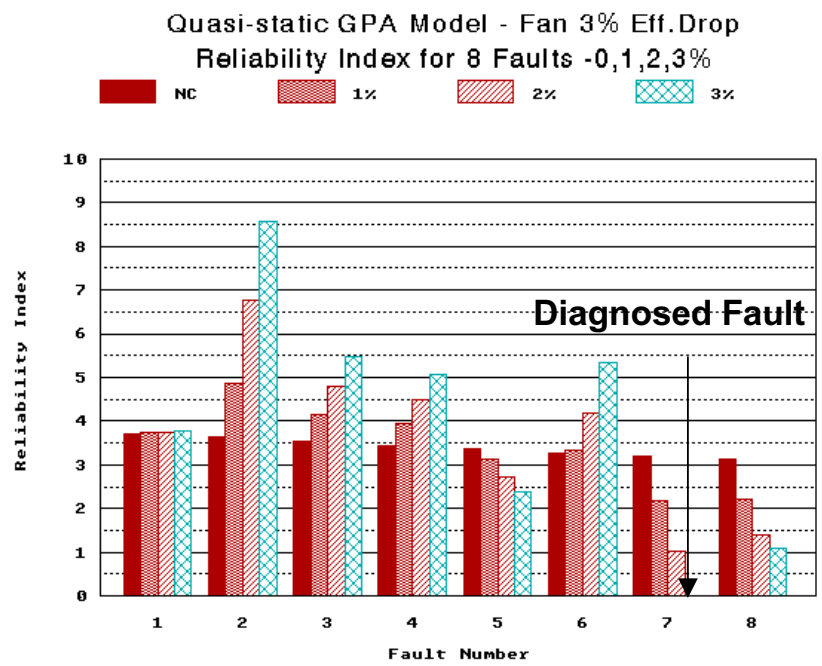
Quasistatic Model:

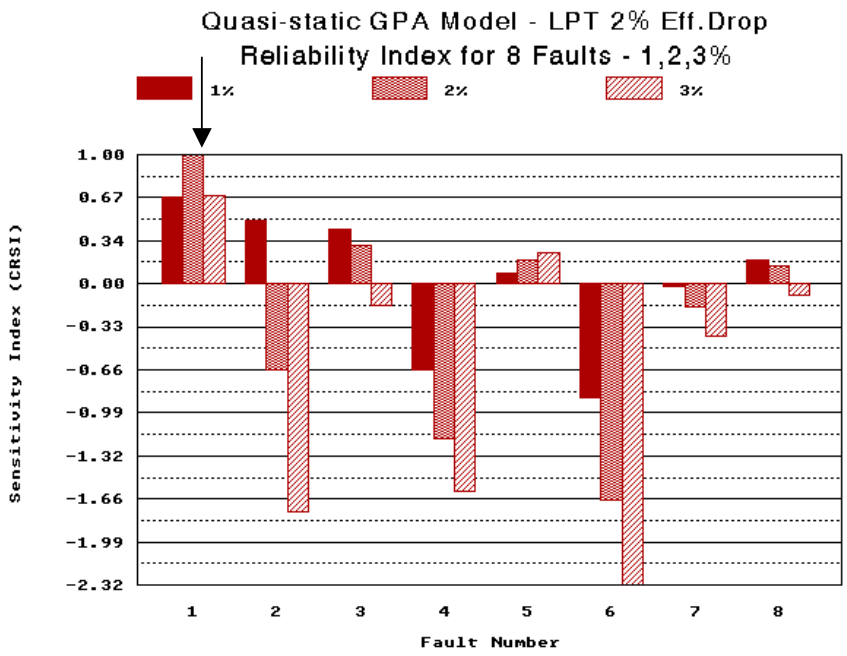
7,8	5,6	3,4	1,2

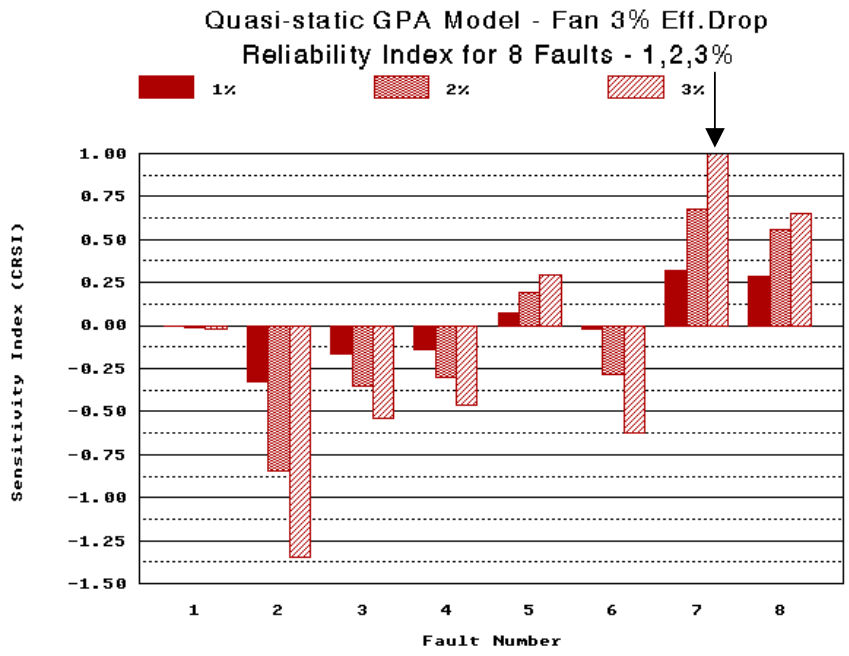
Transient Model:

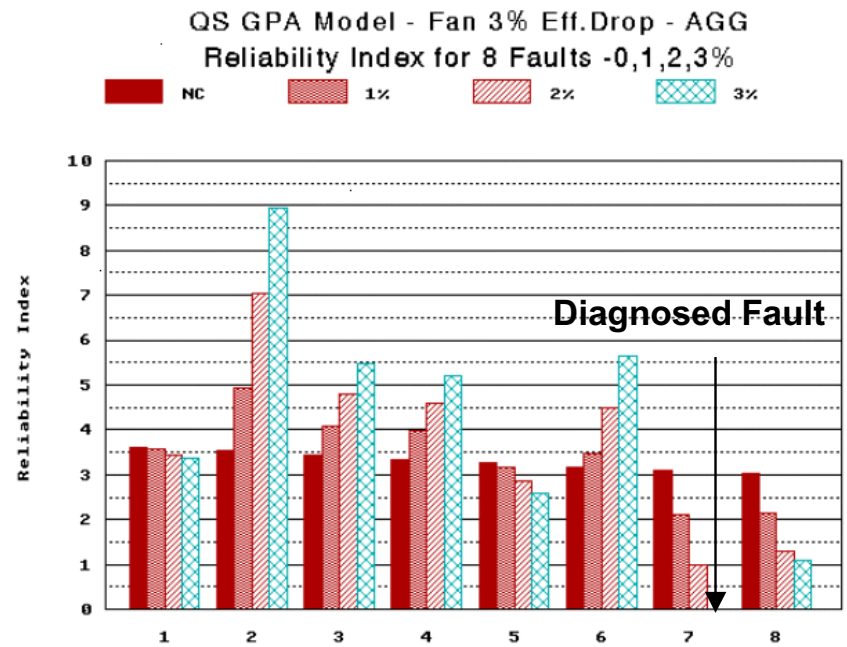
6,7	4,5	3	1,2

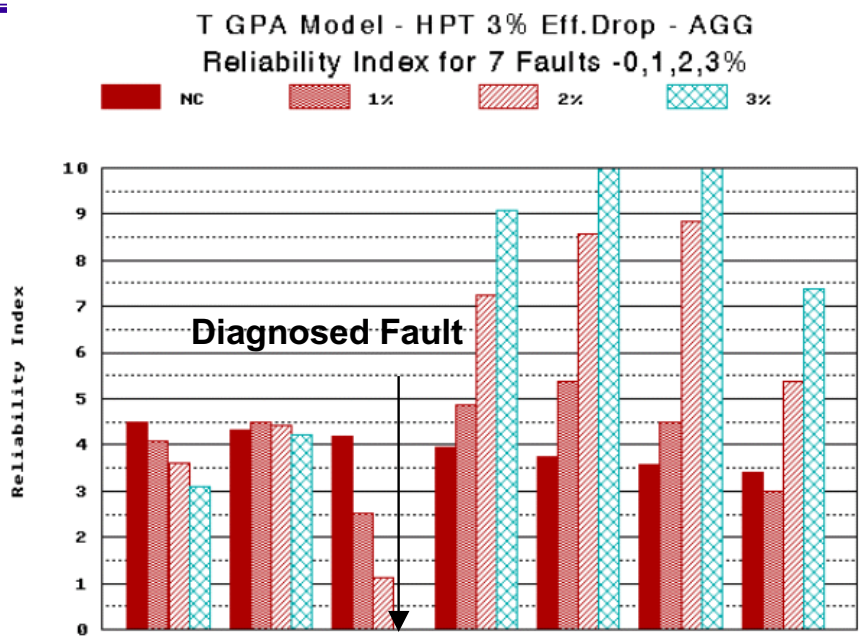

Quasi-static GPA Model - Lpt 2% Eff.Drop
Reliability Index for 8 Faults -0,1,2,3%
NC
1%
2%
3%
Diagnosed Fault
Reliability Index
Fault Number

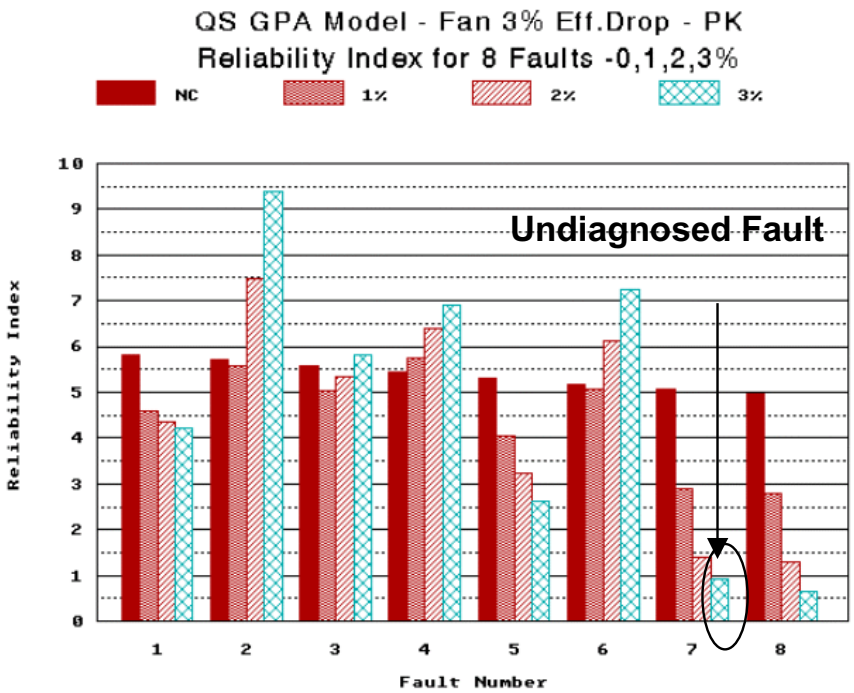

Quasi-static GPA Model - Fan 3% Eff.Drop
Reliability Index for 8 Faults -0,1,2,3%
NC
1%
2%
3%
Diagnosed Fault
Reliability Index
Fault Number

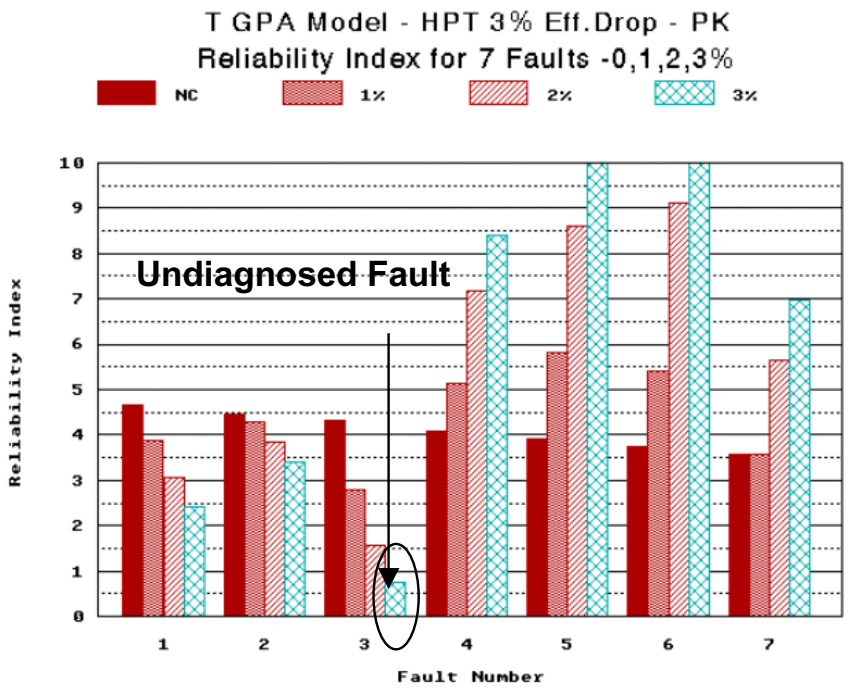

Quasi-static GPA Model - LPT 2% Eff.Drop
Reliability Index for 8 Faults - 1,2,3%
1%
2%
3%
Sensitivity Index (CRSI)
Fault Number


Quasi-static GPA Model - Fan 3% Eff.Drop
Reliability Index for 8 Faults - 1,2,3%
1%
2%
3%
Sensitivity Index (CRSI)
Fault Number


QS GPA Model - Fan 3% Eff.Drop - AGG
Reliability Index for 8 Faults -0,1,2,3%
NC
1%
2%
3%
Reliability Index
Diagnosed Fault

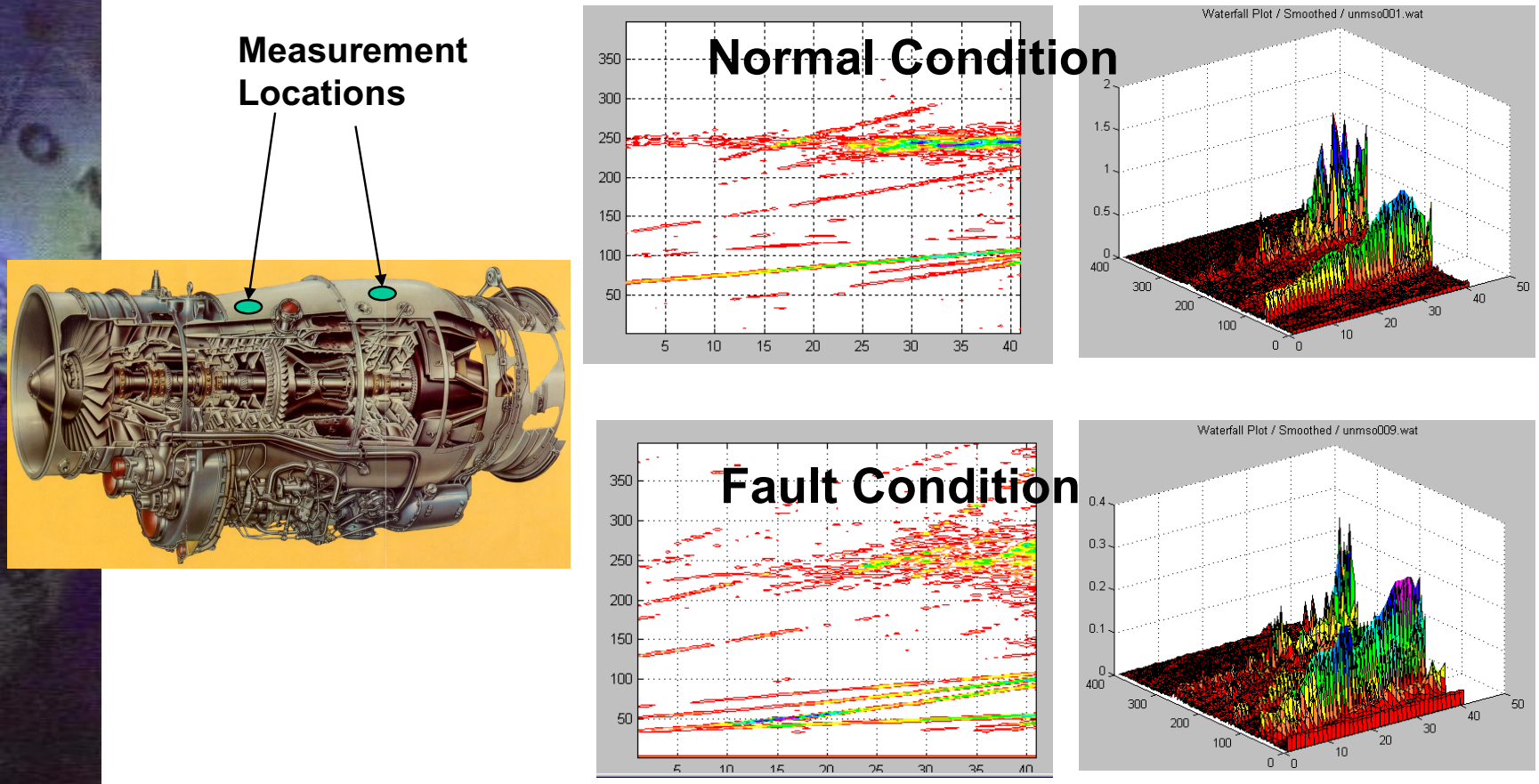

T GPA Model - HPT 3% Eff.Drop - AGG
Reliability Index for 7 Faults -0,1,2,3%
NC
1%
2%
3%
Reliability Index
Diagnosed Fault


QS GPA Model - Fan 3% Eff.Drop - PK
Reliability Index for 8 Faults -0,1,2,3%
NC
1%
2%
3%
Reliability Index
Undiagnosed Fault
Fault Number


T GPA Model - HPT 3% Eff.Drop - PK
Reliability Index for 7 Faults -0,1,2,3%
NC
1%
2%
3%
Reliability Index
Undiagnosed Fault
Fault Number

Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

Vibration-based Fault Diagnostics

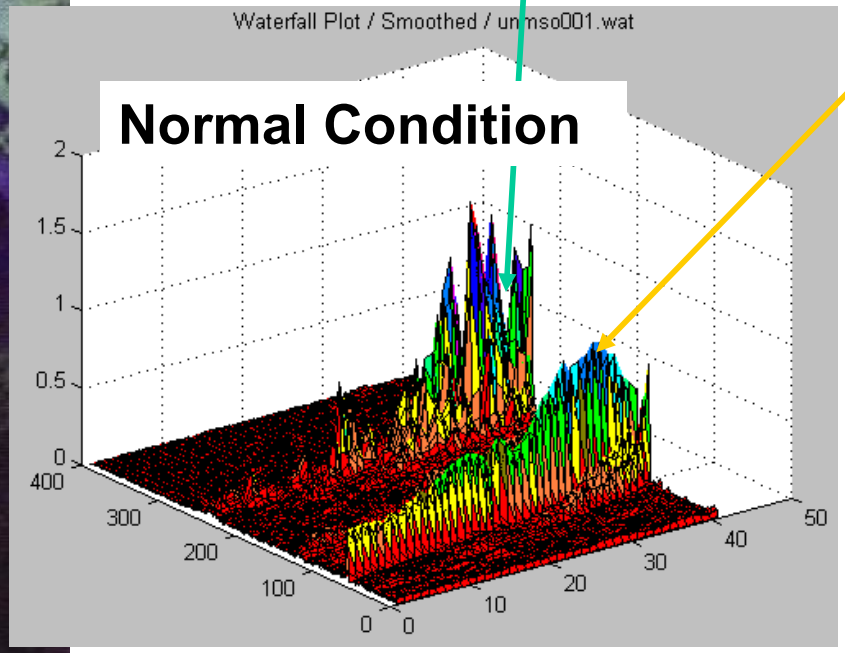


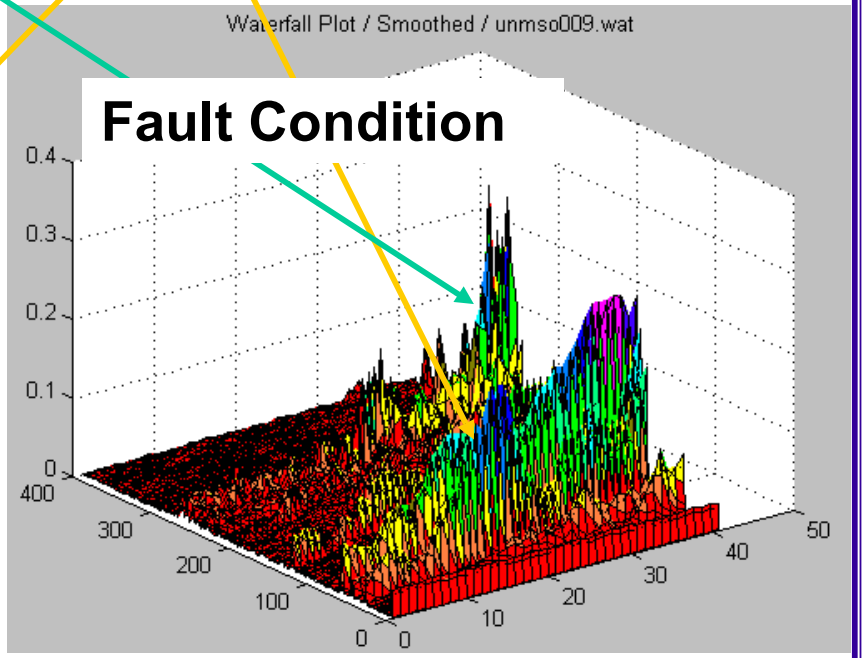
Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

Track-Order Profiles

LP Track-Order Profile

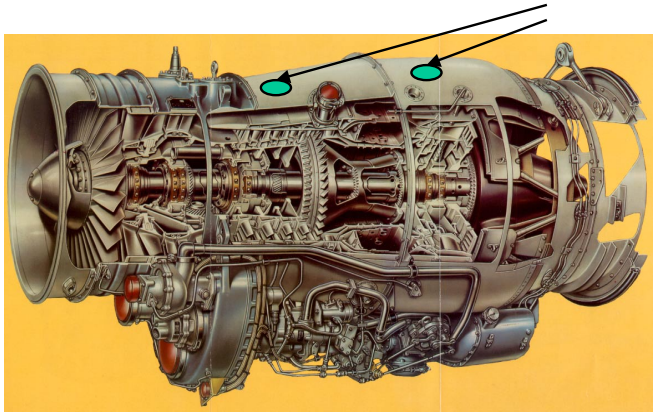
HP Track-Order Profile

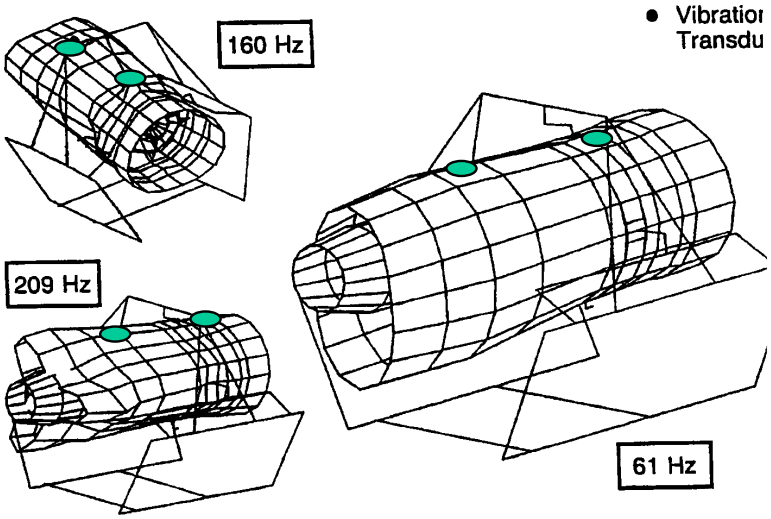




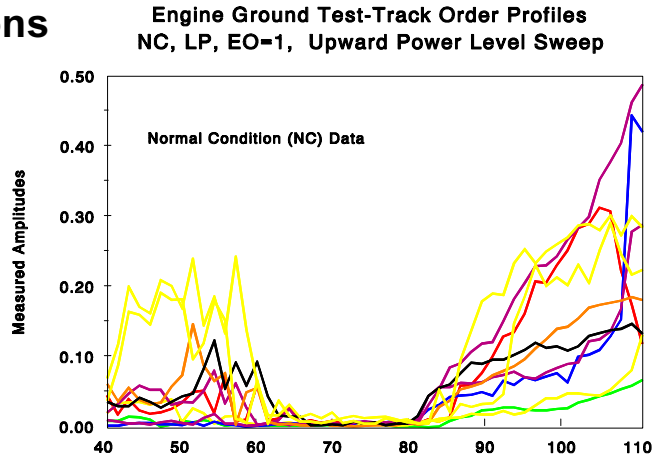
Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

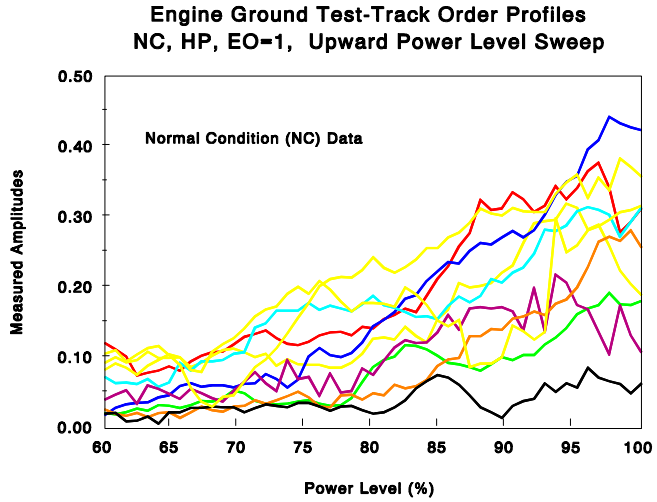
Measurement Locations

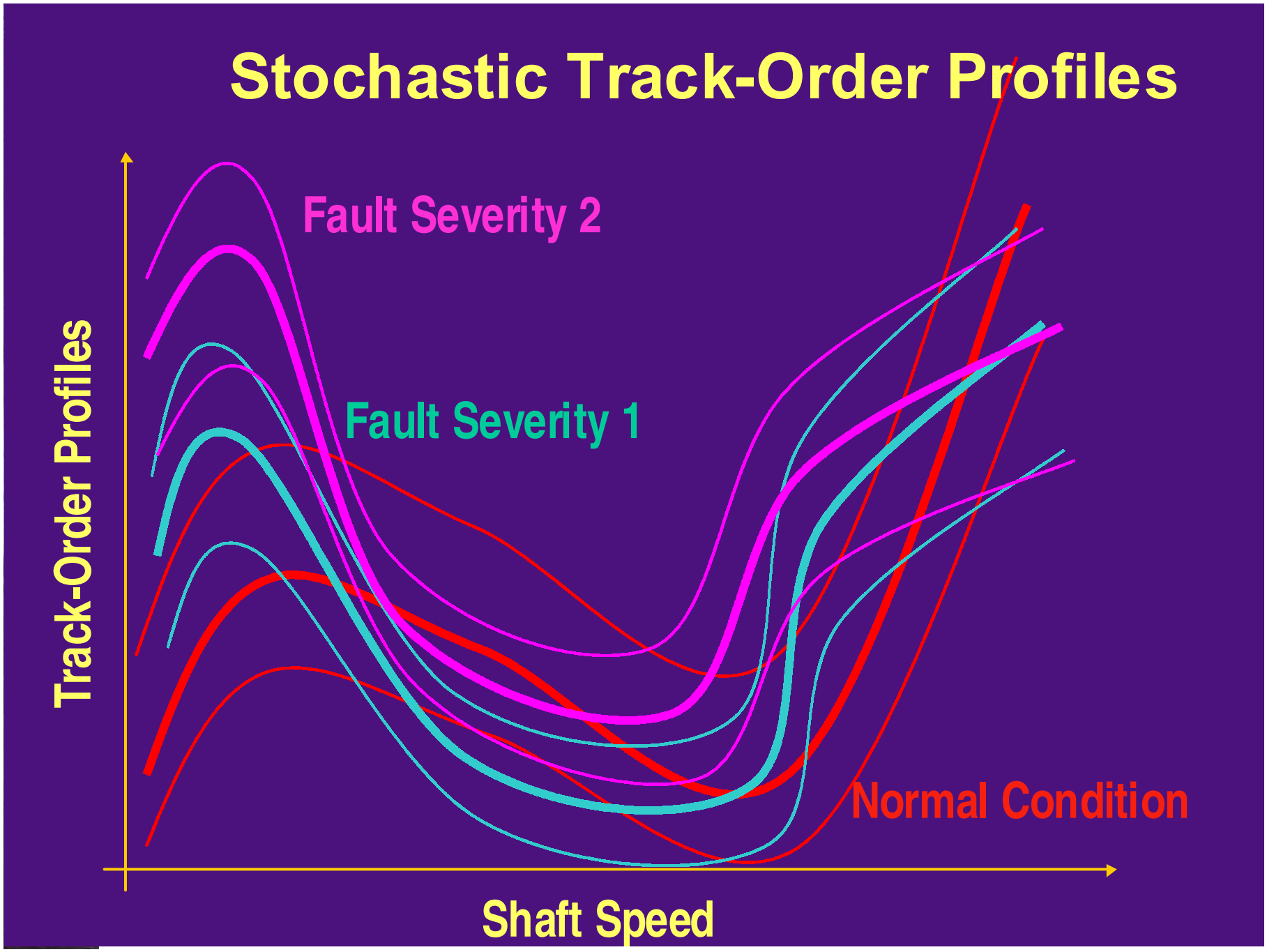




After H. Carr, 1993



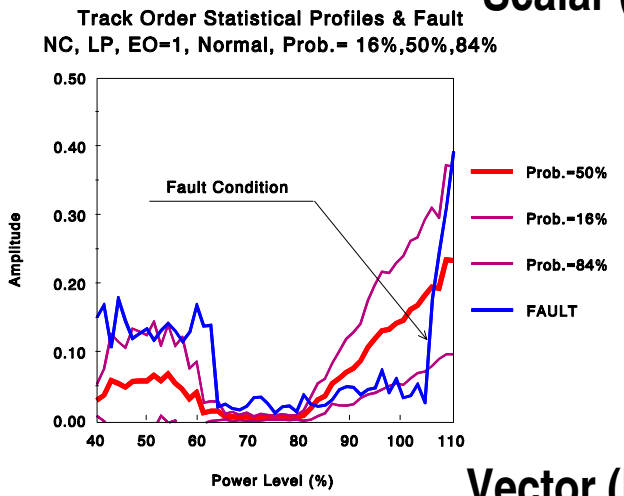


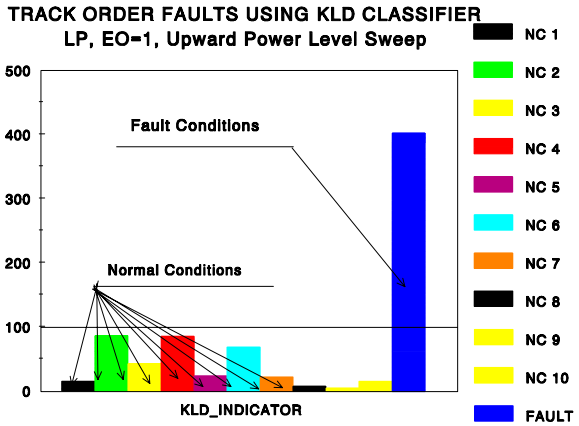

Stochastic Track-Order Profiles
Fault Severity 2
Fault Severity 1
Normal Condition
Track-Order Profiles
Shaft Speed

Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

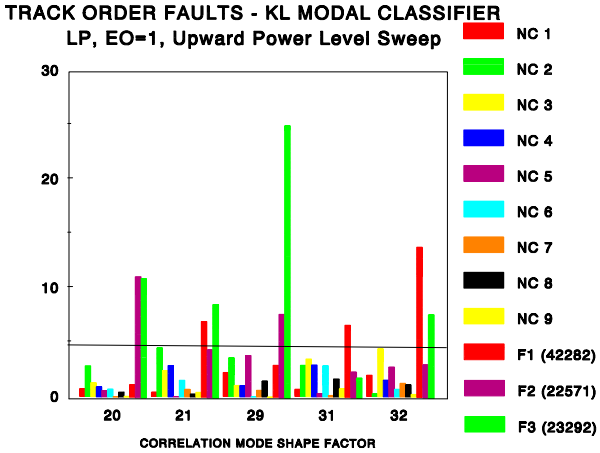
Identification of Typical Non-Detectable Faults

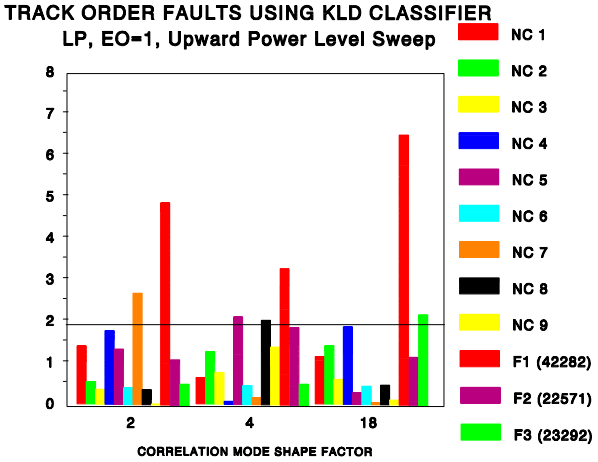
Scalar (Global) Classifier for Fault Detection/Severity

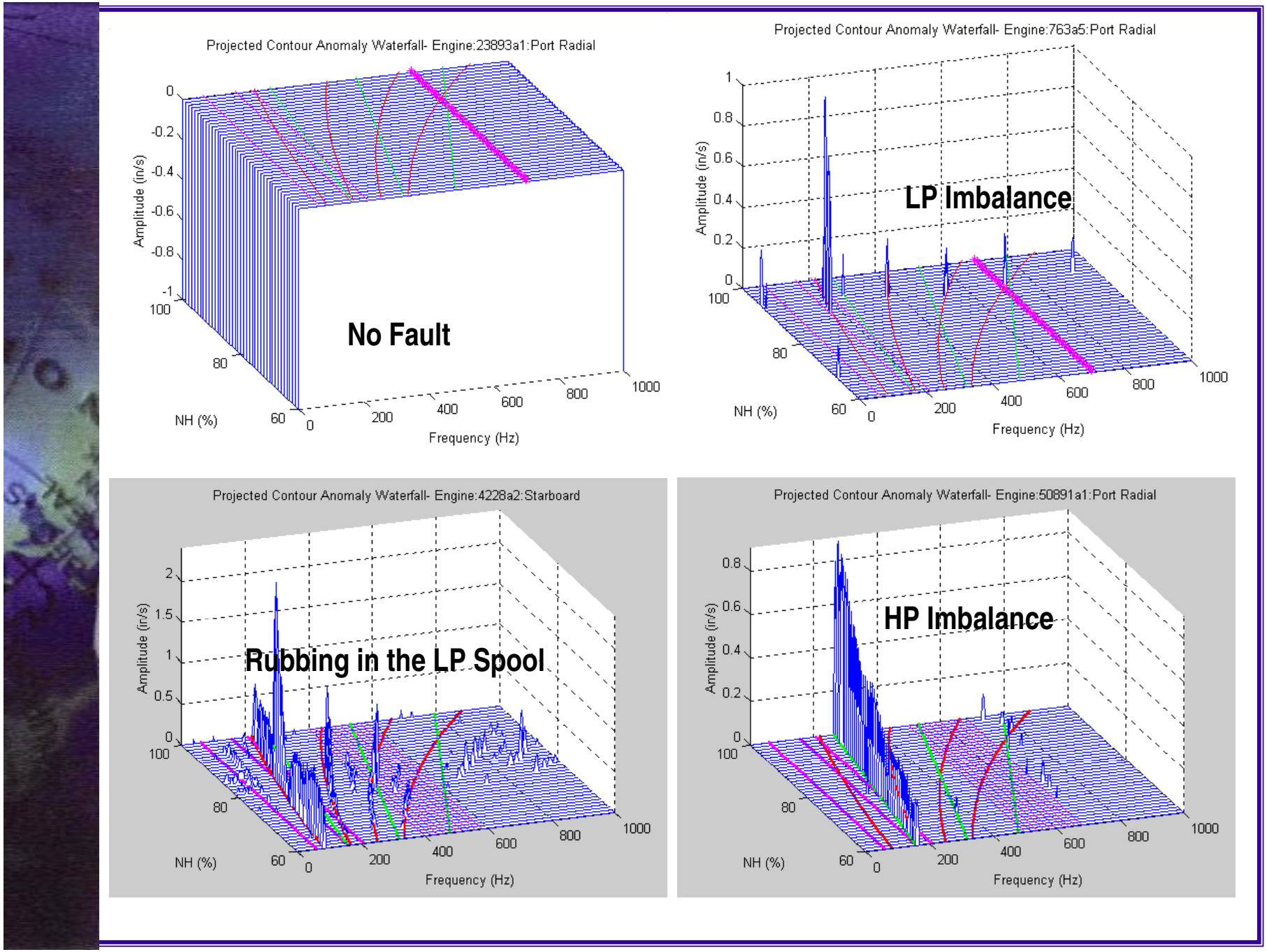


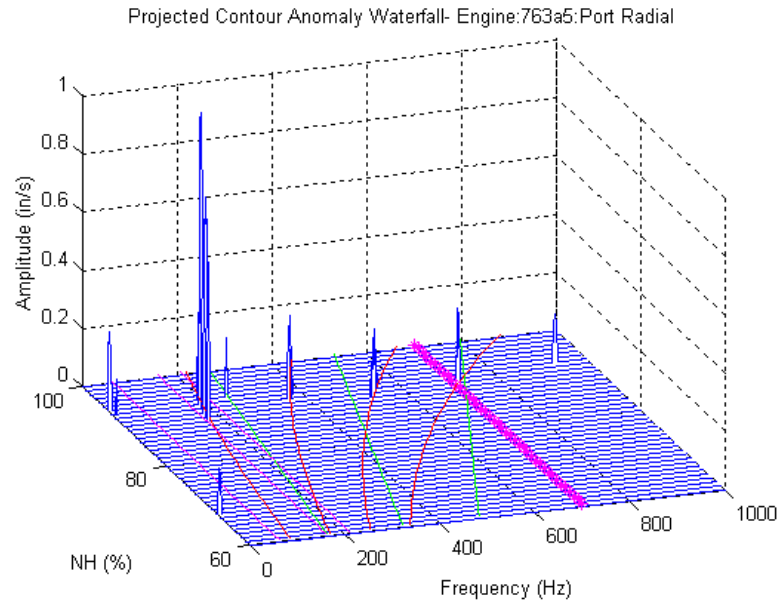


Vector (Modal) Classifier for Fault Diagnostic



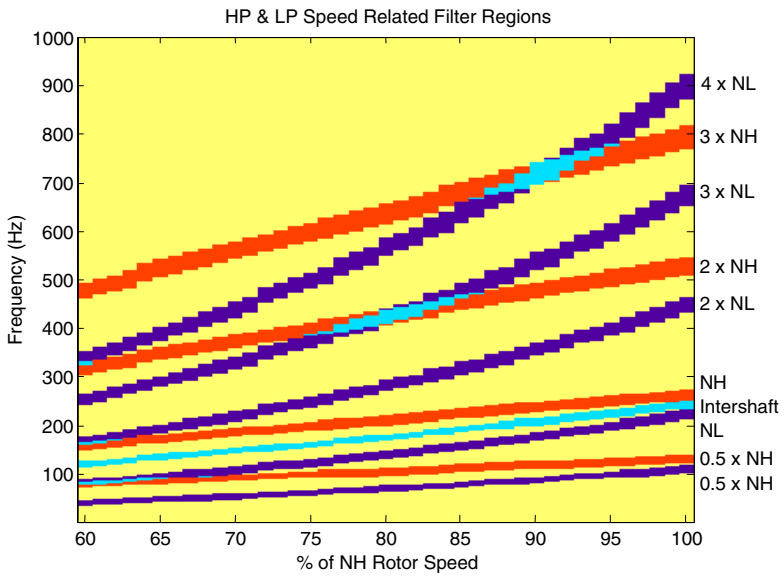



Projected Contour Anomaly Waterfall- Engine:23893a1:Port Radial
No Fault
Amplitude (in/s)
NH (%)
Frequency (Hz)
Projected Contour Anomaly Waterfall- Engine:763a5:Port Radial
LP Imbalance
Amplitude (in/s)
NH (%)
Frequency (Hz)
Projected Contour Anomaly Waterfall- Engine:4228a2:Starboard
Rubbing in the LP Spool
Amplitude (in/s)
NH (%)
Frequency (Hz)
Projected Contour Anomaly Waterfall- Engine:50891a1:Port Radial
HP Imbalance
Amplitude (in/s)
NH (%)
Frequency (Hz)

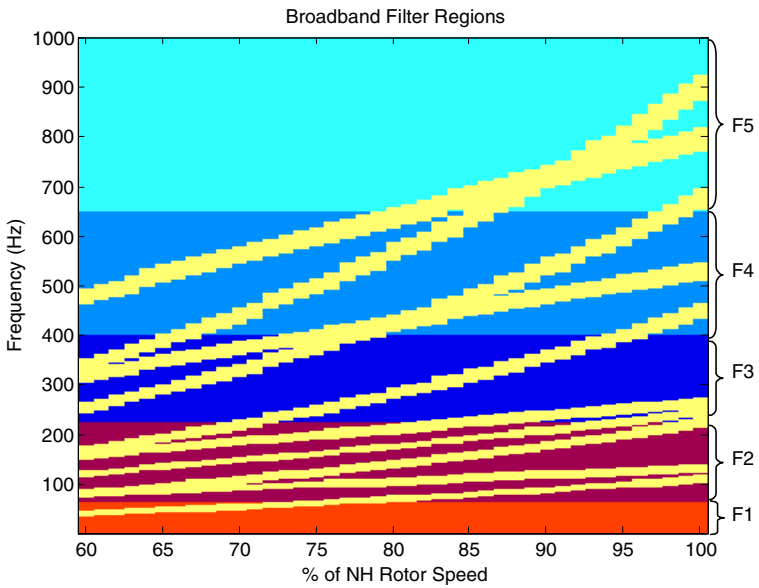


- LP freq. & sb. & sp. harmonics
- HP freq. & sb. & sp. harmonics
- Magenta casing/disk frequencies

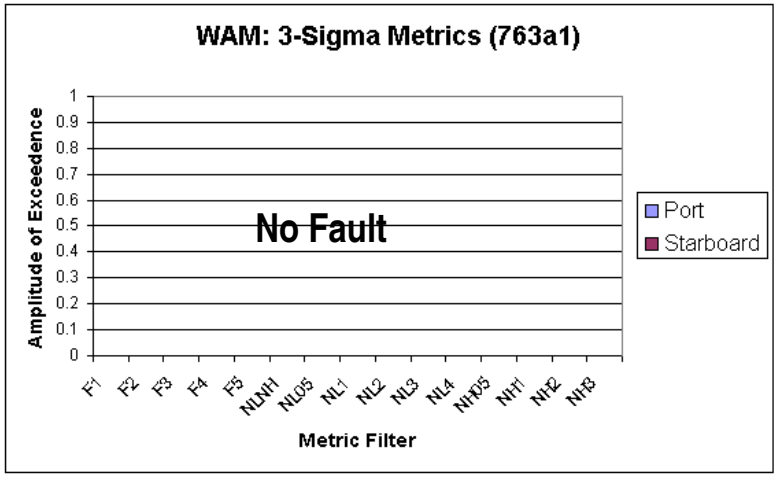
Variable Narrow Bands

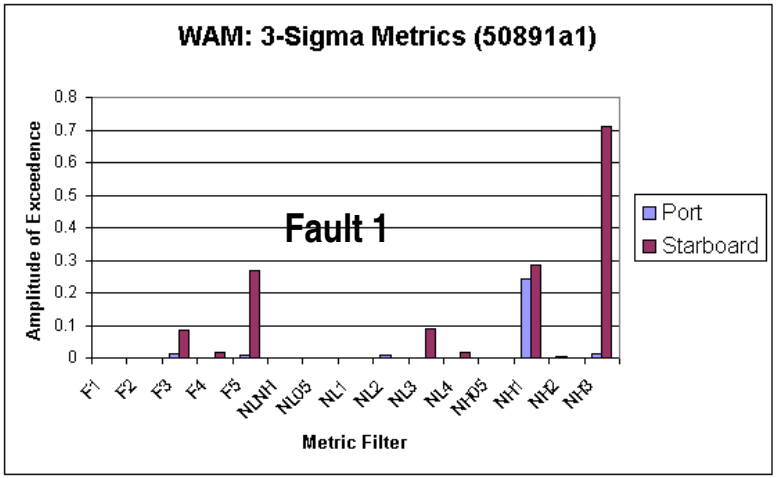


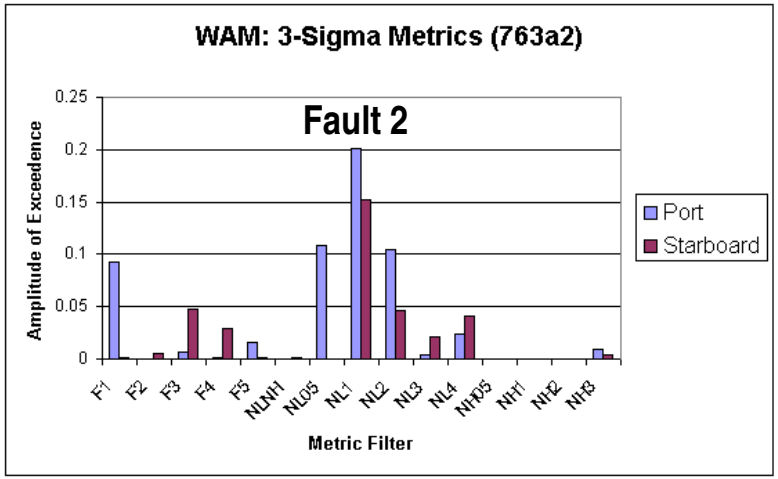
Variable Broad Bands

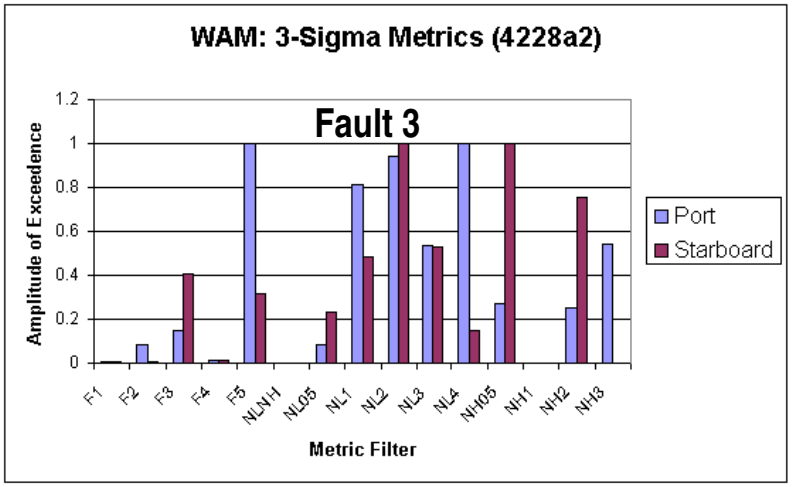


Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System

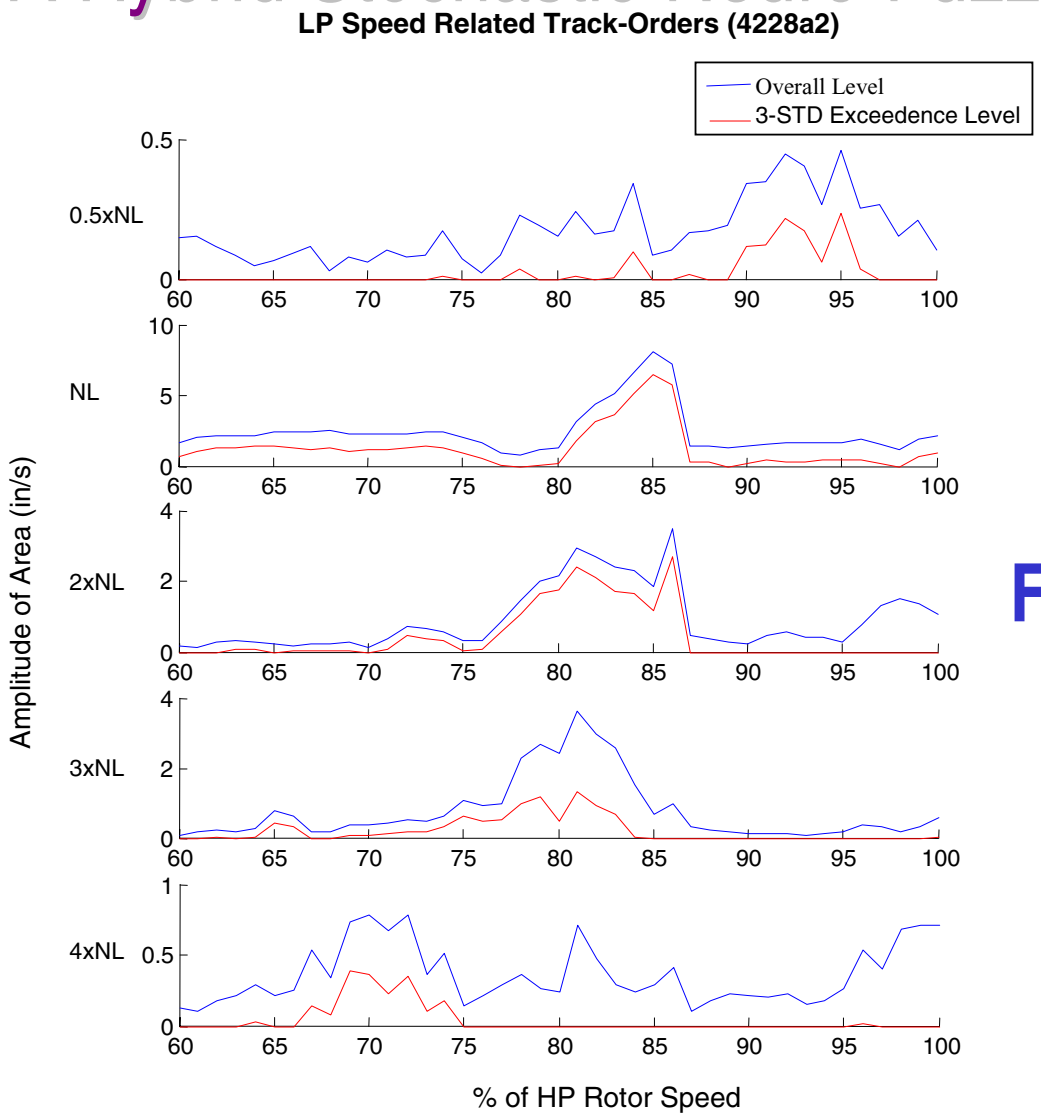








Engine Health Risk Management Using A Hybrid Stochastic-Neuro-Fuzzy System



Feature Profiles

Engine Health Risk Management Using A Hybrid Stochastic-Fuzzy Inference System

Concluding Remarks:

1. **StoFIS** is a combination of advanced stochastic modeling with an adaptive neuro-fuzzy modeling for engine performance using in-flight data

2. **StoFIS** is capable of extracting and using more refined statistical information for fault classification and prognostic, than a typical EHMS based on a standard neural-net fuzzy logic-inference approach (standard AI fuzzy-logic approach may loose some significant stochastic variability details)

3. **StoFIS** is the basis of a future robust Prognostic EHMS

NESTEM-QRAS: A Tool for Estimating Probability of Failure

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N&R Engineering & Management Services
Cleveland, Ohio 44135

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National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

An interface between two NASA GRC specialty codes, NESTEM and QRAS has been developed. This interface enables users to estimate, in advance, the risk of failure of a component, a subsystem, and/or a system under given operating conditions. This capability would be able to provide a needed input for estimating the success rate for any mission.

NESTEM code, under development for the last 15 years at NASA Glenn Research Center, has the capability of estimating probability of failure of components under varying loading and environmental conditions. This code performs sensitivity analysis of all the input variables and provides their influence on the response variables in the form of cumulative distribution functions.

QRAS, also developed by NASA, assesses risk of failure of a system or a mission based on the quantitative information provided by NESTEM or other similar codes, and user provided fault tree and modes of failure.

This paper will describe briefly, the capabilities of the NESTEM, QRAS and the interface. Also, in this presentation we will describe stepwise process the interface uses using an example.

NESTEM-QRAS: A Tool for Estimating Probability of Failure

By

Dr. Bhogilal M. Patel and Dr. Vinod K. Nagpal

N&R Engineering, Cleveland, OH

And

Vincent A. Lalli, Dr. Shantaram S. Pai

and Jeffrey J. Rusick

NASA Glenn Research Center, Cleveland, OH

5th Annual FAA/Air Force/NASA/Navy Workshop

Cleveland, OH

June 11-13, 2001

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Outline of Presentation

- Tool Overview
- Tool Components
  - NESTEM
  - QRAS
- Risk Assessment Process
- Example problem
- Benefits of the tool

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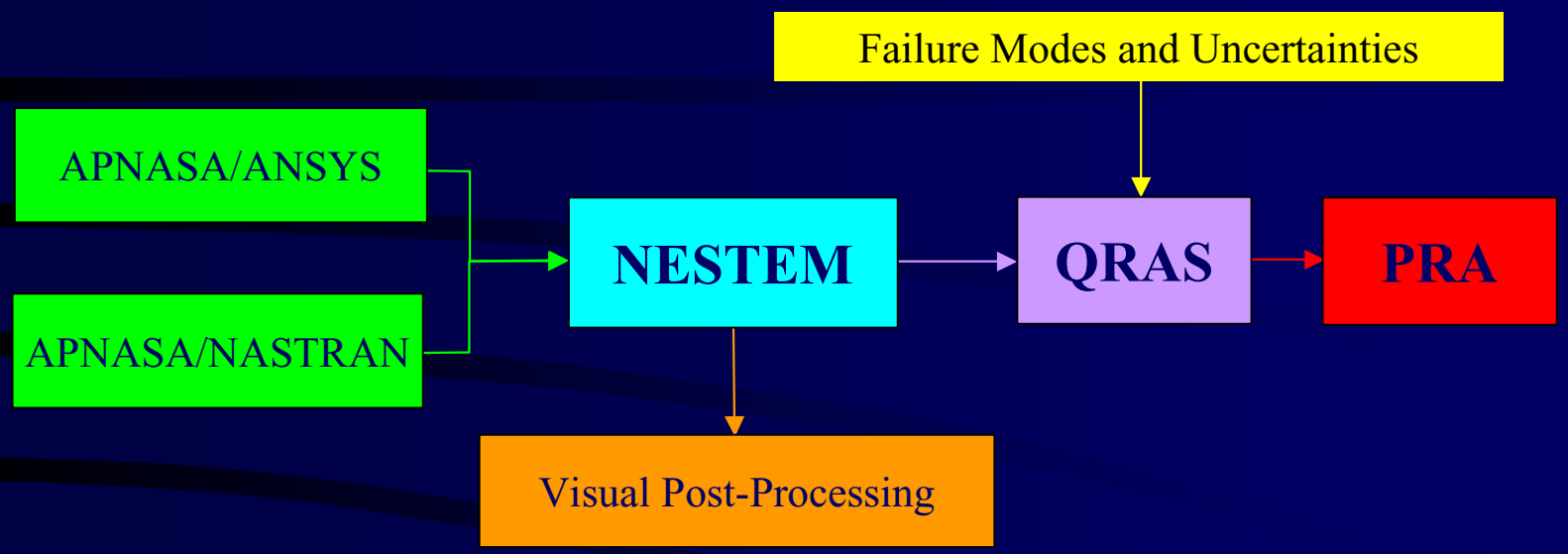
Tool Overview



- NESTEM interfaces with APNASA/ANSYS or NASTRAN.
- Visual results in ANSYS environment
- QRAS for engine system Probabilistic Risk Assessment (PRA).

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NESTEM

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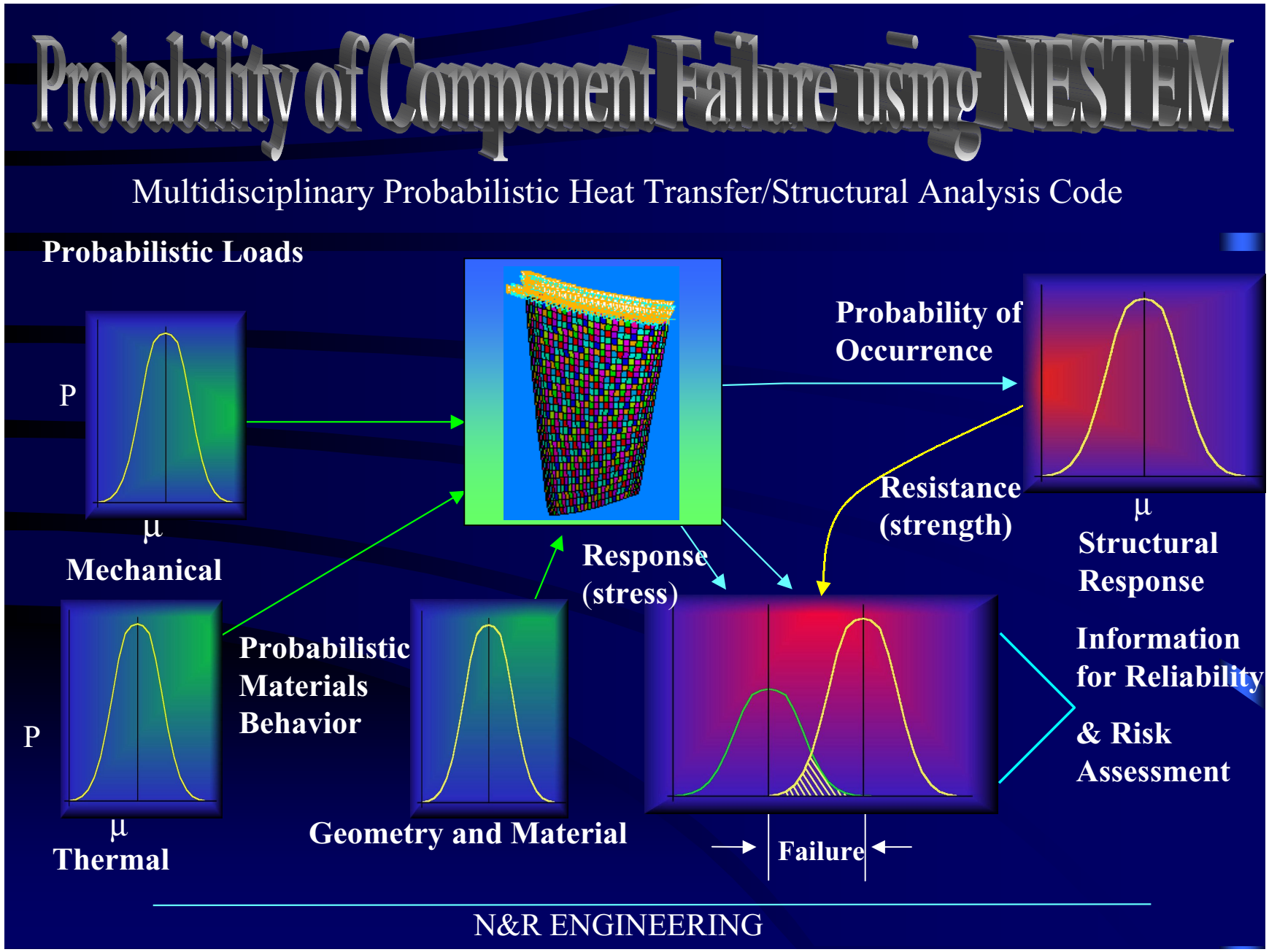
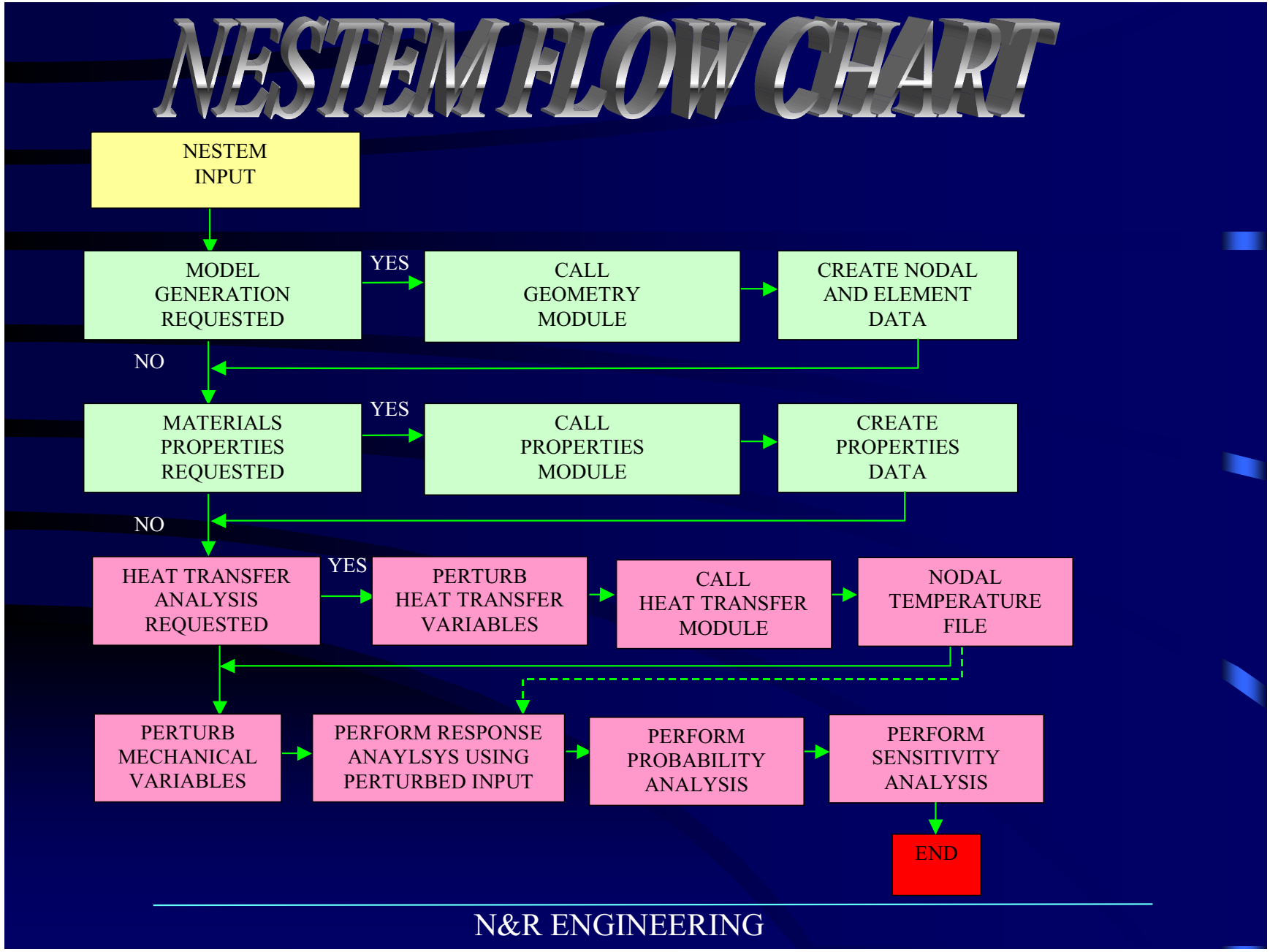

Probability of Component Failure using NESTEM
Multidisciplinary Probabilistic Heat Transfer/Structural Analysis Code
Probabilistic Loads
P
μ
Mechanical
P
μ
Thermal
Probabilistic Materials Behavior
Geometry and Material
Response (stress)
Probability of Occurrence
Resistance (strength)
μ
Structural Response
Information for Reliability & Risk Assessment
Failure
N&R ENGINEERING


NESTEM FLOW CHART
NESTEM INPUT
MODEL GENERATION REQUESTED
YES
CALL GEOMETRY MODULE
CREATE NODAL AND ELEMENT DATA
NO
MATERIALS PROPERTIES REQUESTED
YES
CALL PROPERTIES MODULE
CREATE PROPERTIES DATA
NO
HEAT TRANSFER ANALYSIS REQUESTED
YES
PERTURB HEAT TRANSFER VARIABLES
CALL HEAT TRANSFER MODULE
NODAL TEMPERATURE FILE
PERTURB MECHANICAL VARIABLES
PERFORM RESPONSE ANAYLSYS USING PERTURBED INPUT
PERFORM PROBABILITY ANALYSIS
PERFORM SENSITIVITY ANALYSIS
END
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NESTEM Capabilities

- Generates or allows users to import a finite element model from commercial codes such as ANSYS or NASTRAN
- Generates laminate properties from constituent properties in case of composites
- Performs probabilistic heat analysis by perturbing heat transfer variables
- Quantifies influences of uncertainties in material properties and geometry, mechanical and thermal loads on structural responses

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NESTEM Capabilities

- Generates probability distributions of the response variables based on quantified influences of uncertainties. This feature provides complete ranges of variation in response variables

- This information is very useful for assessing risk of failure, cost or allowable risk and developing maintenance schedule

- Ranks all variables in the order of their influences on response variables. This information is critical for being cost effective

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NESTEM Capabilities

- Estimates fatigue life for random loading
- Post processes results in user's selected environment
- Works on PC and workstation platforms

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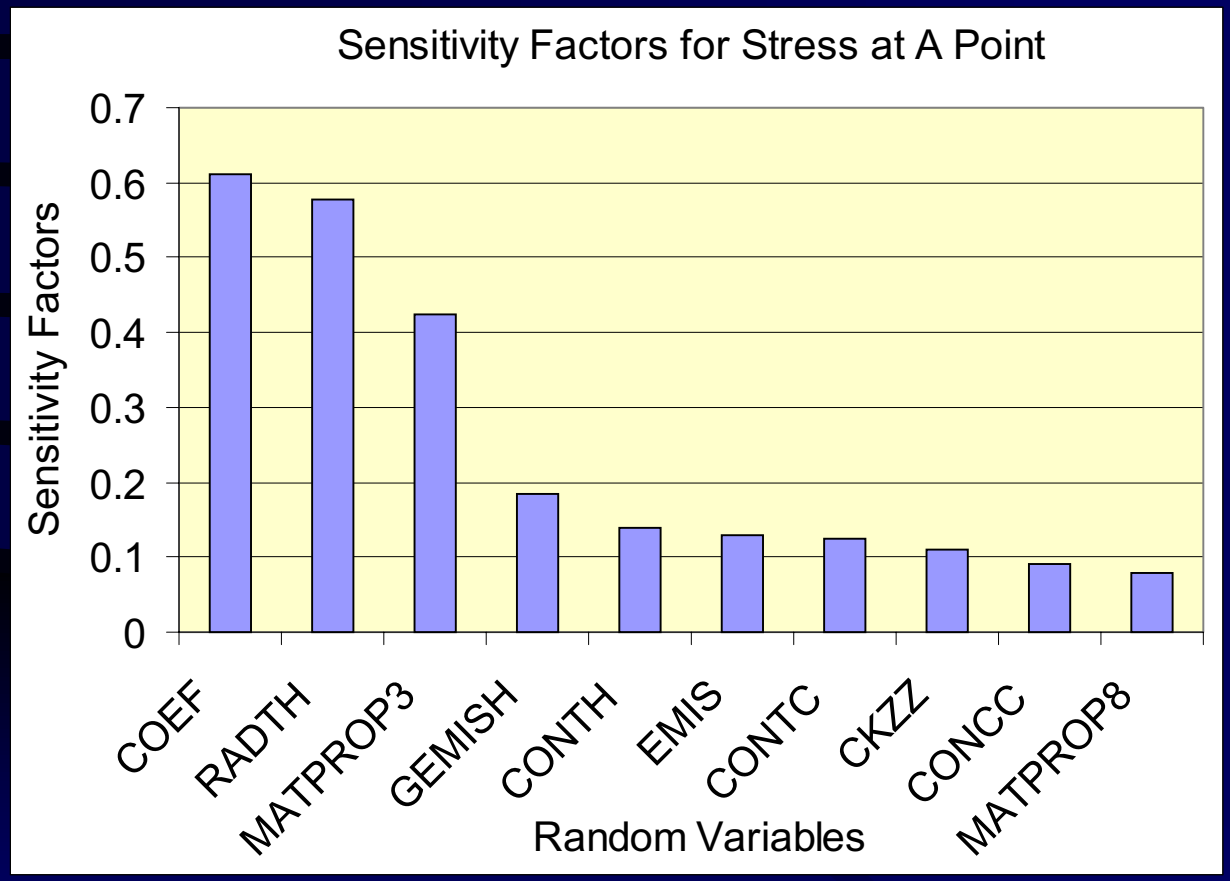
Plot of Sensitivity Analysis



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QRAS

QUANTITATIVE RISK ASSESSMENT SYSTEM

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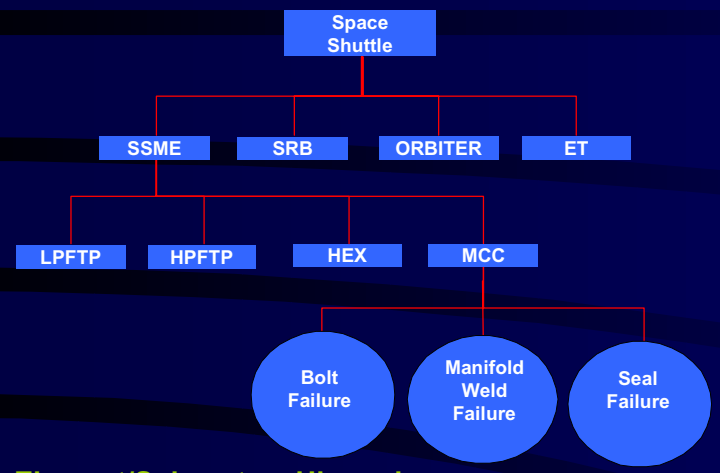
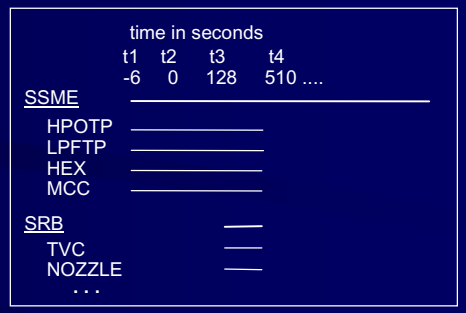
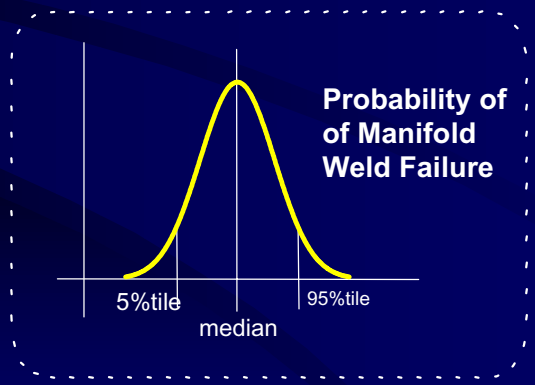
QRAS



Element/Subsystem Hierarchy



Mission Timeline



Initiating Event

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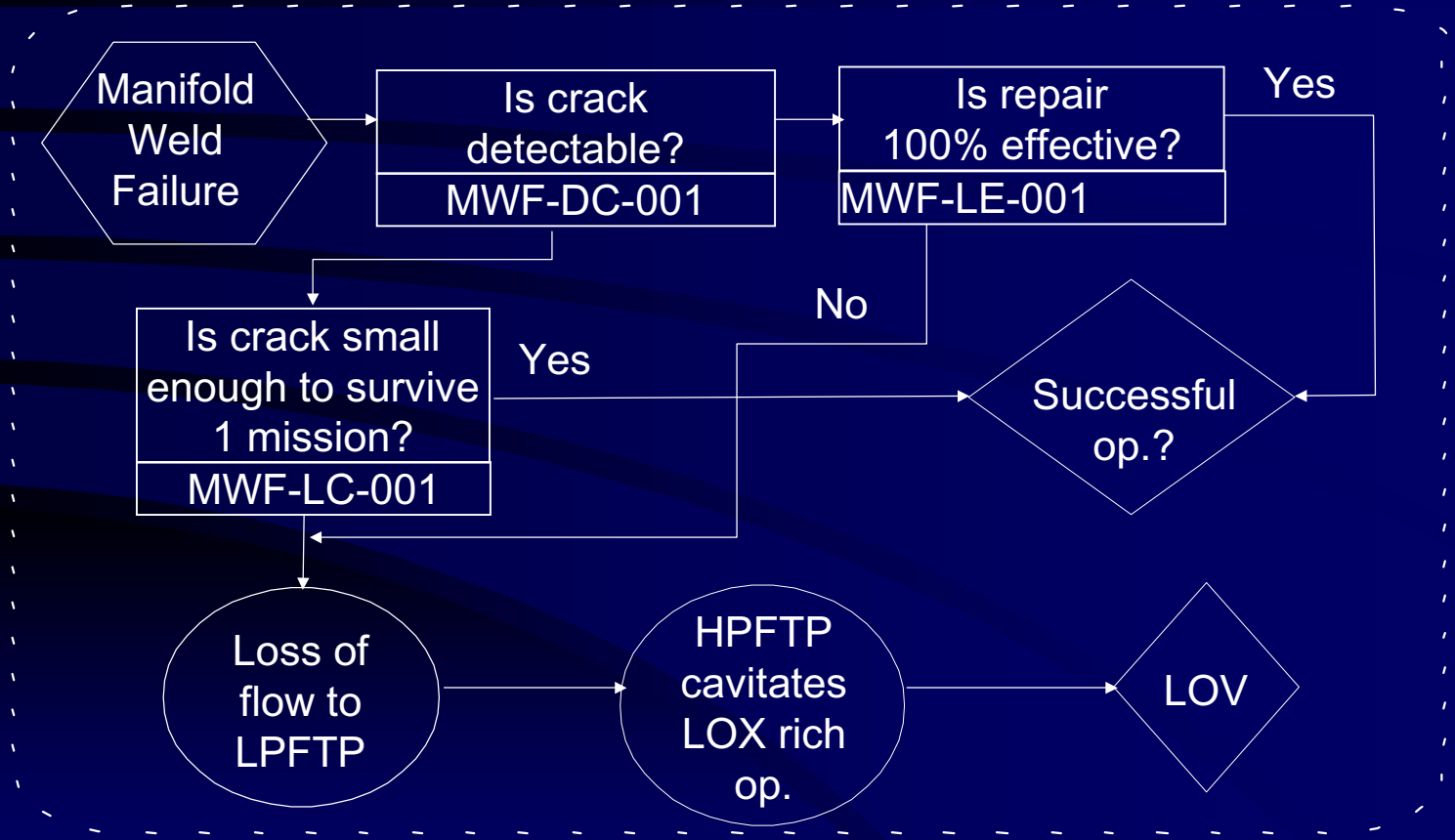
QRAS



Event Sequence Diagram

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QRAS

Risks by :

1. Space Shuttle
2. Element
3. Subsystem

Risks Ranked :

1. Over entire Shuttle
2. Within Element
3. Within Subsystem, etc.

Probabilistic Risk Assessment

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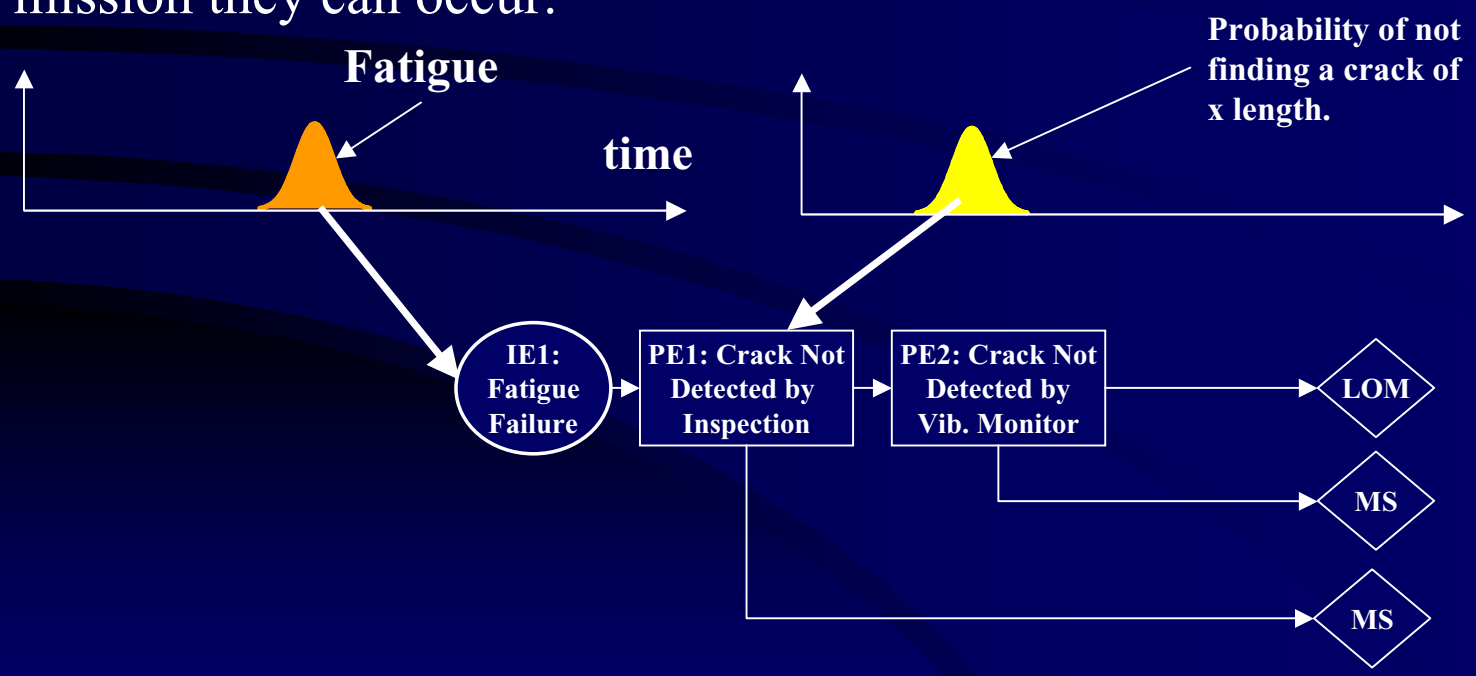
Risk of Failure

(Using NESTEM, experience, test data, field data, etc.)

Probabilities are assigned to the failure modes and to the mitigating events. Failure modes are quantified as to when in the mission they can occur.



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NESTEM-QRAS Interface

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Risk Assessment Process

Create QRAS Database
- Fault tree
- Mission timeline
- Event sequence diagrams
- Failure modes
- Quantify risk of failure

Risk of Failure from other Sources

Risk of Failure from NESTEM analysis

Update the QRAS database using NESTEM output

QRAS analysis

- Risk of failure
- Loss of mission
- Mission success
- Sensitivity Analysis

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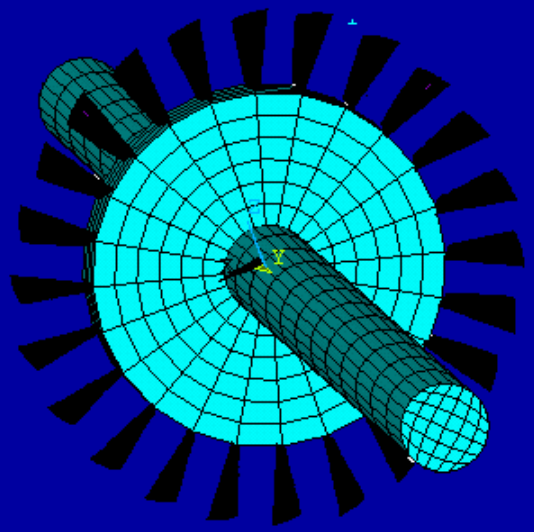
Example Problem



Shaft-Rotor-Blade Assembly

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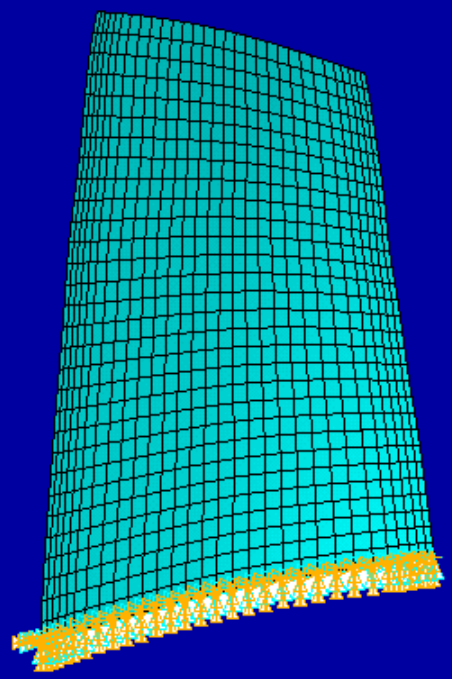
Example Problem



Blade

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Example Problem

Example problem Input (Starting Phase):

Component	Risk of failure (C)	Mitigation event (E)	Timeline	Mode of failure
Shaft	0.0	.0925	0-360	Strength
Rotor	0.03905	.0705	0-360	Strength
Blade	0.001438	0.007050	0-360	Strength

(Uniform distribution is assumed)

Example problem output:

Probability of Loss of Mission from QRAS analysis = 0.02763

Benefits of NESTEM-QRAS Tool

This tool provides:

- Risk of failure of individual component
- Risk of failure of a system
- Quantitative ranking of components by degree of risk
- Means to reduce risk of failure
- Cost effective ways to use resources

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Future Work

- Improve the capability of the tool
- Develop an interface between NESTEM and SAPHIRE

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Contact for this tool

Vincent A. Lalli

NASA Glenn Research Center,
Cleveland, OH

(216) - 433 - 2354

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Issues in Modeling System Reliability

Tom Cruse (Consultant)

Chuck Annis (PWA, ret./Consultant)

Jane Booker (LANL)

David Robinson (Sandia)

Rob Sues (ARA Inc.)

Speaker defined issues

- Question: *How to combine data from a wide variety of testing programs, simulation/physics-based models, subsystem testing, materials experimentation, etc. to augment traditional system level testing?*
- *We are never able to know the true answer (risk, P_f, likelihood) but can only estimate that answer; what confidence can we have in the result?*

What are the issues?

- Statistical formalisms versus pragmatic numerics?
- Language?
- Statistical methods versus reliability-based design methods?
- Professional bias?
- Real issues that need to be identified and resolved prior to certifying designs?

Goals for today

- I will moderate and record the session
- We will try to identify key areas of agreement
- We also try to identify key remaining issues
- We will seek to define follow-on efforts

Issues in Modeling System Reliability
Panel Discussion

Jane M. Booker, Ph.D.
Fellow of the American Statistical Association

Engineering Analysis Group,
Los Alamos National Laboratory

Lack of Test Data— Limits Conventional Reliability

- Test Ban treaties
- Environmental policies
- Different production complex
- Retiring expertise
- Shrinking budgets
- Aging weapons in stockpile

All these and more translate to less and less test data available to certify the nuclear physics package for nuclear weapons systems at Los Alamos.

Must Certify Weapons—
Mission Impossible?

Requires new way of thinking about performance and new methods to address the simple sounding task of:

Let's gather up all we know and how well we know it (uncertainty) and combine it to estimate performance.

At Los Alamos we have developed a methodology based on statistics, engineering, cognitive science, computer science and physics to do just that.

A New Approach to Performance—PREDICT

Developers: Mary Meyer, Jane Booker, Tom Bement

PREDICT—Performance and Reliability Evaluation with Diverse Information Combination and Tracking.

Two successful applications with sparse data:

Delphi Automotive Systems—birth to death development of new auto system designs

Los Alamos Nuclear Weapons Program—performance estimation of the aging nuclear physics package

PREDICT—1999 R&D 100 Award

Some Issues

- Quantification
- Characterizing and Propagating Uncertainties
- Integrating Information
- Handling Complex, Evolving Systems
- Handling New Information
- Prediction and the Unknown
- Measuring Success

Special Panel Session:

Issues with Modeling System Reliability Using Probabilistic Methods

5th Annual FAA/AF/NASA/Navy Workshop
Application of Probabilistic Methods

David G. Robinson, PhD

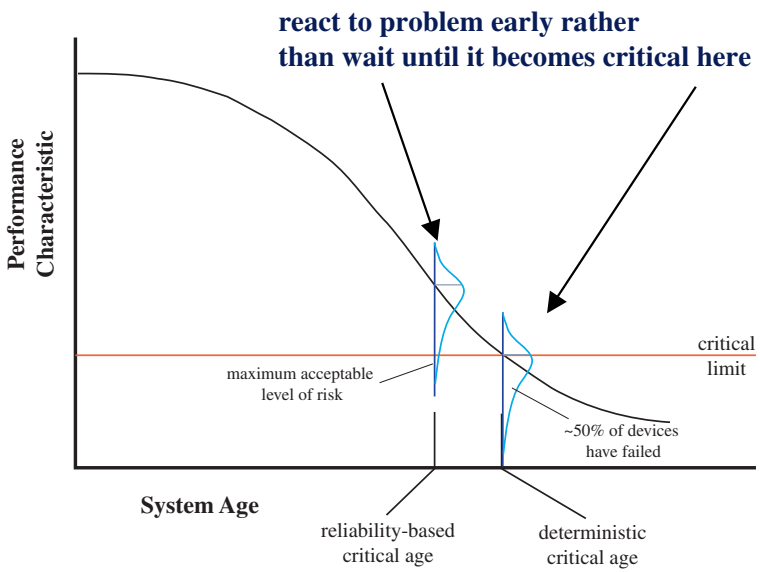
Sandia National Laboratories

Risk and Reliability Department

E: drobin@sandia.gov
P: 505-844-5883
F: 505-844-3321
http://reliability.sandia.gov/crax/robin.html
http://reliability.sandia.gov/crax

Why use probabilistic methods?

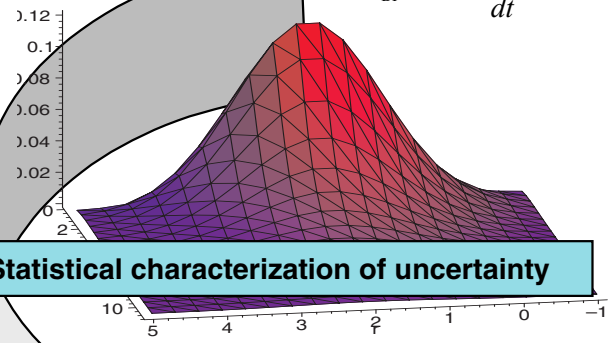
- Integration of subsystem ⇒ system reliability
- More efficient use of materials
- Provide an objective means of prioritizing design or manufacturing alternatives based on their impact on reliability
- Provide a quantitative measure for <u>anticipating</u> potential problems
- Identify areas where additional testing or data collection would contribute most to increasing confidence in the life prediction estimates



PM allow for an integrated assessment of the impact of uncertainty at all levels of the system

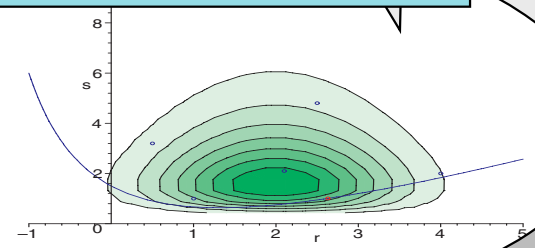
System Model (FEM, empirical, etc.)

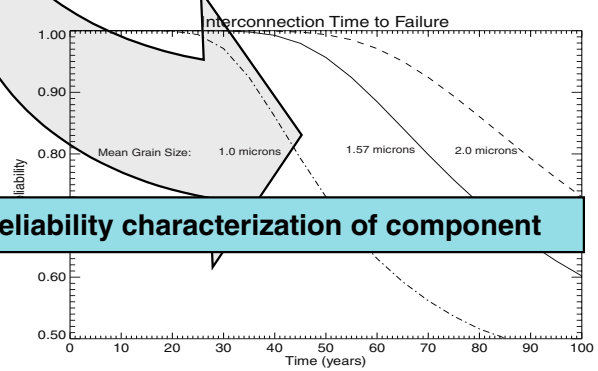
$$R_{BP} = \frac{d(\Delta R / R_0)}{dt} = kP_{Cl_2}^{x}\left\{1 - \exp\left[-\left(\frac{RH}{\eta}\right)^{\beta}\right]\right\}\exp\left[-\frac{E_a}{RT}\right]$$



Statistical characterization of uncertainty

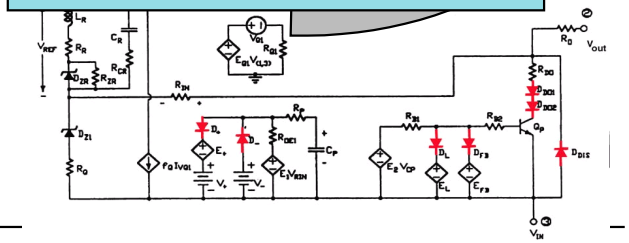
Identification of important parameters





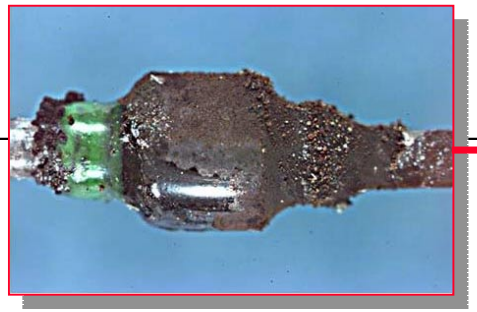
Reliability characterization of component

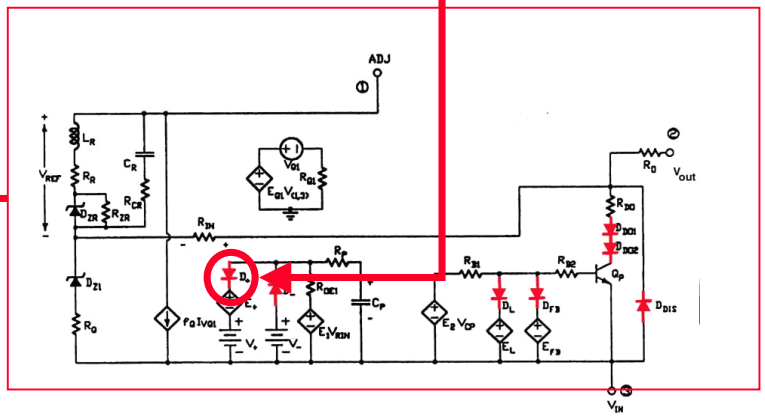
Impact on system level reliability

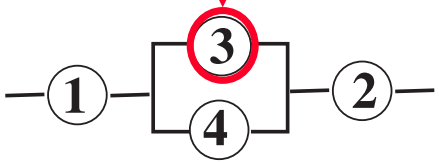


Levels of Analysis

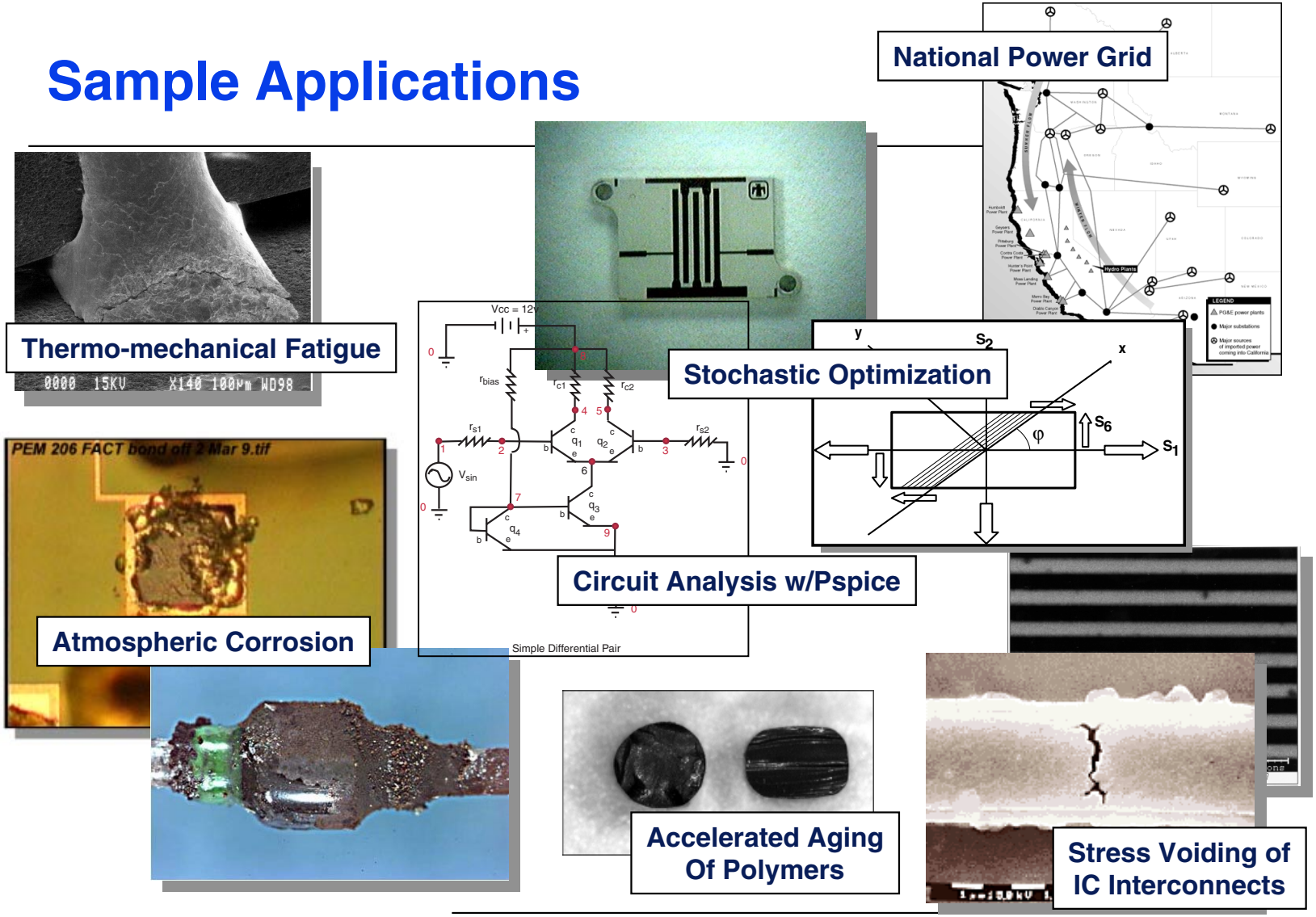
- Physics-based models
- Component models
- System models



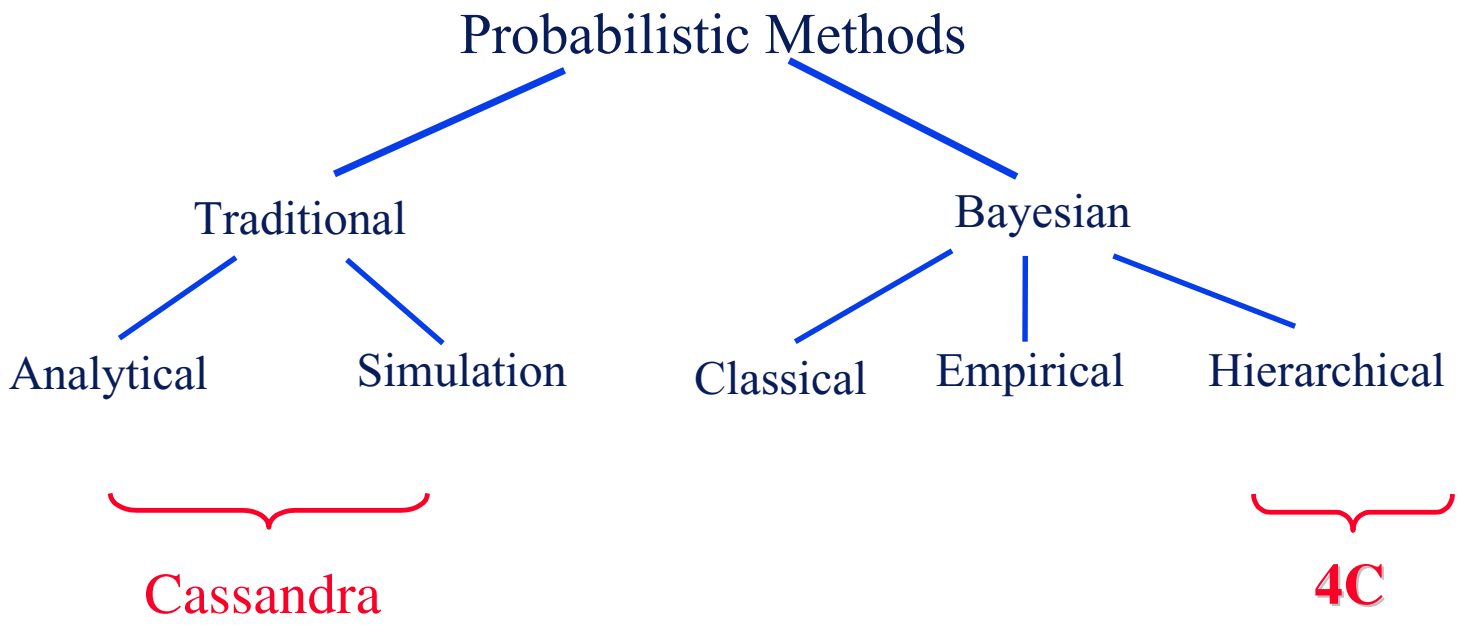




Sample Applications

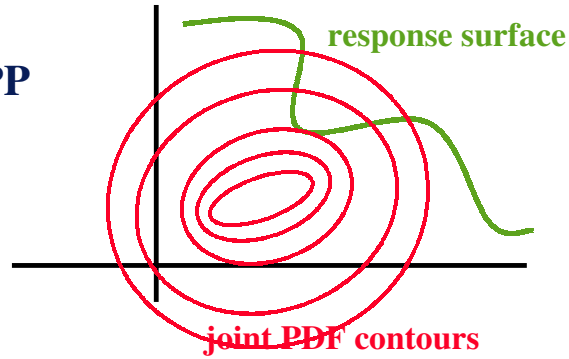


Family Tree

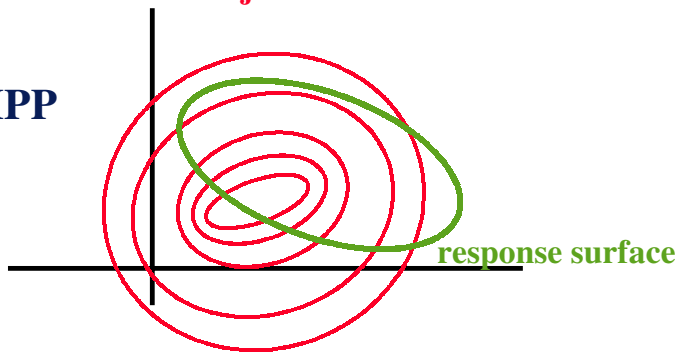

Probabilistic Methods
Traditional
Bayesian
Analytical
Simulation
Classical
Empirical
Hierarchical
Cassandra
4C

Issues: Traditional: Analytical

1. (-) Nonlinear response surface with single MPP



2. (-) Smooth response surface with multiple MPP



3. (-) Number of function evaluations for moderate number of random variables

Issues: Traditional: Simulation

1. (-) Classical Monte Carlo requires many function evaluations
   a) (+/-) no stat/prob background required
   b) (-) requires large number of simulations for accurate result
2. Variance reduction methods (e.g. LHS)
   a) (+) have demonstrated potential in a wide range of applications
   b) (-) computer implementation for large, complex problems poses some difficulty (e.g. restart or resampling)
3. Importance sampling
   a) (-) very efficient for finding single probability but full CDF can be costly
   b) (-) multiple MPP can make problem difficult to formulate
4. Quasi-Monte Carlo
   a) (+/-) can be more efficient than LHS, but not always
   b) (+) restart/resampling easier
   c) (-) potential (uninvestigated) problems with very high dimension sampling
5. New Sandia Field Analysis Method
   a) (+) very efficient and has restart and resampling capability, but
   b) (?)still very new and unproven

Issues: Bayes: Classical

1. (+) Tighter confidence interval due to more efficient use of data
2. (+) Confidence bounds on reliability
3. (-) Characterization of prior information -
   a) Results can be sensitive to selection of prior
   b) Choice of prior distributions often driven by computational ease rather than reality
4. (-) Aggregation of data (subsystem/system) can lead to very different conclusions about confidence limits

Issues: Bayes: Empirical

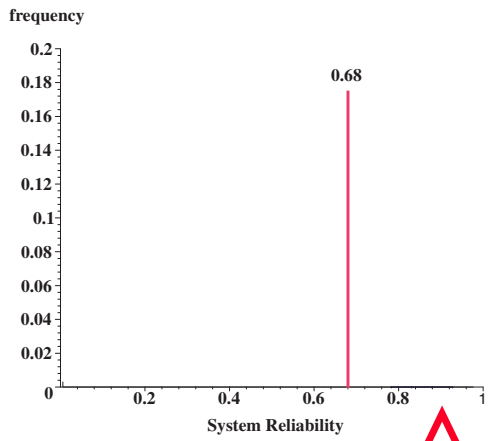
1. (+) Tighter confidence interval due to more efficient use of data
2. (+) Confidence bounds on reliability
3. (-) Characterization of prior information -
   a) Results can be sensitive to selection of prior but less than classical Bayes
   b) Choice of prior distributions often driven by computational ease rather than reality
   c) Incorporation of prior information requires data to be effectively used twice
4. (-) Aggregation of data (subsystem/system) can lead to very different conclusions about confidence limits

Issues: Bayes: Hierarchical

1. (+) Tighter confidence interval due to more efficient use of data
2. (+) Confidence bounds on reliability
3. Characterization of prior information -
   a) (-/+) results are much less sensitive to selection of prior
   b) (+) choice of prior distributions is more arbitrary than classical Bayes
4. (+) Aggregation of data (subsystem/system) is straightforward
5. (?) Number of simulations

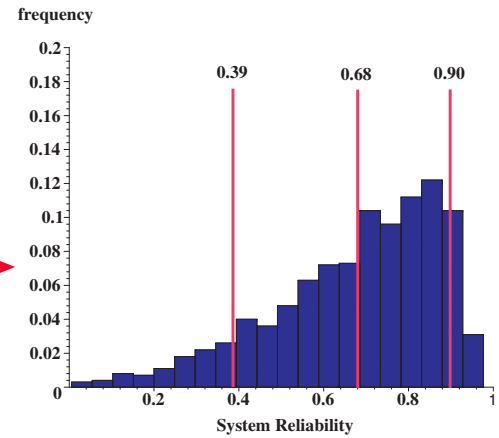
- Notes:
  - HB is still a relatively new technique in the field of reliability
  - Most investigations have proposed it as an alternative to classical Bayes where there is difficulty in realistically characterizing prior information.
  - Very few papers describing its use in structural reliability (2-3?)
  - Focus of current system and structural reliability research at Sandia

Comparison

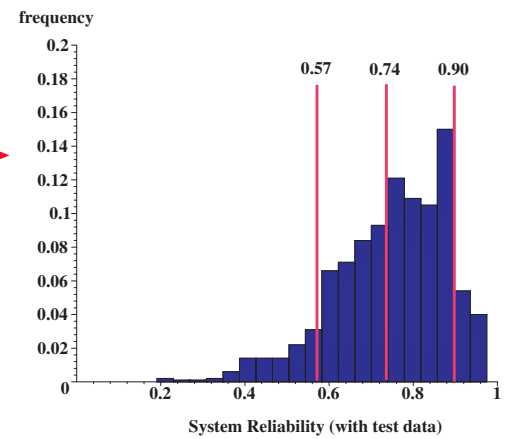


Classical Uncertainty Analysis

Hierarchical Bayesian Approach



HB Approach with test data



Backup Slides

NDA Tools and Techniques

- Traditional uncertainty analysis tool box - **Cassandra**
  - **Research** tool to explore new uncertainty analysis methods
  - **Applications** tool to asses stockpile reliability
  - CRAX (user interface) + Cassandra (engine)
- Hierarchical Bayesian analysis techniques
  - Limited test assets available (cost, regulation, etc.)
  - Growing need to include data from a wide variety of sources
    - » COTS
    - » Derivative hardware
    - » Engineering judgment
  - **4C** software suite is currently being developed to make the tools more accessible

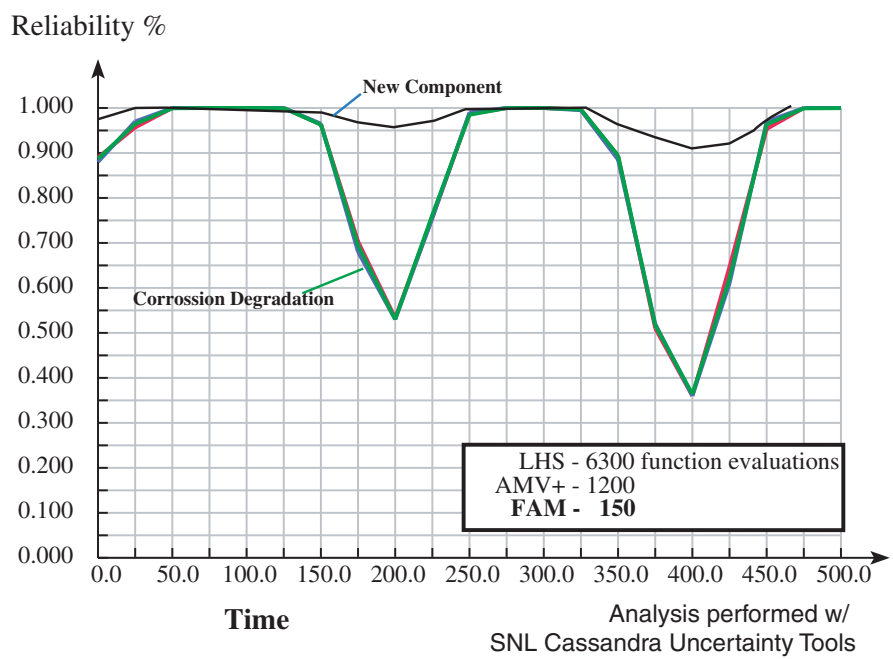
Sandia NDA Software Library - Cassandra

- Cassandra is an uncertainty analysis engine composed of various methods for integrating multidimensional functions of random variables
- Developed in response to:
  - need by engineers to address reliability and aging effects for stockpile safety assessment
  - need to test and validate new methods for structural reliability and uncertainty analysis methods
  - avoid 're-inventing the wheel' for each new reliability problem

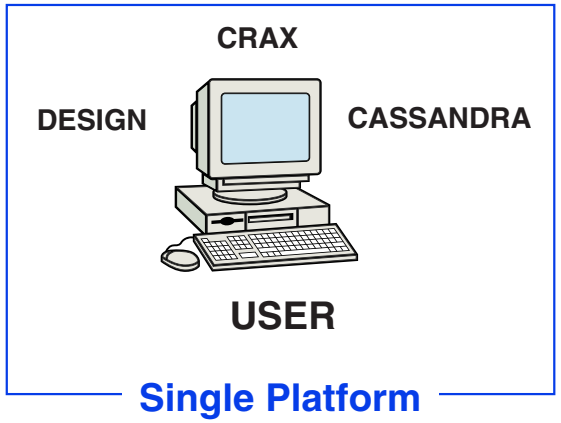
- Sampling
  - Pseudo -Monte Carlo
    - » Latin Hypercube
    - » Adaptive Importance Sampling
  - Quasi -Monte Carlo
    - » Hammersley
    - » Halton (normal and skipped)
    - » Sobol
    - » Iterative QMC (SNL unique)
- Analytical
  - MVFOSM
  - FORM/SORM
    - » Rackwitz-Fiessler,
    - » Hoenbichler-Rackwitz
    - » Tvedt
    - » RGMR
    - » AMV/AMV+
- Field Analysis (SNL unique)
  - Combination of quasi-MC and analytical methods

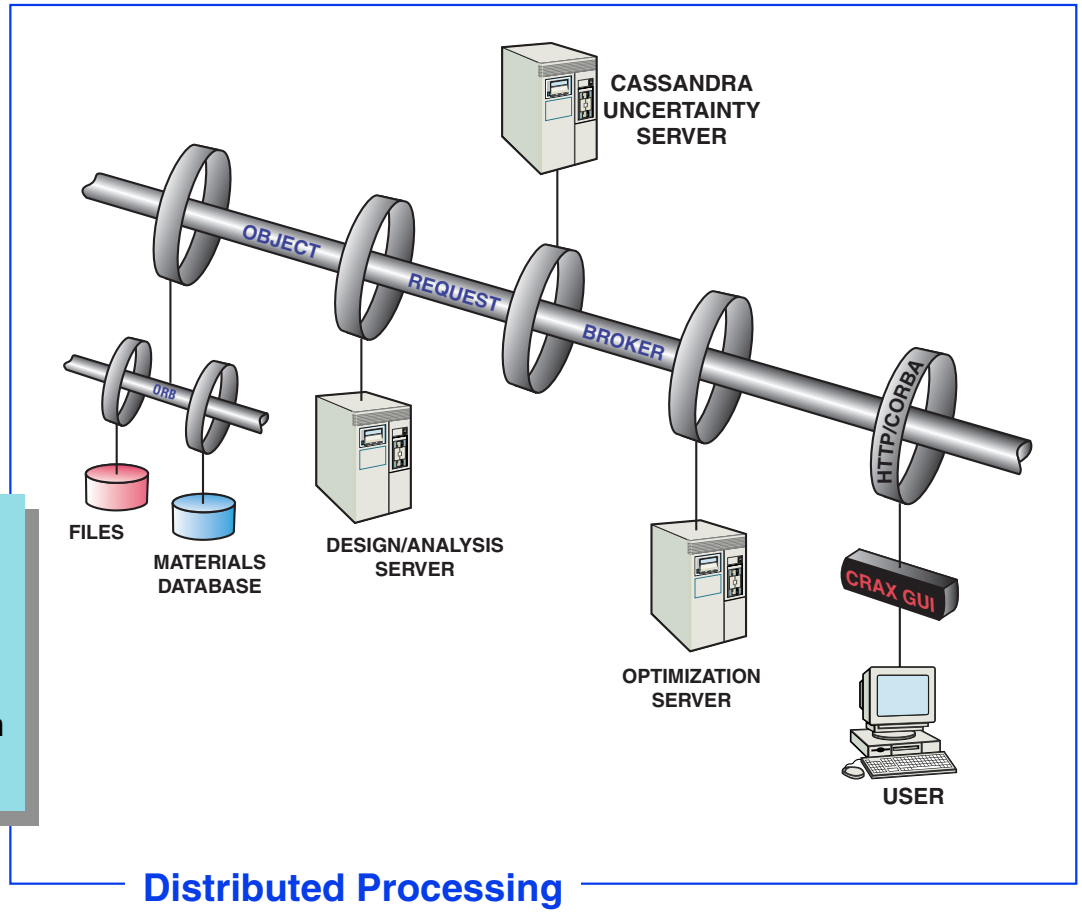
SNL Unique NDA Algorithms - Cassandra

- Complex FEM, FDM and electrical circuit models can take on the order of days for one execution
- Traditional uncertainty analysis methods require hundreds or even thousands of computer simulations
- SNL unique analysis algorithms within the Cassandra library provide the capability to achieve more accurate results with significantly few computer simulations



Processing Architecture





Analysis can be accomplished on single platform or as part of a distributed computational environment and the network configuration describing where computations are conducted can be changed 'on the fly'

Growing Problems

- As systems grow, and become more complex, the cost of system failure is leading to an increased emphasis on accurately characterizing system reliability
- However, actual system data is becoming cost prohibitive
- Even simulation data can be costly and time consuming to acquire
  - FEM, FDM and electrical circuit models can take on the order of days for one execution
  - Traditional uncertainty analysis methods require hundreds or even thousands of computer simulations
- Question: *How to combine data from a wide variety of testing programs, simulation/physics-based models, subsystem testing, materials experimentation, etc. to augment traditional system level testing?*

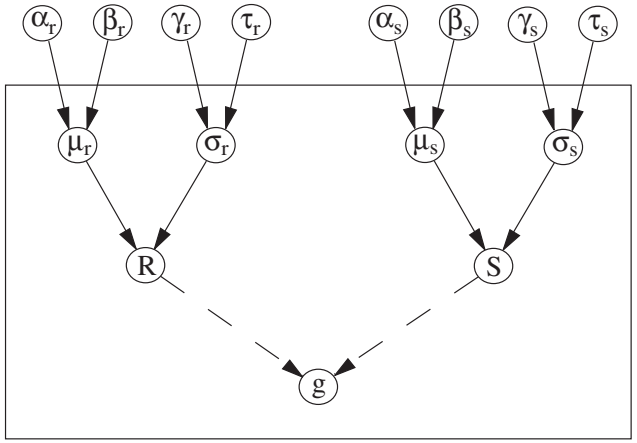
Bayesian Methods

- Bayesian methods provide a structured, logical approach to combining data from a variety of sources
- The use of the conditional logic structure of Bayesian methods results in a more efficient use of all information
- Example -
  - bag of 7 green and 5 red balls
  - Test 1:
    - » Without replacement pick a ball from the bag and observe color
    - » Pick a second ball from the bag
      - The predicted color of the second ball depends on the previous result
  - Test 2:
    - » Without replacement pick a ball from the bag and do not observe color
    - » Pick a second ball from the bag and observe that it is green.
      - Does knowing that the second is green change the probability that the first ball picked was red or green?
  - The use of data in a conditional manner provides additional insight into problems not otherwise possible and is the key to benefit of using Bayesian techniques.

Hierarchical Bayesian Methods

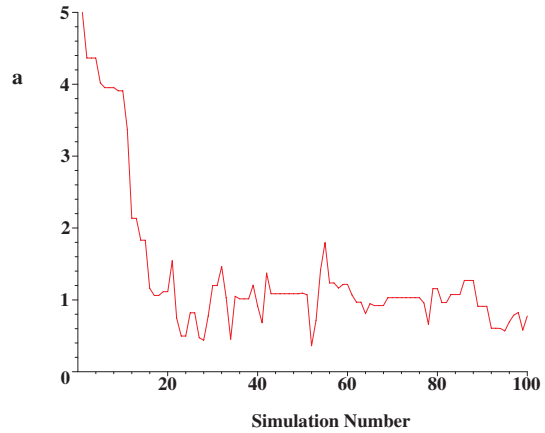
- Major complaint with Bayesian methods is the bias the can enter into the assessment as a result of choosing prior distributions.
- An alternative that makes the analysis much less sensitive to this prior information is hierarchical Bayesian methods
- Bayesian methods assume that the parameters of the random variables are again random variables.
- HB takes Bayesian methods one step further and lets the parameters of those distributions be random variables.

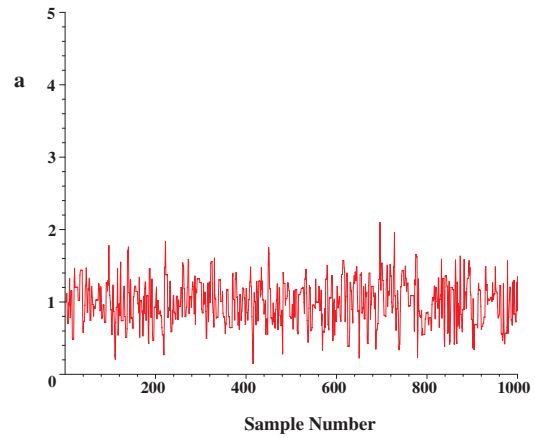
- Result:
  - Good: predictions are less sensitive to prior assumptions
  - Bad: mathematics of random variables becomes very complex
  - Solution: Markov Chain Monte Carlo simulation



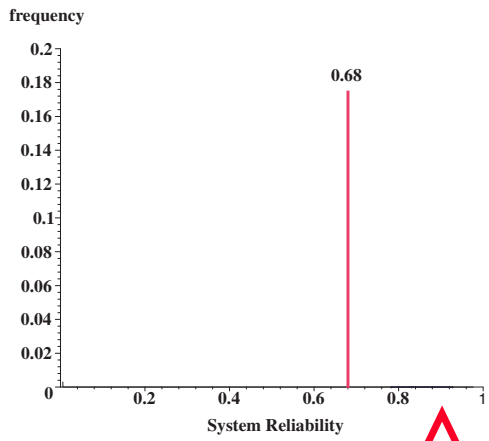
Markov Chain Monte Carlo

- MCMC is a family of simulation techniques
  - Metropolis-Hasting
  - Gibbs
  - Adaptive rejection sampling
- The random variables are assumed to come from a steady state distribution of a recurrent Markov process.



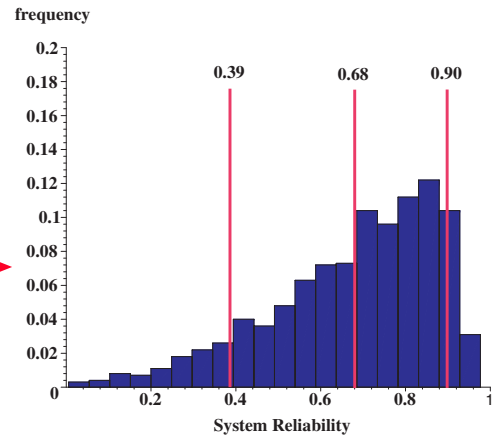


Comparison

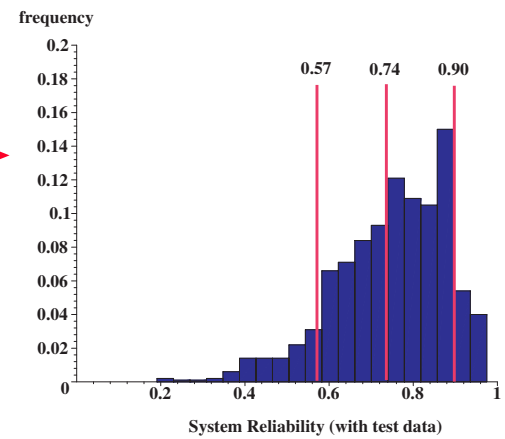


Classical Uncertainty Analysis

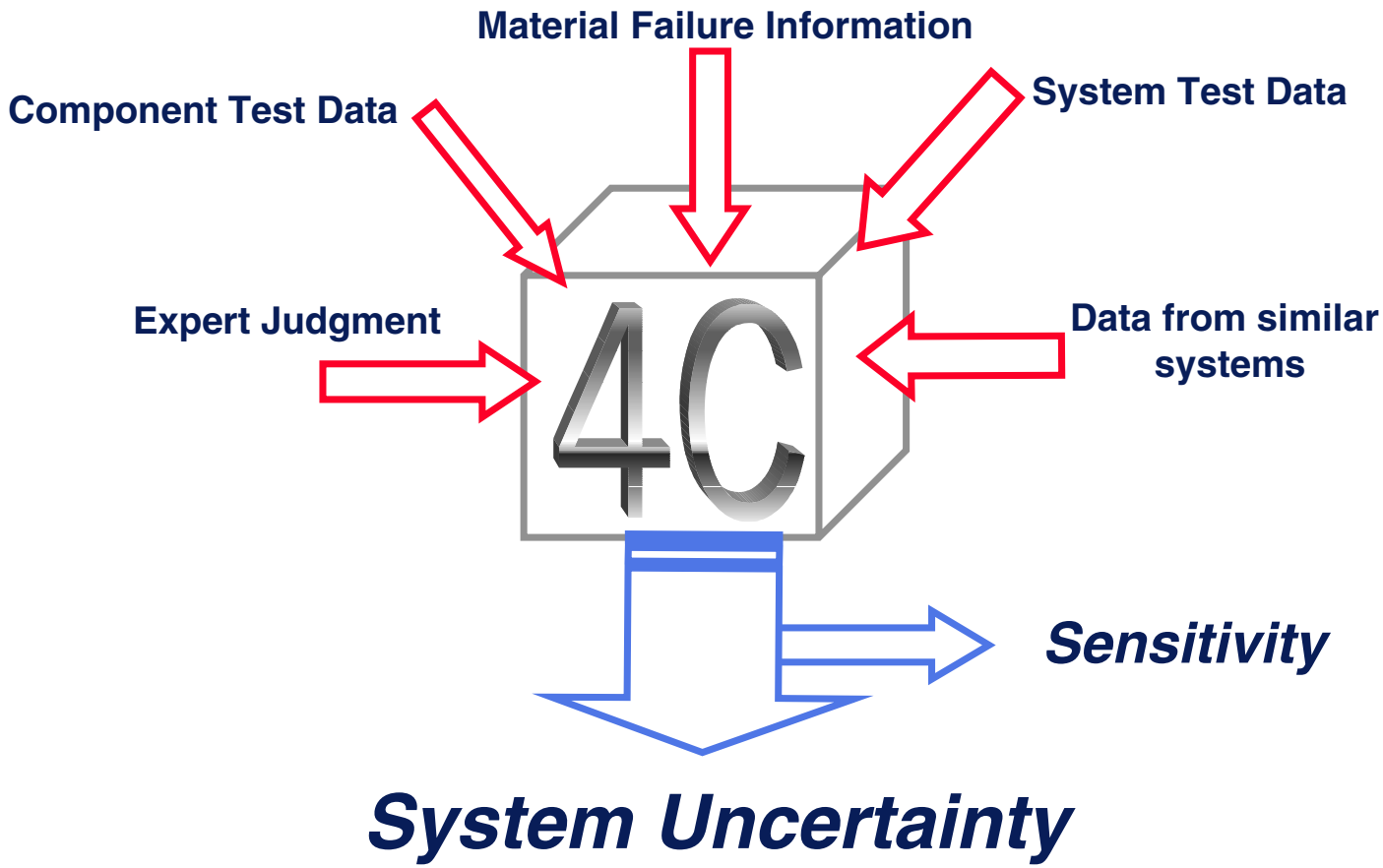
Hierarchical Bayesian Approach



HB Approach with test data



4C Software Library



NASA/CP—2002-211682

5th Annual FAA/Air Force/NASA/Navy Workshop on the Application of Probabilistic Methods to Gas Turbine Engines
June 11-13 2001
Holiday Inn Cleveland West
Westlake, Ohio

Issues and Strategies for Reliability-Based Certification Methodologies

Panel Session: Chuck Annis (PWA, ret.), Jane Booker (LANL),David Robinson (Sandia), Rob Sues (ARA Inc.)

Introductory Comments
Presented by:
Robert H. Sues (ARA)

Goals and Problems

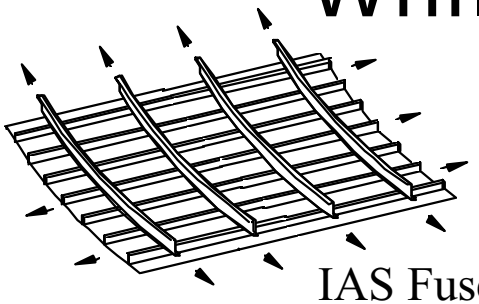
- First the goal:
  - Analytic certification of structures is meant to be a means to reduce the amount of testing while achieving a given confidence level and rely to a greater extent on modeling techniques for structure certification.
- What problem(s) do we need to solve?
  - We need to be able to evaluate design confidence (reliability).
  - We need to be able to evaluate how testing affects confidence.
  - We need ways to design tests so that they maximize our knowledge gain

Lots of Methods Proposed to Solve These Problems

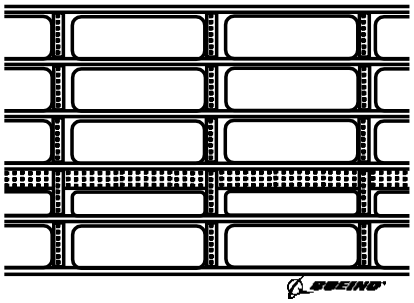
- There are problems with all the methods
- The methods are not a silver bullet
  - The methods will NOT eliminate the need for testing
  - Probabilistics doesn't make analytic certification possible
  - The methods will NOT tell us the true P_f
- But, the methods CAN help
  - Reduce the amount of testing
  - Design the tests to improve confidence in the analytic methods and the design
  - Identify the risk contributors so we can improve the design

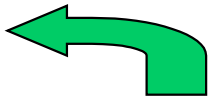
Reliability-Based Design Saves Weight While Maintaining Safety

Sponsor: NASA/Langley

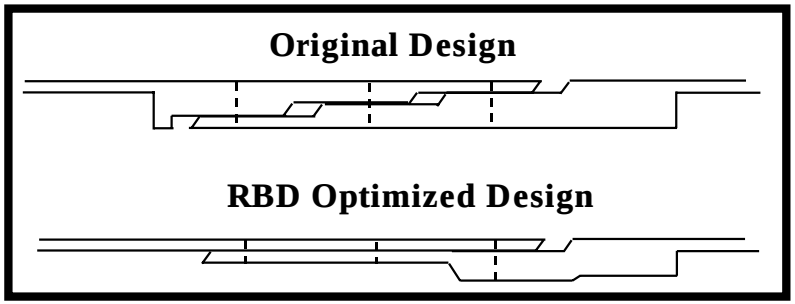


IAS Fuselage Panel

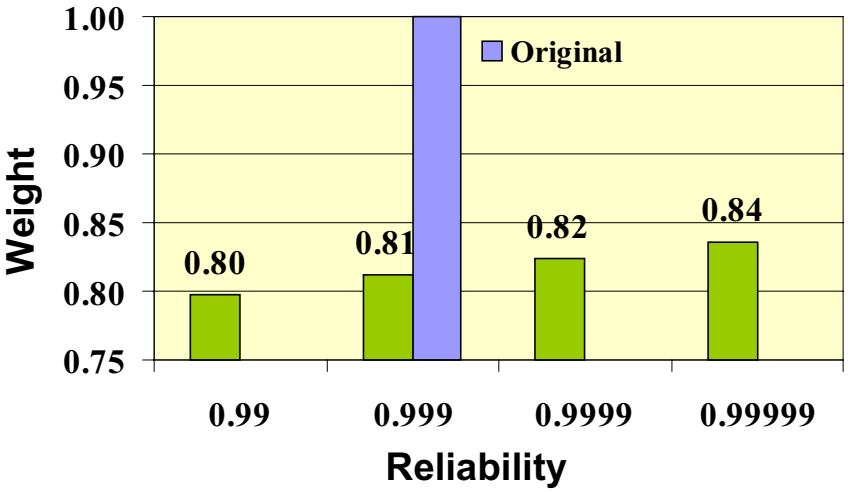




Lap Joint

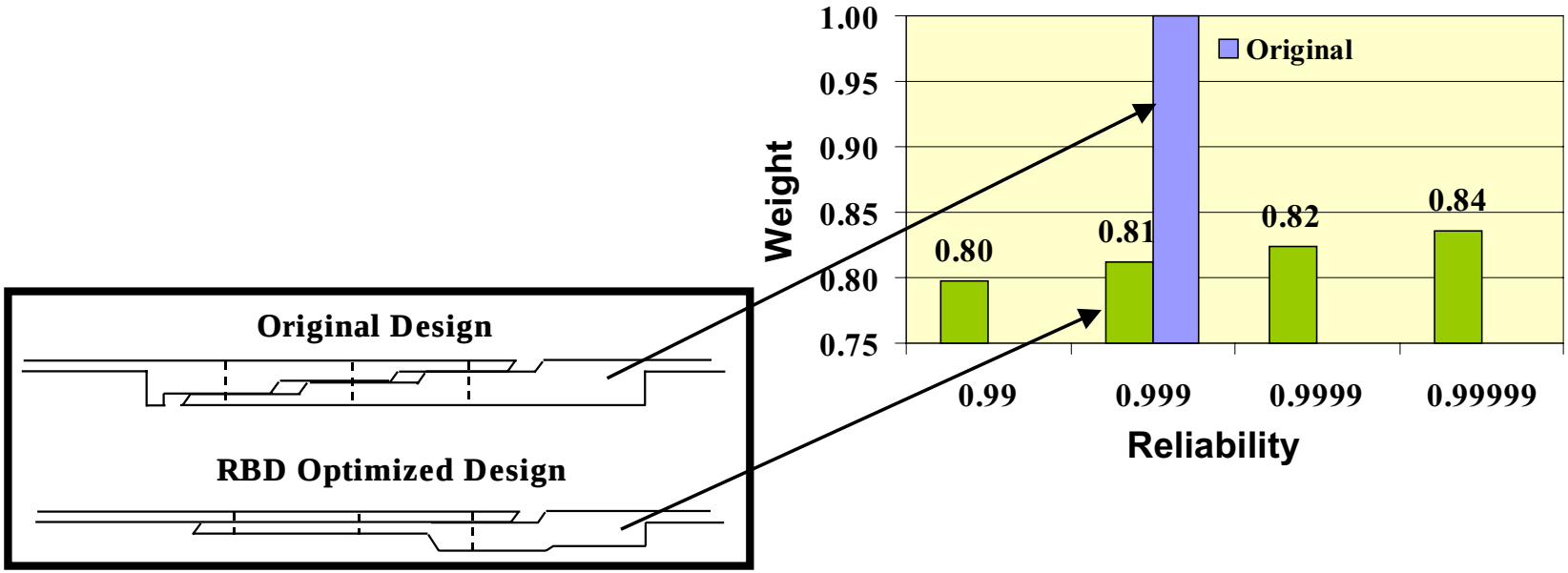


- **Probabilistic Fatigue Life Analysis of IAS Step Lap Joint**
- **19% weight reduction --- same reliability**
- **Information on safer designs available**



Reliability-Based Design Saves Weight While Maintaining Safety

Sponsor: NASA/Langley



How do I view the issues and roadblocks?

- Errors in probabilistic analysis methods
  - Deterministic model error
  - Use of model approximations in probabilistic
  - Uncertainty characterization
  - Probabilistic calculation
- Misunderstanding of probabilistic methods
- Lack of standardized procedures and demonstrated successes
- Lack of widely used and understood tools
- Computational and modeling complexity

Roadblocks and Solutions

- Immature technology prone to numerical and accuracy problems ➔ error estimation methods, self-selecting algorithms, guidelines on applicability
- Too difficult to apply in test environment ➔ RB test design procedures, RB model validation procedures
- Requires specialized expertise ➔ more training, standardization/codification, more demonstration problems
- Too difficult to implement ➔ better integration with existing CAE tools
- Too time consuming to model ➔ standardized and/or automated procedures, more demonstration problems
- Too time consuming to compute ➔ numerical methods R&D, parallel processing

A Probabilistic Approach to Anomalies in High Energy Turbine Discs

Richard S.J. Corran
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During the last decade the work of the Rotor Integrity Sub-Committee of the Aerospace Industries Association has been directed to reducing the probability of burst of high energy rotors whose failure may hazard the airframe. AC 33.14.1, recently issued, represents the first fruits of this work and addresses the potential failure of titanium rotor hubs through the presence of hard alpha particles introduced in the melt process. Current work is directed at the possibility of failure of a hub due to an anomaly introduced during the manufacturing processes. Both of these potential failures have occurred previously in well publicised events. This paper gives a review of the RISC work in the light of the AC and reports on the current state of material cleanliness as evidenced by recent reports of finds in billet material. This is followed by an account of the current work on surface damage tolerance. As a first consideration, work is aimed at anomalies arising in holemaking in turbine discs. The strategy is to derive an underlying rate and size distribution captured in an exceedance curve which will allow individual Original Equipment Manufacturers (OEMs) to determine whether special measures for achieving increased quality of manufacture are required. In this development key decisions must be made about how the probability of burst should be estimated and how experience in the past can be used to determine the underlying exceedance curve. Finally thought must be given to the incorporation of improved controls and how the benefit of these can be captured in the method.

NASA/CP—2002-211682

A Probabilistic Approach to Anomalies in High Energy Turbine Discs

A Status Prepared for the
5th Annual FAA/Air Force Workshop on the
Application of Probabilistic Methods to Gas Turbine Engines

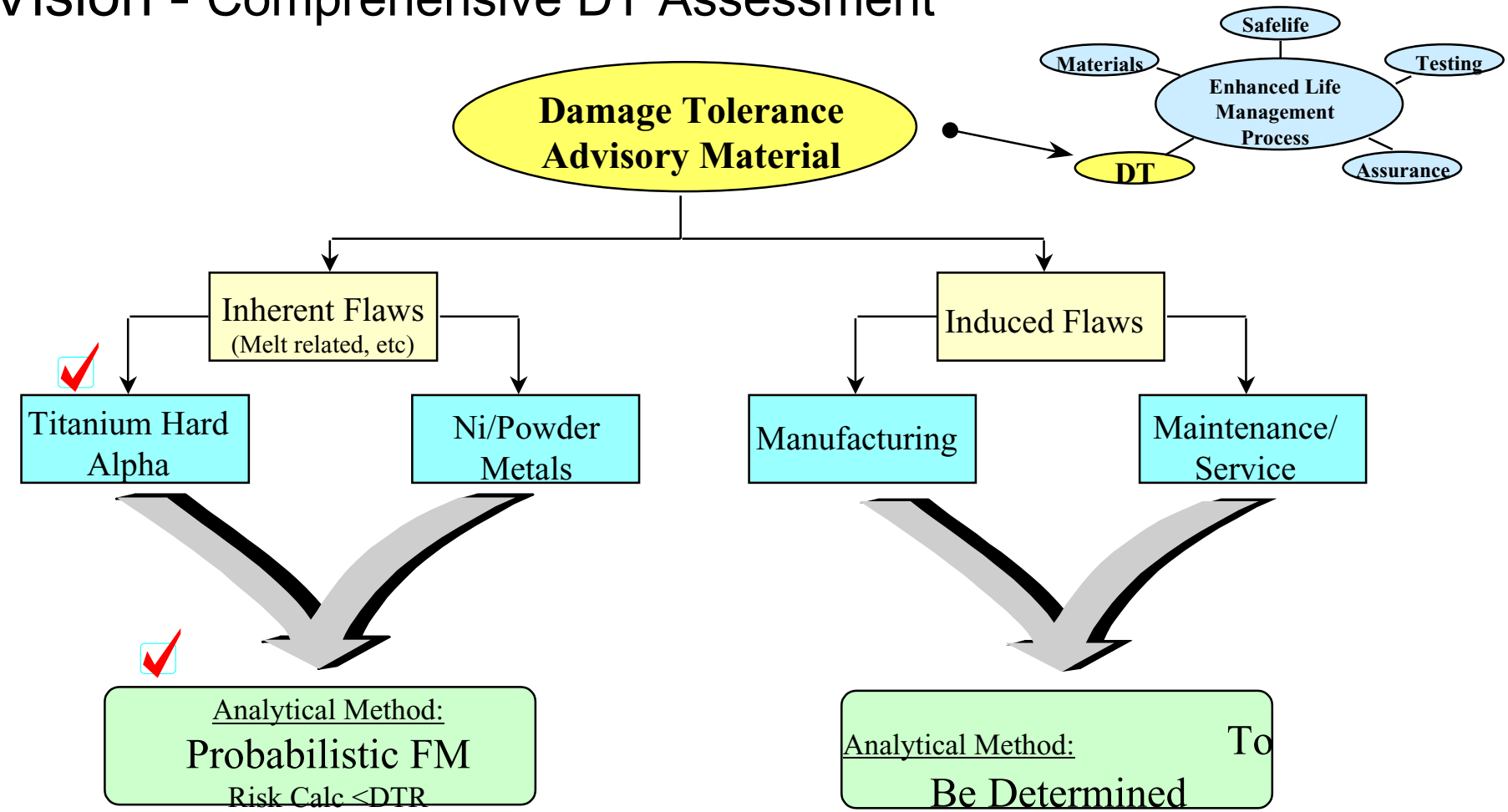
Richard S J Corran
AIA Rotor Integrity Sub-Committee

June 2001

Objectives of talk

- What are anomalies
- Why a probabilistic approach?
- What's been achieved
- What's in progress
- When and what will it deliver?

Vision - Comprehensive DT Assessment



- Analysis Tool calibrated by Test Case
- Criteria Calibrated by Experience

Driving Forces - Sioux City

ACCIDENT

UAL 232, July 19, 1989 - Sioux City, Iowa

- DC10-10 crashed on landing
- In-Flight separation of Stage 1 Fan Disk
- Failed from cracks out of material anomaly
- - Hard Alpha produced during melting
- Life Limit: 18,000 cycles. Failure: 15,503 cycles.
- 111 fatalities
- FAA Review Team Report (1991) recommended:
  - Changes in Ti melt practices, quality controls
  - Improved mfg and in-service inspections
  - Lifing Practices based on damage tolerance

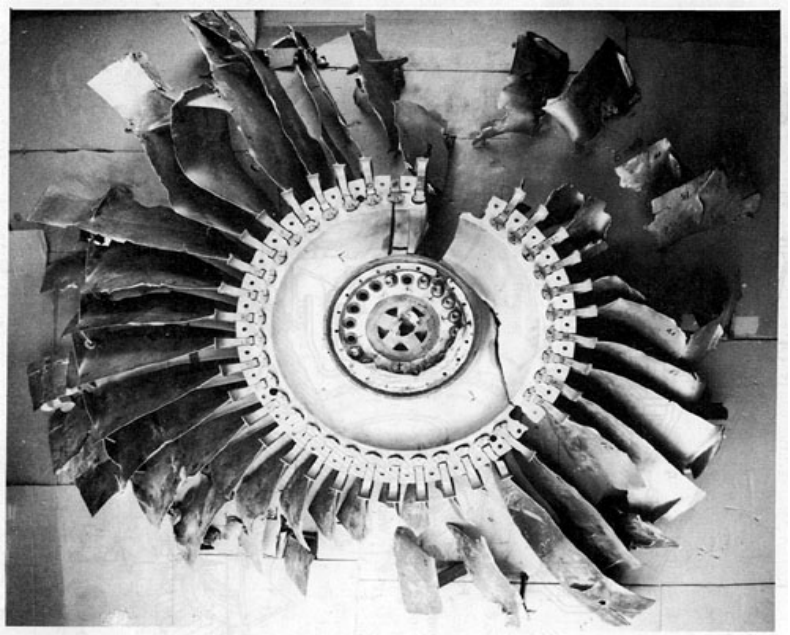


Figure 18.--No. 2 engine stage 1 fan disk (reconstructed with blades).

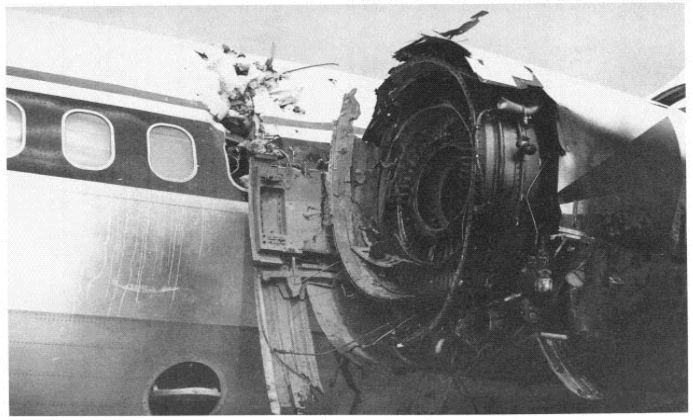
- Sioux City disk failure was the catalyst for unprecedented levels of industry/FAA cooperation regarding rotor safety ⇒ FAA Ti Initiative
- AIA Rotor Integrity Sub-Committee (RISC) established to develop new lifing strategies

Driving Forces - Pensacola

ACCIDENT

DL 1288, July 6, 1996 - Pensacola, Florida

- MD-88 engine failure on take-off roll
- Pilot aborted take-off
- Stage 1 Fan Disk separated; impacted cabin
- Failure from abusively machined bolthole
- Life Limit: 20,000 cycles. Failure: 13,835 cycles.
- 2 fatalities
- NTSB Report recommended ...
  - Changes in inspection methods, shop practices
  - Fracture mechanics based damage tolerance



- Represented second major premature failure of a Stage 1 fan disk in recent years due to unanticipated and undetected damage
  - Focused RISC activities on surface Damage Tolerance methodology development
  - Spawned FAA Enhanced In-Service Inspection and Rotor Manufacturing initiatives

Introduction

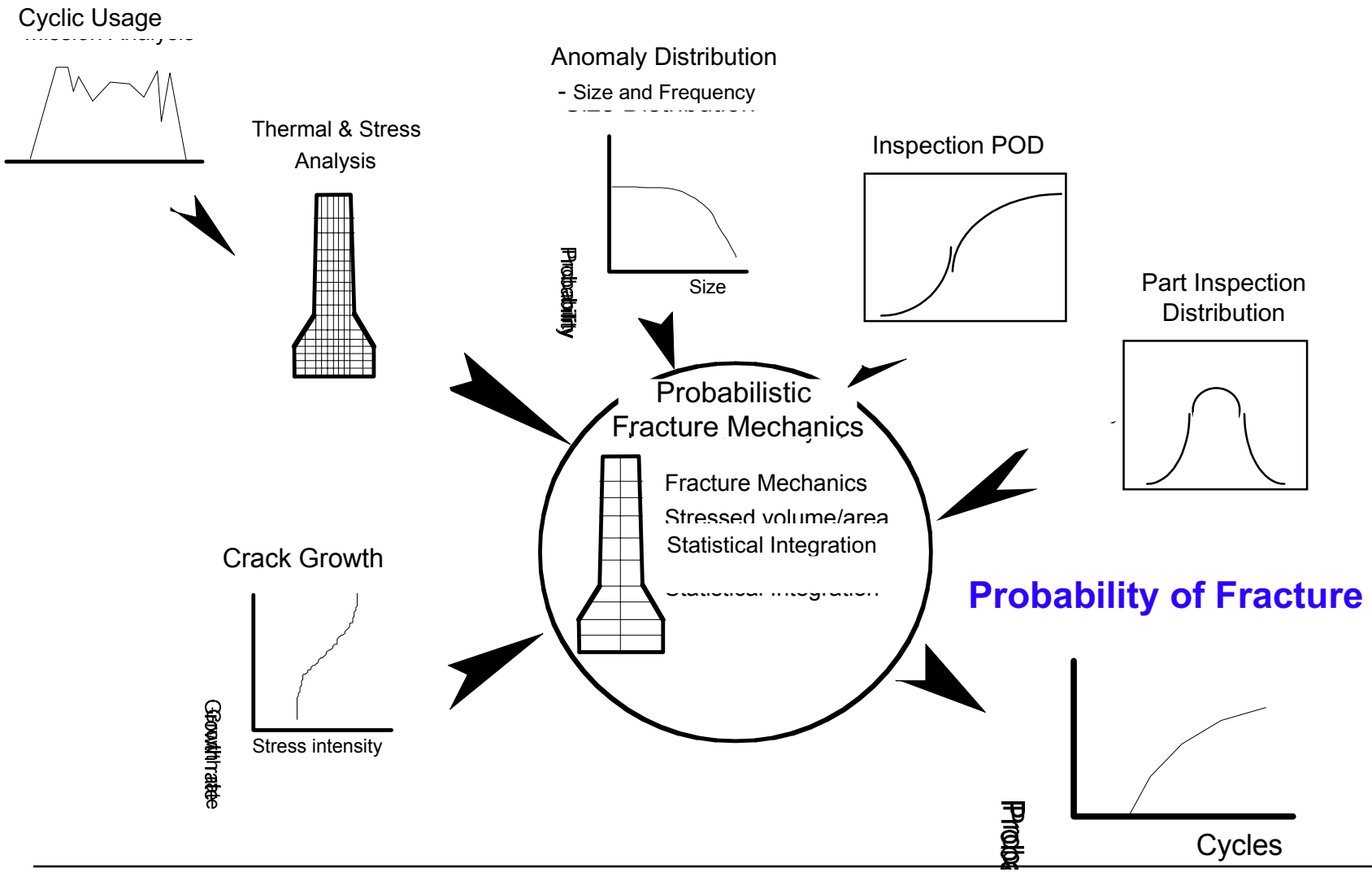
- Modern engines have excellent reliability and safety records
- Nevertheless, uncontained disk failures do occasionally occur
- Industry and FAA have been working to reduce these failure rates

  with some measure of success
  - over the past 5 years, 66% drop in rate of events that hazard the aircraft
  - but effects being offset by growth in commercial fleet
- Recent experience ⇒ primary causal factors for uncontained failures are material, manufacturing, and maintenance/usage induced anomalies
- "classical" failures (LCF, creep, etc) trending down
- Engine Manufacturers recognize the need to address the potential for unanticipated anomalies, and to adopt a Damage Tolerance Philosophy and are actively working to implement it

Why a probabilistic approach?

- Anomalies occur rarely, e.g.
  - » 1 per million lbs. of titanium
  - » 1 in a million holes manufactured
- Controls are aimed to reduce/eliminate the occurrence of anomalies, but …
  - » Can't be 100% effective
  - » Difficult to determine when adequate controls are in place
  - » Without quantitative assessment, <u>all</u> measure which reduce the risk must be accepted.
- However:-
  - » Probabilistic assessment requires benefit of controls to be assessed
  - » Hence can determine when controls meet similar level to known good experience
  - » The more effective the control, the grater the benefit
  - » The probabilistic approach encourages the use of effective controls

Probabilistic Fracture Mechanics Methodology



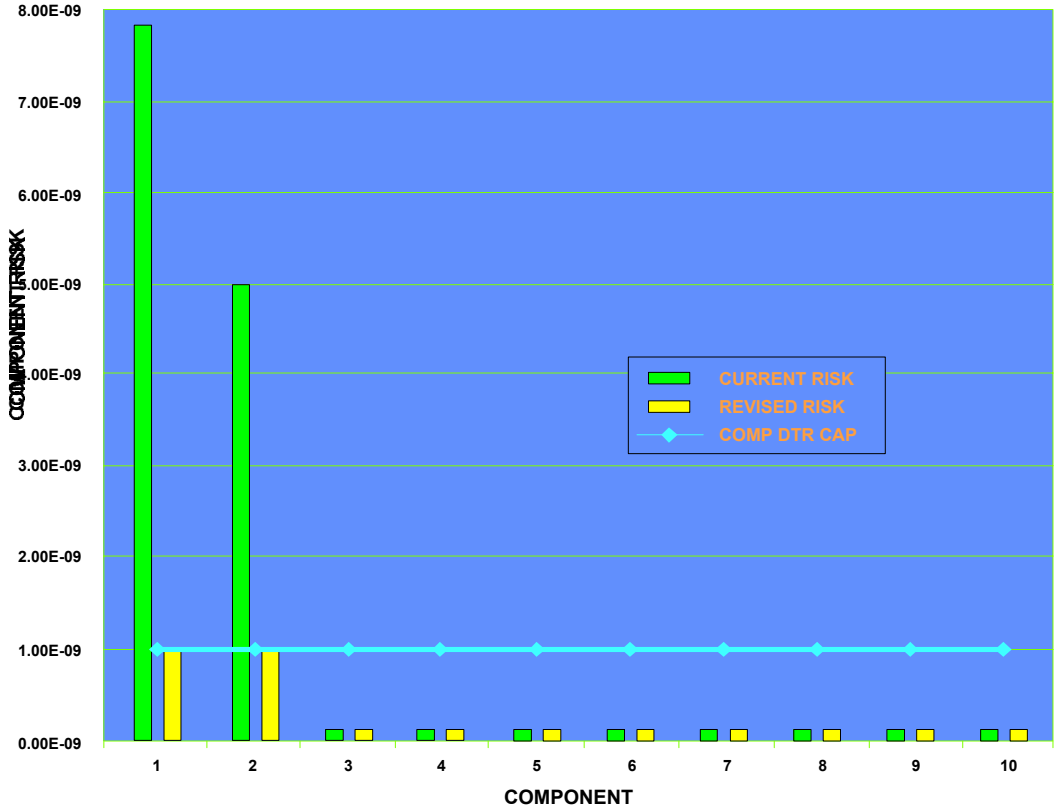
Relative Risk Reduction - Commercial Fleet Simulation

Example 1

2 HIGH / 8 LOW RISK COMPONENTS

Component DTR CAP Controlled = 1.0XE-9

Event Reduction Ratio = 4.9

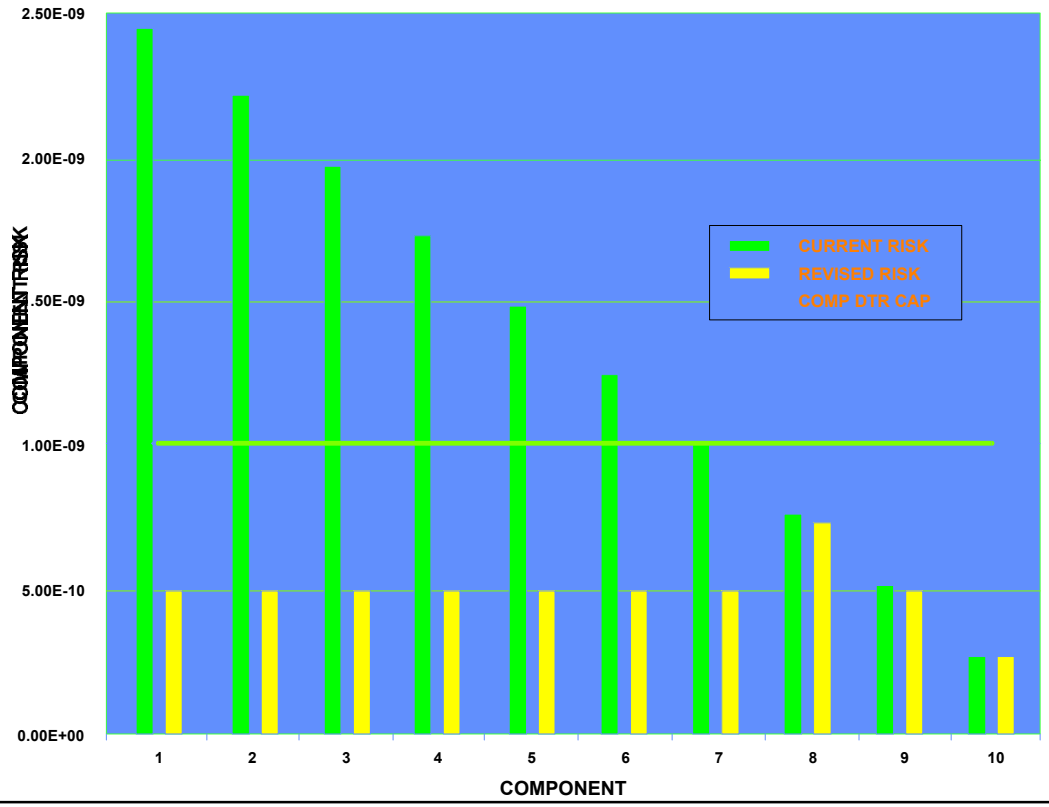


Relative Risk Reduction - Commercial Fleet Simulation
Example 2

DECREASING COMPONENT RISK PROFILE FOR 10 COMPONENTS

Engine DTR CAP Controlled = 5.0XE-9

Event Reduction Ratio = 2.7

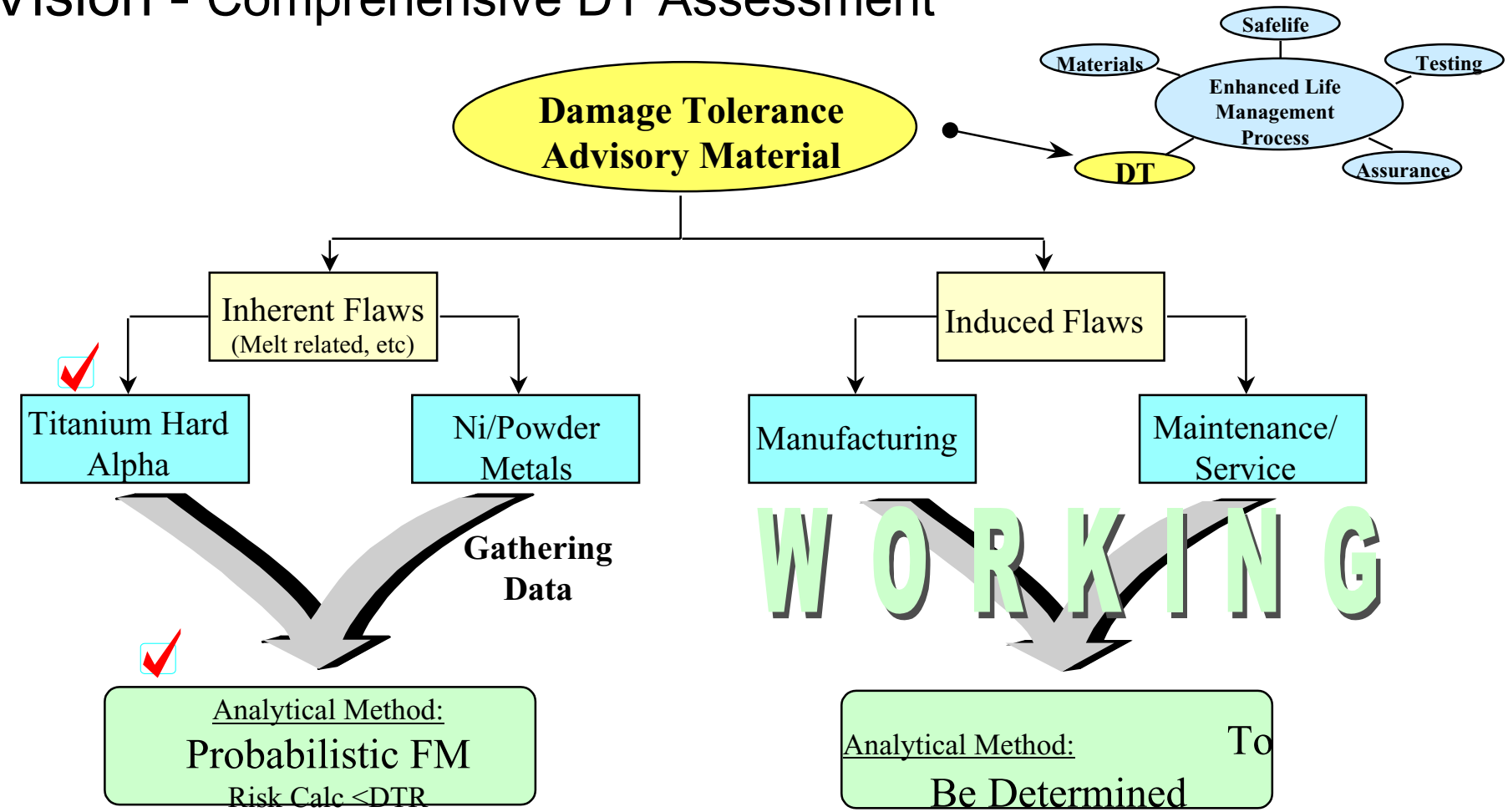


What's been achieved?

- Report to FAA describing Damage Tolerant approach to melt anomalies in Titanium
- TRMD project to develop method of probabilistic assessment
- Co-ordination with Engine Titanium Consortium over development and evaluation of inspection methods
- Result:-

- FAA has published Damage Tolerant approach in AC 33.14.1 in 2001

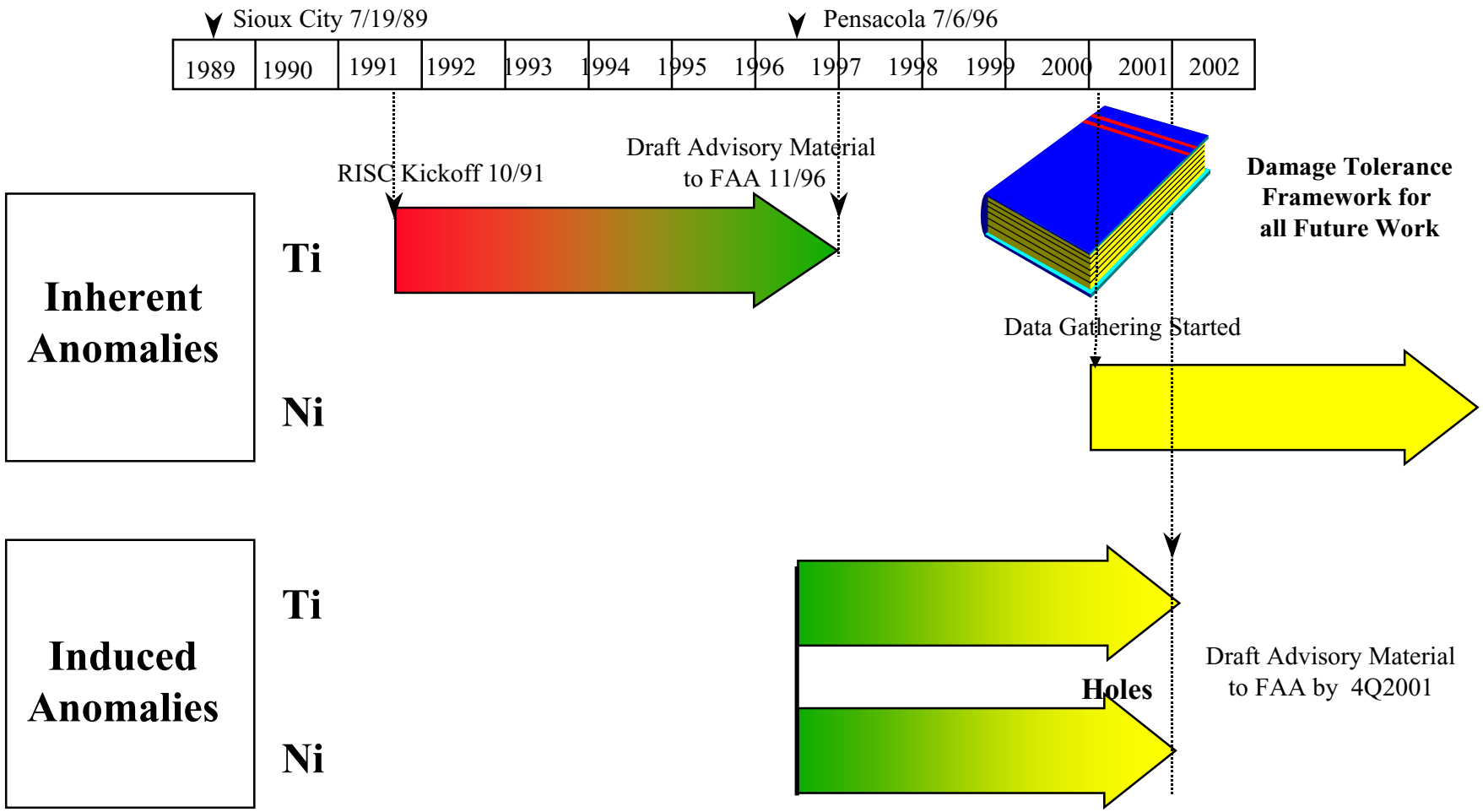
Vision - Comprehensive DT Assessment



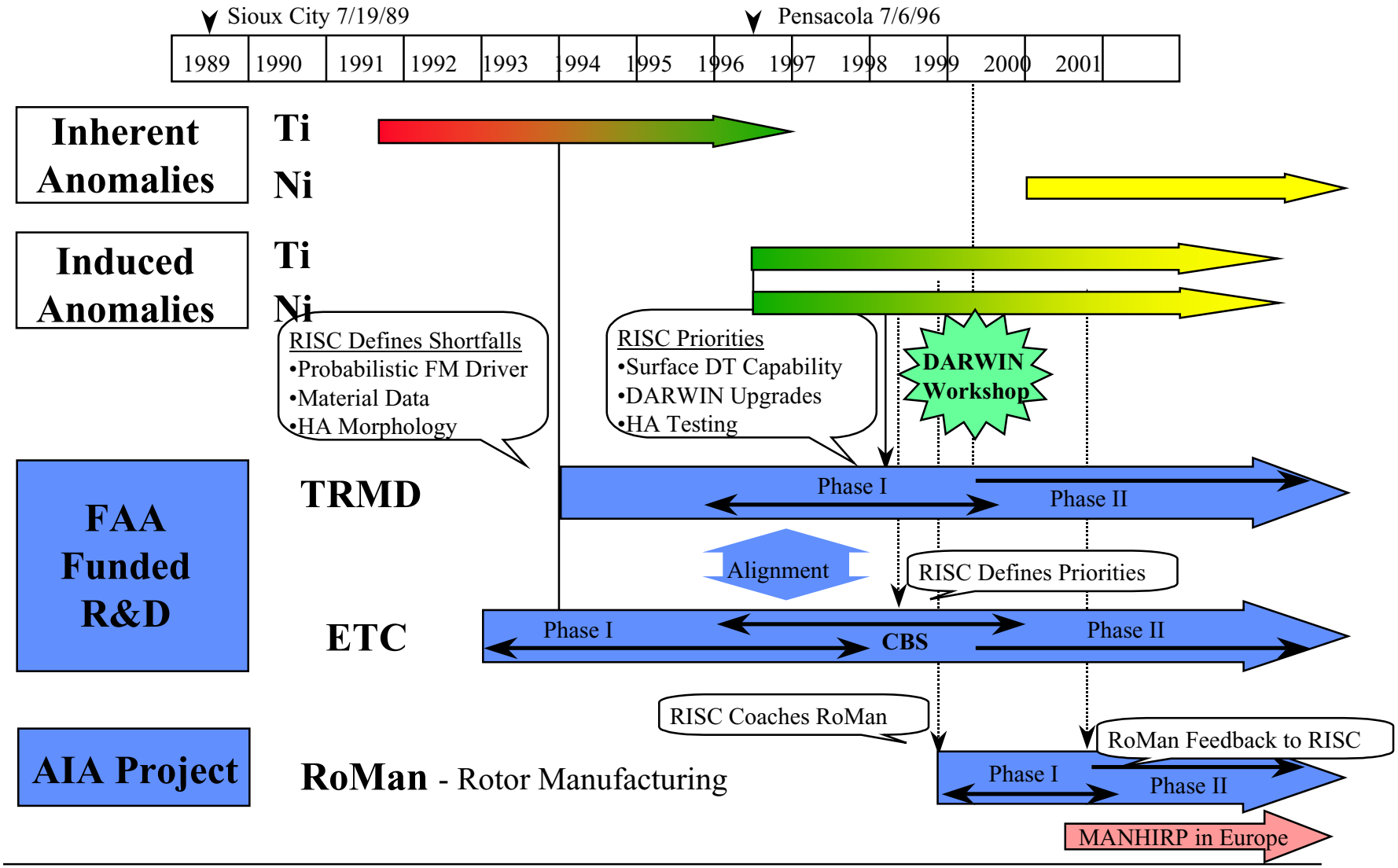
- Analysis Tool calibrated by Test Case
- Criteria Calibrated by Experience

- Probabilistic FM?
- Deterministic FM?

RISC Schedule



RISC Schedule - Linkage to R&D and AIA RoMan Project



Summary

- RISC has developed an Industry approach to Damage Tolerance which is based on a probabilistic assessment of anomalies
- This has become an Industry Standard through AC 33.14.1
- RISC is now systematically tackling other anomaly types known to have caused cracking:-
  - » Inherent (melt) anomalies in Cast & Wrought Nickel Alloys
  - » Manufacturing damage in holes - Report due in coming year
- In the longer term, the intention is to tackle:-
  - » Handling damage
  - » Other manufacturing damage
- RISC efforts have been supported by complementary AIA project on Rotor Manufacturing (RoMan)

Watch this space!

Turbine Rotor Material Design

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Email: gleverant@swri.org

Presentation Titles at Workshop:
"Turbine Rotor Material Design" Gerald R. Leverant
"Crack Nucleation & Growth Data & Modeling" McClung
"Darwin™ Enhancements for Probabilistic Risk Assessment" Enright & Millwater

ABSTRACT

Premium grade titanium alloys are used for fan and compressor rotors and disks in aircraft turbine engines. Occasional upsets during processing can result in the formation of metallurgical anomalies referred to as hard alpha (HA). Although rare, low-cycle fatigue cracks initiated by HA have led to uncontained engine failures that resulted in fatal accidents such as the incident at Sioux City, Iowa in 1989. In a report issued by the Federal Aviation Administration (FAA) after the accident at Sioux City, it was recommended that a damage tolerance approach be implemented to explicitly address HA anomalies, with the objective of enhancing conventional rotor life management methodology. The probabilistic, damage tolerance code developed in this program for low-cycle fatigue of titanium rotors/disks is intended to supplement, not replace, the current safe-life design. The code is called Design Assessment for Reliability with Inspection (DARWIN™) and was developed in collaboration with General Electric, Honeywell, Pratt & Whitney, and Rolls-Royce. DARWIN integrates finite element stress analysis, fracture mechanics analysis, non-destructive inspection simulation, and probabilistic analysis to assess the risk of rotor fracture. The code has been readied for industrial use and has been licensed to several OEM's. Supplementary tasks being performed in this program in support of code implementation include the generation of fatigue crack growth data for Ti-64, Ti-6242, and Ti-17 in high vacuum; determination of the crack initiation behavior of artificial and natural HA defects embedded in plates and disks of Ti-64; and development of a forging microcode to predict the movement, shape and orientation of HA anomalies during processing from ingot to billet and from billet to a disk forging.

Turbine Rotor Material Design

Program Team:
General Electric
Honeywell
Pratt & Whitney
Rolls-Royce
Southwest Research Institute

Sponsor: Federal Aviation Administration
FAA Technical Monitor: Joe Wilson
SwRI Program Manager: Gerald Leverant

5th Annual FAA/Air Force/NASA/Navy Workshop:
Application of Probabilistic Methods to Gas Turbine Engines

June 12, 2001

Turbine Rotor Material Design

Program Goals

- Develop a probabilistically-based damage tolerant design code to augment the current safe-life philosophy for life management of commercial aircraft gas turbine rotors and disks.

- Provide supplementary material/anomaly characterization and modeling to support the enhanced life management process.

Industrialization of DARWIN™

- Engine manufacturers request that SwRI provide ongoing support for DARWIN™.
- FAA grants intellectual property rights to SwRI.
- U. S. government receives royalty-free license.
- SwRI is providing full support and enhancements.
- Licensing to OEM's is underway.

Turbine Rotor Material Design

- Phase I: (8/95 - 9/99) — Hard alpha anomalies in titanium

- Phase II: (4/99 - 3/04)
  - Hard alpha anomalies in titanium
  - Machining/maintenance-induced surface anomalies
  - Anomalies in cast/wrought and P/M nickel

Turbine Rotor Material Design

Background

- Periodic adverse events have been associated with microstructural, manufacturing, and maintenance-induced anomalies in aircraft gas turbine rotors/disks during the past 30-35 years.
- A commercial DC-10 airliner crash-landed at Sioux City, IA, in 1989 as a result of an uncontained titanium fan disk failure attributed to a hard alpha inclusion.
- In 1990, the “FAA Titanium Rotating Component Review Team Report” recommended consideration of incorporating risk management and damage tolerance concepts into design procedures for critical, high energy components in commercial engines.
- The AIA Rotor Integrity Subcommittee (RISC) was formed in 1991 to implement these recommendations.

Turbine Rotor Material Design

Program Motivation

- The current safe-life philosophy for life management of rotors/disks does not account for undetected material, manufacturing, and maintenance-induced anomalies.
- As RISC formulated an enhanced life management process based on probabilistic damage tolerance methods and employing opportunity inspections, it became apparent that the emerging process could be significantly enhanced by R&D that addressed identified shortfalls in technology and data.
- The enhanced predictive tool capability and supplementary material/anomaly behavior characterization and modeling derived from the R&D program will provide direct support for the implementation of FAA Advisory Circular 33.14 and for additional improvements in those guidelines.

Turbine Rotor Material Design

Accomplishments to Date

- A probabilistic design code (DARWIN™) has been developed for hard alpha in titanium that integrates finite element stress analysis, fracture-mechanics-based LCF life assessment, material anomaly size distributions, probability of anomaly detection by NDE, and inspection schedules to compute the risk of rotor disk failure. The FAA has stated that use of DARWIN™ is an acceptable means of compliance with AC33.14. Enhancement of the code to handle machining and maintenance-induced surface anomalies in all disk alloys is underway.
- Vacuum fatigue crack growth data have been obtained for Ti-64, Ti6242, and Ti-17 as a function of temperature and mean stress (R). Work is underway on IN718 and Waspaloy.
- Monotonic and cyclic crack initiation and early crack growth data on specimens and LCF life data on spin-pit-tested disks have been obtained on Ti-64 containing seeded and natural hard alpha anomalies of various nitrogen contents. Additional specimen testing is underway.

Turbine Rotor Material Design

Accomplishments to Date

- A deformation microcode has been developed and integrated with the commercially-available DEFORM™ forging code. The integrated product is intended for predicting the change in shape and orientation of hard alpha anomalies of various nitrogen contents during material reduction from ingot to billet to final forged product. Validation of the code is underway based on the results of forging trials conducted on seeded billets.

- A code, called GROW, has been developed to predict the dissolution rate of hard alpha in liquid titanium. Calibration of the code is underway.

- Extensive UT NDE data has been generated on billets, pancake forgings, disk forgings, and semi-finished spin pit disks containing seeded and natural hard alpha anomalies.

Darwin™ Home Page

Crack Nucleation and Growth Data and Modeling

Task Manager: Craig McClung (SwRI)

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Yancey Gill (Honeywell)

Darryl Lehmann (P&W)

5th Annual FAA/USAF/NASA/USN Workshop

Application of Probabilistic Methods to Gas Turbine Engines

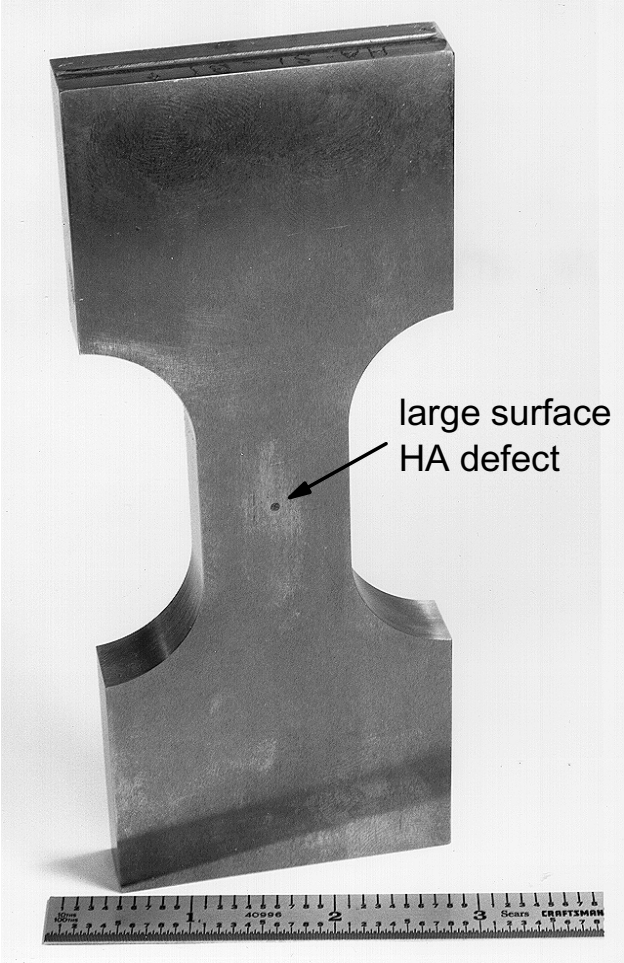
Outline

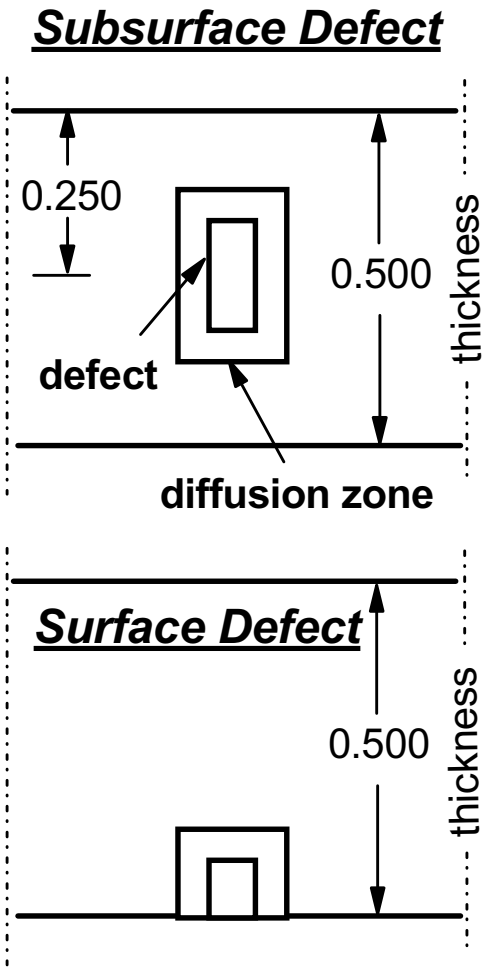
- Crack nucleation in hard alpha defects
  - Static and fatigue loading
  - Fatigue crack growth into surrounding matrix
- Thermal residual stresses in and near HA
  - Experimental measurement of CTE
  - Analytical estimation of residual stresses
  - Effect of residual stresses on cracking behavior
- Vacuum FCG behavior for titanium rotor alloys
  - Vacuum FCG testing for Ti-6-4, Ti-6-2-4-2, Ti-17
  - Comparisons of vacuum vs. air FCG rates
- Spin pit tests on rotors with HA defects
  - UT and fractographic inspections

Crack Nucleation in Hard Alpha: Motivation and Plan

- Are all HA inclusions always cracked at start of life?
- Experimentally characterize crack formation in HA inclusions
  - static and cyclic loading
- Primary focus on testing synthetic HA inclusions
  - manufactured by GE CR&D
  - high nitrogen core (1.6-6%) with surrounding diffusion zone
- Limited testing with natural HA inclusions
  - specimens extracted from RMI contaminated billets at ETC
- Characterization of cracking
  - nonvisual techniques (esp. AE) for real-time monitoring
  - post-test fractography and sectioning

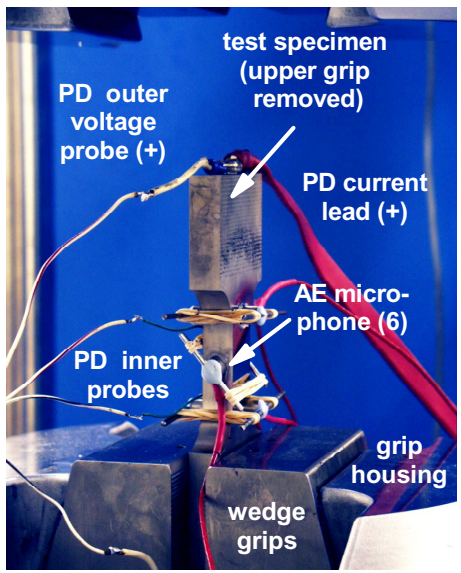
Crack Nucleation in HA: Specimens

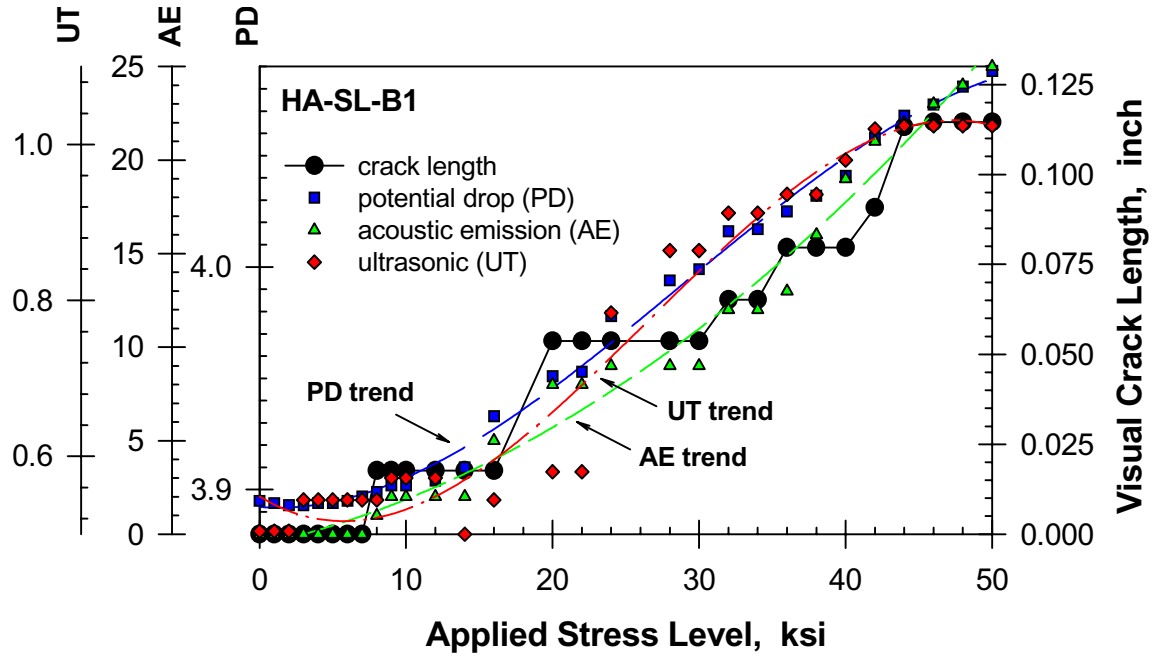




Crack Nucleation in HA: Statically Loaded Surface Defects

- Agreement between visual and nonvisual indications
- Most defects crack at relatively low monotonic stresses

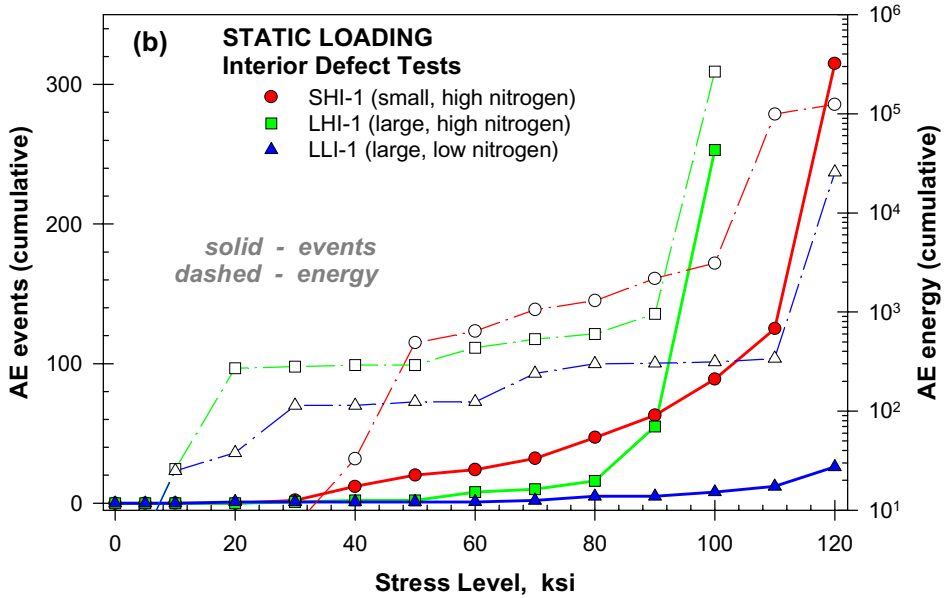




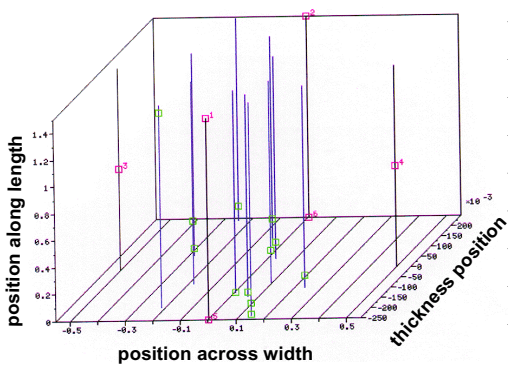
AE Response for Statically Loaded Interior Defects

- A few early events, but most activity occurs in bursts above 80-100 ksi

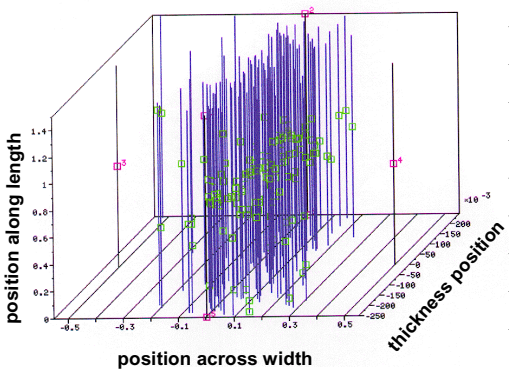
Specimen LHI-1
Large, high nitrogen
interior defect
static loading condition



AE events *(at 90 ksi)*

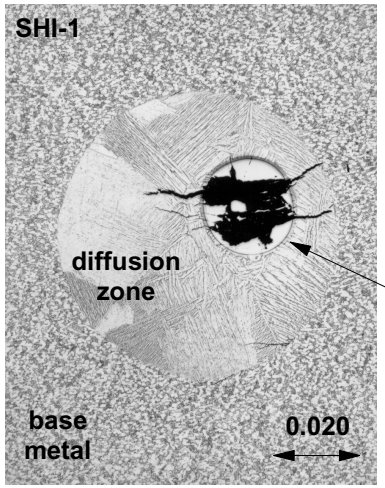


AE events *(at 100 ksi)*



Typical Cracking for Statically Loaded Interior Defects

- Shattered core in high N defects at high stress
- Limited core cracking at lower stresses
- Little cracking in low N defect at 120 ksi



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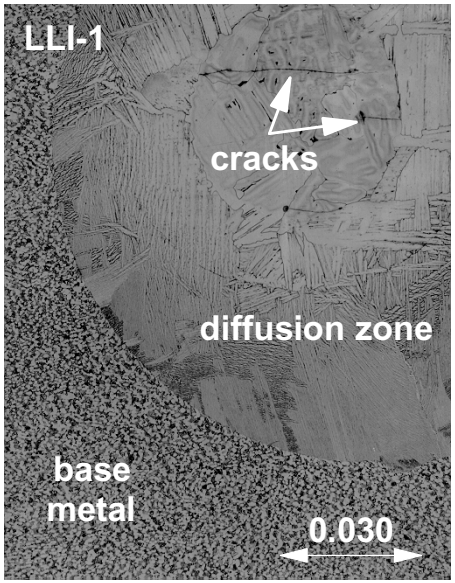
(a)



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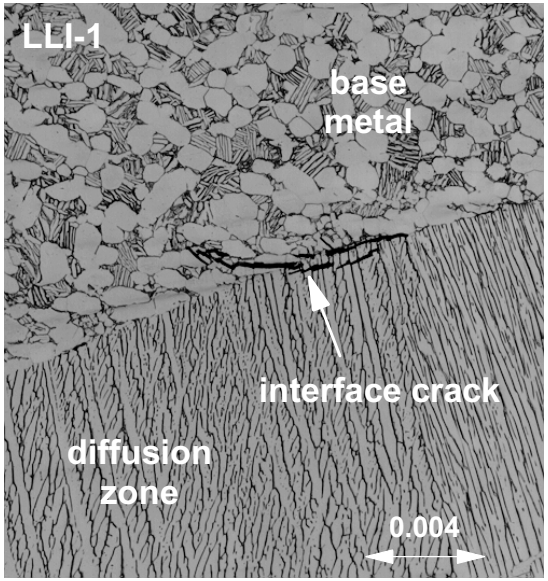

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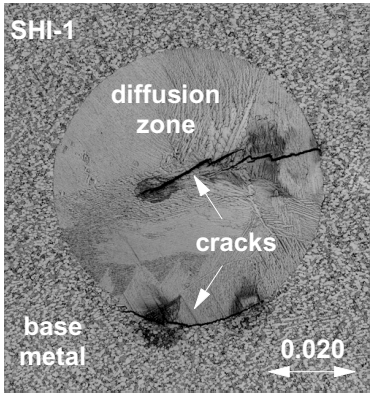

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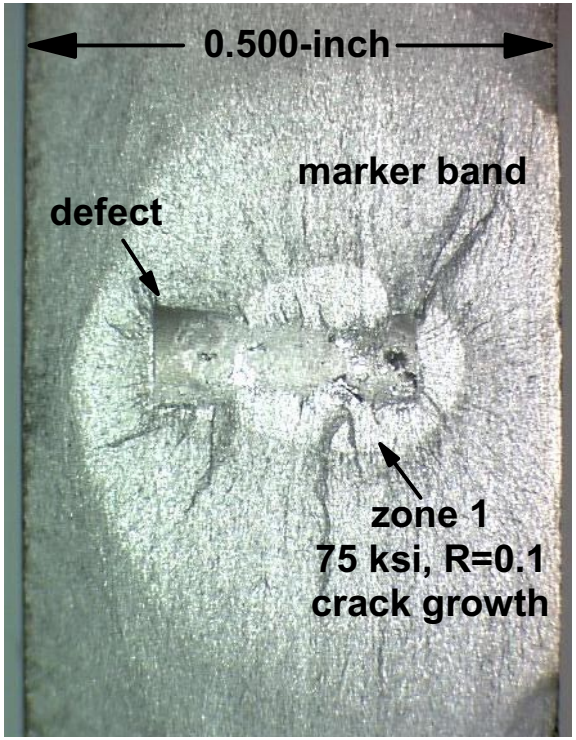
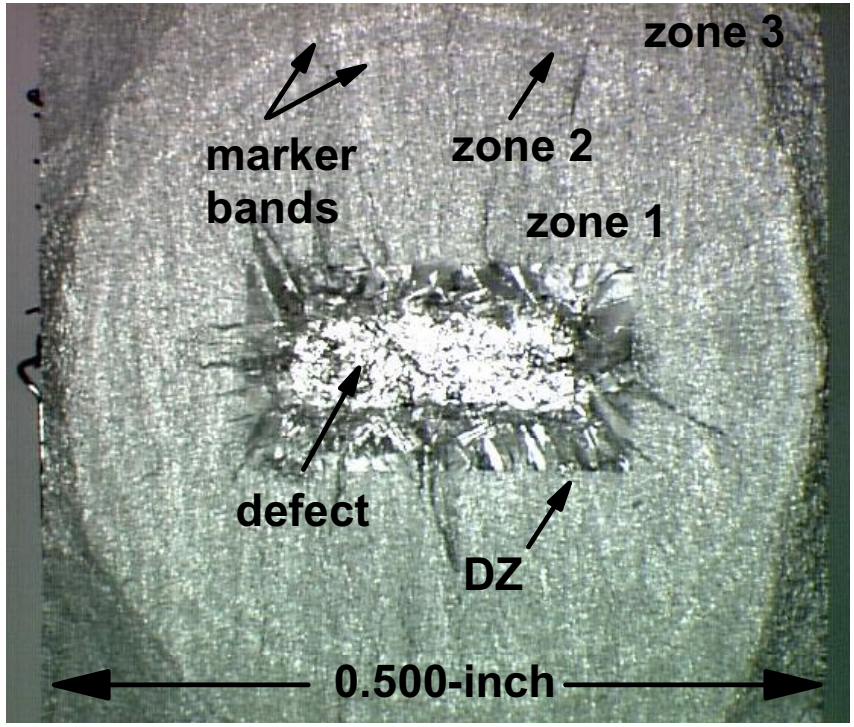
(b)

Fatigue Tests with Synthetic Internal HA Defects

LLI-2 (large defect, low nitrogen)



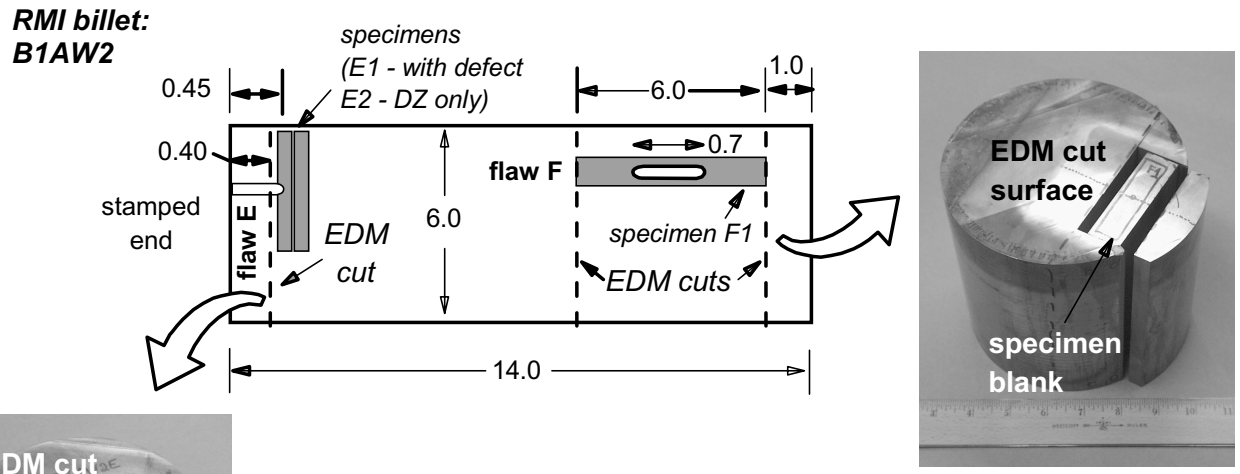
LMI-1 (large defect, medium nitrogen)

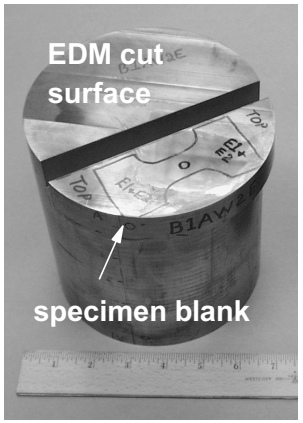


Fatigue Tests with Synthetic Internal HA Defects

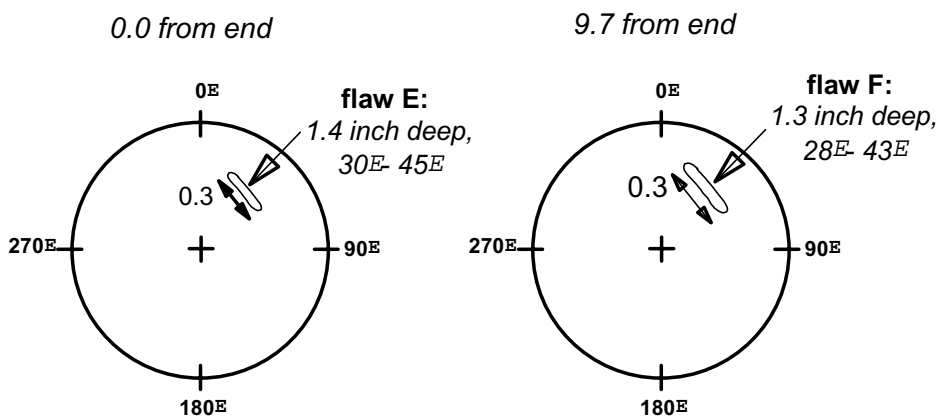
- Marker bands confirm matrix FCG rates vs. vacuum data
- AE signals indicate some early defect cracking
- Calculated FCG life shorter than experimental life for crack growth into matrix
  - 75 ksi σ_{max} : 2.5K cycles predicted vs. 10K - 20K cycles applied
- Possible effects of residual stresses around defect
  - surface vs. internal behavior under static loading
  - no crack growth for nominal $\Delta K > \Delta K_{th}$

Specimens with Natural HA Defects





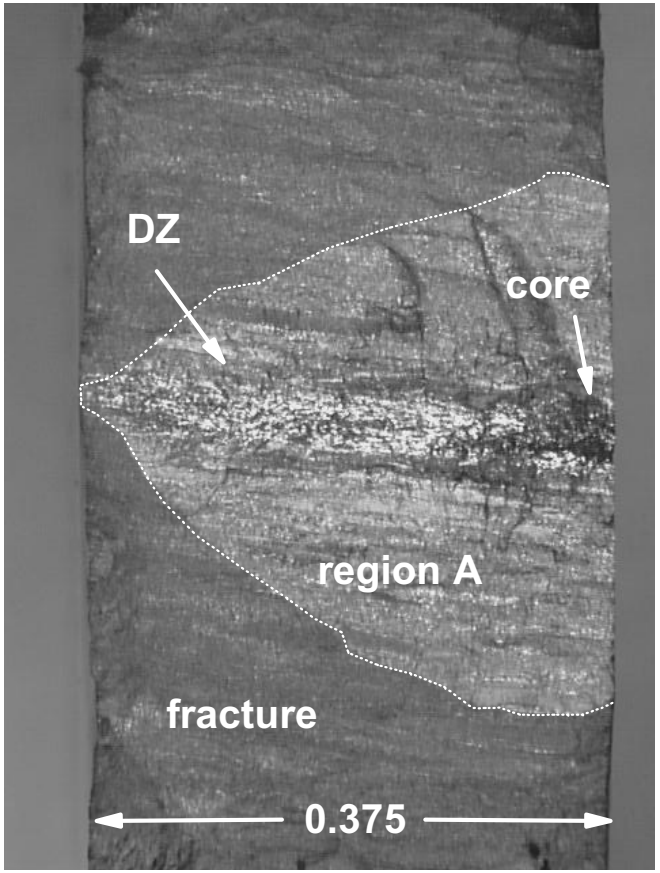
billet end views *(from stamped end)*



Fatigue Test with Natural Surface HA Defect

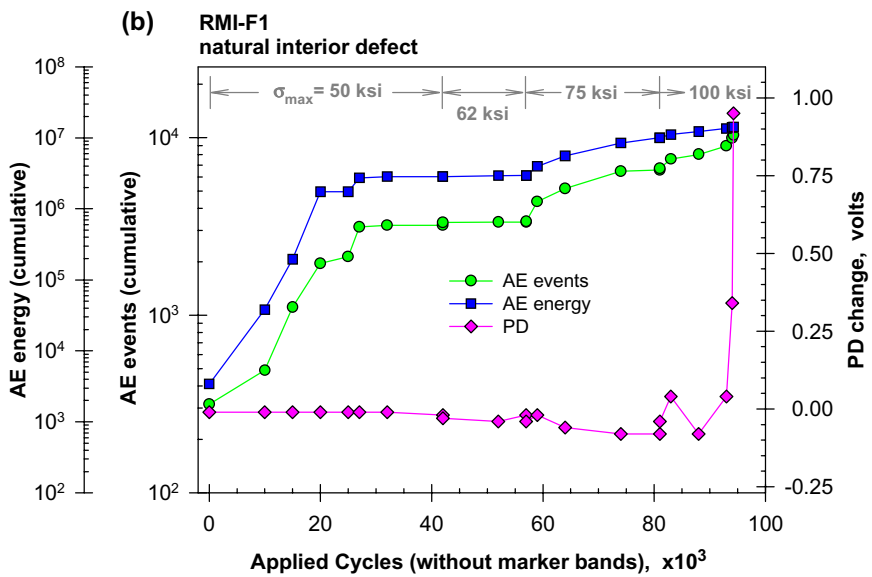
- Fractography indicates crack nucleation at defect core and subsequent progressive cracking along diffusion zone and through matrix
- Diffusion zone was not extensively cracked early in life

RMI-E1 (surface)

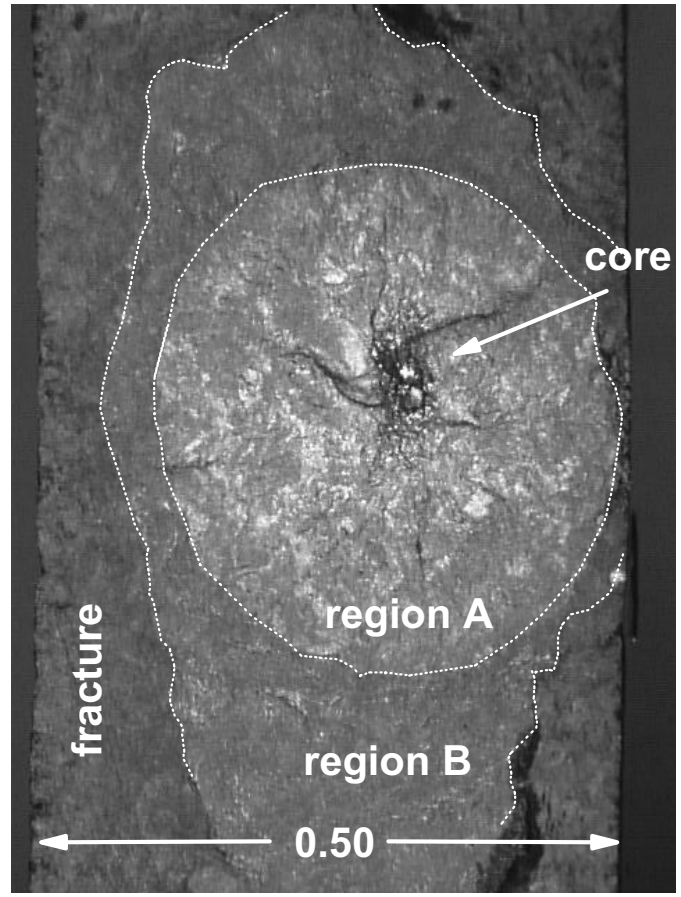


Fatigue Test with Natural Internal HA Defect

- Similar behavior to synthetic internal defects
- AE indicates early defect cracking
- Higher stresses, more cycles required to grow crack into matrix



RMI-F1 (interior)



Residual Stresses at HA
Introduction

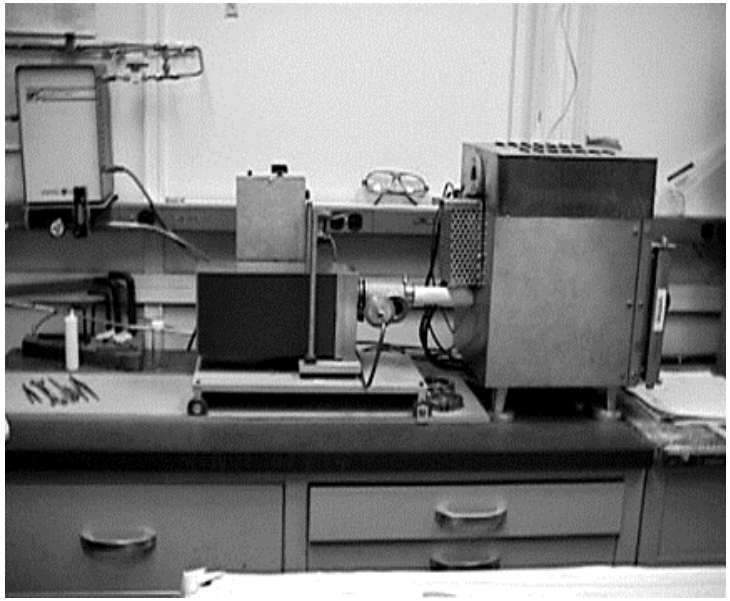
- Coupon tests on HA seeded specimens gave surprisingly high static and fatigue strengths for embedded defects
- Possible explanation: residual stresses at and near the HA
  - Caused by differential thermal expansion
- Approach
  - Make suitable HA specimens at a variety of N levels and measure CTE over the relevant temperature range
  - Use resulting CTE values in mechanics analyses to predict the residual stress distributions around the HA particle
  - Evaluate the potential effects on fatigue and fracture

    → onset of crack formation in the HA

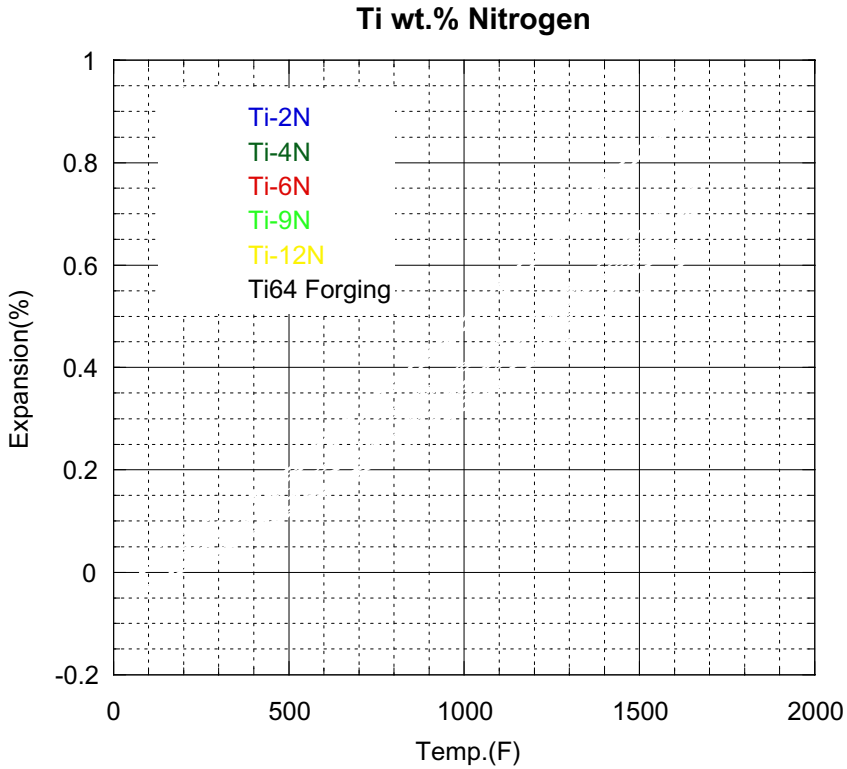
    → fatigue crack growth into the matrix

Residual Stresses at HA
Coefficient of Thermal Expansion

- Measurements performed by GE CR&D
- HA CTE is lower than Ti-6-4 CTE

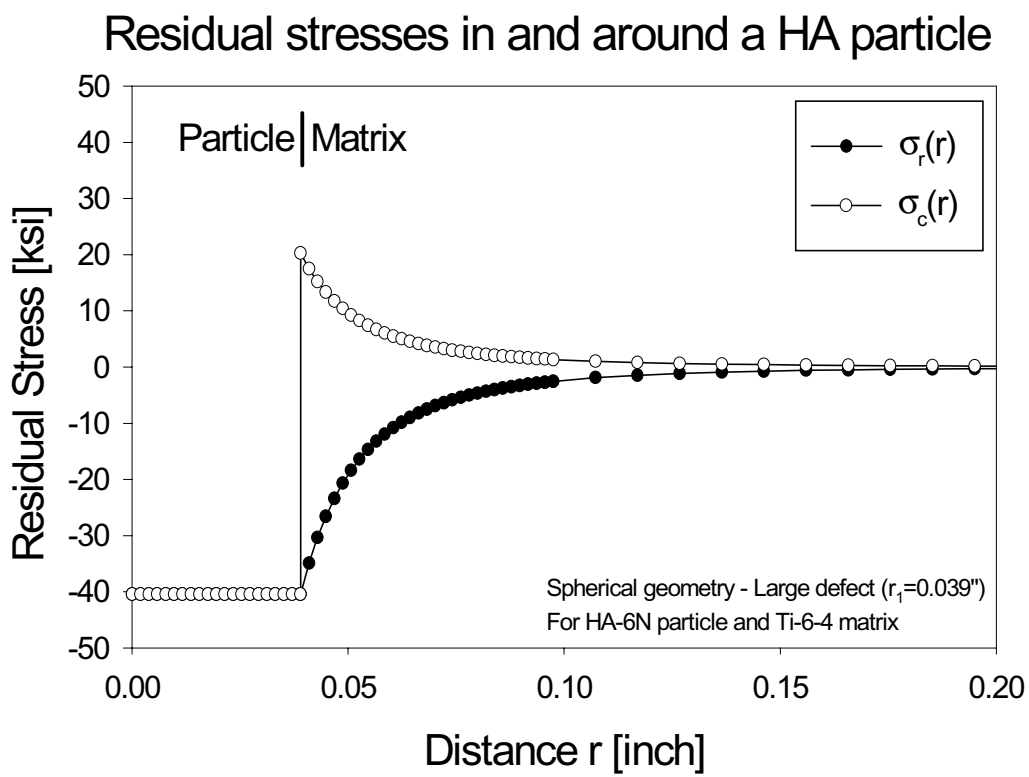


Push-rod dilatometer



Residual Stresses at HA
Residual Stress Distribution

- Due to CTE differences during the cooling process
- Based on elastic solution from Brooksbank and Andrews (1969)
  - Solutions available for spherical and cylindrical particles



Residual Stresses at HA
Onset of HA Cracking

- Cracking was observed in subsurface HA defects at significantly higher stresses than surface defects
  - Surface defects—at nominal stresses of 5-20 ksi
  - Subsurface defects—at nominal stresses of 80-115 ksi
- Approach
  - Quantify residual stresses associated with HA
  - Determine pressure for the existing stress state
  - Predict fracture using empirical model developed by Chan
  - Compare with experimentally observed stresses at fracture

Residual Stresses at HA
Fracture Strength of HA (Chan)

- Fracture strength of HA in uniaxial compression (Y_n)

$$Y_n = 382.26 + 31.43 * N \ \ [\text{MPa}]$$

- Normalized fracture strength

$$\frac{Y_i}{Y_n} = \left[1.4 + 0.94 * \log\left(\frac{P}{Y_n}\right)\right]$$

where Y_i = Fracture strength for a given stress state

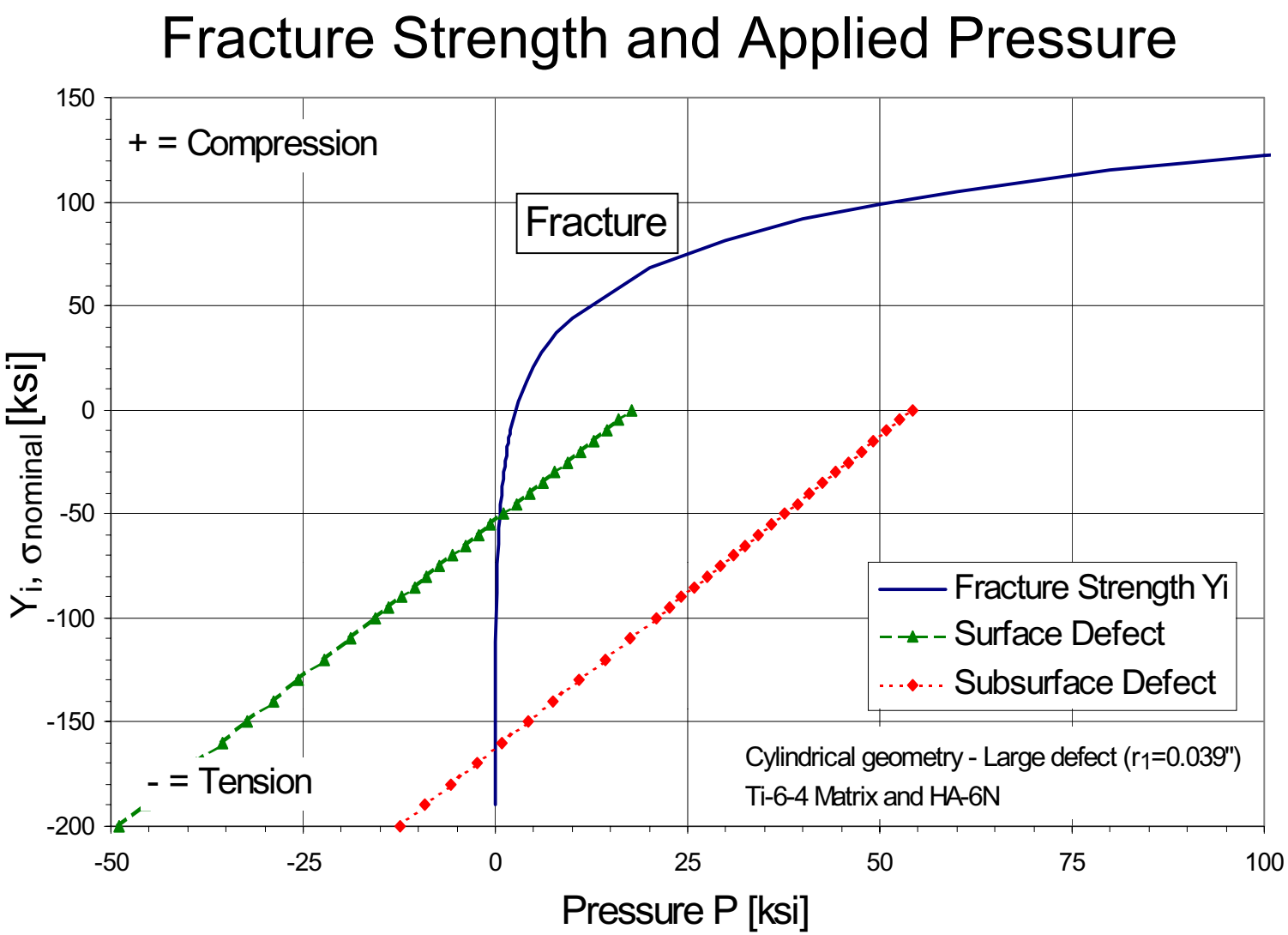
P = Pressure

- Pressure determined from principal stresses

$$P = (\sigma_{11} + \sigma_{22} + \sigma_{33})/3$$

$$P = ((\sigma_r + \sigma_{nom}) + \sigma_c + \sigma_z)/3$$

Residual Stresses at HA
Fracture Criteria

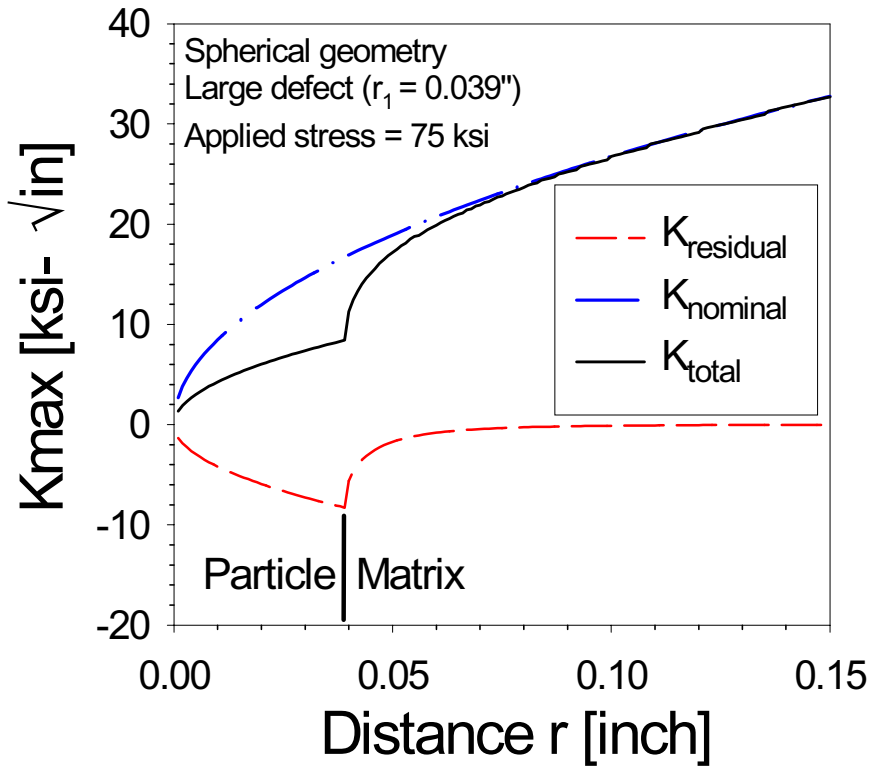


Residual Stresses at HA
Influence on Crack Growth into Matrix

- Phase I coupon tests on seeded specimens gave higher than expected fatigue strengths for embedded defects
- Approach
  - Quantify residual stresses associated with HA
  - Determine the stress intensity factor and R-ratio
  - Compare with fatigue crack growth threshold values
  - Evaluate impact on fatigue crack growth life (work in progress)

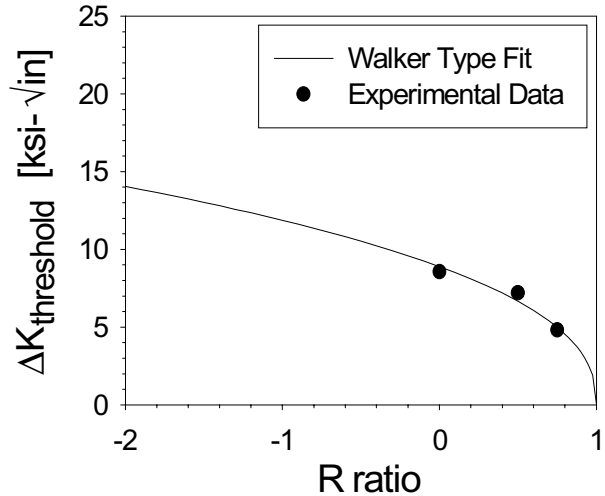
Residual Stresses at HA
Stress Intensity Factor

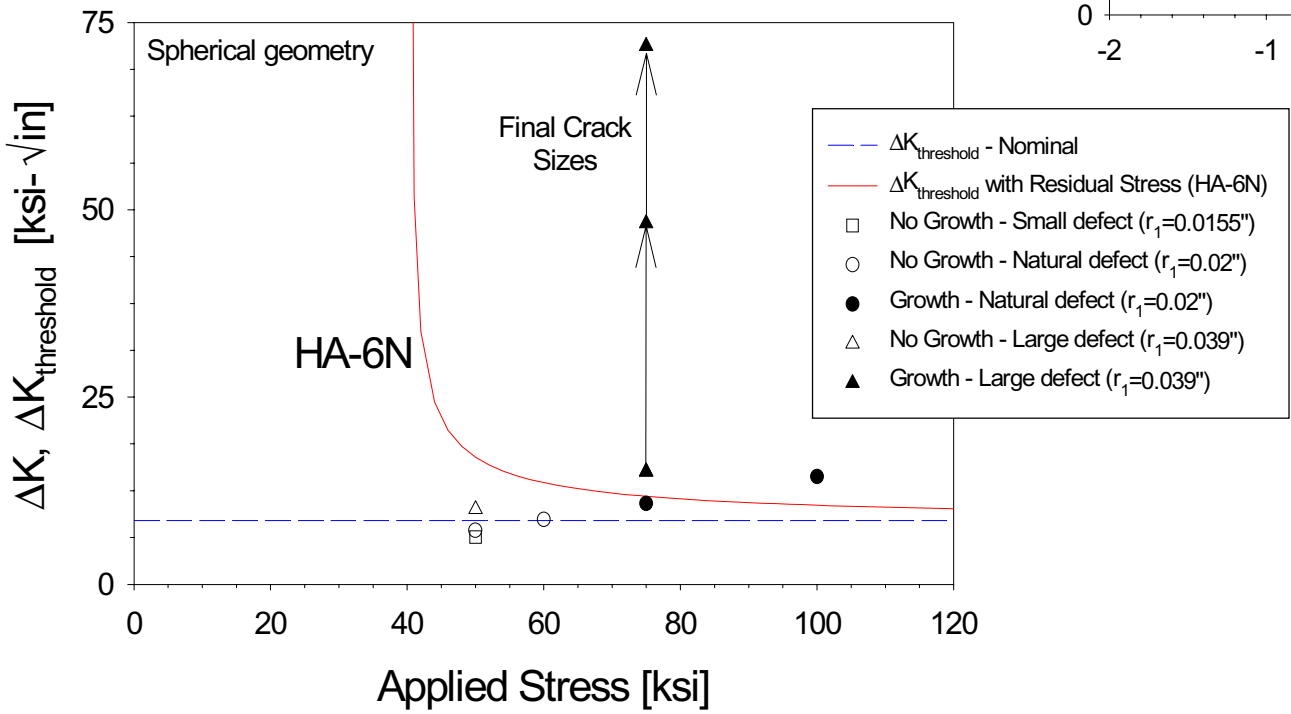
- K determined for a crack emanating from a particle
  - Superposition of residual stresses and nominal applied stress using the weight function approach
  - Initial crack size is equal to particle size



Residual Stresses at HA
Analytical Modeling

- Residual stress causes an R-ratio shift
  - e.g., σ_{max} = 75 ksi $\rightarrow$ R = -0.95
  - $\Delta K_{threshold}$ is a function of R
- Threshold values consistent with tests





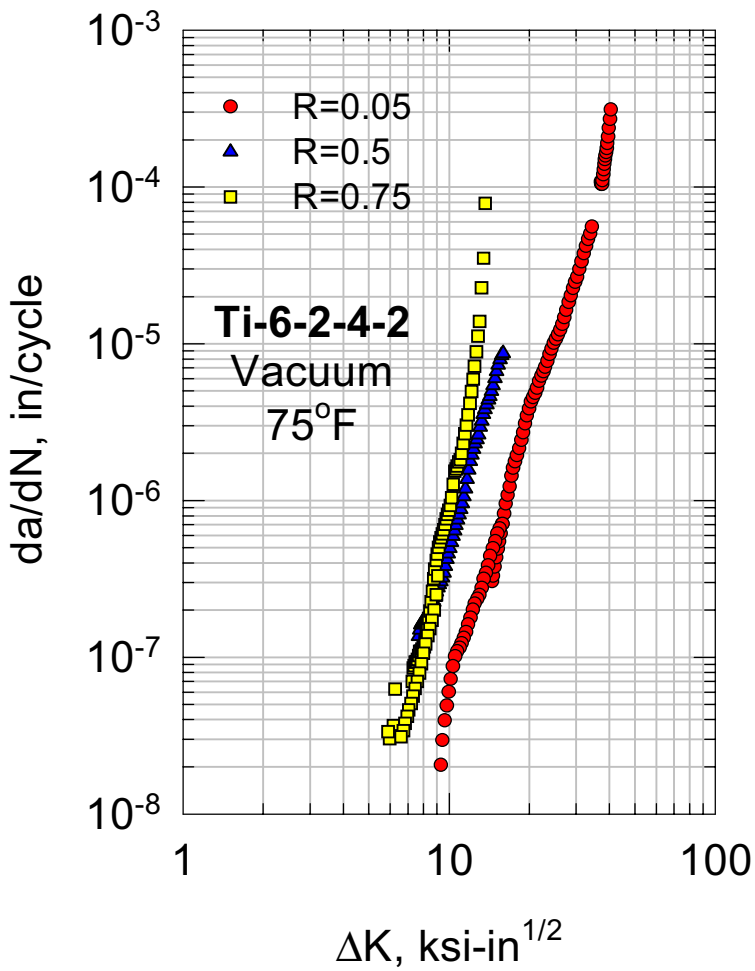
Residual Stresses at HA
Crack Growth Findings

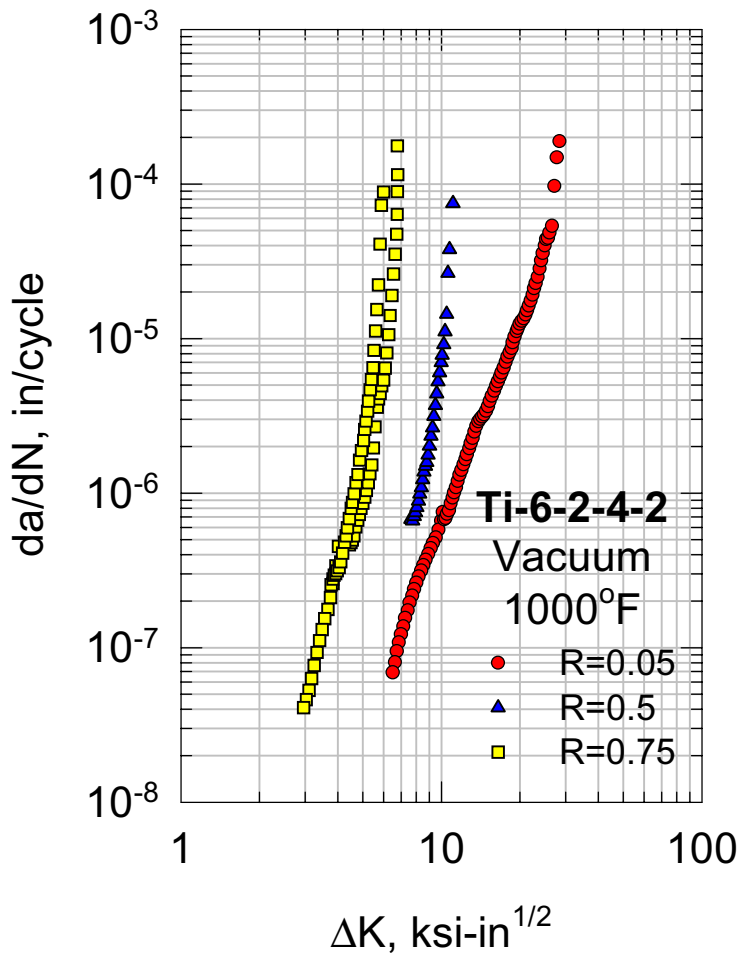
- Compressive stresses in HA cause a decrease in stress ratio
  - Residual stresses increase the apparent threshold for growth
- Model appears to explain the experimental observations
  - Some ambiguities remain due to complex nature of the problem
- Model provides guidance for design implications of residual stresses
  - At high stresses (above 80-90 ksi), influence is negligible
  - At low stresses (below 40-50 ksi), influence may be great
  - At intermediate stresses, influence unclear because of ambiguities

Vacuum FCG Testing of Titanium Rotor Alloys: Background

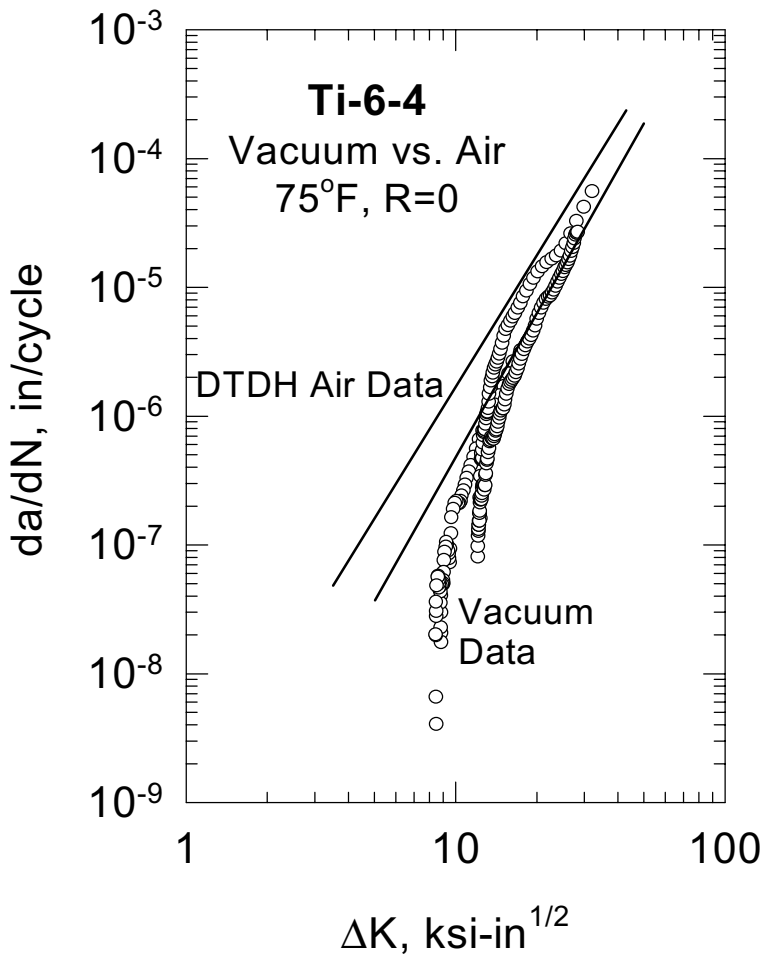
- HA anomalies are usually subsurface
  - Fatigue cracks embedded for at least some of life
  - Isolated from atmosphere (vacuum-like environment)
- Vacuum FCG rates for Ti alloys can be very different from air
- Need adequate FCG data for rotor design and reliability analysis
- Data generated for four Ti rotor alloys at multiple *R, T* values
  - Ti-6-4, Ti-6-2-4-2 (FG and CG), Ti-17
  - R = 0, 0.5, 0.75 (0.6 for Ti-17)
  - T = RT to 400°F (Ti-6-4), 1000°F (Ti-6-2-4-2), 750°F (Ti-17)
  - Testing currently underway on IN-718 and Waspaloy
- Follow conventional engine company FCG test procedures
  - Machine small SC(T) and SEN(B) specimens from production forgings
  - Constant load and K-gradient histories with DCPD crack measurement
  - Testing performed at GEAE (Barney Lawless) and Honeywell (Yancey Gill)
- Perform regressions of vacuum data for FCG eqns in DARWIN™

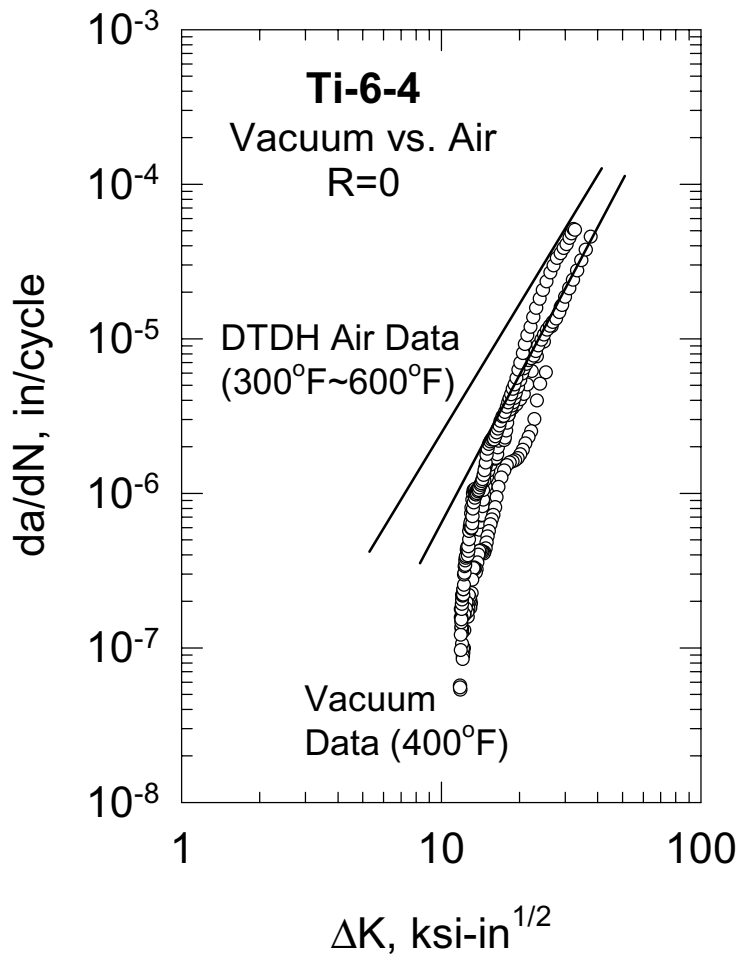
Vacuum FCG Testing: Sample Results



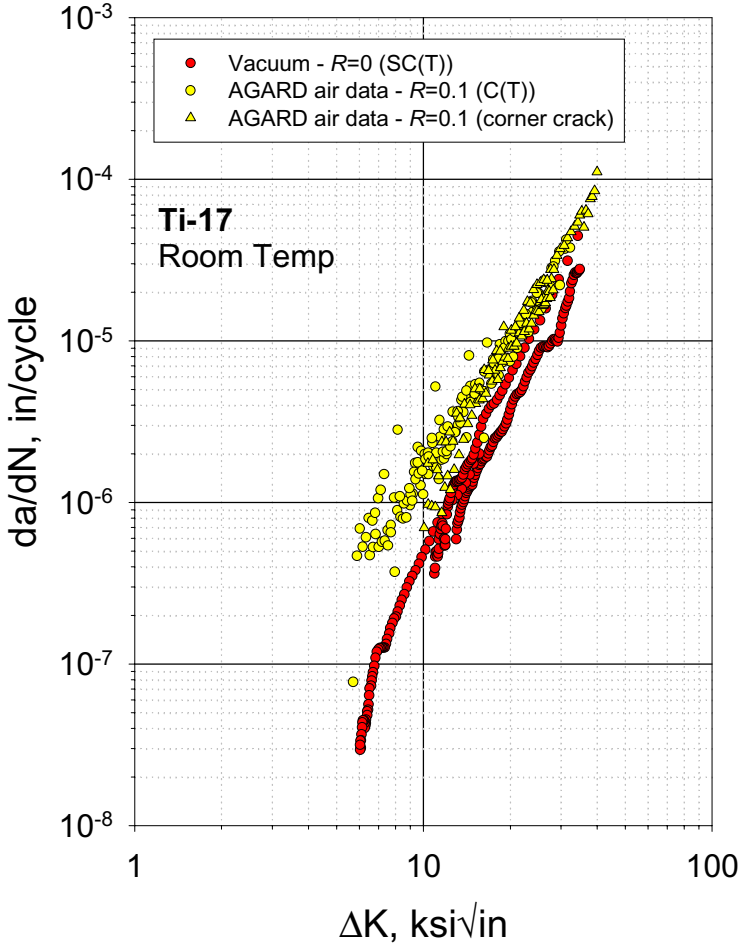


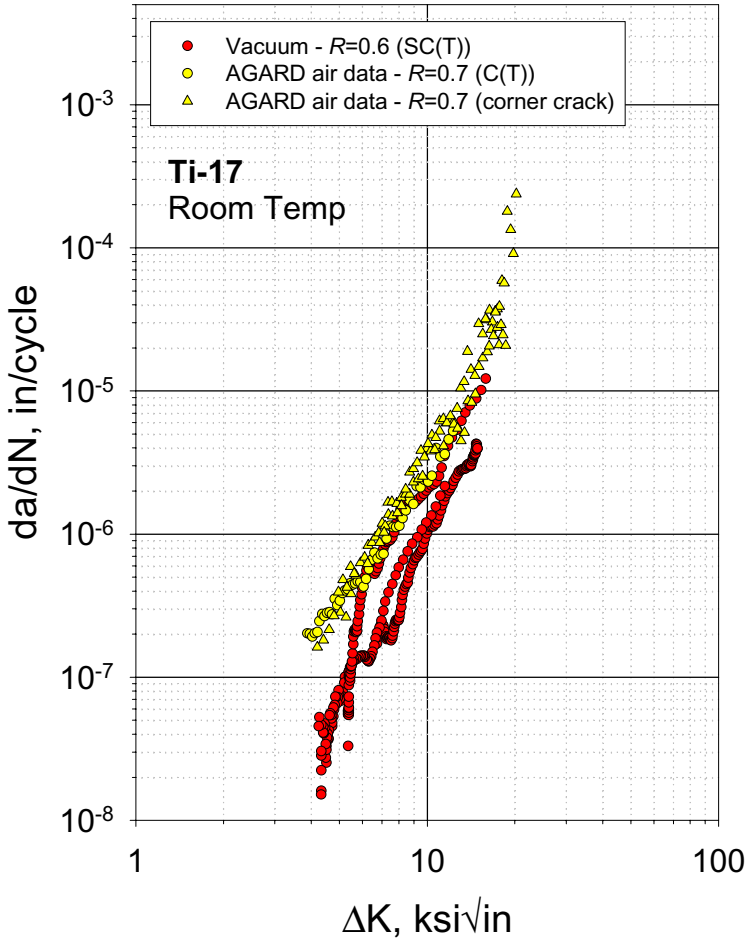
Vacuum FCG Testing: Comparisons with Air Data





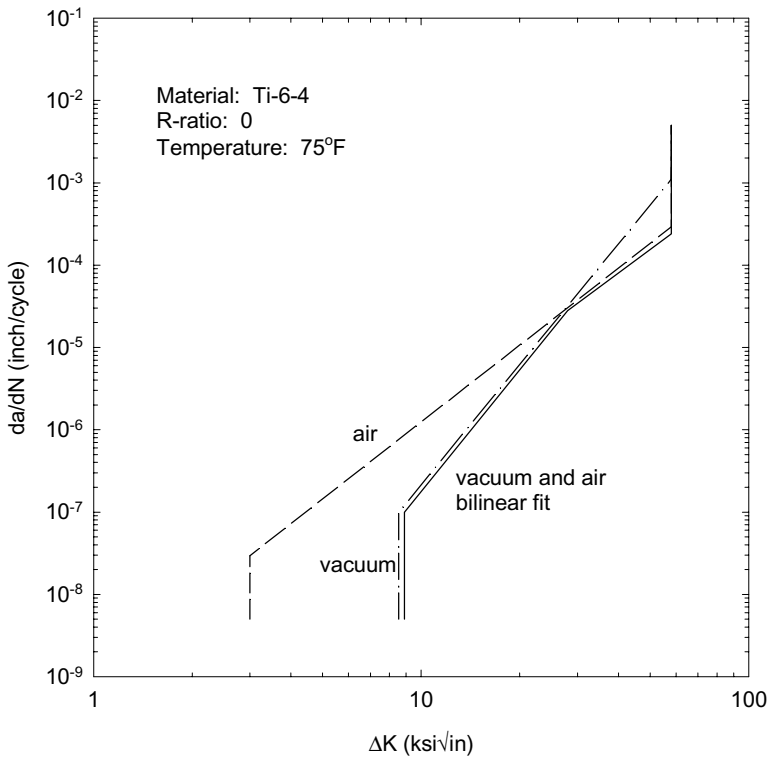
Vacuum FCG Testing: Vacuum vs. Air Data for Ti-17

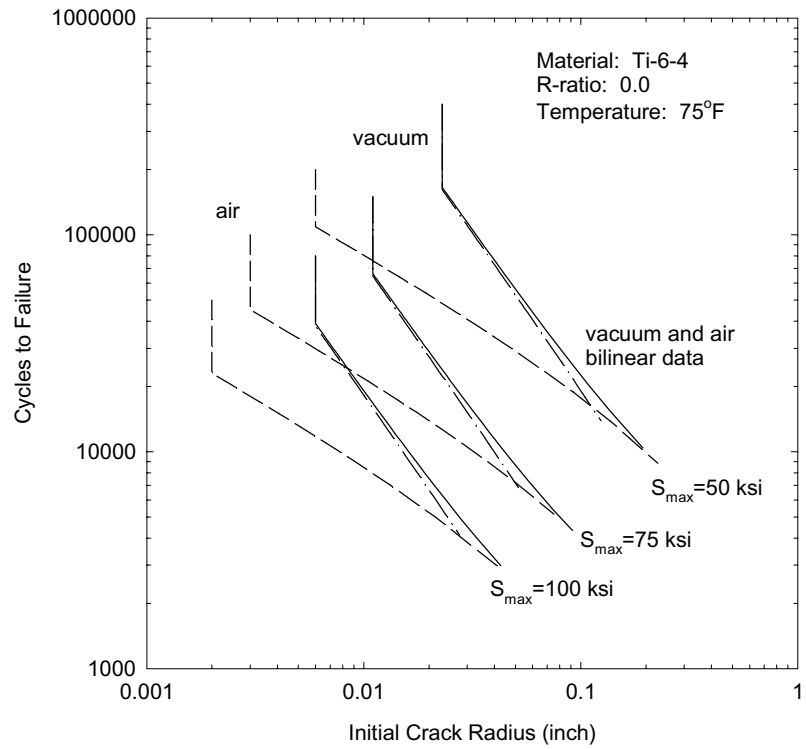




Vacuum FCG Testing: Significance for FCG Life

- How much difference does vacuum vs. air data make for calculated FCG lifetime?
- Compare for embedded flaw, Paris eqns, 75°F, R = 0





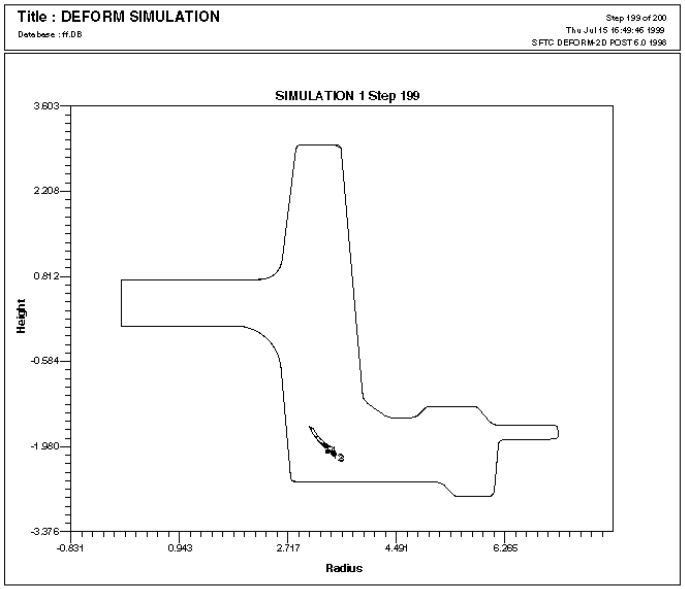
Spin Pit Tests on Rotors with HA Defects

- Make/select billets with single artificial/natural HA defect
- Forge billet into sonic shape with defect in known critical location (guidance from DEFORM calculations)
- Conduct spin pit tests (goal: appreciable crack growth)
- UT inspections before and after spin cycling
- Post-test fractography to characterize crack growth
- Compare with FCG predictions based on vacuum data
  - (work in progress)

- Spin pit testing directed by P&W (Darryl Lehmann), conducted at Test Devices

Spin Pit Testing: Sonic Shape Disks

- Two disks with natural HA (from ETC CBS)
- One disk with artificial HA (created by GE CR&D)

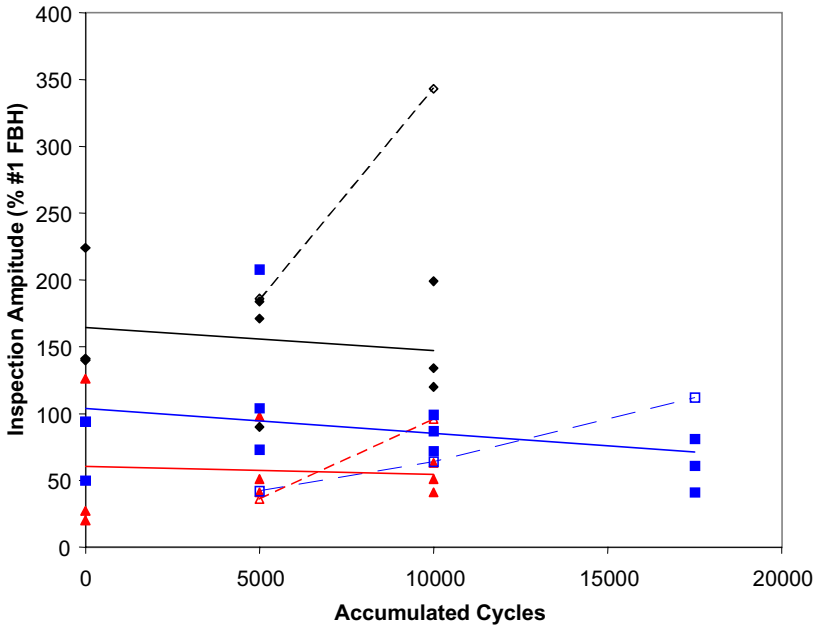


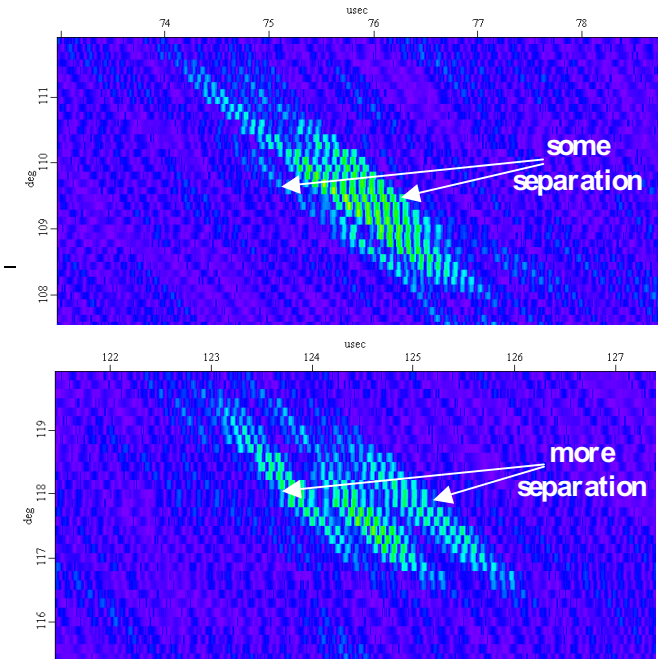
Spin Pit Testing: Summary

- Initial spins of each disk for 10,000 cycles
  - Speeds selected based on FCG calculations
  - Initial UT inspections inconclusive regarding crack growth
- Further spin testing at higher speeds
  - Disks SB-6 and B3W2E both burst at ~15K-16K total cycles
    - Crack monitoring system did not indicate growth until last cycle
    - One side of fracture surface on each ruptured disk was preserved
  - Disk B1BW3B successfully completed 17,500 total cycles
    - UT inspection clearly indicated crack growth
    - No further spin testing conducted
    - Further UT inspections to be conducted before disk is cut up

Spin Pit Testing: UT Inspection Results

- Normal UT inspections exhibited slight decreases in signal amplitude with continued cycling
- Angled UT inspections exhibited increases in amplitudes
- Signal separation in angled scans indicates crack growth



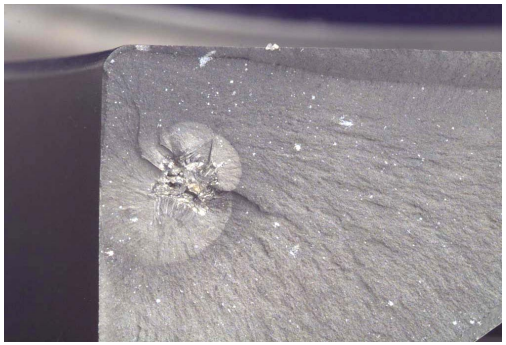


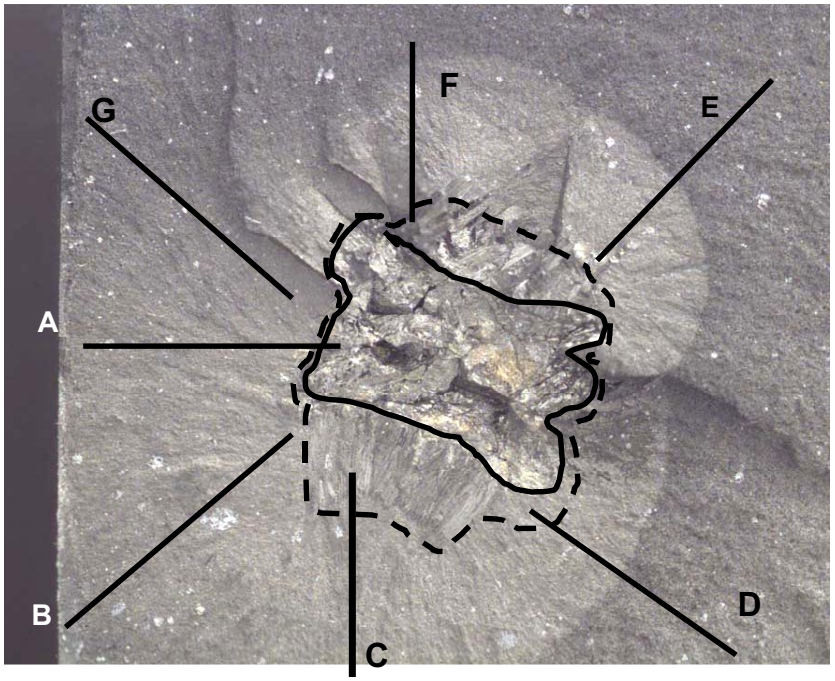
Spin Pit Testing: Post-Test Fractography

- SB-6

Core ———

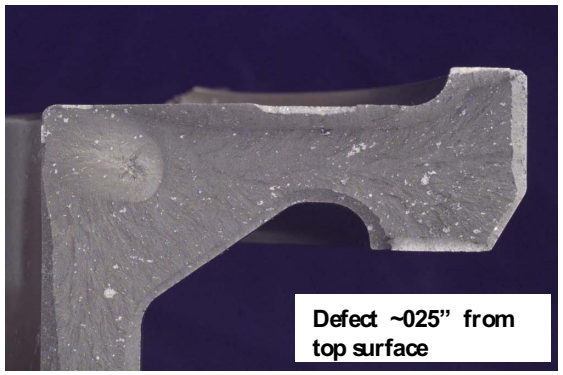
Diffusion zone - - -

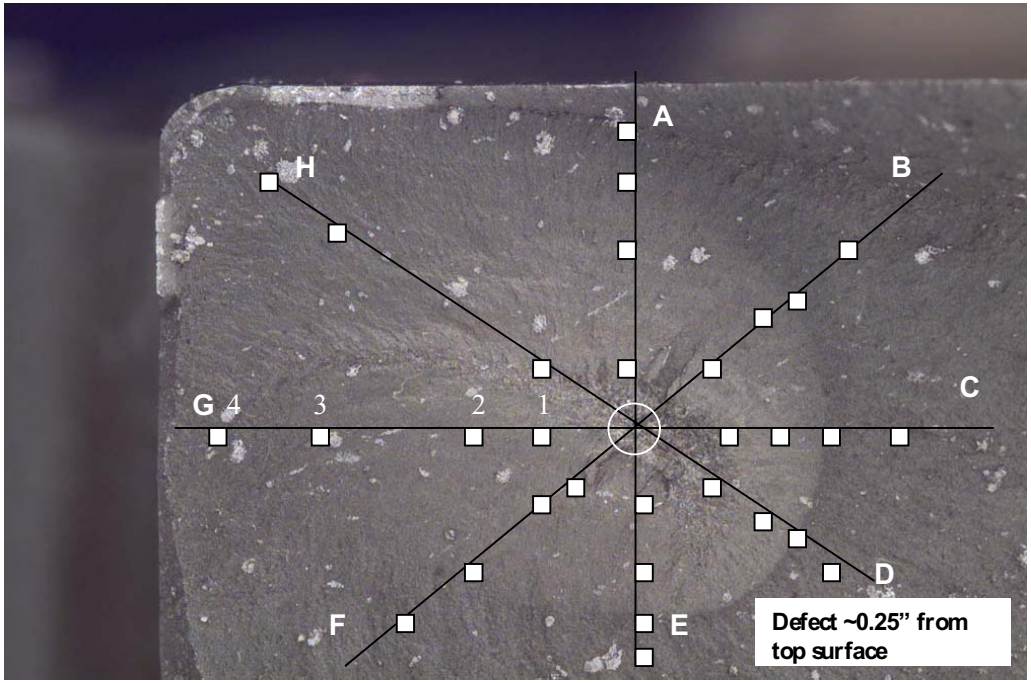




Spin-Pit Testing: Post-Test Fractography

- B3W2E





Crack Nucleation and Growth: Summary

- Crack nucleation in HA defects
  - Internal defects crack at much higher static stresses than surface
  - FCG into matrix occurs less easily than expected
  - Matrix FCG rates agree with vacuum data
- Residual stress effects on HA cracking behavior
  - CTE measured for HA with various N contents
  - Residual stress/fracture models consistent with test results
- Vacuum FCG behavior for rotor alloys
  - Design data generated for Ti-6-4, Ti-6-2-4-2, Ti-17 at multiple R, T
  - Vacuum exhibits higher ΔK_{th}, slower da/dN, longer N than air
- Spin pit tests on rotors with HA defects
  - Normal UT decreases, shear UT increases with crack growth
  - Fractography in progress to evaluate vacuum FCG predictions

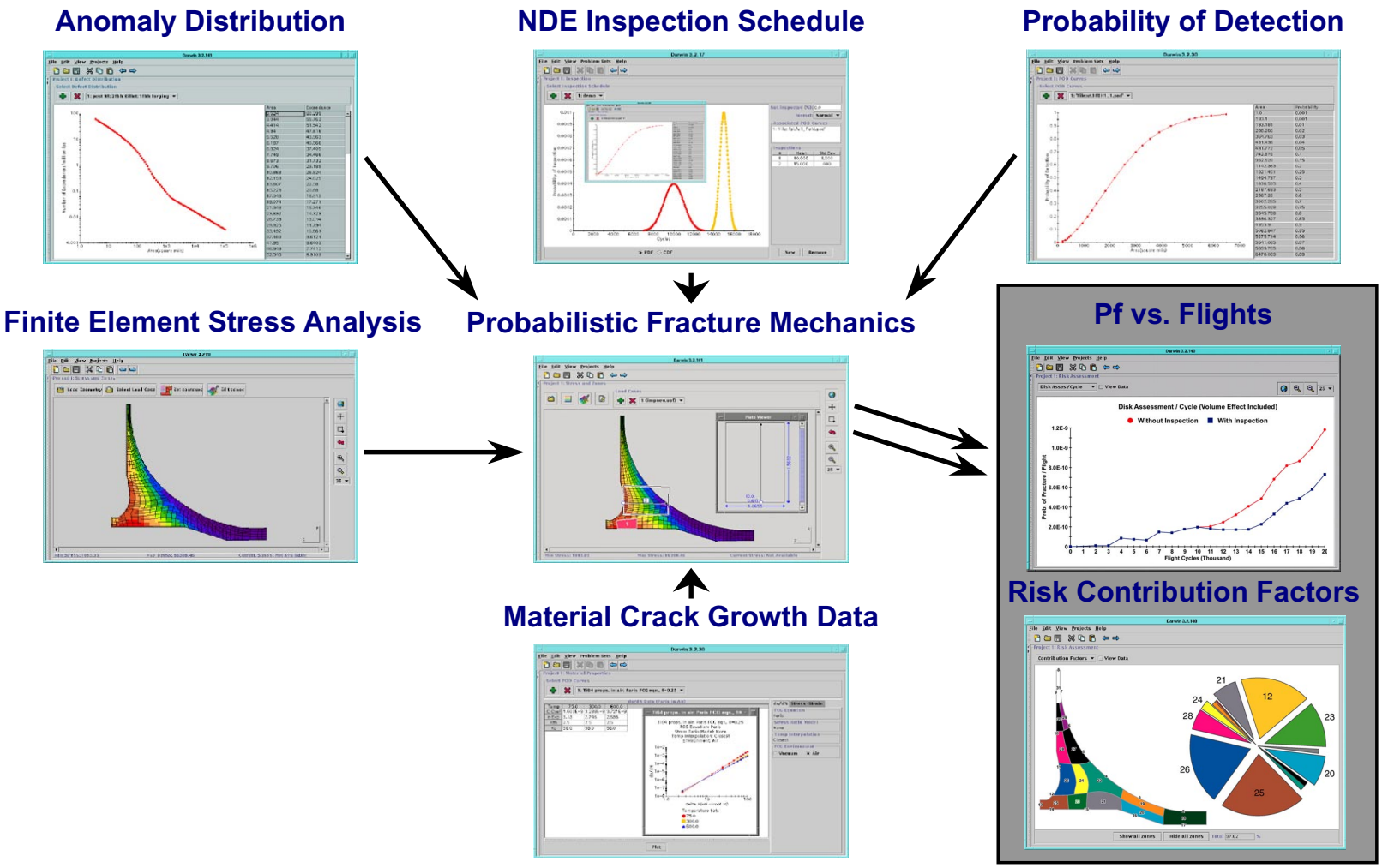
NASA/CP—2002-211682

DARWIN™ Enhancements for Probabilistic Risk Assessment

Harry Millwater
Mike Enright
Southwest Research Institute

5th FAA/Air Force/NASA/Navy workshop on the
Application of Probabilistic Methods to Gas Turbine Engines
June 11-13, 2001
Cleveland, OH

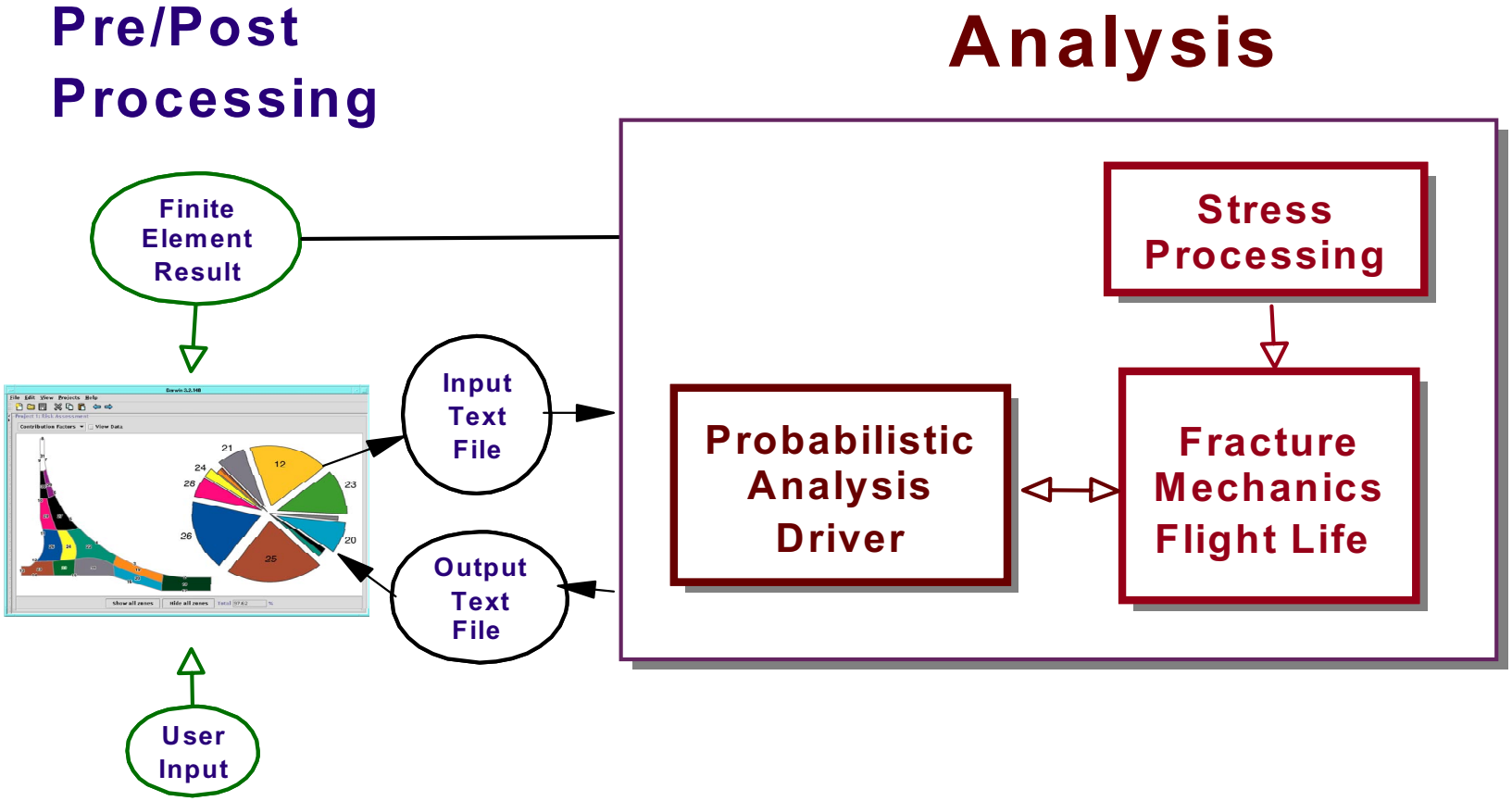
DARWIN™ Overview



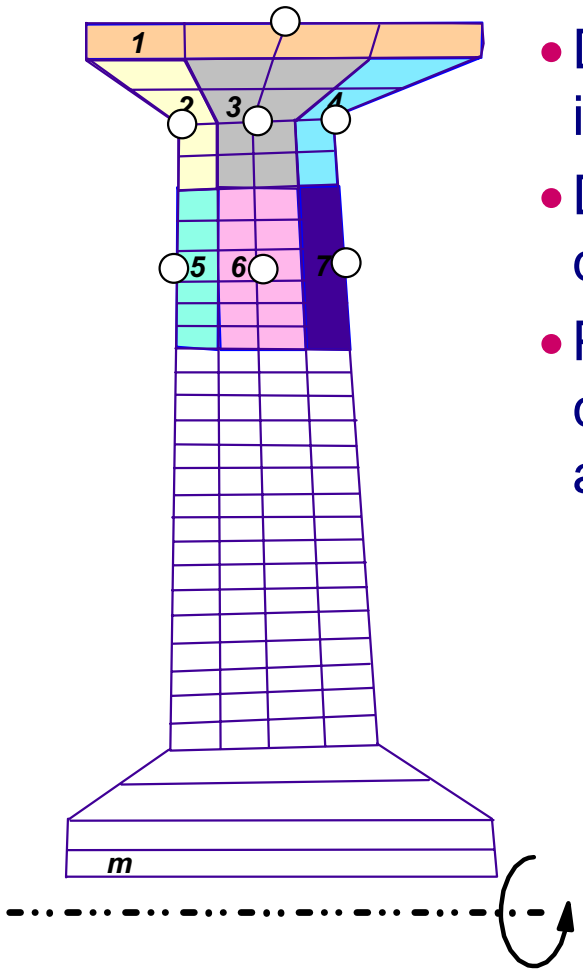
DARWIN™ Status

- 3.3 Delivered Jan 2000
  - GUI enhancements, web site distribution of code
- 3.4 - April 2001
  - Improved K solutions
  - Inspection transition with defect, e.g., embedded -> surface
- 3.5 - Summer 2001
  - Element subdivision
  - Zone refinement
- 4.0 - End of 2001
  - Initial version for surface damage (maintenance/machining induced defects)

DARWIN™ Code Structure



Zone-based Risk Assessment



- Define zones based on similar stresses, inspections, defect distributions, lifetimes
- Defect probability determined by defect distribution, zone volume
- Probability of failure assuming a defect computed using Monte Carlo sampling or advanced methods

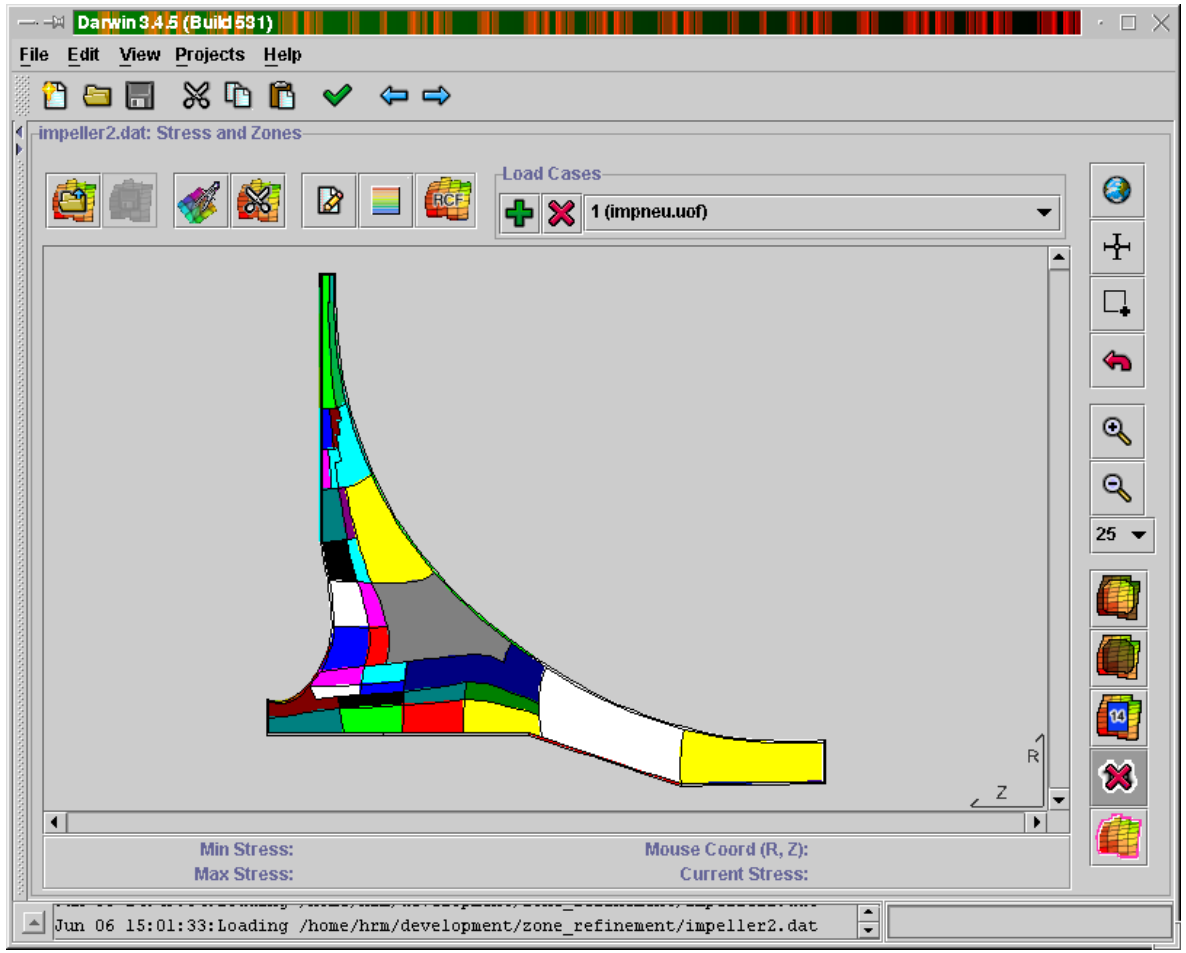
Prob. of having a defect

Prob. of failure given a defect

$$P_i = P_i[A] * P_i[B|A] \text{ - zone}$$

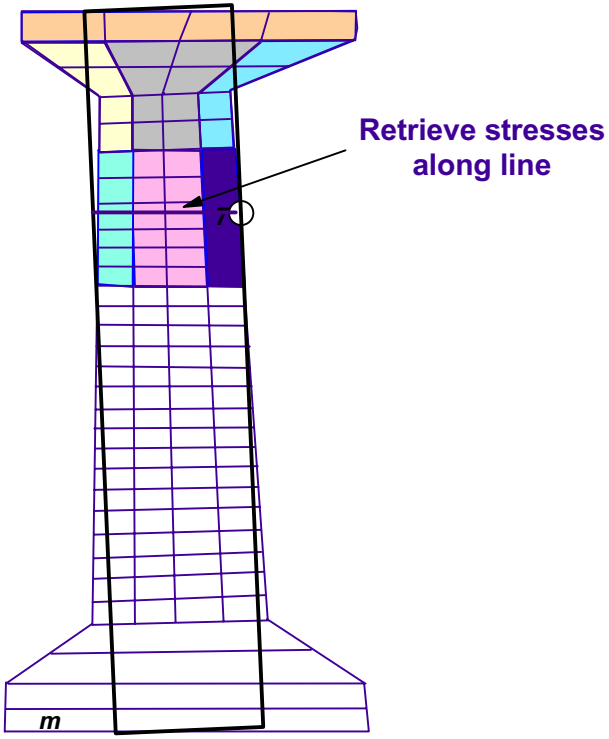
$$P_{fDISK} \cong \Sigma P_i \text{ - disk}$$

Zoned Impeller Model

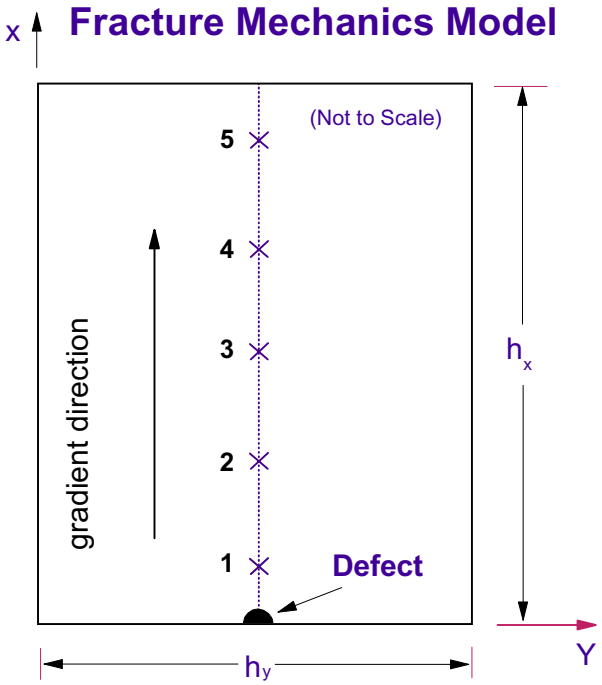


Fracture Mechanics Model of Zone

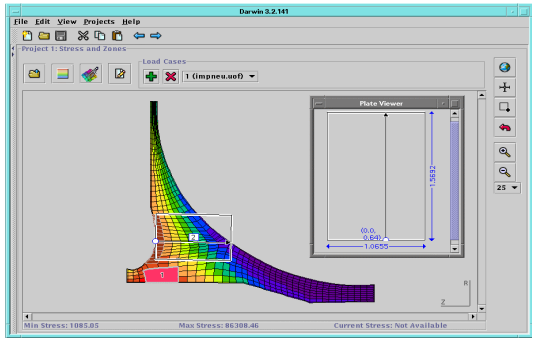
Finite Element Model



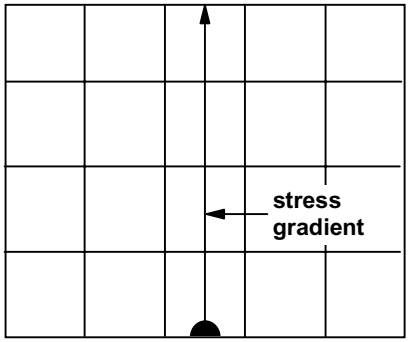
Fracture Mechanics Model



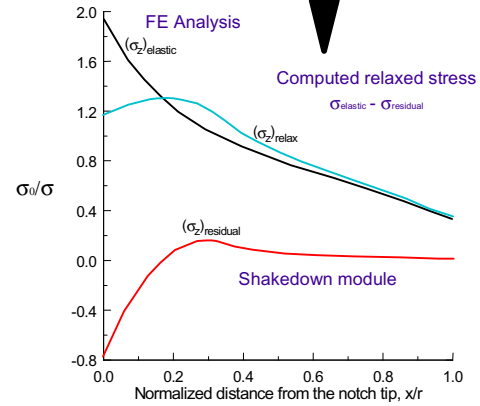
Stress Processing



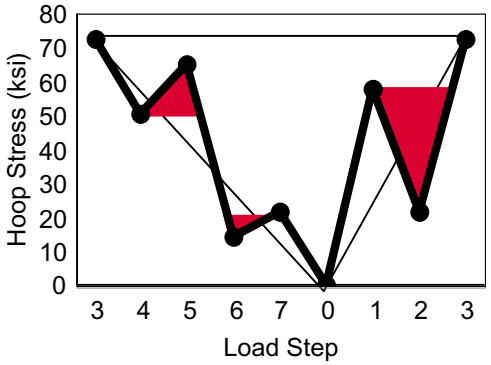
FE Stresses and zone definition



Stress gradient extraction



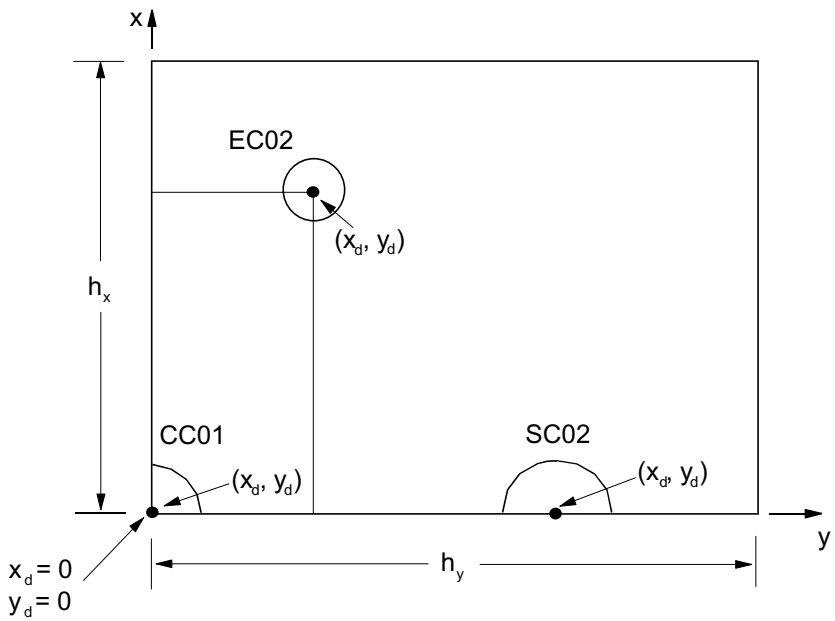
Residual stress analysis



Rainflow stress pairing

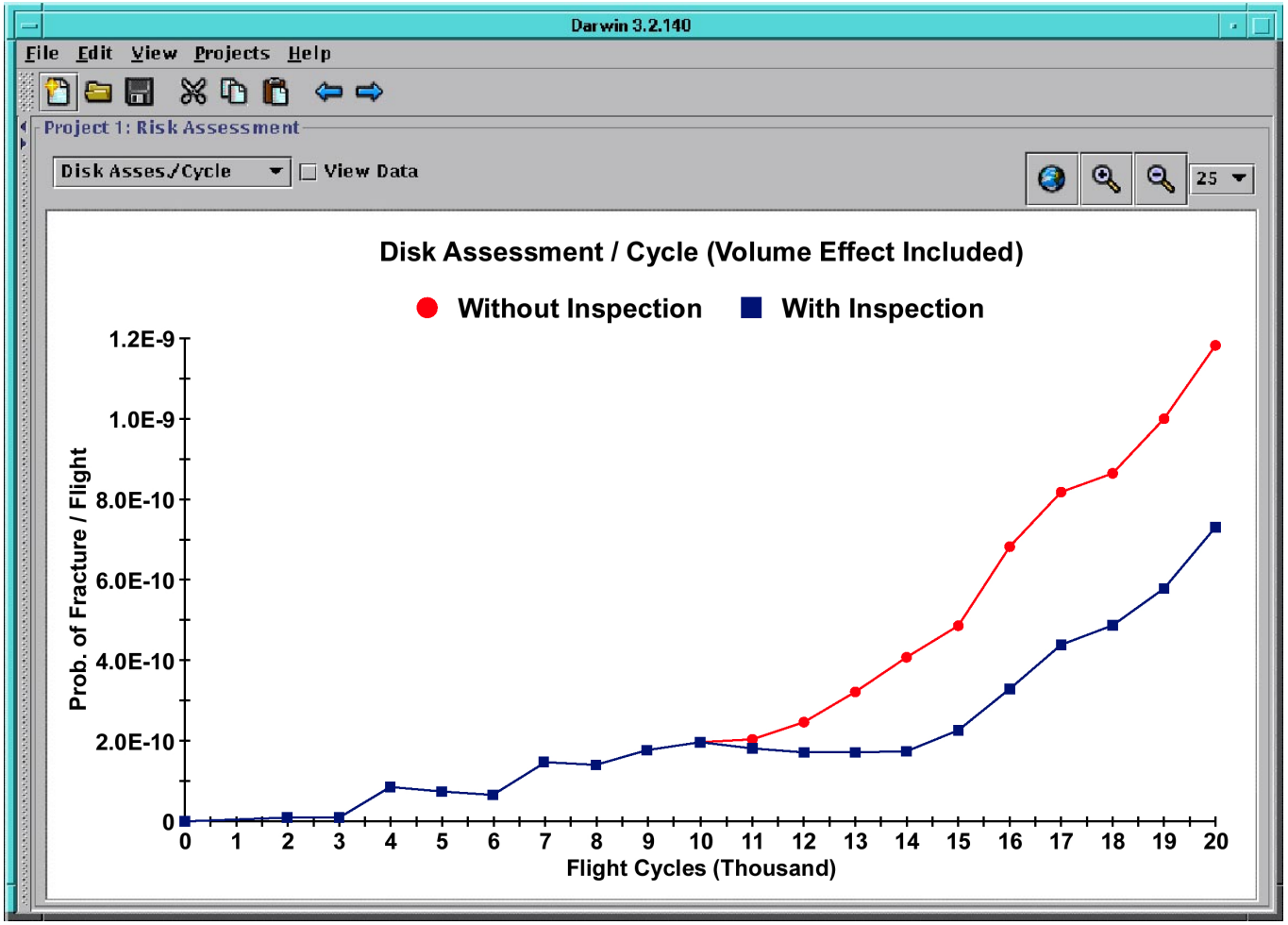
Fracture Mechanics Module

- Flight_Life: default FM module
  - Tailored for rotor problems
  - Relatively fast
- FCG analysis of crack in plate
- K solutions for embedded, surface, corner, and through cracks
- Full crack transitioning
- Variety of common FCG eqns
- Variety of common stress ratio methods

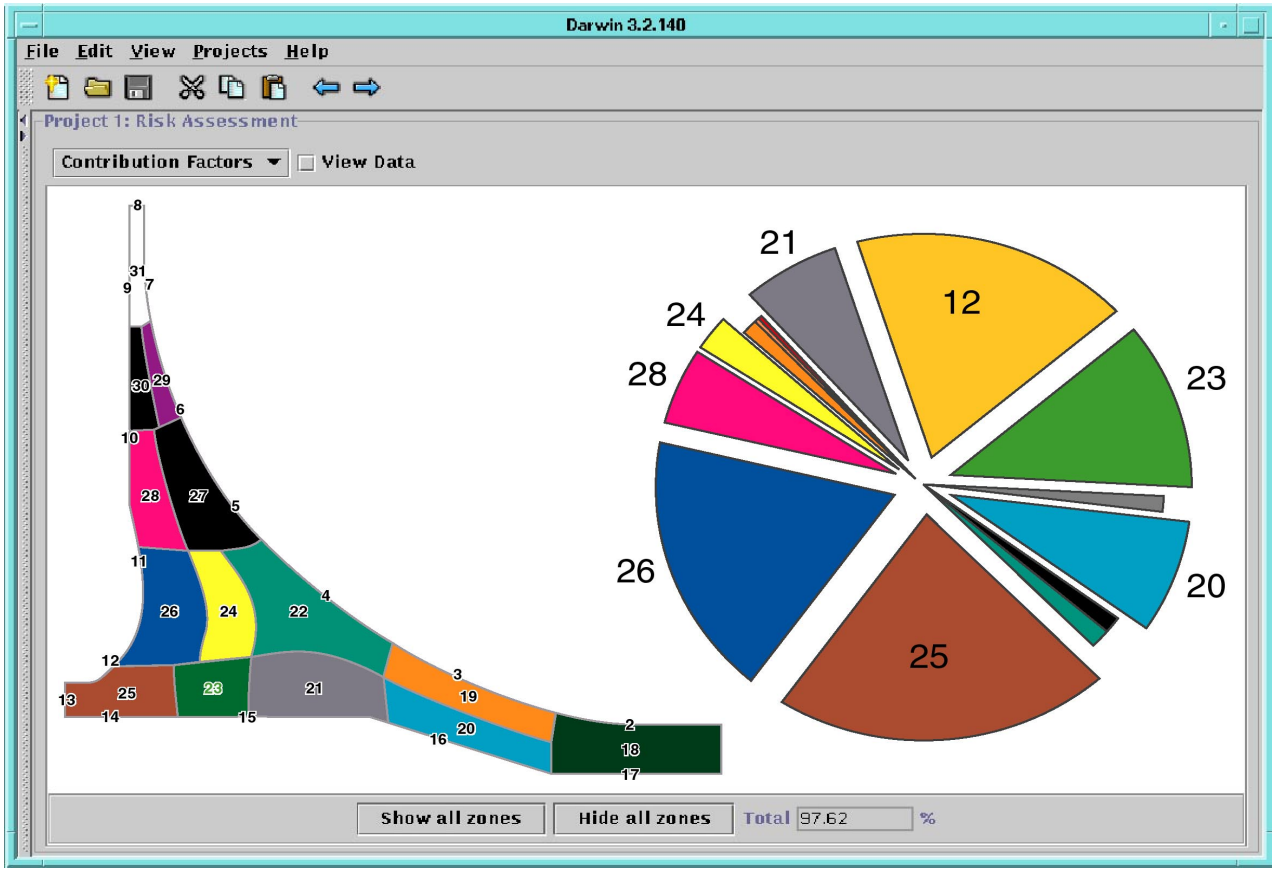


- Alternatively, link DARWIN™ with user-supplied FM
  - User-supplied module, e.g., NASGRO
  - User-supplied a vs. N results

Risk Assessment Results



Risk Contribution Factors



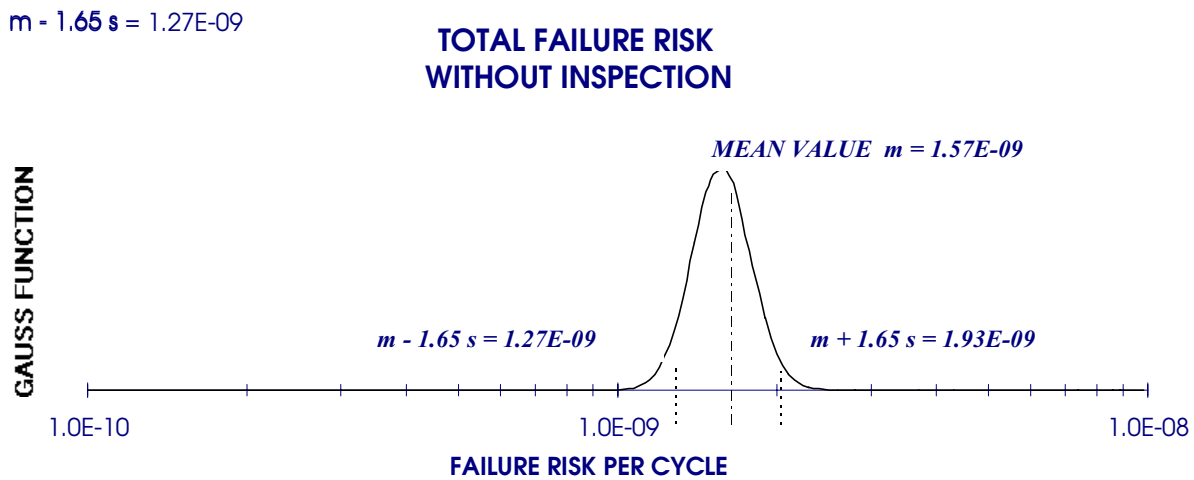
- Relative comparison of risk amongst zones

Motivation

- Advisory Circular 33.14 outlines a test case problem and a lower and upper risk limit that a risk assessment code must be able to obtain for the test case.
- Risk limits initially set with the flaw in the center of the zone but the flaw then moved to the life limiting location and provision made for zone refinement.

Motivation

- DARWIN analysis (version 3.3) with a coarse FE mesh, flaw in life limiting location and a reasonable number of zones did not give results within the AC risk limits.

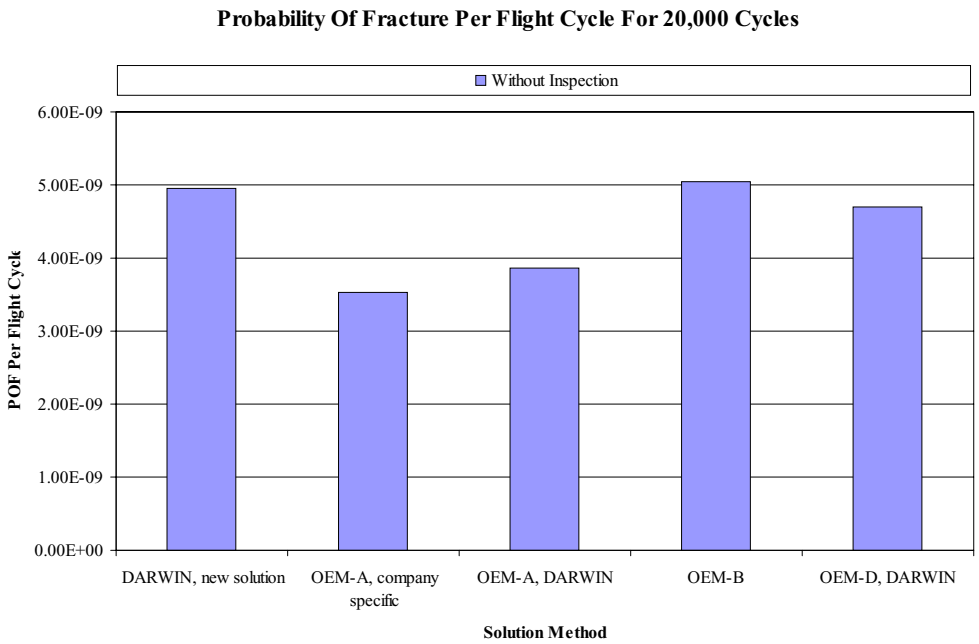


- Spawned a detailed comparison of DARWIN with OEM codes.

Motivation

- Detailed comparison of DARWIN with OEM's probabilistic fracture codes.
  - Deterministic comparison of embedded, surface, & corner crack fatigue behavior for multiple zones
  - Compare risk

- DARWIN found to agree well
  - but several enhancements identified



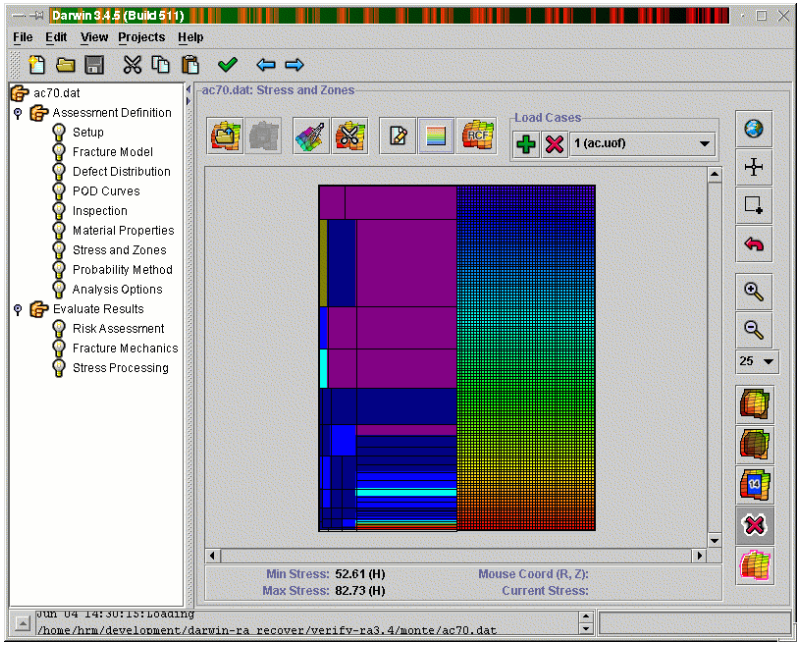
DARWIN Enhancements Identified

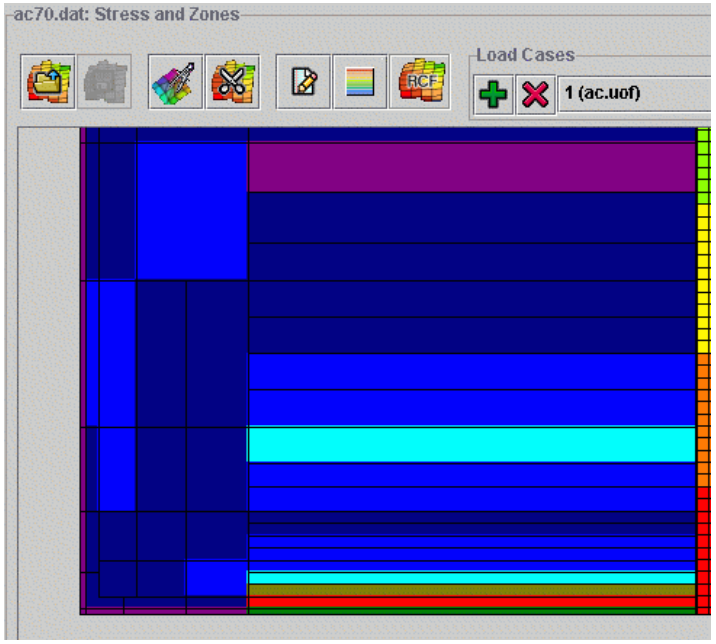
- Suggested DARWIN enhancements:
  - K solution for surface crack expanded from a/c ≤1.0 to 2.0

    ⇒DARWIN 3.4
- Risk zones smaller than a finite element are sometimes required.
- A consistent strategy for zone refinement is needed to reduce the dependence of the solution on the user's expertise.

Element Refinement Example

- Subsequent DARWIN analysis with improved crack transitioning, fine mesh and 70 zones yields a solution within AC limits.
- Pf wo insp = 1.79E-9

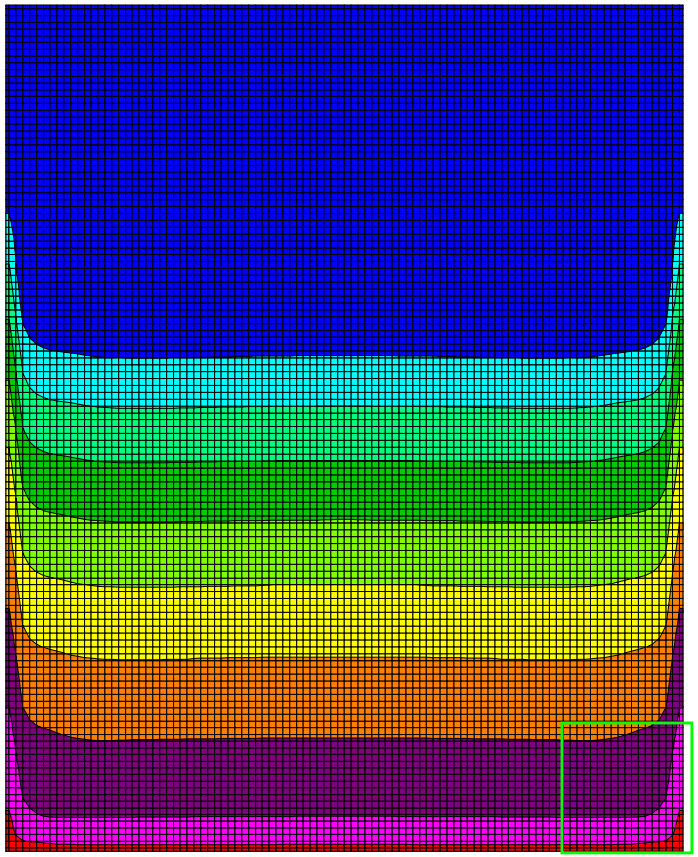




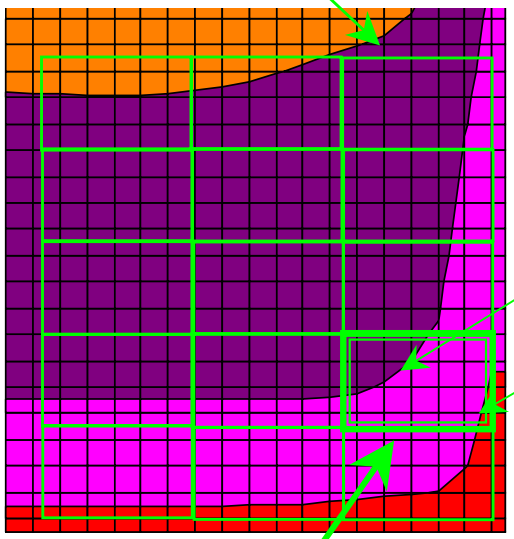
Courtesy Pratt & Whitney

Mesh Size Dependence

Life from a 10x10 mil Flaw



"Coarse" Mesh Overlay



Greater than 20% change in life across single "element"

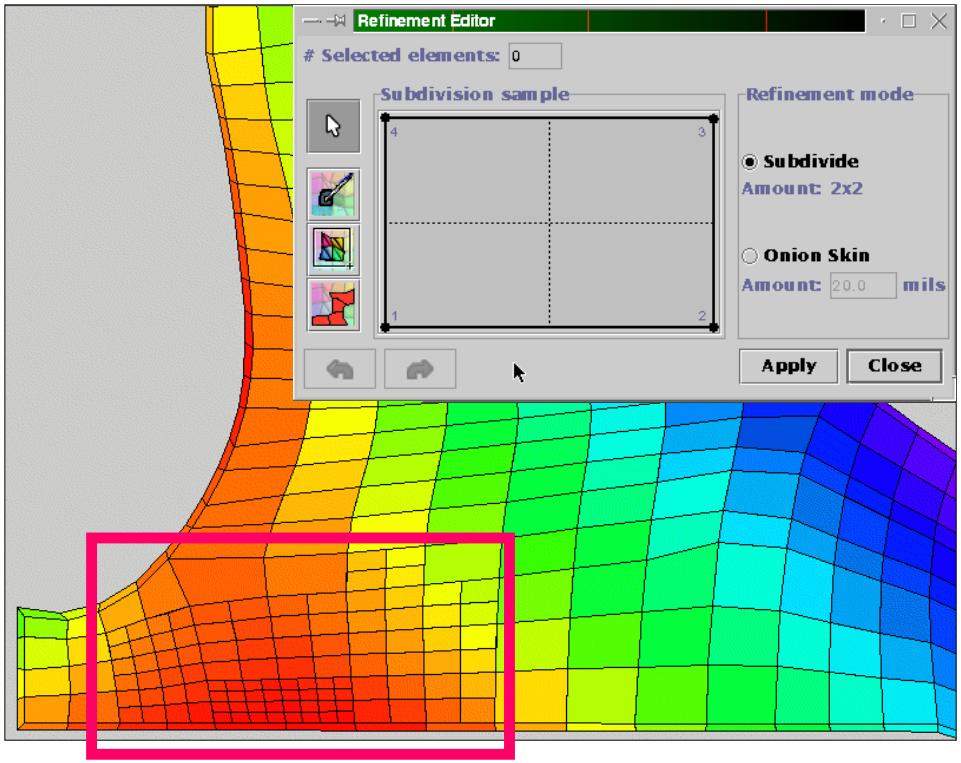
Risk variation > Stress Variation

Courtesy GEAE

Element Subdivision

- Elements may be subdivided (repeatedly) to provide the desired resolution for zone creation.

  ⇒ DARWIN 3.4.5 (under review)

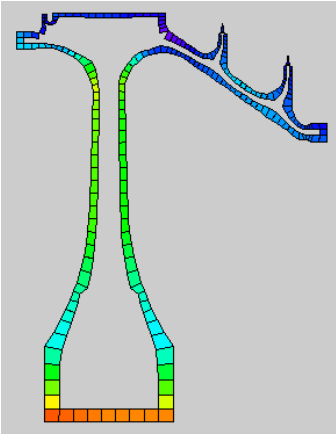


Element subdivision from original FE mesh

Onion Skinning

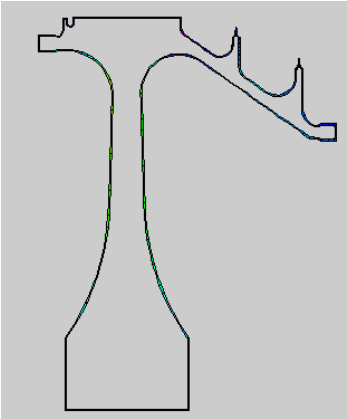
- A thin layer of elements required to model surface zones
  - DARWIN will subdivide surface elements to develop a layer of elements of desired thickness, e.g., 20 mils

⇒DARWIN 3.4.5 (under review)



Original Mesh

Onion Skinned Mesh



Courtesy MTU

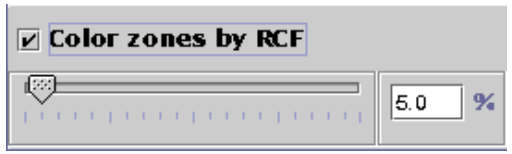
DARWIN Zone Refinement Capability

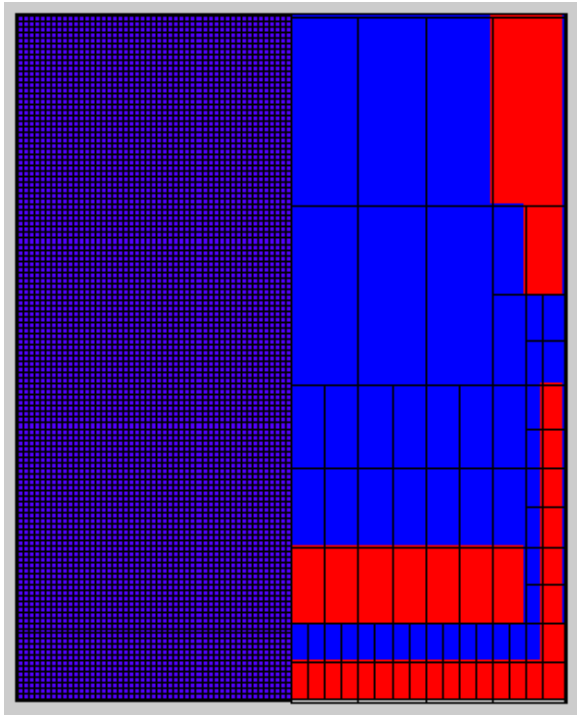
- Risk number computed by DARWIN dependent on the zone breakup (although will converge from the high side)

- Features
  - Robustness
    - ⇒ Should always work for any well posed problem
    - ⇒ Solution should converge to correct solution
  - Simple - easy to understand, not hidden nor confusing
  - Extension of current approach
  - Quality of the risk solution obtained should not be dependent on the experience of the user
  - Quality of the risk solution obtained should be only weakly dependent on the initial zone breakup

Zone Selection

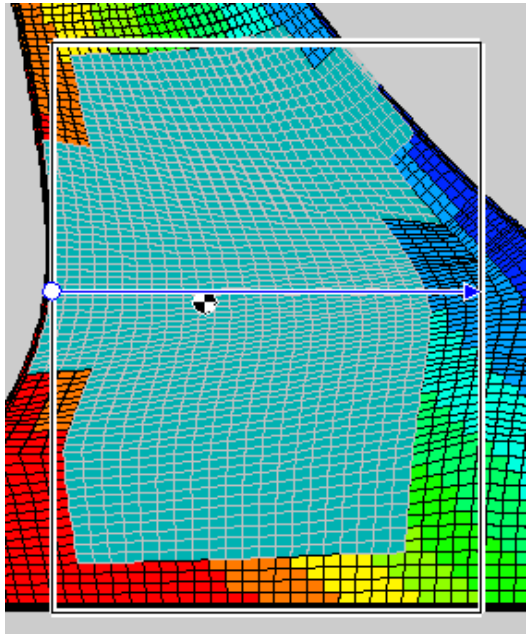
- User defines initial zones (corner, surface, embedded)
- DARWIN risk assessment carried out
- Select *potential* zones to be refined based on Risk Contribution Factor(RCF)
  - RCF (w or w/o inspection) > Δ, e.g., 5%
    - $\Rightarrow$ Zone RCF < Δ, no refinement
    - $\Rightarrow$ Zone RCF > Δ, possible refinement

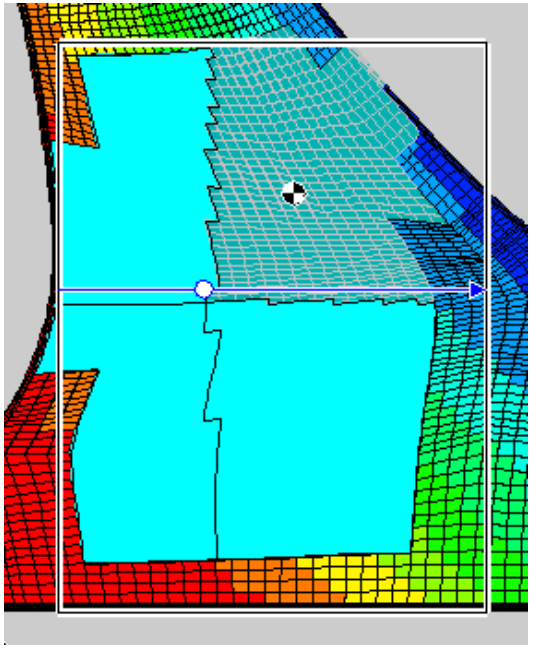




Generate Potential Subzones

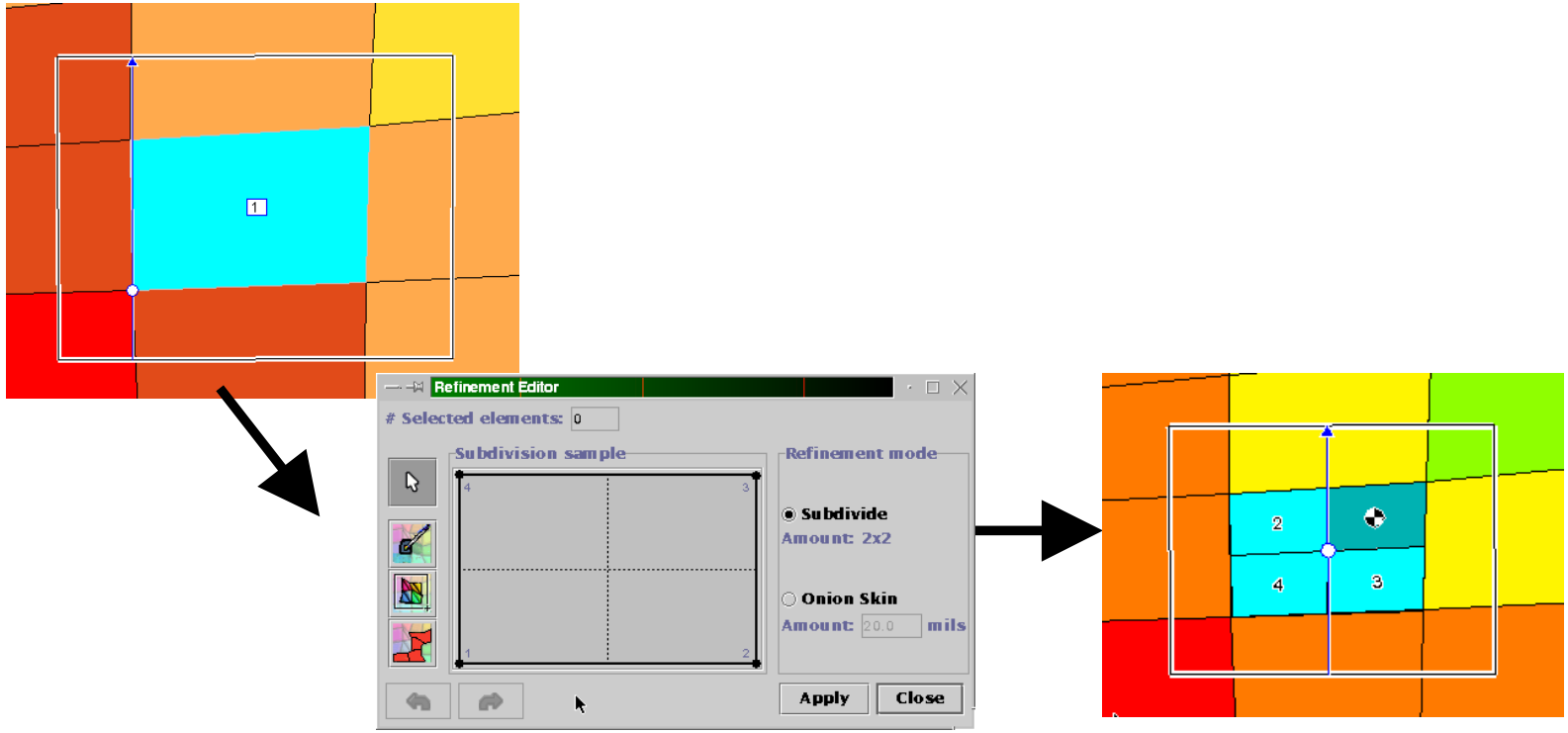
- Determine material in each subzone
  - ⇒Use centroid equation
  - ⇒embedded -> 4 (or 3) zones, surface -> 2 zones





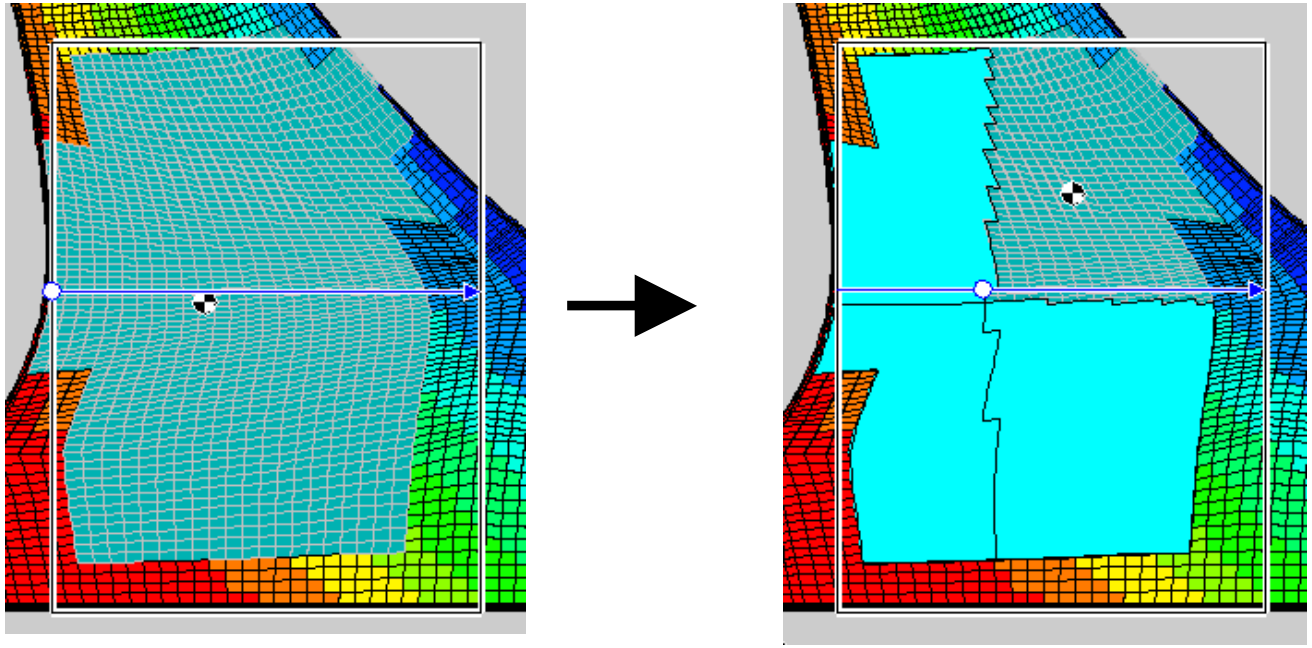
Subdivide Elements

- Zones that have only a few elements, subdivide into more elements as previously described



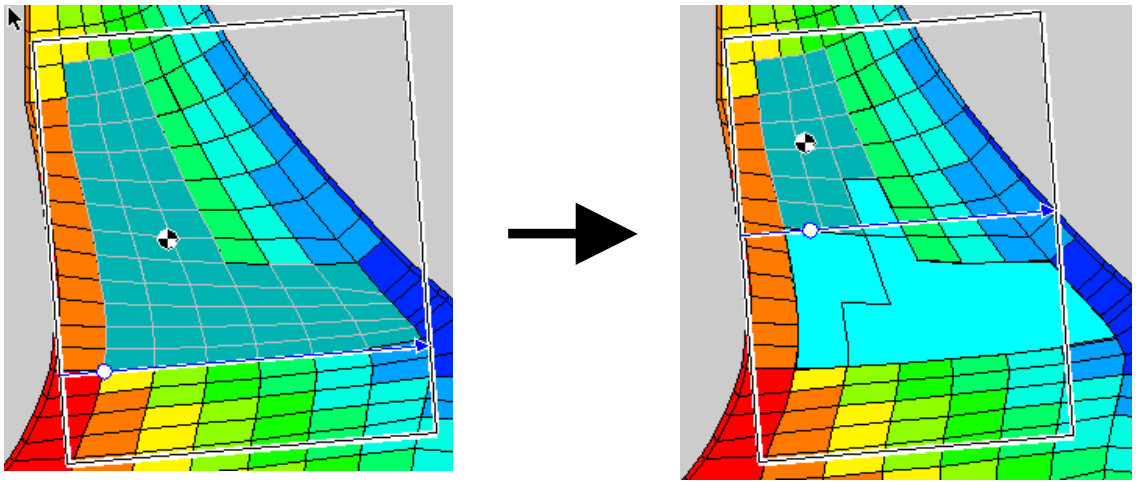
Generate Potential Subzones

- Place flaw
  - ⇒Geometrically closest to flaw in parent zone



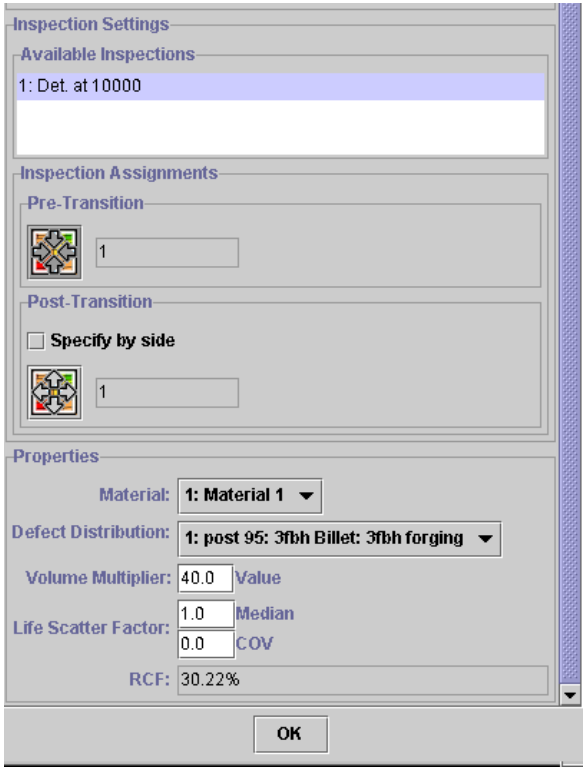
Generate Potential Subzones

- Define plate
  - ⇒Use same plate as parent zone (new crack is inside existing plate), same gradient direction
  - ⇒Clip front and back along gradient line if necessary
  - ⇒If new flaw location is outside parent plate, move plate if possible. If not possible, warn user.



Generate Potential Subzones

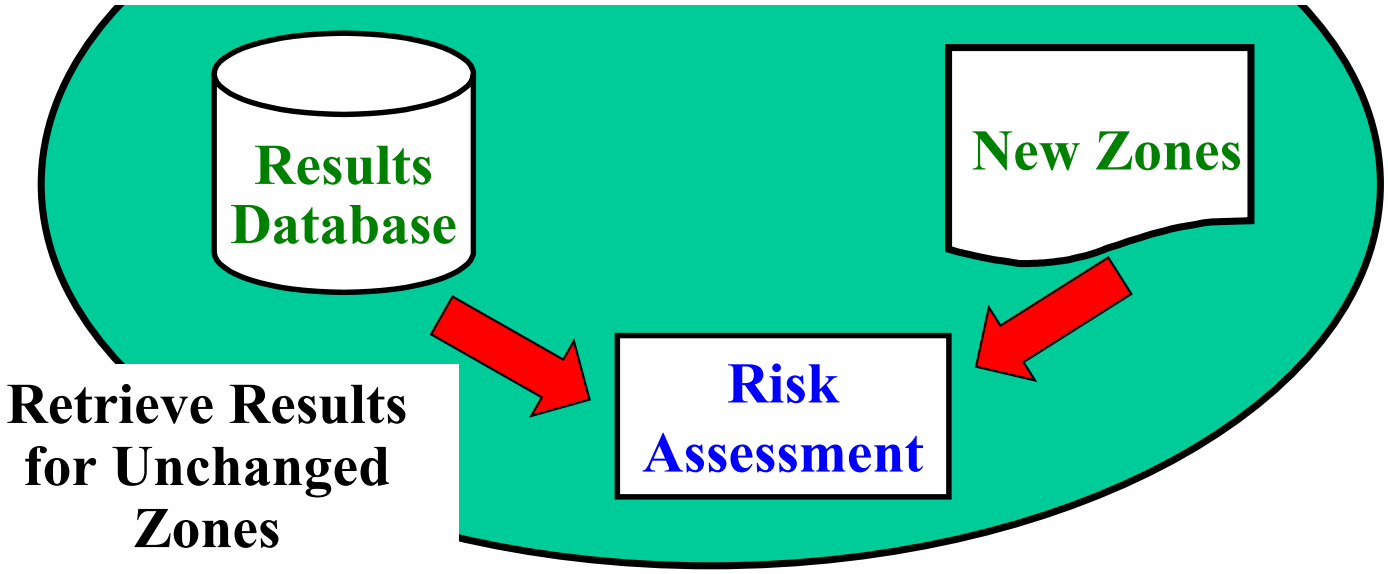
- Inherit the following properties from parent
  - ⇒volume multiplier,
  - ⇒inspection schedules,
  - ⇒material no.,
  - ⇒crack type,
  - ⇒crack plane,
  - ⇒defect distribution,
  - ⇒# samples



Note: ALL generated potential subzones may be edited by user before analysis.

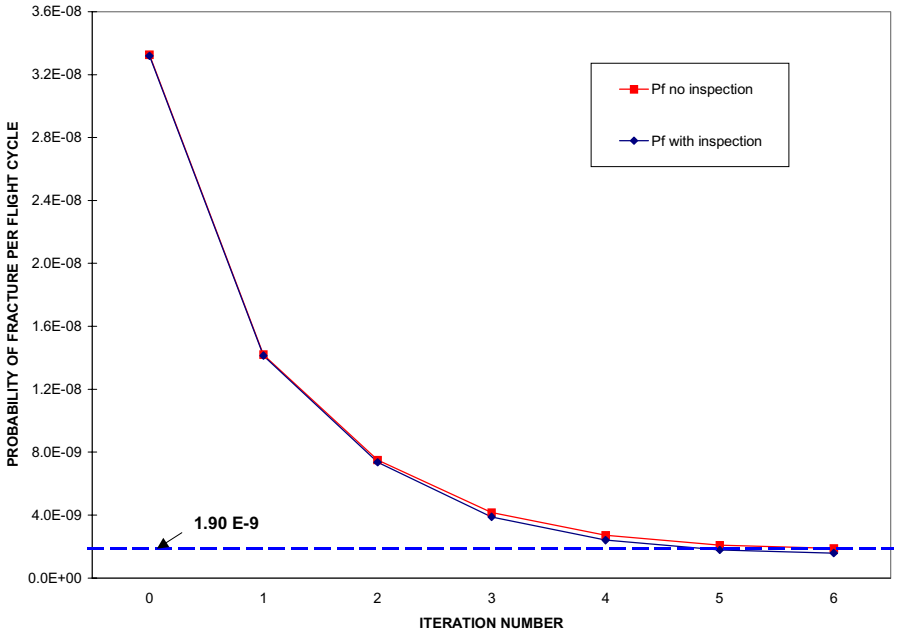
Compute Risk for New Zones

- Read risk results from unchanged zones <-- Restart Capability
- Compute risk for new zones
- Sum risks and compute new risk contribution factors

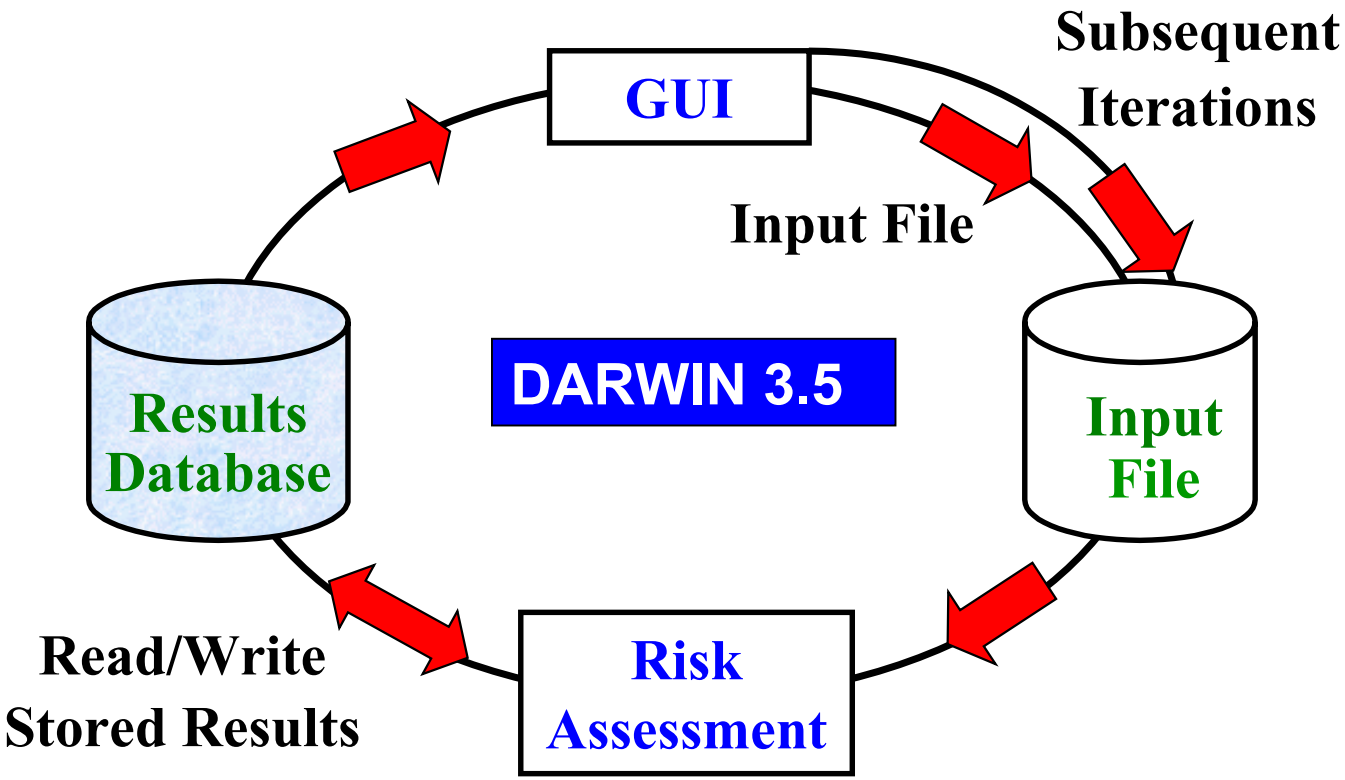


Convergence Criteria

- Examine stop criteria - user implemented
  - If risk < L (target risk)
  - All RCFs < target
  - If (disk risk(i+1) - disk risk(i))/disk risk(i) < E

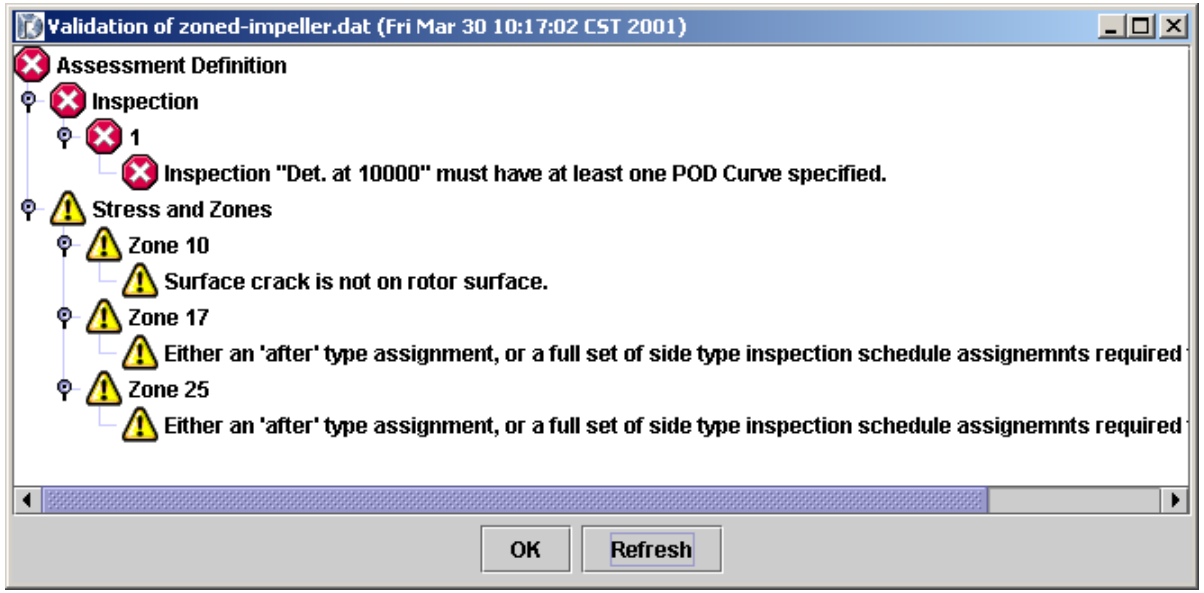


Zone Refinement Procedure



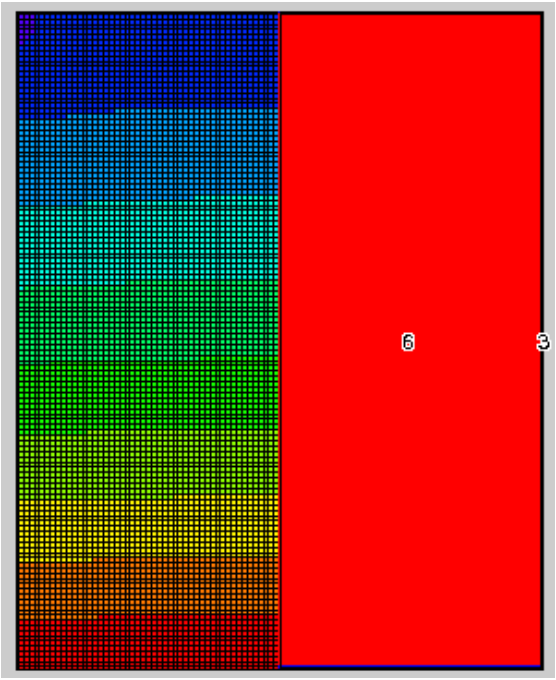
Checks

- DARWIN should implement checks and flag zones or results that look suspicious. The user may then review the zoning and the results. Corrections can be made and the analysis restarted.

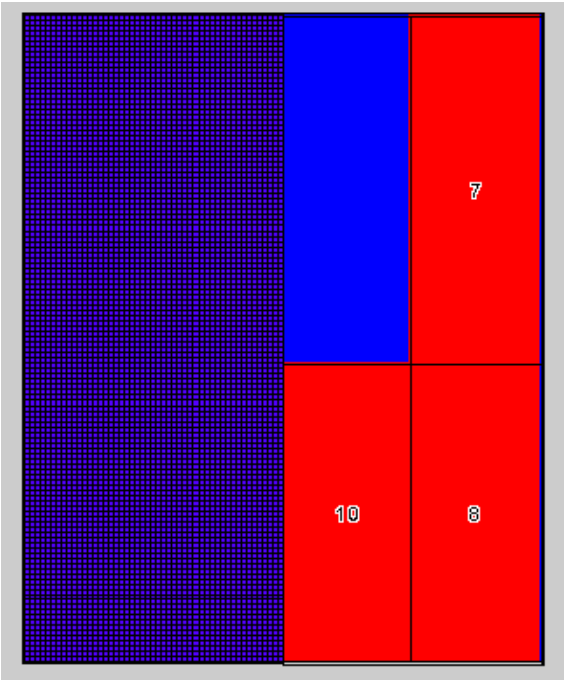


Validate option - checks input data

Example: AC Test Case



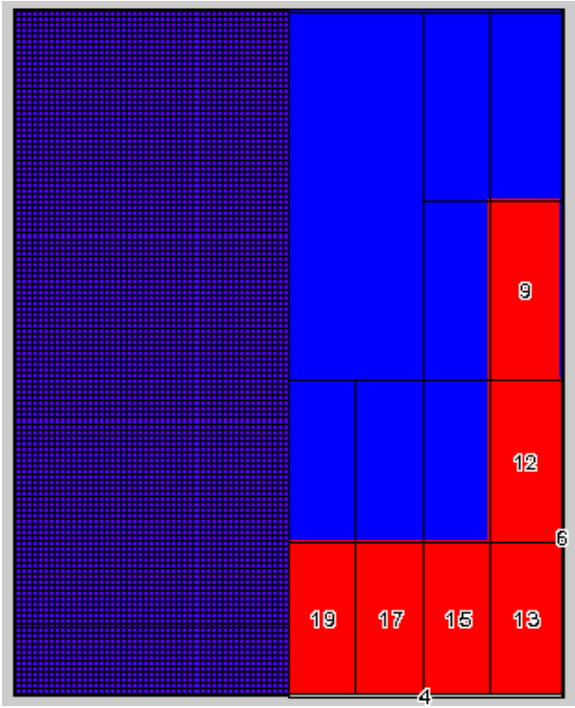
6 Zones



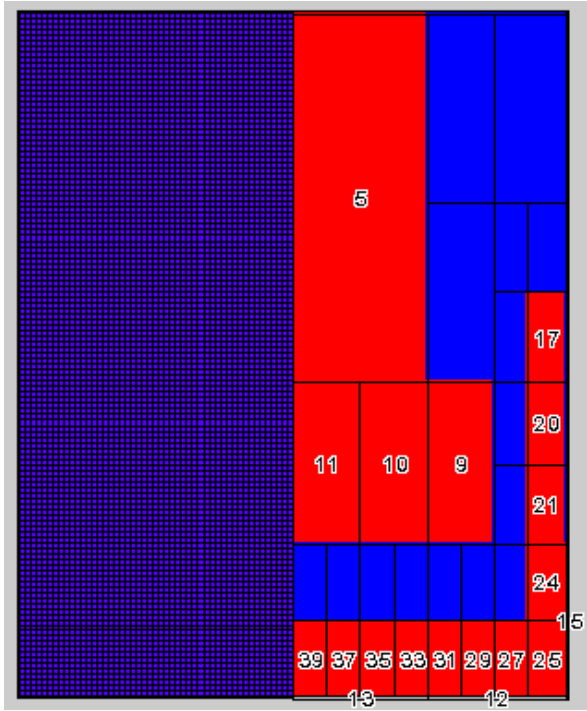
10 Zones

Note: Red zones contribute > 1% of (total) disk risk

Example: AC Test Case (cont)



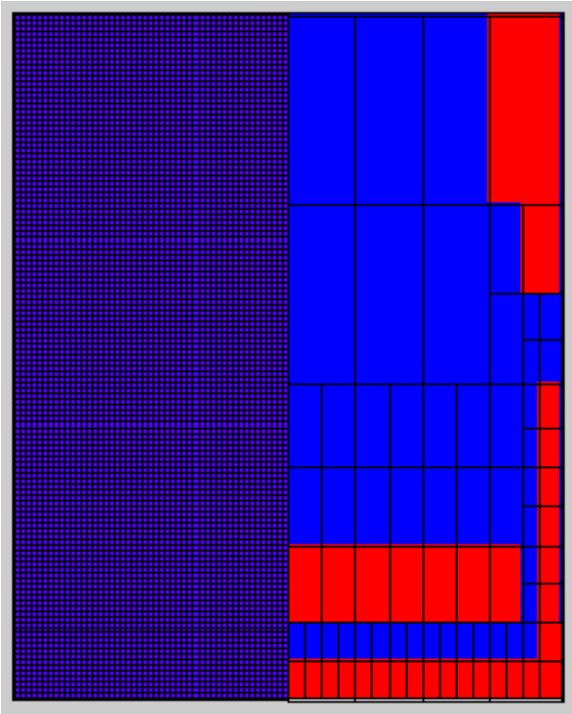
19 Zones



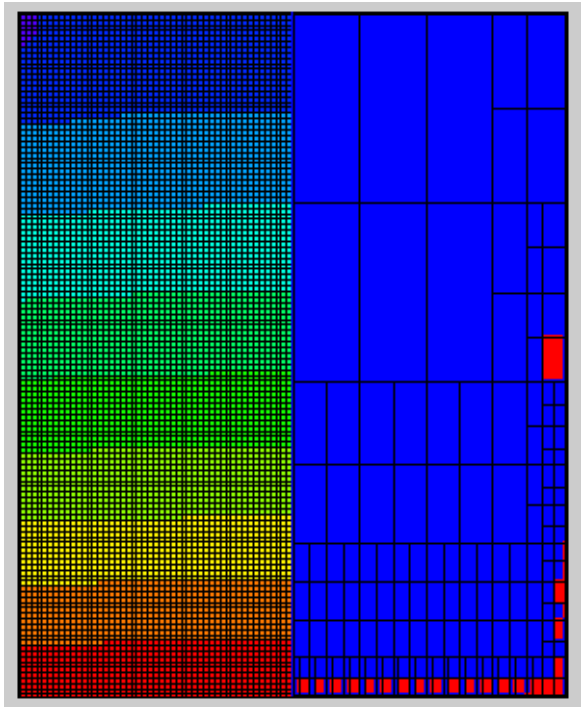
39 Zones

Note: Red zones contribute > 1% of (total) disk risk

Example: AC Test Case (cont)



91 Zones



192 Zones

Note: Red zones contribute > 1% of (total) disk risk

Summary and Conclusions

- Analysis using DARWIN V3.3 on AC test problem motivated new capabilities.
  - Element refinement implemented in an easy-to-use manner to allow zone dimensions of any size.
  - Zone refinement strategy delineated and tools implemented to provide the user an approach to consistently and conveniently converge on the risk solution.
  - New features will be released in DARWIN 3.5 - summer 2001.

More Information

- See web site at **www.darwin.swri.org**
- Publications
- Demo version
  - Gov’t agencies get free license
- Tutorials
- Mailing list signup

Ceramic Inclusions In Powder Metallurgy Disk Alloys: Characterization And Modeling

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Powder metallurgy alloys are increasingly used in gas turbine engines, especially as the material chosen for turbine disks. Although powder metallurgy materials have many advantages over conventionally cast and wrought alloys (higher strength, higher temperature capability, etc.), they suffer from the rare occurrence of ceramic defects (inclusions) that arise from the powder atomization process. These inclusions can have potentially large detrimental effect on the durability of individual components. An inclusion in a high stress location can act as a site for premature crack initiation and thereby considerably reduce the fatigue life. Because these inclusions are exceedingly rare, they usually don't reveal themselves in the process of characterizing the material for a particular application (the cumulative volume of the test bars in a fatigue life characterization is typically on the order of a *single* actual component). Ceramic inclusions have, however, been found to be the root cause of a number of catastrophic engine failures. To investigate the effect of these inclusions in detail, we have undertaken a study where a known population of ceramic particles, whose composition and morphology are designed to mimic the "natural" inclusions, are added to the precursor powder. Surface connected inclusions have been found to have a particularly large detrimental effect on fatigue life, therefore the volume of ceramic "seeds" added is calculated to ensure that a minimum number will occur on the surface of the fatigue test bars. Because the ceramic inclusions are irregularly shaped and have a tendency to break up in the process of extrusion and forging, a method of calculating the probability of occurrence and expected intercepted surface and embedded cross-sectional areas were needed. We have developed a Monte Carlo simulation to determine the distributions of these parameters and have verified the simulated results with observations of ceramic inclusions found in macro slices from extrusions and forgings. The ultimate goal of this study will be to use probabilistic methods to determine the reliability detriment that can be attributed to these ceramic inclusions.

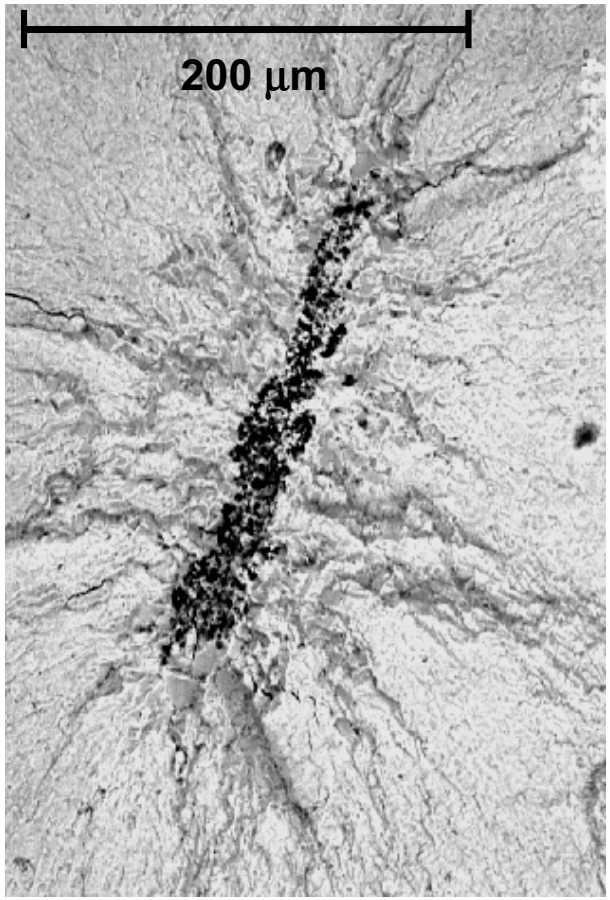
5th Annual FAA/Air Force/NASA/Navy Workshop on the
Application of Probabilistic Methods to Gas Turbine Engines

CERAMIC INCLUSIONS IN POWDER METALLURGY DISK ALLOYS: CHARACTERIZATION AND MODELING

Pete Bonacuse - US Army Research Laboratory
Pete Kantzos - Ohio Aerospace Institute
Jack Telesman and Tim Gabb– NASA Glenn Research Center
CPT Rob Barrie – US Army

Recipients of this report may further disseminate it only as directed by the UltraSafe Propulsion Project Manager, Susan Johnson, NASA Glenn Research Center, Cleveland, Ohio 44135-3191

Fatigue Crack from Inherent Ceramic Defect



- Inherent to powder process (unavoidable)
- Can cause significant life debit
- Large inclusions exceedingly rare
- Cost prohibitive to study the effect of naturally occurring inclusions on life

Scope of Work

- Develop life prediction methodology to account for effect of random defects in PM alloys
  - Seeding study (in progress)
    - Characterization of known populations of inclusions (seeds)
    - Characterize incubation of cracks from defects
    - Mapped back to natural inclusions in unseeded material
  - Modeling
    - Simulation of seed volumetric distribution to determine occurrence probability
    - Incubation model to match observed incubation life distributions

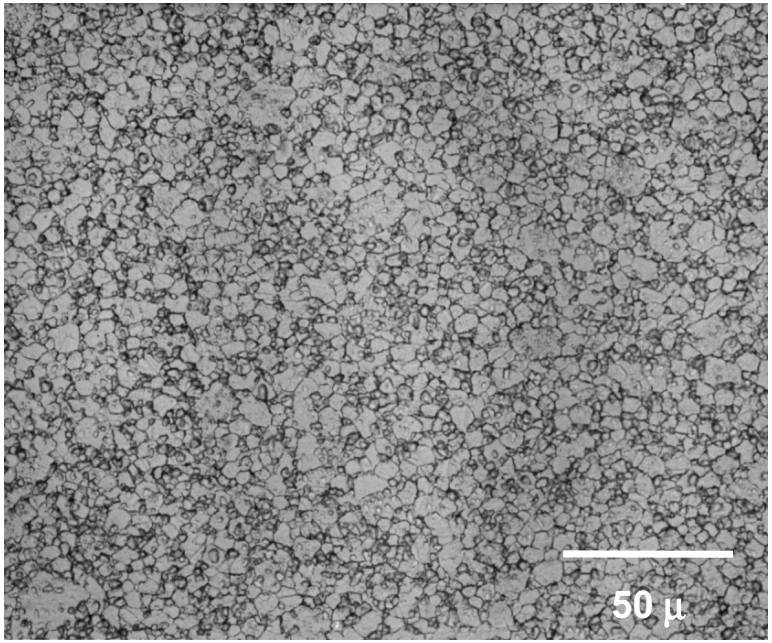
Modeling Inputs Critical!

Material Parameters

270 MESH PRODUCTION QUALITY UDIMET 720 POWDER FROM SPECIAL METALS

Processing Conditions

HIP
EXTRUDE
ISOFORGE
SUBSOLVUS HEAT TREAT

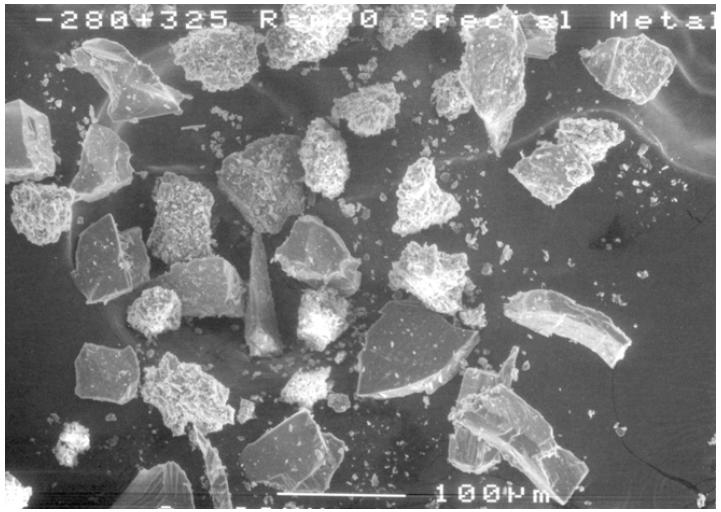


Same conditions for both seeded and Unseeded material

Seeding Parameters

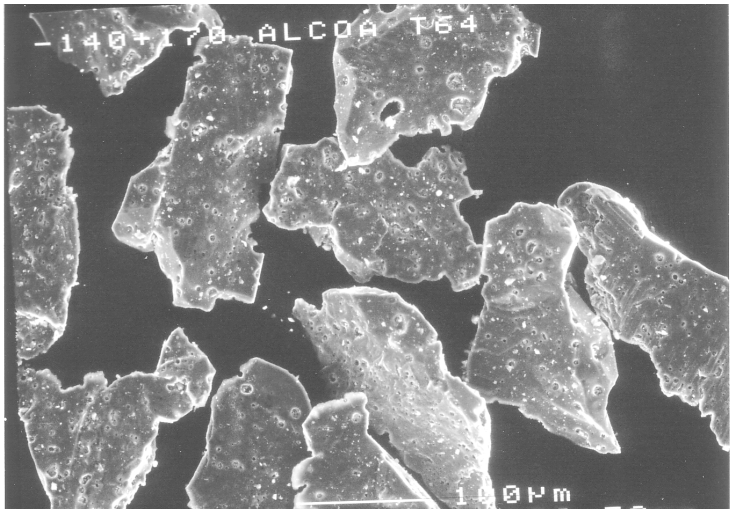
The seeds used were both alumina-rich

Ram90



- Used in the repair furnaces and crucibles
- -270+325 Mesh: A size distribution typical of production powder
- Type II : Soft
- Seeding Rate: 5300 seeds/in^3

Alcoa T64



- Used as crucible material
- -140+170 mesh: Size distribution chosen to simulate a contamination event
- Type I : Hard
- Seeding Rate: 1140 seeds/in^3

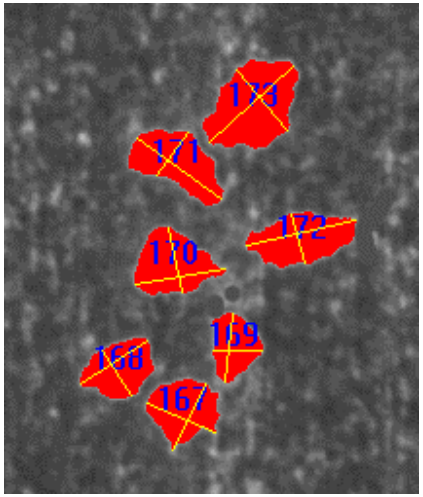
Seeding rates chosen to provide an acceptable number of surface connected inclusions

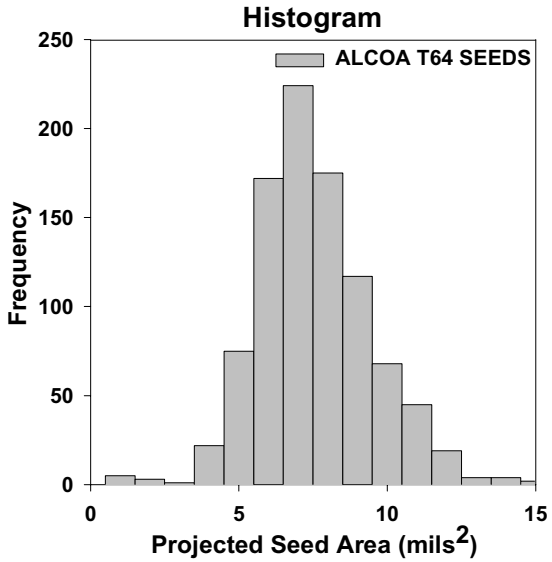
Seed Characterization
Effect of Processing on Seeds

Seed size distributions were determined in situ:

- Initial input size distribution of seeds (using image analysis)
- After Blending (Using the HLS process)
- After Extrusion (Using Metallography and image analysis)
- After Forging (Using Metallography and image analysis)
- After Machining LCF bars (Using SEM and image analysis)
- After Testing (Using SEM and image analysis)

Seed Characterization
A Priori Seed Size Distributions





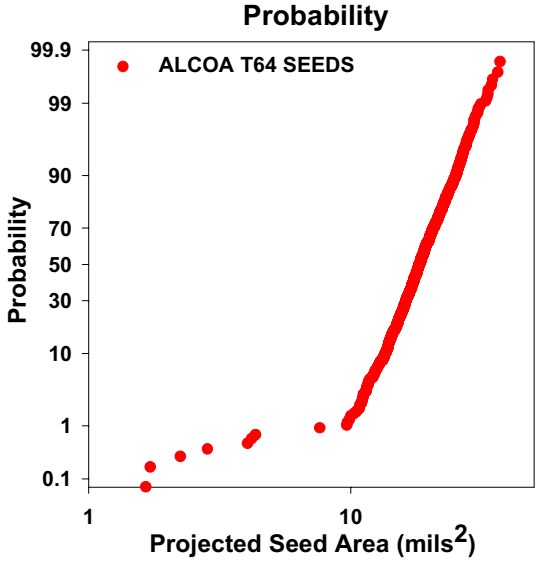
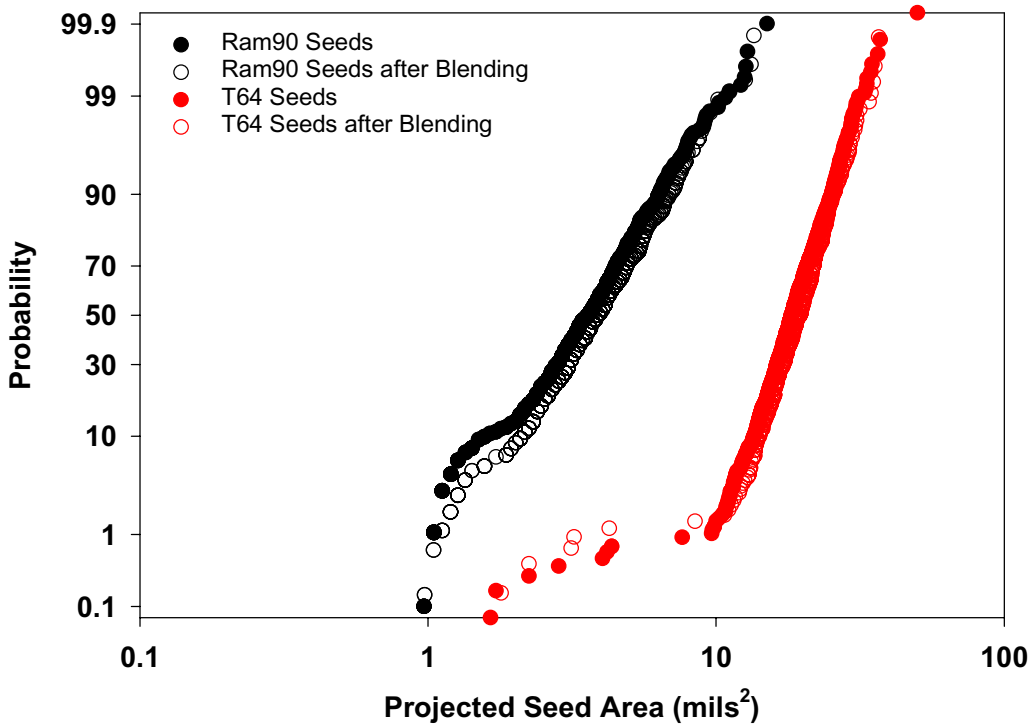


Image analysis used to determine: Projected Seed areas, Maximum Seed length, and Perpendicular Seed length

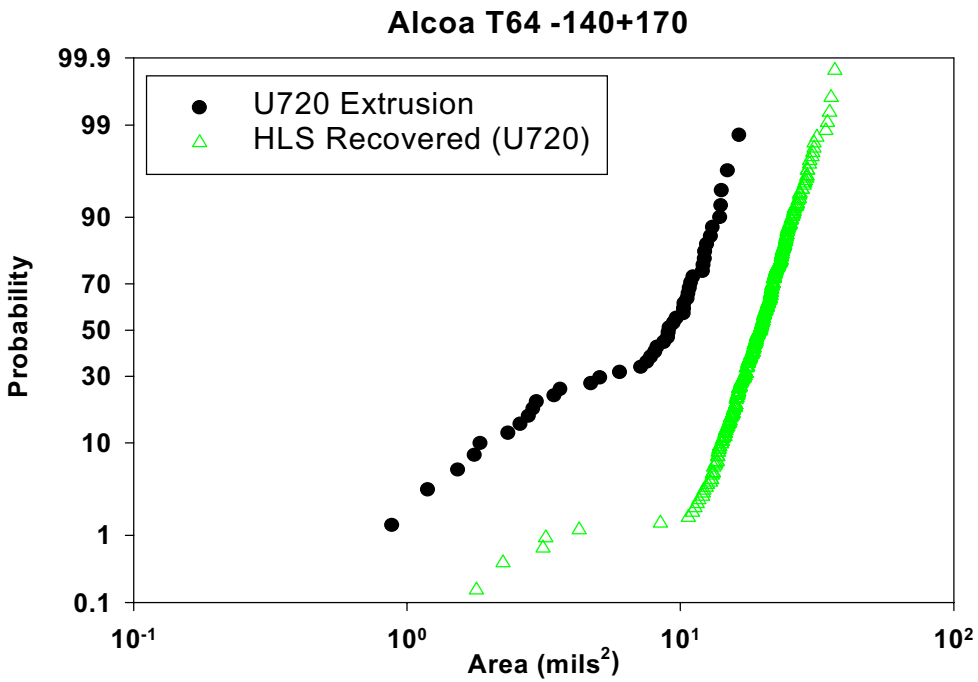
Seed Characterization After Blending

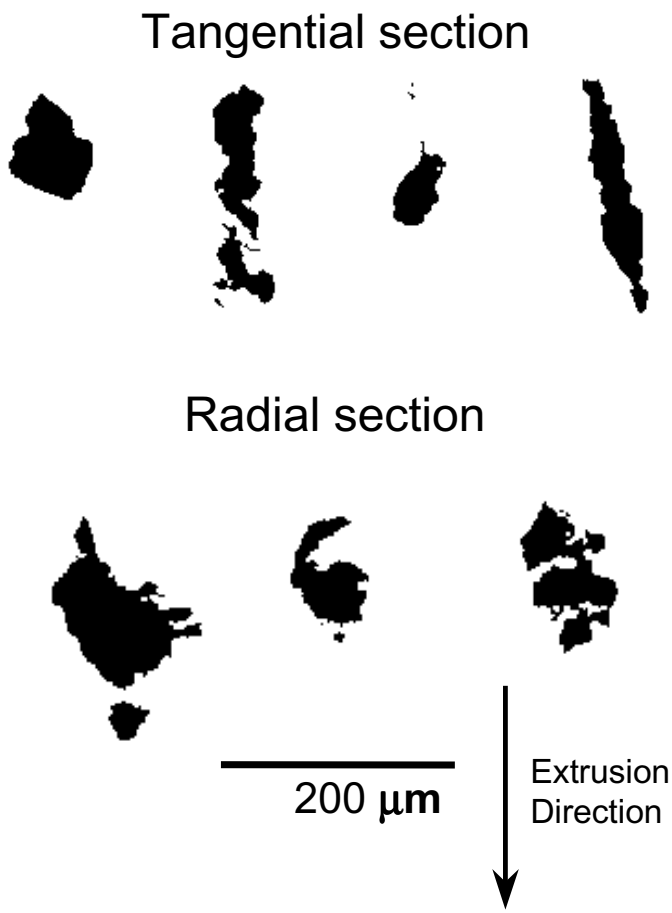
After seeding and blending the powder, the HLS process was used to recover the seeds



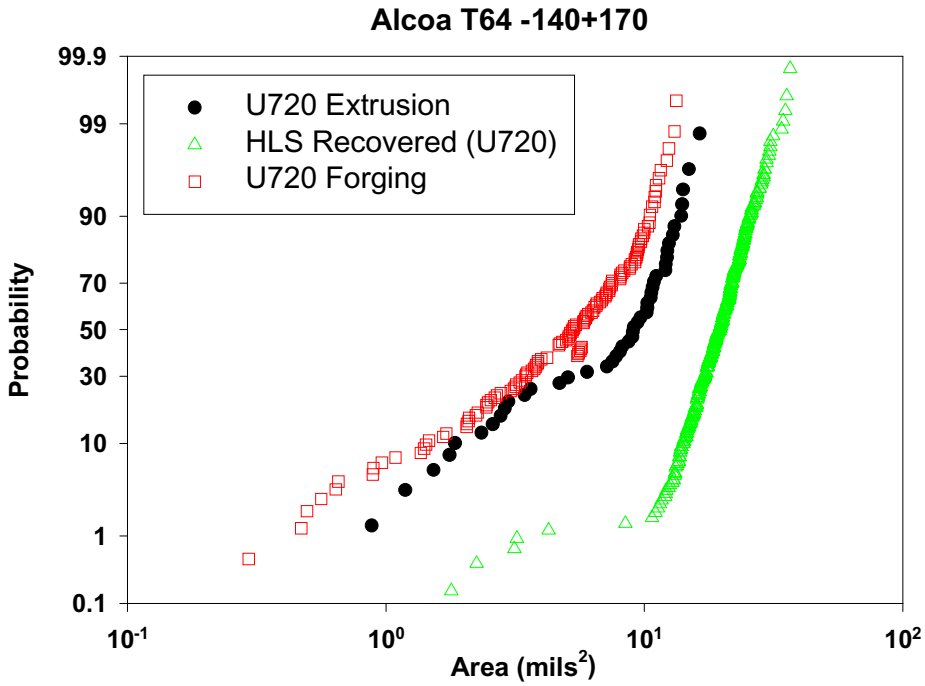
Blending had negligible effect on the seed size distribution

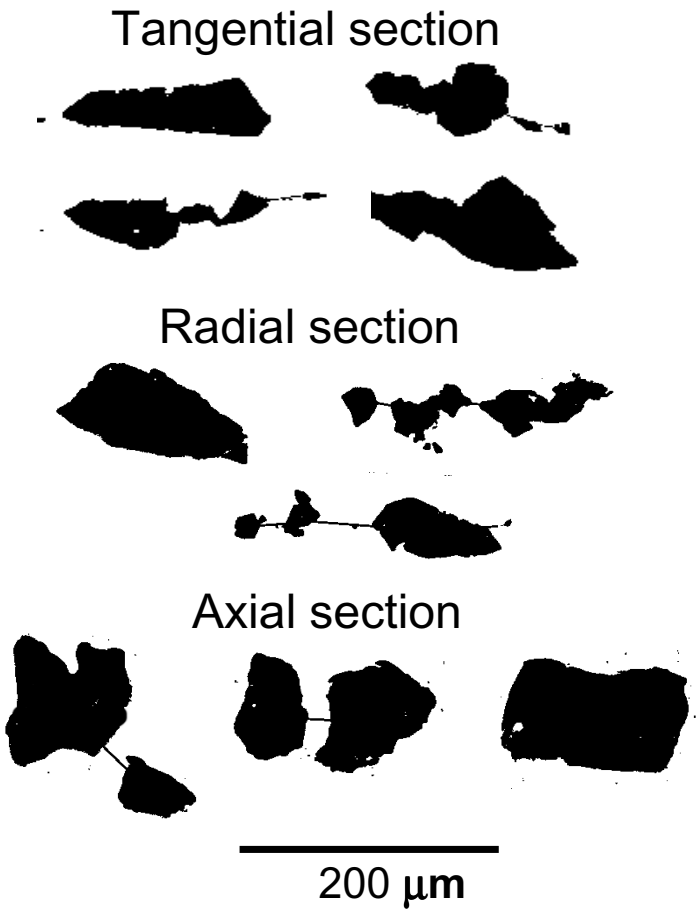
Seed Characterization After Extrusion



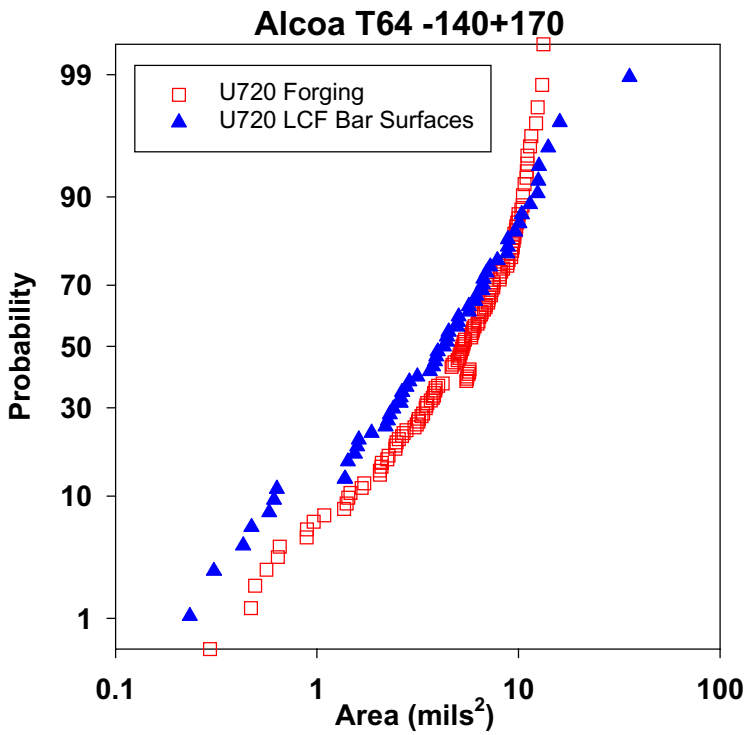


Seed Characterization After Forging

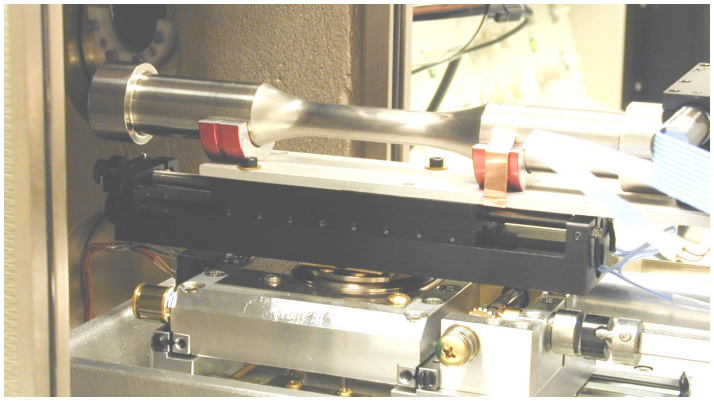


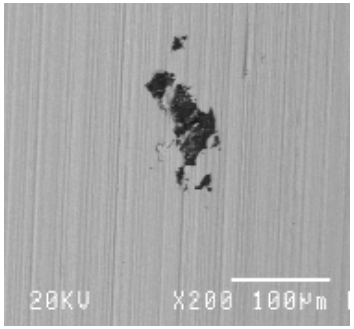


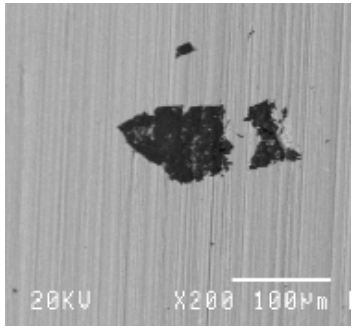
Seed Characterization: LCF Bar Surfaces



SEM Rotary Stage

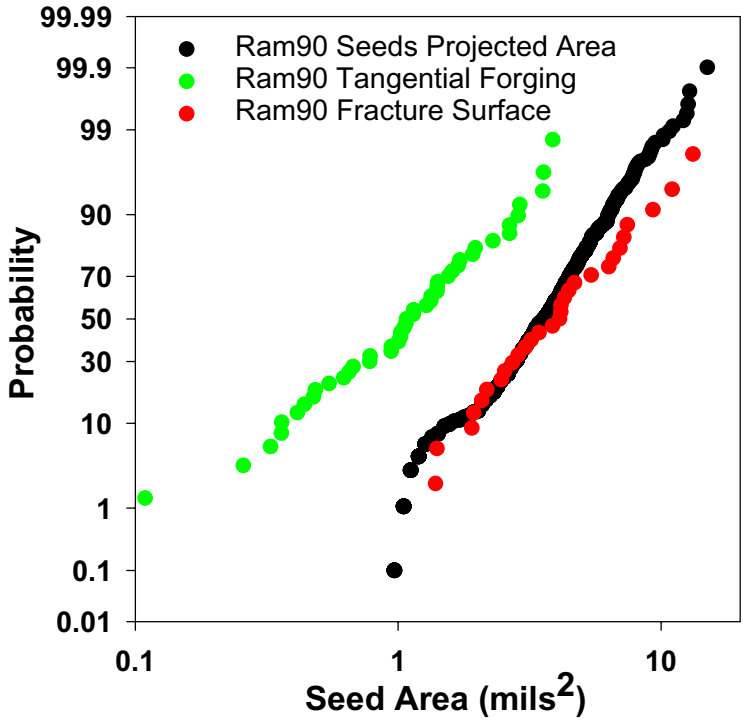


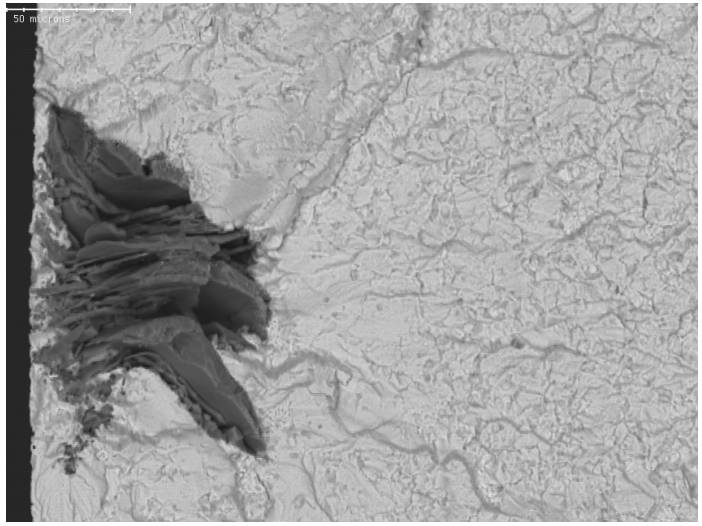




- **Interrupted Testing**
- **Crack initiation and incubation**

Seed Characterization
Fractography



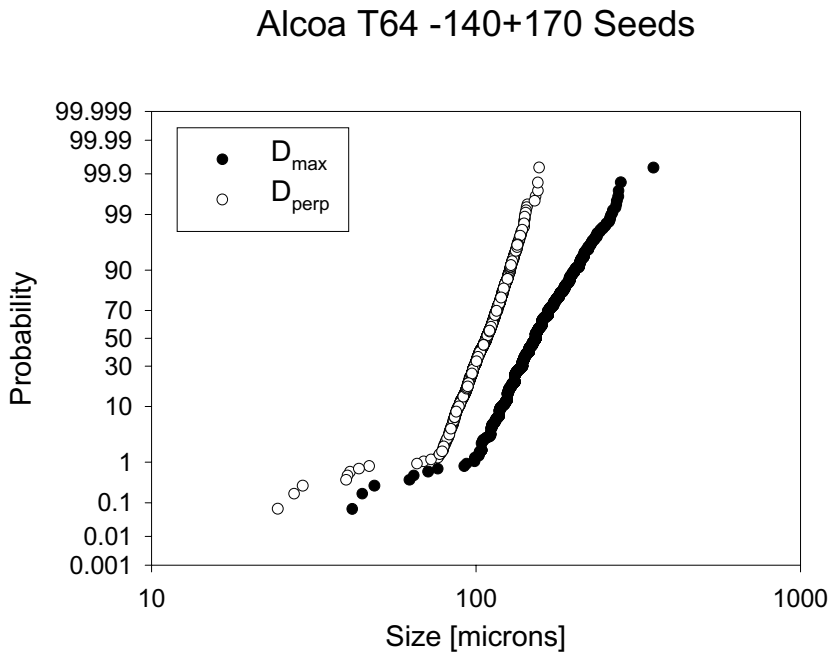


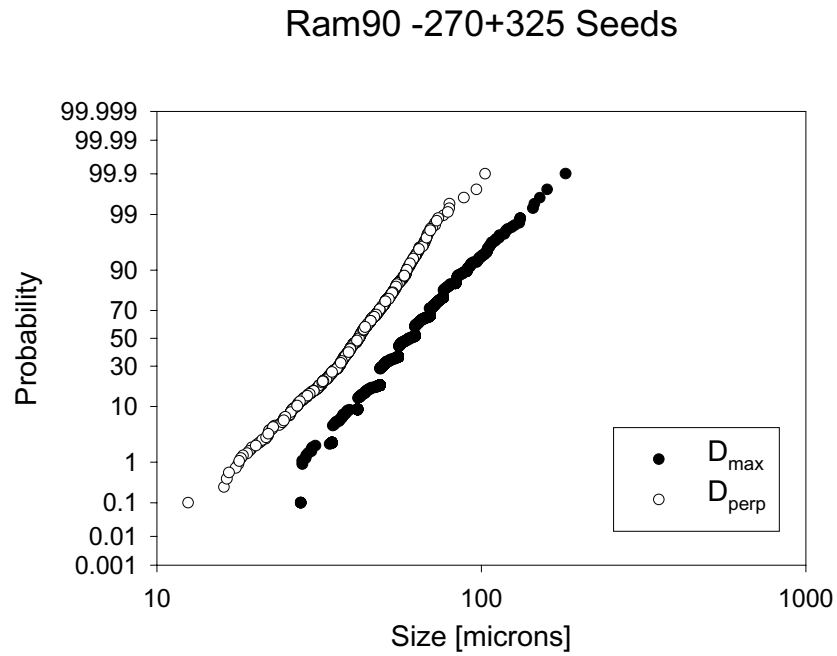
- All specimens thus far failed from seeds
- Most initiation sites were on the surface
- Most seeds causing failure seemed to have the bulk of their volume within the specimen
- As expected their size distribution is large

Simulation of Inclusion Spatial Distribution

- Assumptions:
  - Inclusions are randomly distributed in the volume (Poisson distributed)
  - Inclusions can be modeled as ellipsoidal particles
  - Ellipsoids may have preferred orientations
  - Inclusion size distribution can be modeled by three correlated log-normal distributions (max, min seed dimensions and assumed third dimension)
- Random Variables:
  - Number of inclusions in specimen volume (Poisson distribution)
  - **x**, **y**, and **z** coordinates (uniform distributions)
  - **a, b, and c** inclusion dimensions (correlated log-normal distributions)
  - Inclusion rotations: ϕ, θ, and ψ (correlated normal distributions)

Seed Size Distributions





Methodology

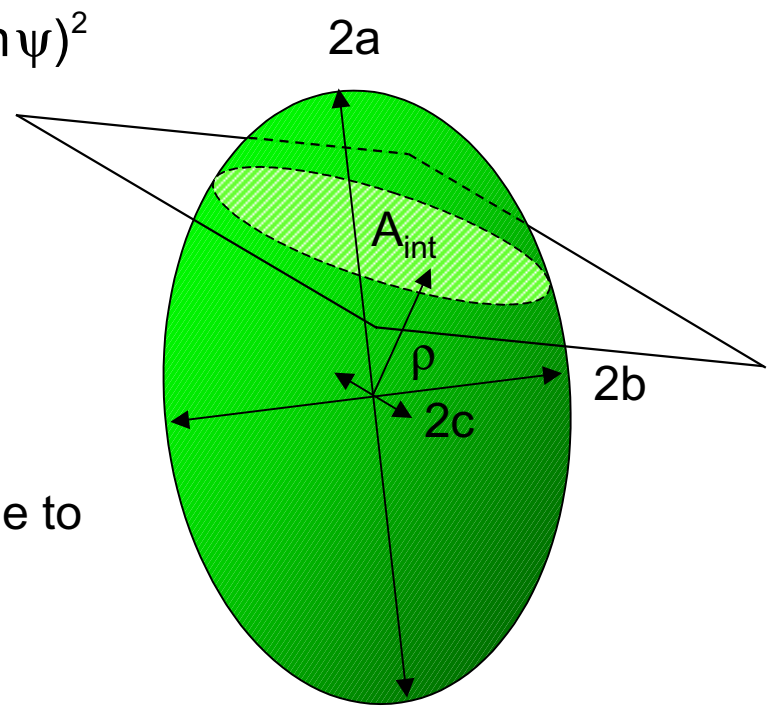
- Generate Poisson distributed number of inclusions
- Generate for each particle:
  - x, y, and z coordinate from uniform distributions
  - a, b, and c dimensions from correlated log-normal distributions
  - ϕ, θ, and ψ rotations from correlated normal distributions
- Determine, for each inclusion
  - intersects specimen surface?
    - calculate intercepted area
  - interferes with other inclusions?

Entire process repeated to determine distribution of expected surface intercepts, areas, etc.

Intercepted Area Solution for 3D Ellipsoid

$$\Phi = a^2(-\sin\phi\cos\theta\sin\psi + \cos\phi\cos\psi)^2$$
$$+ b^2(-\sin\phi\cos\theta\cos\psi - \cos\phi\sin\psi)^2$$
$$+ c^2(\sin\phi\sin\theta)^2$$

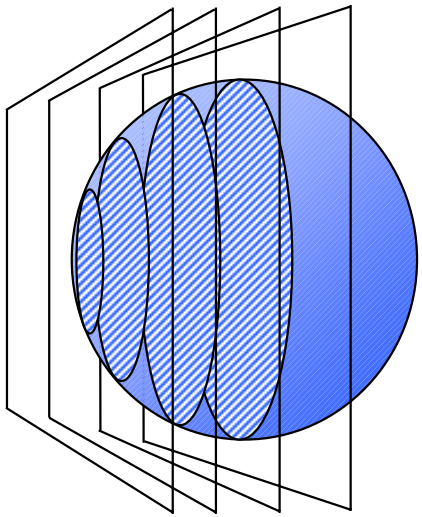
$$A_{int} = \pi abc\frac{\Phi - \rho^2}{[\Phi]^{3/2}} = \pi abc\frac{1 - \rho^2/\Phi}{\sqrt{\Phi}}$$

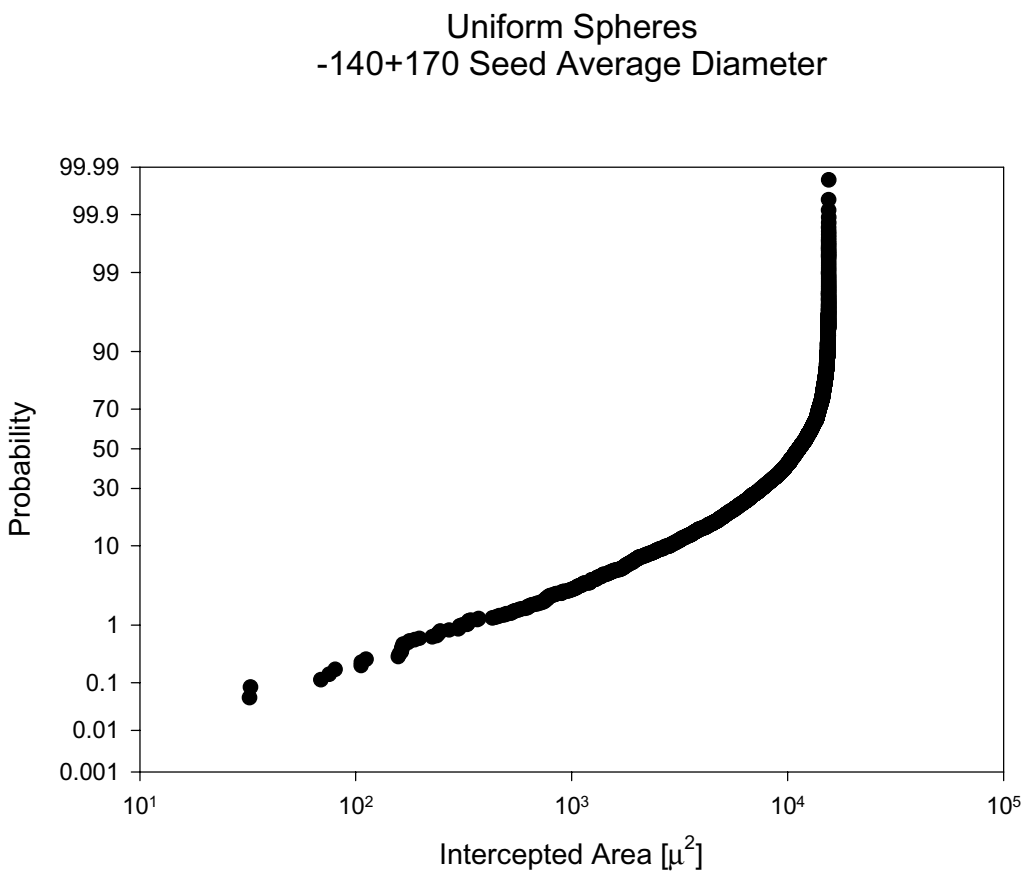


Where:

- ρ = distance from sectioning plane to centroid
- a, b, c = ellipsoid dimensions
- ϕ, θ, ψ = rotation angles

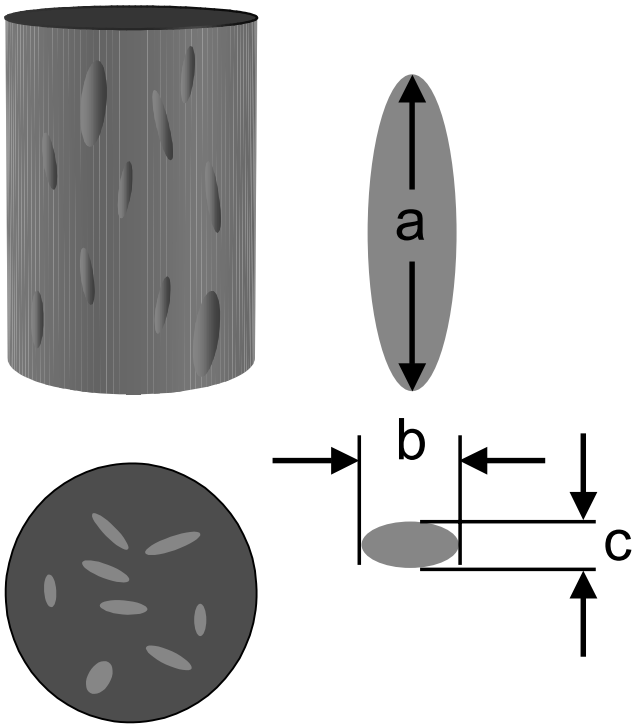
Intercepted Area Distribution – Uniform Spheres



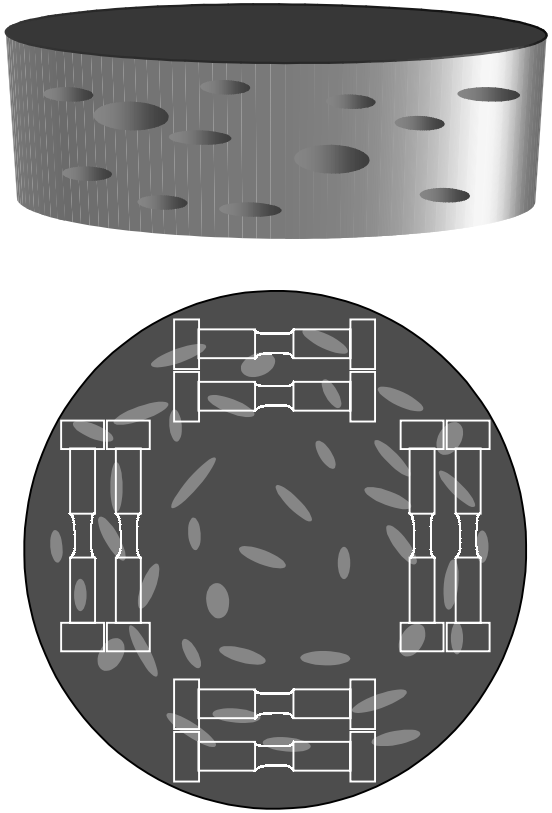


Model Inputs: Seed Orientations

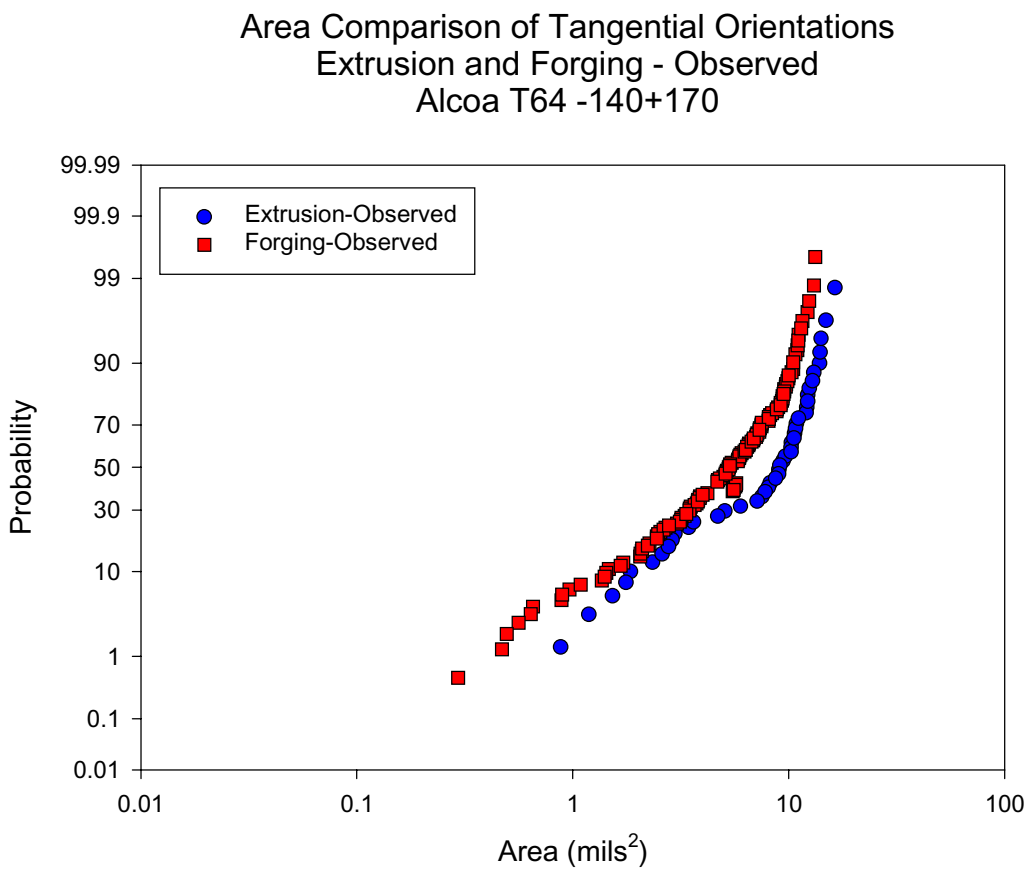
Extrusion



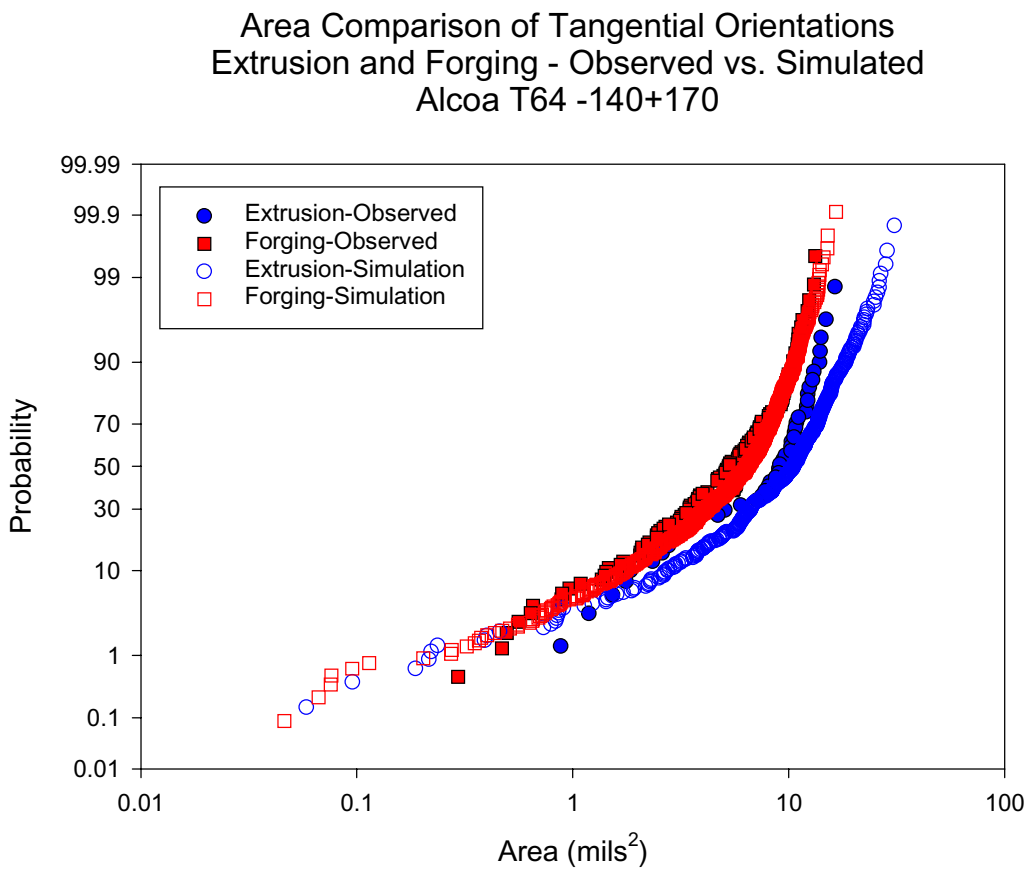
Forging



Intercepted Surface Area

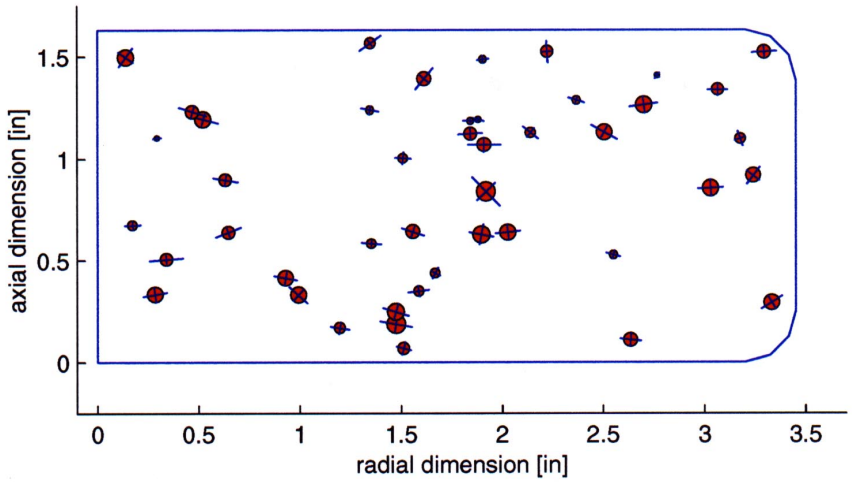


Intercepted Surface Area



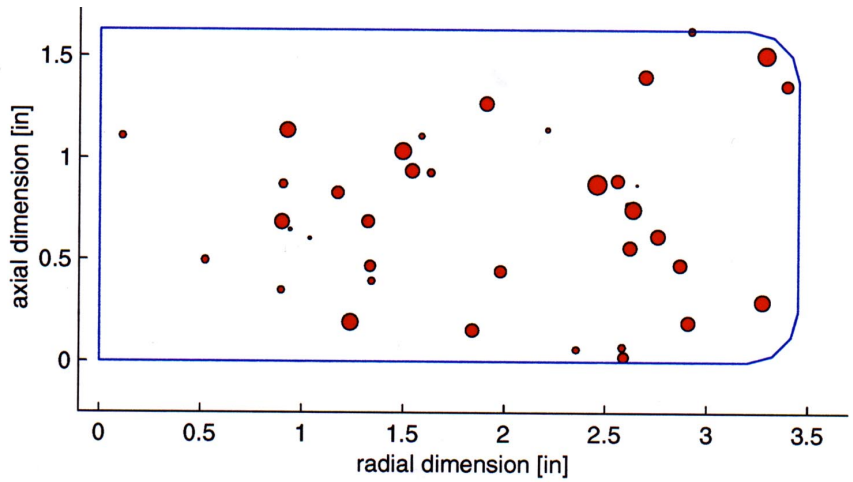
Model Comparisons
Seed Maps for Alcoa T64 Forging Chord Slices

Actual Metallographic Observations



Average # of Intercepts:	43
Mean Area/Seed [mils^2]:	5.74
Area/Seed SD [mils^2]:	3.35

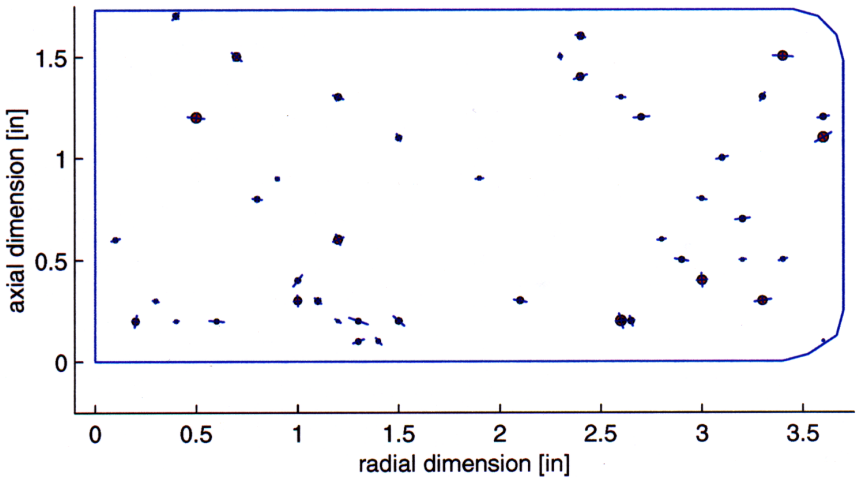
Prediction



Average # of Intercepts:	38.4
Mean Area/Seed [mils^2]:	6.38
Area/Seed SD [mils^2]:	3.17

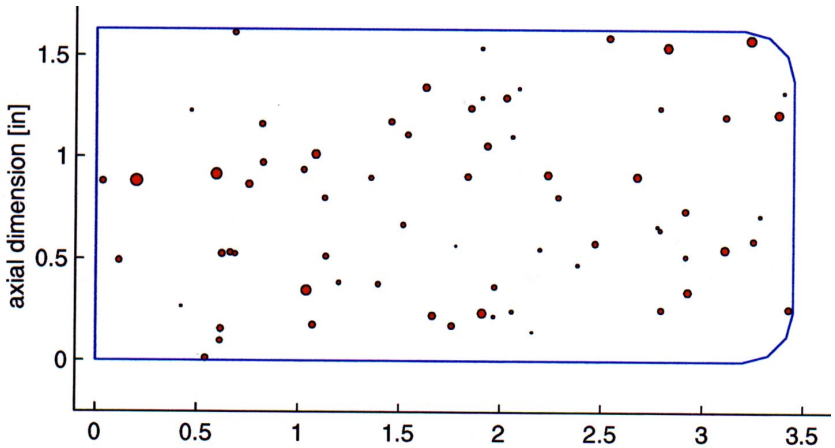
Model Comparisons
Seed Maps for Ram90 Forging Chord Slices

Actual Metallographic Observations



# of Intercepts:	45
Mean Area/Seed [mils^2]:	1.35
Area/Seed SD [mils^2]:	0.94

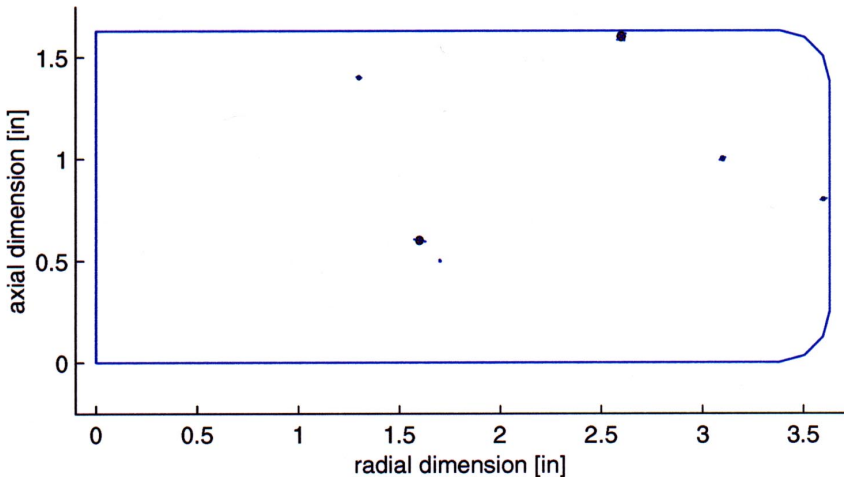
Prediction



Average # of Intercepts:	75.4
Mean Area/Seed [mils^2]:	1.18
Area/Seed SD [mils^2]:	0.85

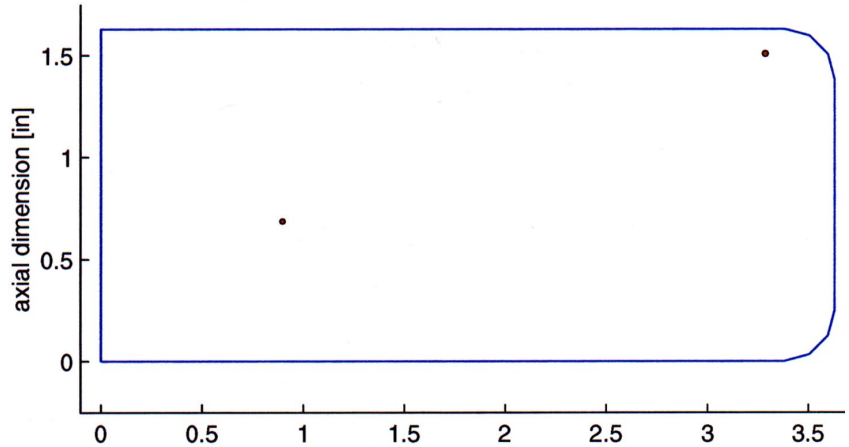
Model Comparisons
Inclusion Maps for Unseeded Forging Chord Slices

Actual Metallographic Observations



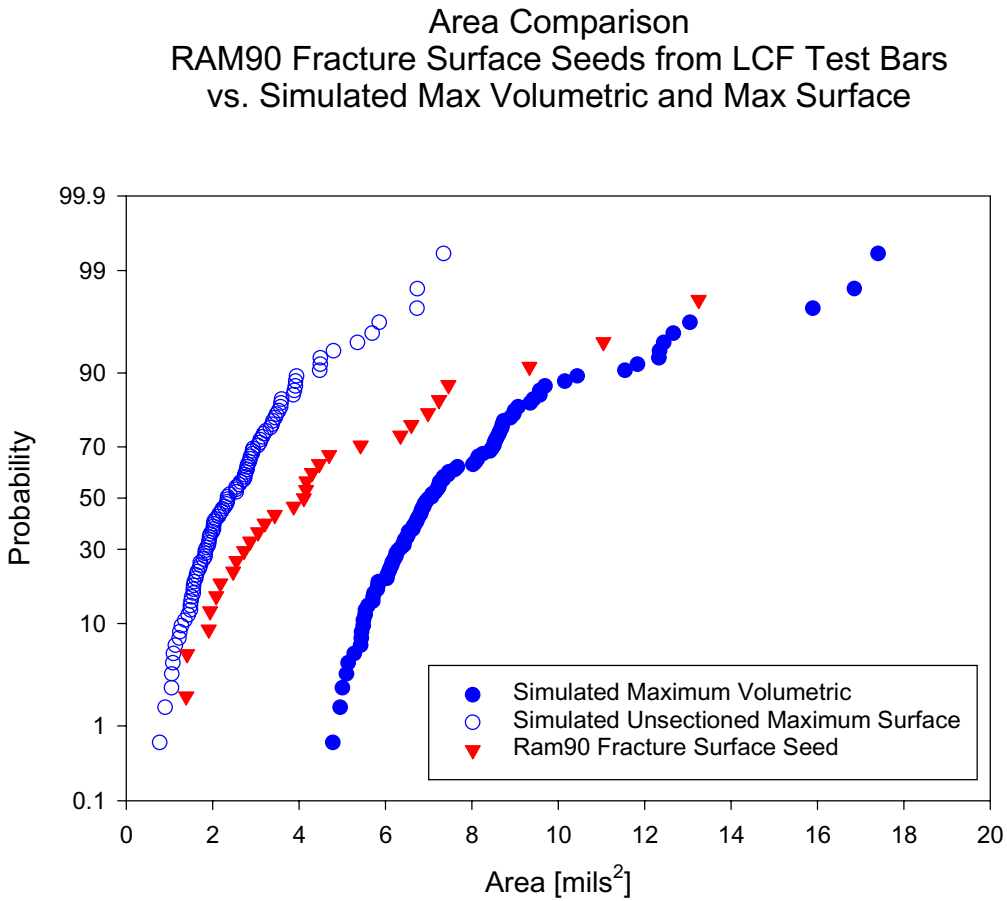
# of Intercepts:	6
Mean Area/Seed [mils^2]:	1.02
Area/Seed SD [mils^2]:	1.0

Prediction



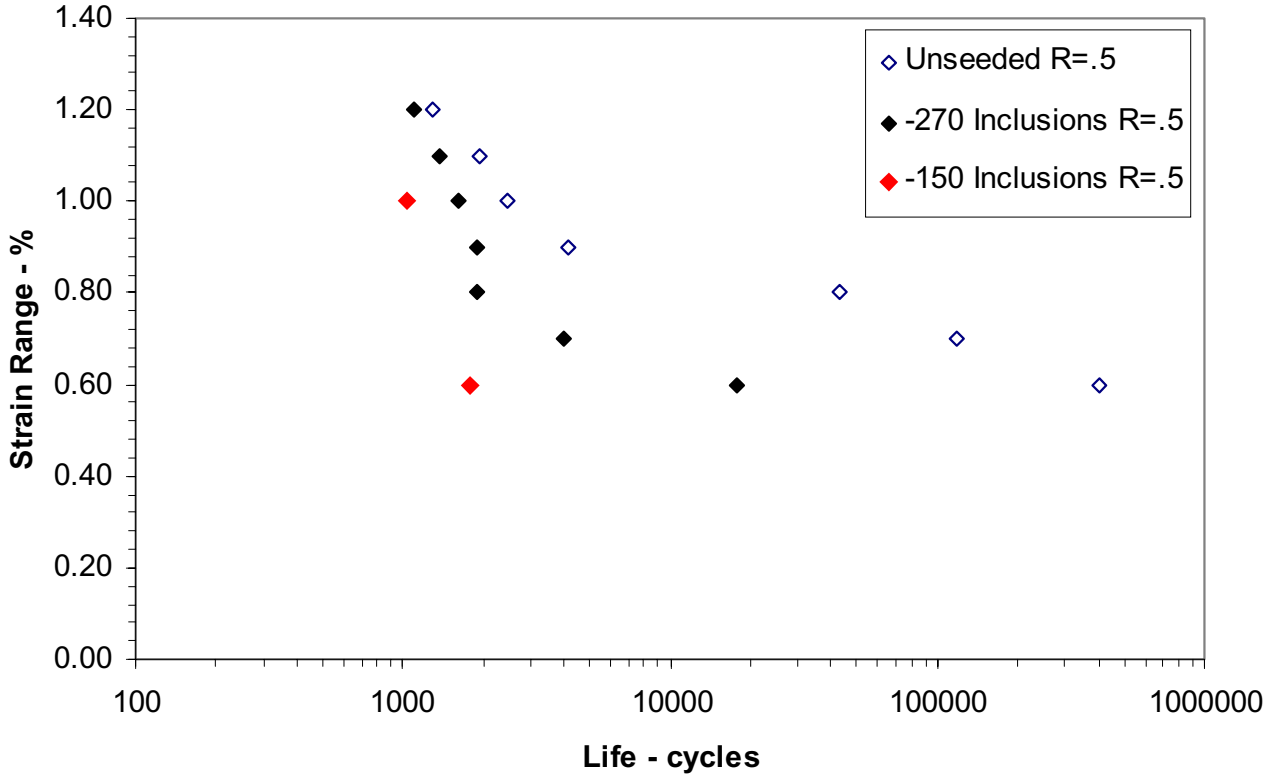
Average # of Intercepts:	0.42
Mean Area/Seed [mils^2]:	0.2
Area/Seed SD [mils^2]:	0.02

Fracture Surface Seeds



Preliminary LCF Results

LCF Life at 1200°F, R = 0.5



Summary

- Seeding study underway to characterize effect of ceramic inclusions on part life
- Monte-Carlo Simulation Model adequately estimates occurrence rate and intercepted area distributions of seeded inclusions
- Preliminary LCF results promising
- Ultimate goal: determine effect of naturally occurring ceramic inclusions on component reliability

Material Parameters

270 MESH PRODUCTION QUALITY UDIMET 720 POWDER FROM SPECIAL METALS

Processing Conditions

Same conditions for both seeded and unseeded material

HIP: 2025F / 15Ksi / 3hrs / cleaned to 9”dia

EXTRUDE: 5hr presoak / 2019F / 6:1 ratio
3.5”dia x 6.5”-7.0” mults

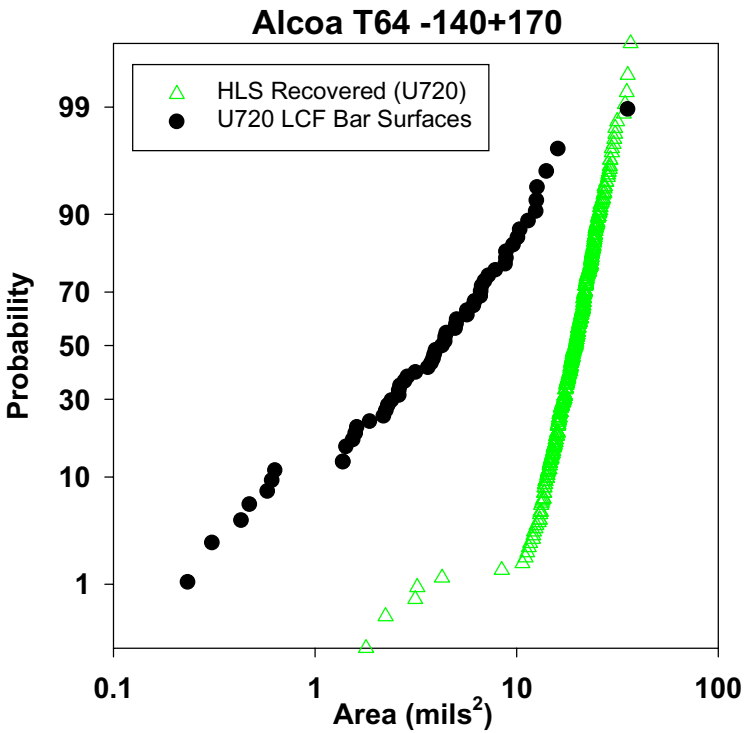
ISOFORGE: 1.5hr presoak / 2000F / 0.1 $^{in}/_{in}$/min
75% upset / final thickness 1.6”

Heat treat Conditions

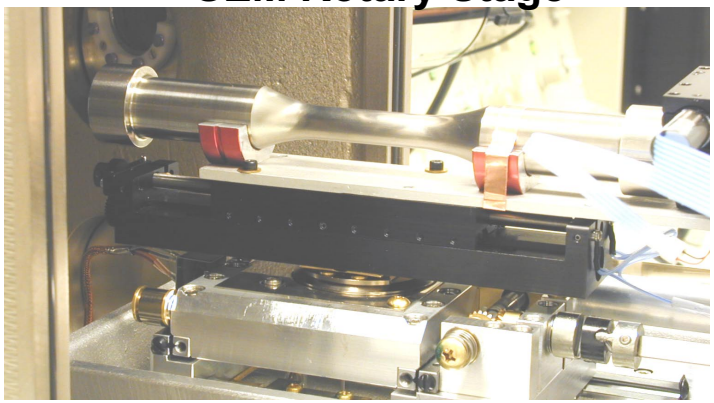
SUB SOLVUS SOLUTION: 2050F / 3Hrs / DOQ

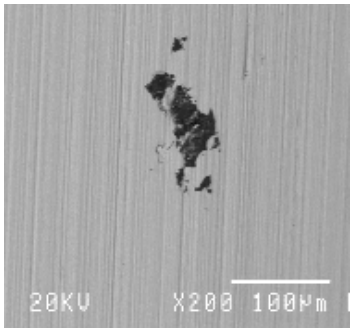
AGING: 1400F / 8Hrs / AC
1200F /24Hrs / AC

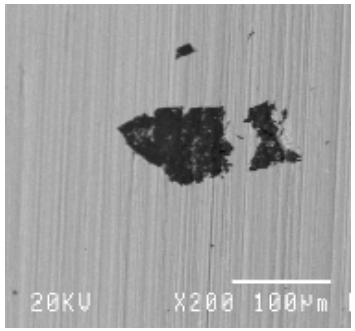
Seed Characterization: LCF Bar Surfaces



SEM Rotary Stage

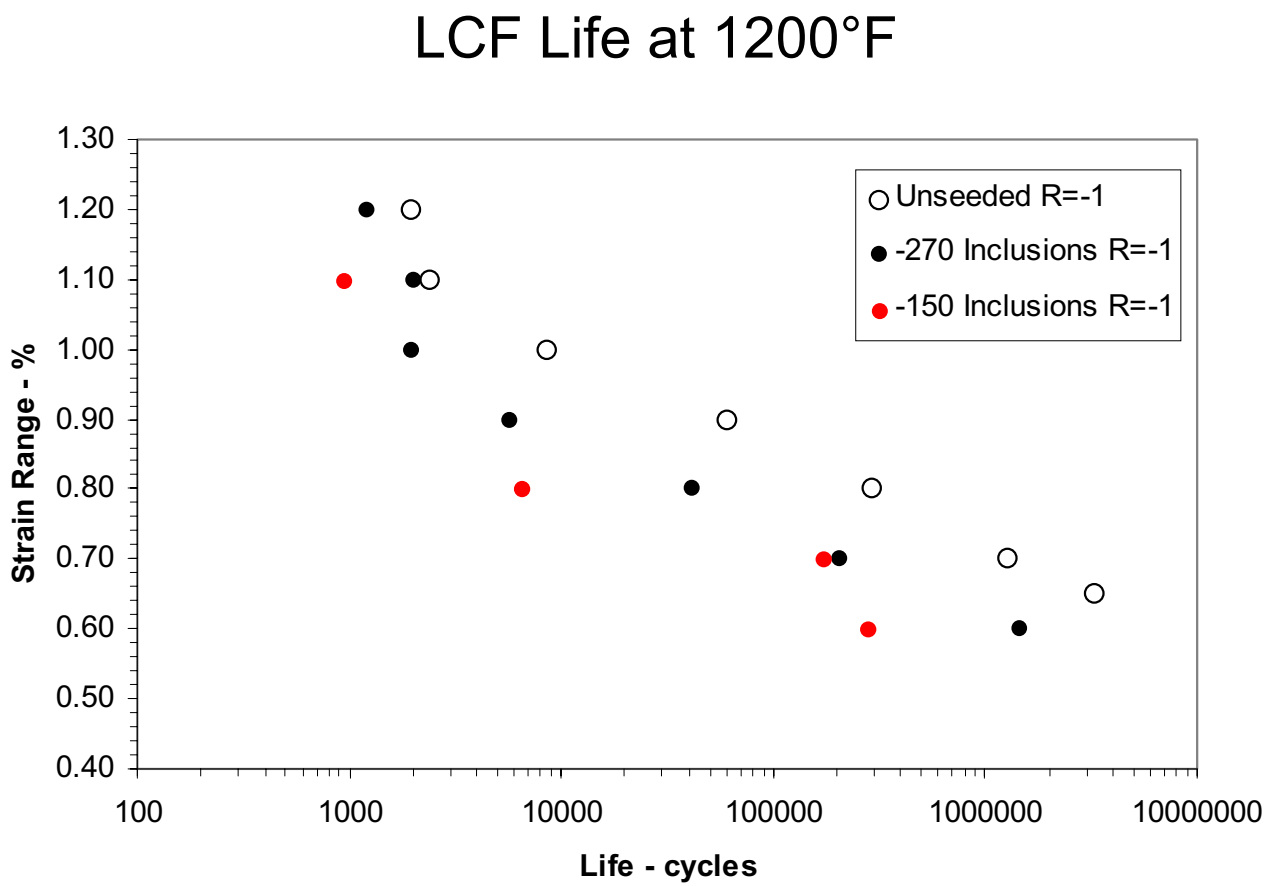




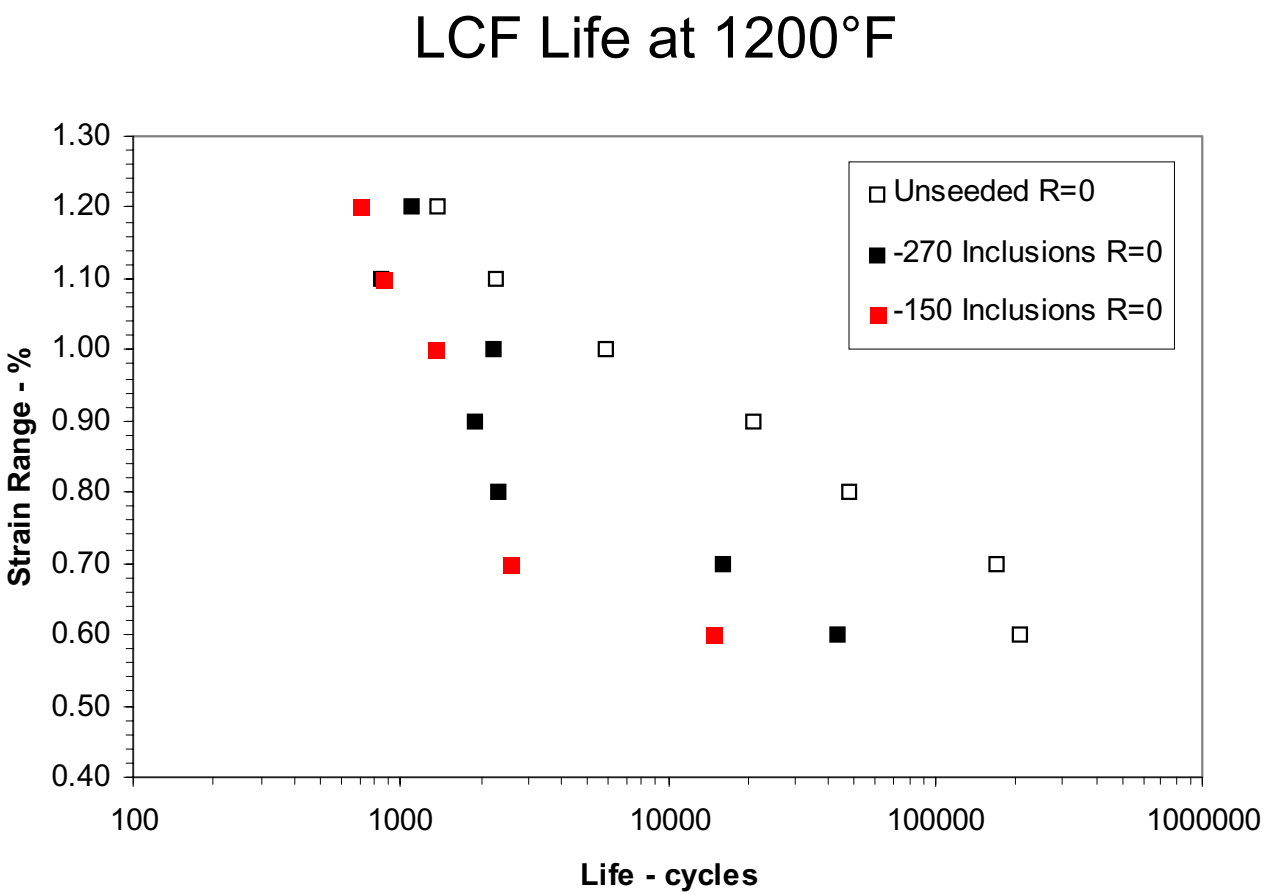


- Interrupted Testing
- Crack initiation and incubation

Preliminary LCF Results



Preliminary LCF Results



Integrating the Probability of Burst Over Volume

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Fax: (+44) 1332 240327
Email: Richard.Corran@rolls-royce.com

AC 33.14.1 introduces the concept of a probabilistic assessment of the risk of burst of a high energy rotor in a gas turbine engine from a hard alpha type particle in a titanium rotor disc. The method uses an exceedance curve which gives the probability per unit mass of an anomaly, in this case hard alpha being larger than the given size. Fracture mechanics is used to calculate the size of initial crack which will just fail (or survive) the required life of the part. The probability of burst of the rotor is then simply the integral of:-

$$\Pr(Burst) = \int_{\text{volume}} \Pr(\text{Exceeding } a_{crit}) \text{density}.dv$$

where a_{crit} is the critical crack size for the small volume element dv and the exceedance curve give the Pr(exceeding a_{crit}). In the method described in the AC the component is divided into zones in each of which a_{crit} is assumed constant. In practice it varies continuously across the part. This paper examines different strategies of using Gaussian integration as used in the formulation of the stiffness matrices in finite elements to identify an optimum combination of convergence and minimisation of the number of points at which fracture mechanics need be performed. This recognises that performing the fracture mechanics calculations in such assessments is often the most time consuming aspect of the work.

NASA/CP—2002-211682

Integrating the probability of burst over a volume

Dr R S J Corran & Dr K Pacey

Rolls-Royce plc

Derby UK

The problem

- At every point in the component there is a critical crack size, a_{crit}, which will just fail in the last cycle of the service life
- The material has an underlying cleanliness which gives θ anomalies per unit mass with a size distribution given by:-

$$\Pr(\text{x is largest anomalyin unit volume}) = 1 - e^{-\left(\frac{x}{\eta}\right)^{\beta}}$$

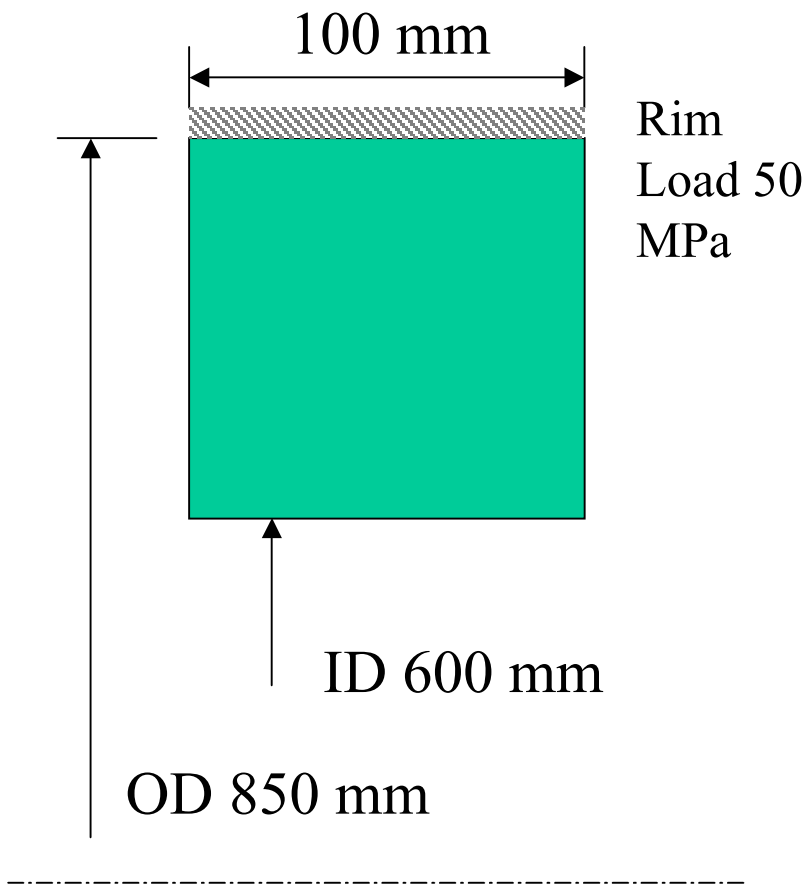
- Then probability of failure is given by:-

$$\Pr(Failure) = \int_{Volume} \Pr(\text{anomaly} > a_{crit})$$

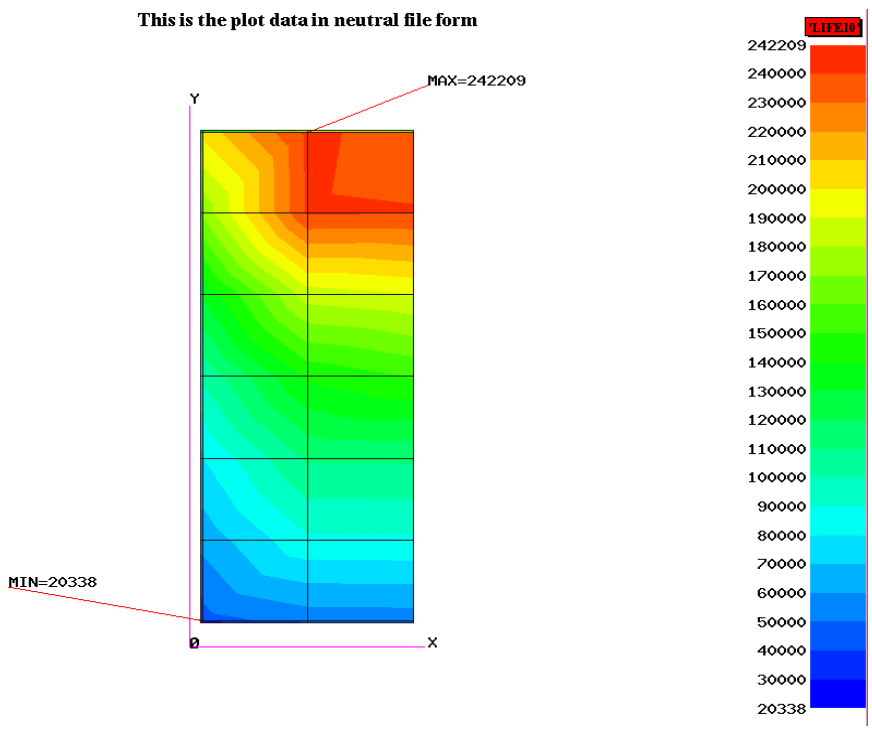
Sample problem

- The test problem from AC 33.14.1

Material Titanium 6/4

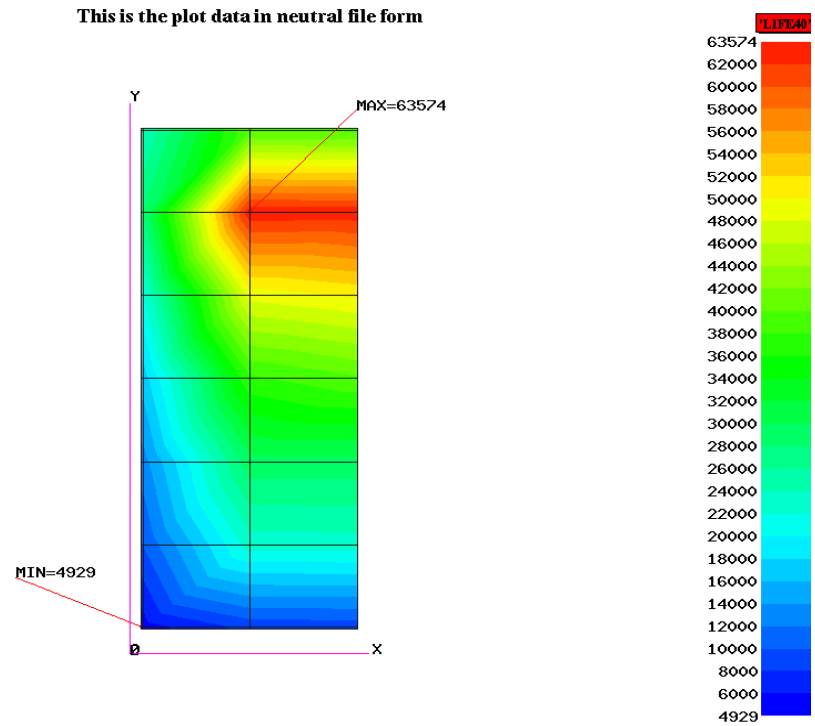


Crack propagation results



Crack Propagation life

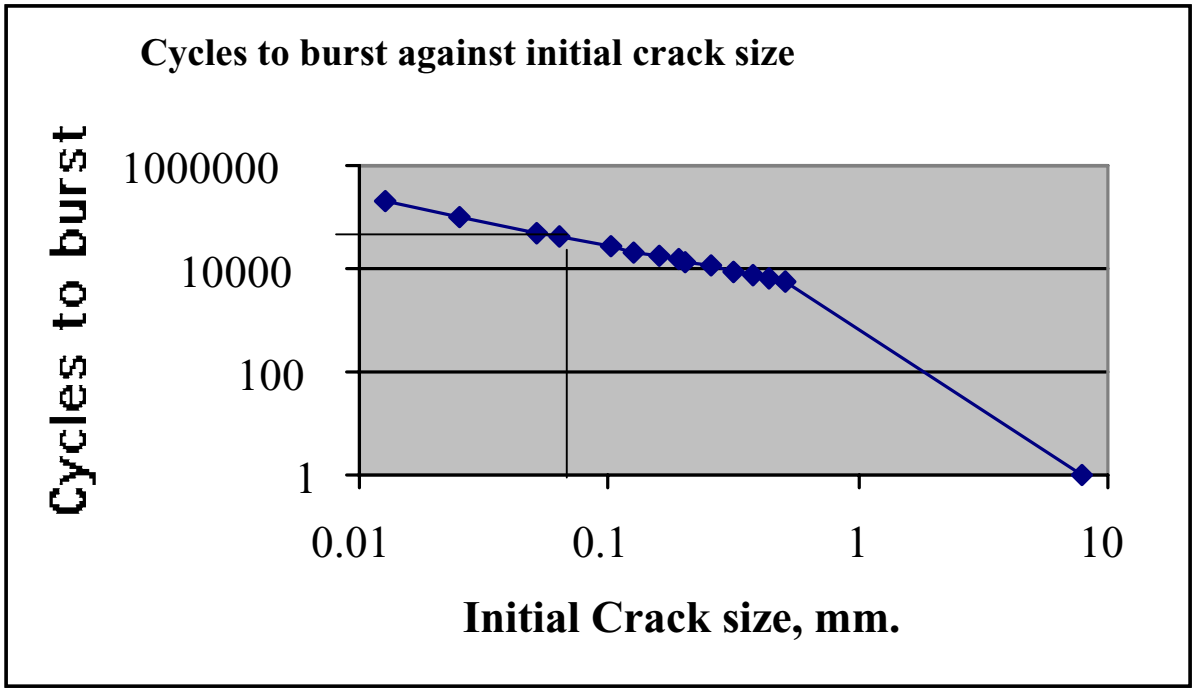
for 0.010” dia. crack



Crack Propagation life

for 0.040” dia. crack

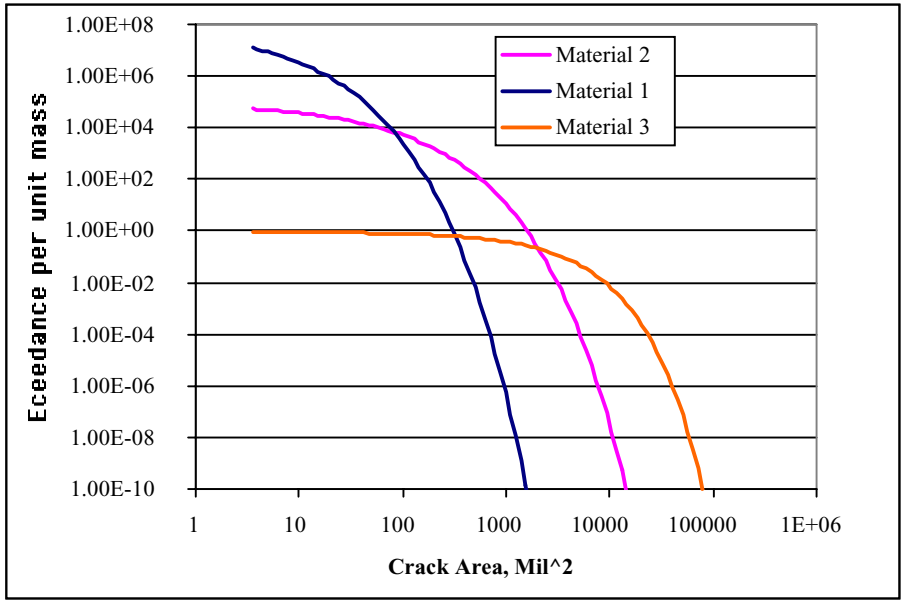
Finding the Critical Crack size, a_{crit}



- For a life of 20000 cycles, $a_{crit} \cong 0.08$ mm

Material Cleanliness

- 3 Imaginary materials used to examine integration:-
- Material 1 has lots of tiny anomalies but few large (e.g. powder)
- Material 3 has rare anomalies but large when they do occur (Ti)
- Material 2 lies between (Ni?)

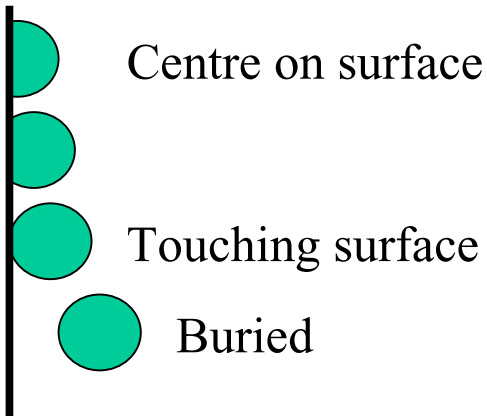


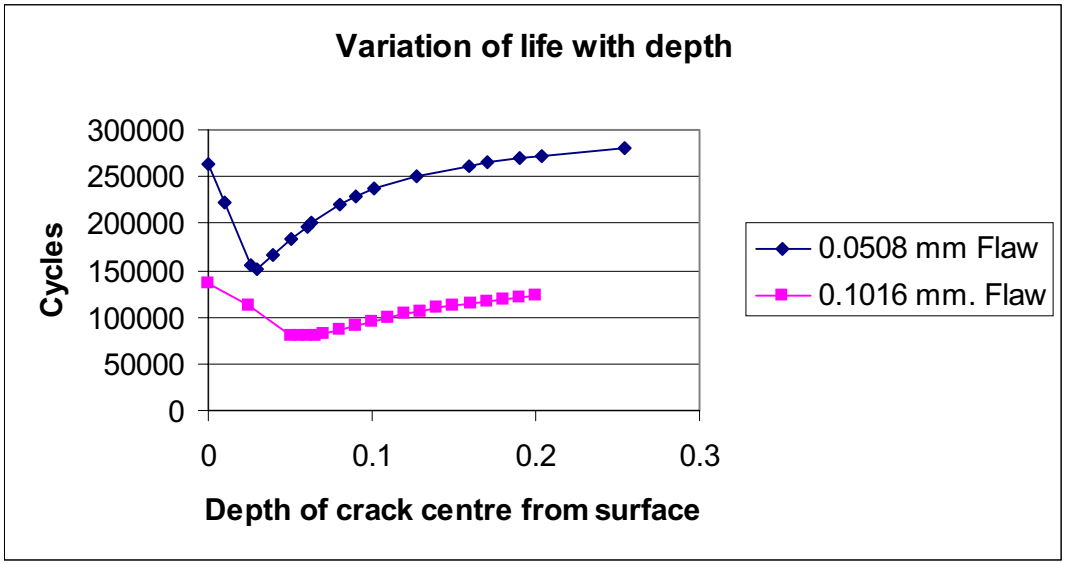
The approach

- Turn the integration into a sum by dividing the component into zones.
- At each “node” calculate the probability of an anomaly > a_{crit} per unit volume
- Integrate in each zone using gaussian methods as for finite elements
- Sum up probability of failure for all zones

What happens at the surface?

- As centre of crack moves away from surface into depth of component, life initially falls and then increases
- Life is a minimum when crack is just touching surface, i.e. radius of crack = depth





Integrating a zone

- Using gaussian integration:-

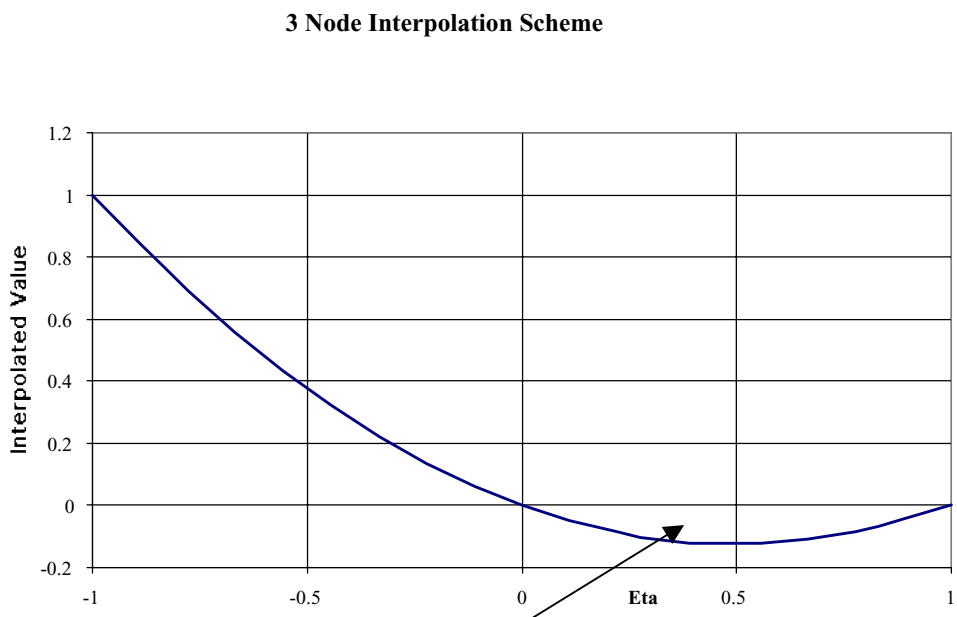
$$\int_{-1}^{1} f(x)dx = \sum_{i=1}^{n} w_i f(x_i)$$

- Values of x_i and w_i are published in tables, e.g. Abramowitz & Stegun (Dover)
- Accurate to polynomial of order 2n-1
- In axi-symmetric body integrate in two dimensions:-

$$\int_{-1}^{1}\int_{-1}^{1} f(x,y)dxdy = \sum_{j=1}^{n}\sum_{i=1}^{n} w_j w_i f(x_i, y_j)$$

Interpolation at integration points

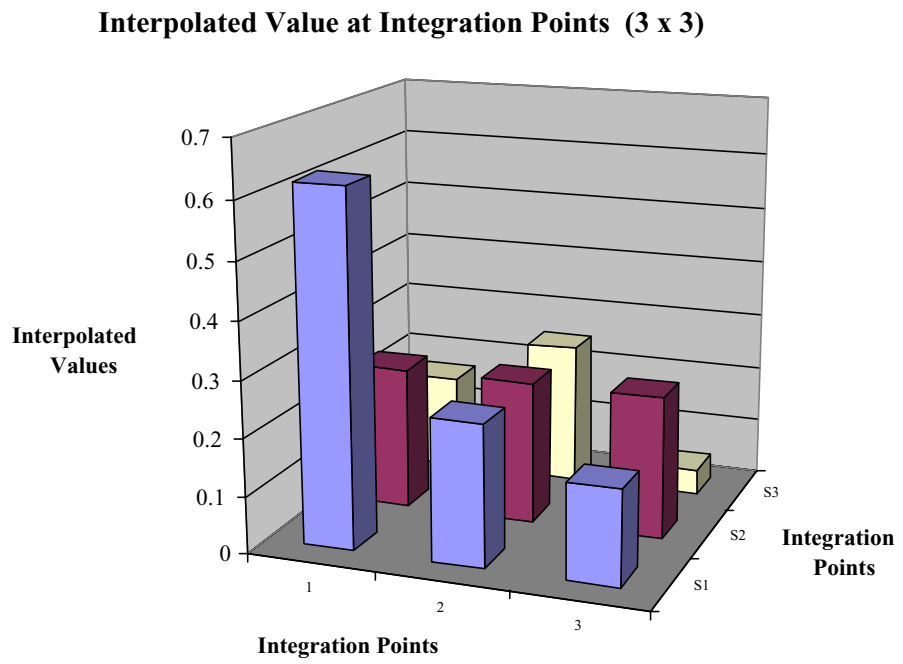
- Interpolation must not produce negative probability
- Hence use of higher order than linear may be dangerous



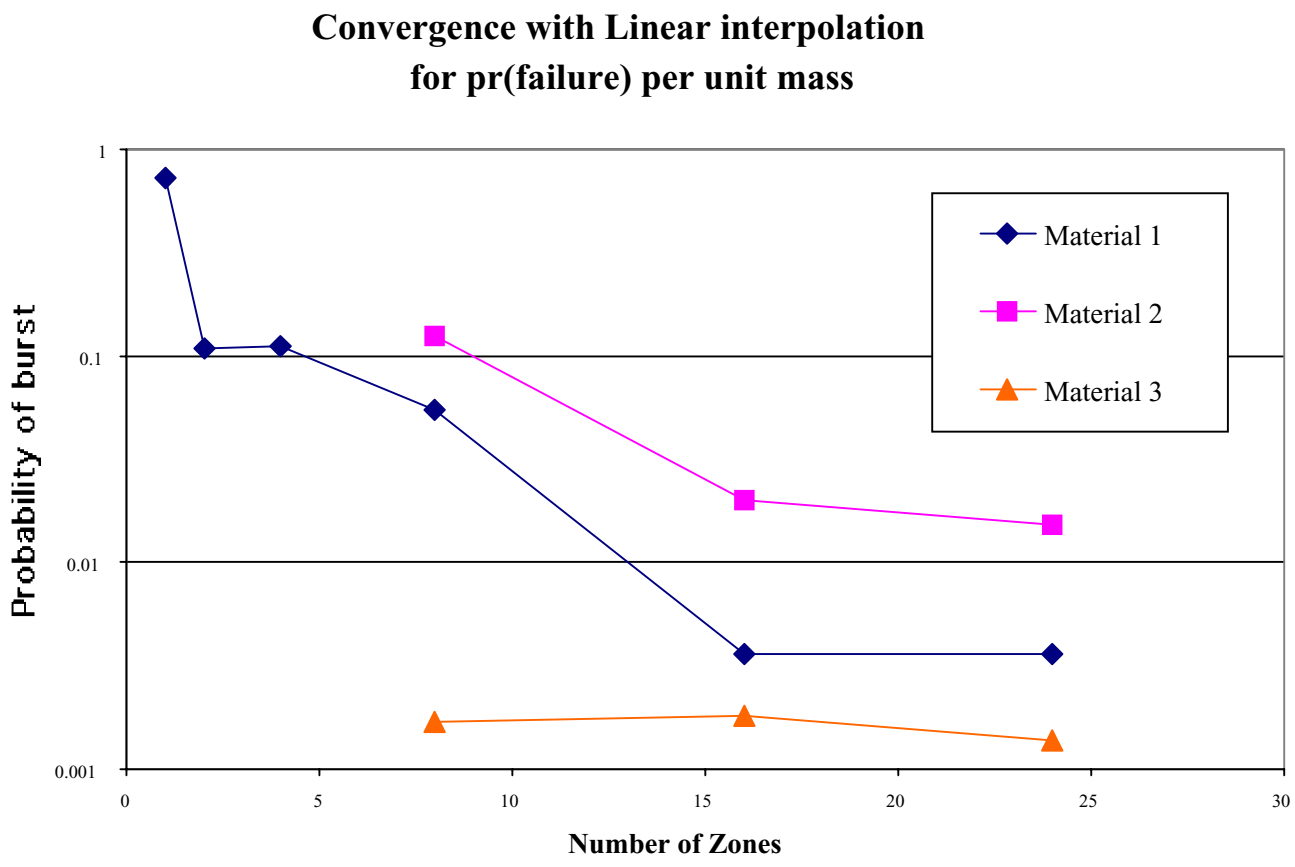
Negative probability

Integration

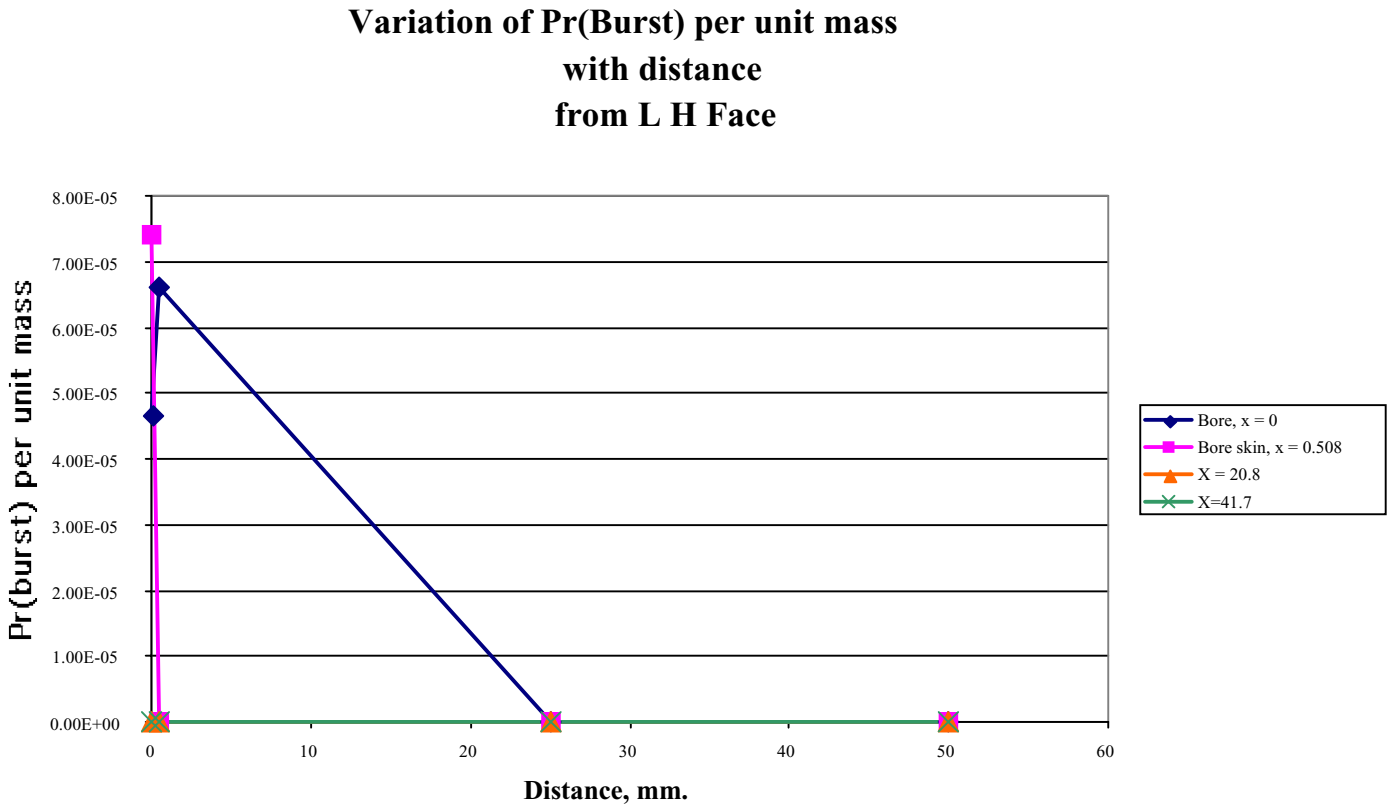
- Simple 3 node triangles will always work
- What about 4 node quad?
- Example has'1' at one corner ad '0' at other three
- It works!



Convergence studies

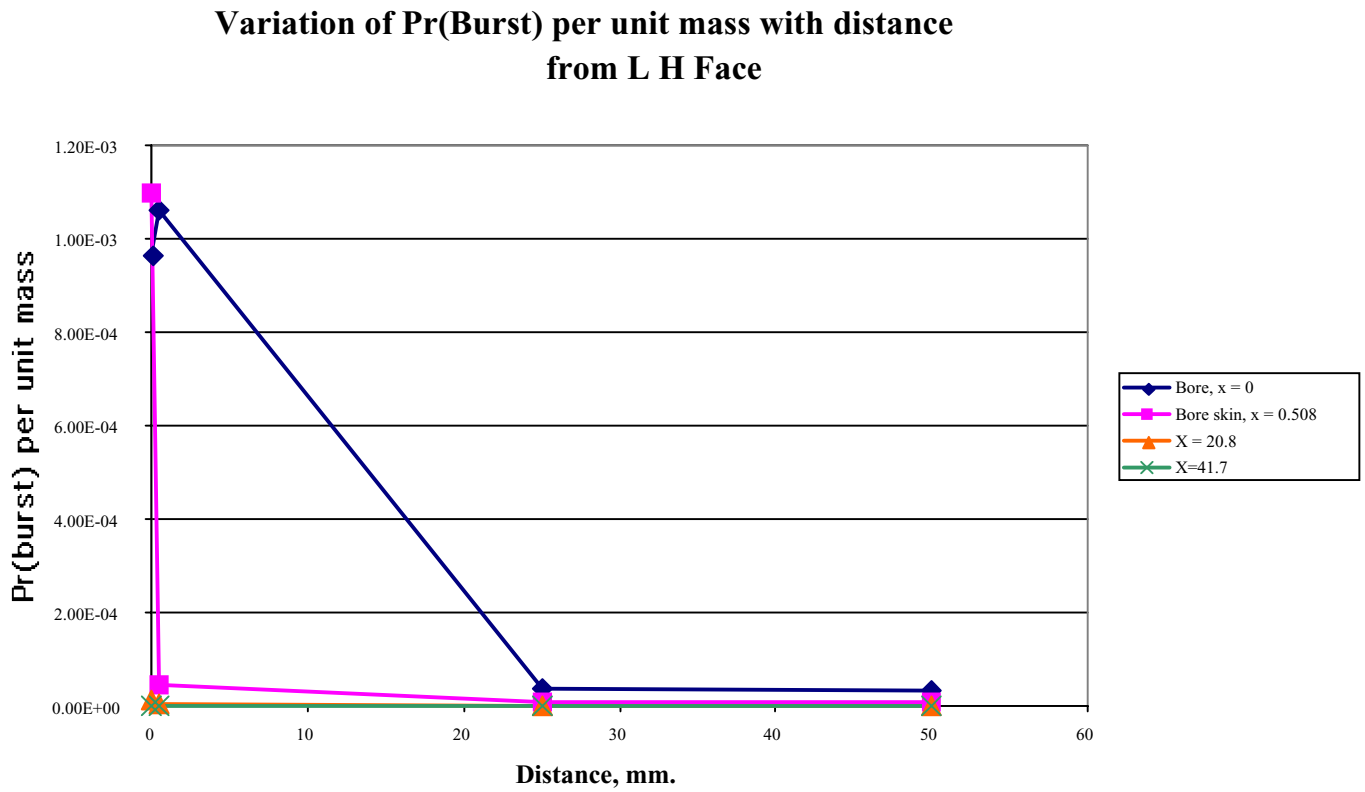


Distribution of probability



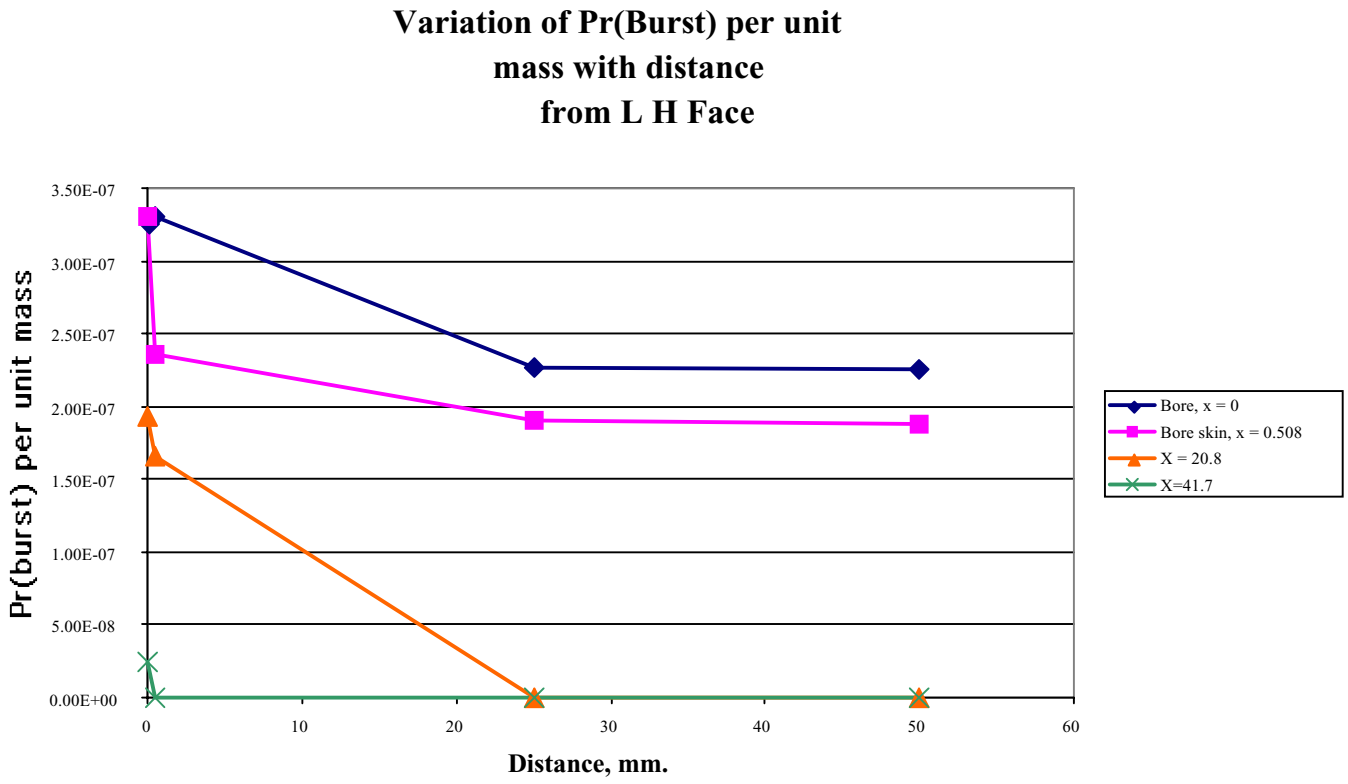
- Material 1

Distribution of probability



- Material 2

Distribution of probability



- Material 3

Recommendations

- Use Gaussian integration
- Only use linear interpolation
  - Either triangles or quads will work
- The size of zones must be small enough to approximate the variation of probability by straight lines
- Pay a lot of attention both at and near surfaces

Summary

- The use of FEM methods of Gaussian integration has been examined
- It works but due to the limitations of always maintaining positive pr(burst), it is restricted to linear interpolation
- Hence the criterion for adequate resolution must be based on a piecewise linear approximation to the variation of pr(burst)

A Perspective on Reliability: Probability Theory and Beyond

Panel Discussion: Issues and Strategies for Reliability-Based Certification Methodologies

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To discuss the applicability of traditional reliability philosophy and analysis, the foundations and fundamentals of probability theory are considered. The discussion will also include alternatives to probability theory and to test data-based reliability growth analysis. The latter is especially important when required test data are absent or difficult/expensive to obtain. Probability approaches include Bayesian methods that can be broadened to include mathematical integration of all available sources of information, including formal use of expert knowledge. In integrating such diverse sources of information, uncertainties must be characterized, quantified and propagated. Methods for these uncertainty issues include probability theory and alternative paradigms of logic such as fuzzy logic. Such methods have been successfully demonstrated in reliability applications in the automotive industry and national defense.

NASA/CP—2002-211682

A Perspective on Reliability: Probability Theory and Beyond

or

What Probability Is and Is Not

Jane M. Booker, Ph.D.
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Definitions of Probability

- The quality or state of being probable; appearance of reality or truth; reasonable ground of presumption; likelihood.
- "Probability is the appearance of the agreement or disagreement of two ideas, by the intervention of proofs whose connection is not constant, but appears for the most part to be so." Locke
- "The whole life of man is a perpetual comparison of evidence and balancing of probabilities." Buckminster
- "We do not call for evidence till antecedent probabilities fail." J. H. Newman
- (Math.) Likelihood of the occurrence of any event in the doctrine of chances, or the ratio of the number of favorable chances to the whole number of chances, favorable and unfavorable.
- Synonyms: Likeliness; credibleness; likelihood; chance

Mathematical Probability

A set function P defined for all sets in a Boolean field F having these properties is referred to as the probability measure on F:

- For every event, E, in Boolean field, F, there is associated a real non-negative number $P(E)$, called the probability of event E.
- If E_1, E_2, … is a countably infinite sequence of mutually disjoint sets in F whose union is in F then

$$P((E_i) = \Sigma P(E_i)$$

- $P(R)=1$ (R is the sample space.)

P is the probability measure (or probability distribution) on the Borel field F— $B(F)$

Probability: A Calculus for the Uncertainty of Outcomes

The *outcome* of E is uncertain.

- $P(E)$ describes the uncertainty about the *outcome*.
- The bet is two-sided and it will be unambiguously settled when E is performed, and the *outcome* is observed.
- Thus, $P(E)$ can be interpreted and made operational.
- Note that probability theory does not tell how to arrive upon a $P(E)$, nor in its abstract form even interpret $P(E)$. This is a job of a statistician/analyst.

Probability: A Calculus for the Uncertainty of Outcomes

A foundation for the theory of probability is:

- A well-defined specification of a set *outcomes*, and its subsets
- An adherence to the *law of the excluded middle*; i.e., any outcome either belongs to a set or does not belong to a set—*Crisp Set*
- A calculus (or algebra) based on some behavioristic axioms, involving numbers between 0 and 1, which can be made operational after *E* is performed.

The Three Axioms of the Calculus of Probability

i) $0 \leq P(A) \leq 1$

ii) $P(A \cup B) = P(A) + P(B) - P(A \cap B)$,

iii) $P(A \cap B) = P(A \mid B)\, P(B)$
$= 0$ if $A \cap B \bullet \varnothing$;

where $P(A \mid B)$ is the conditional probability of A should $w \in B$ and $A \cap B \bullet \varnothing$ which implies event A is independent of event B if $P(A \mid B) = P(A)$ and vice versa.

Probability is Coherent

Interpretations of Probability

At least 11 different theories or interpretations or meanings of probability.

Focus on two with this calculus (coherence)

- Relative Frequency Theory
- Personalistic or Subjective Theory

There is not a unique interpretation of probability

Relative Frequency Theory

FOUNDERS: Aristotle, Venn, von Mises, and Reichenbach

INTERPRETATION:

- Measure of an empirical, objective and physical fact of the external world, independent of human attitudes, opinions, models and simulations.

  To von Mises— descriptive physical science

  To Reichenbach — theoretical structure of physics

- Never relative to evidence or opinion.

- Like mass, it is determined by observations on the nature of the real world.

Relative Frequency Theory

INTERPRETATION (continued):

- **Only** known aposteriori, i.e., **only** upon observation.
- Property of a *collective*, i.e., scenarios involving events that repeat again, and again—e.g., games of chance (like coin tossing) and social mass phenomena (like actuarial and insurance problems).
- Excludes one-of-a-kind or individual events (e.g. Mars lander)

Personalistic or Subjective Theory

FOUNDERS: Borel, Ramsey, Savage, DeFinetti

INTERPRETATION:

- No such a thing as an objective probability, unknown probability or correct probability
- Degree of belief of a given person at a given time — measured in some sense.
- Degree of belief could be expressed as a willingness to bet. Prob{event} = p => willingness to bet \$$p$ in exchange for \$1, should the event occur, and staking \$(1-p) in exchange for \$1, should the event not occur. [two sided bet]
- Accounts for all history (prior to observation or settling the bet) including expertise, mathematical modeling, experience, knowledge, records, etc.)

Includes: Bayesian

Probability — Caught in the Middle

Those insisting on precision or determinism—say probability is too wishy washy.

Those dealing with unknown or struggling with complexity—say it's too exacting, demanding, implying we know more than we do.

So what's a mathematical theory to do that is caught between"determinism" and "truth" ?

Probability Uses — I

- Uncertainty (some kinds)

Probability Cannot Capture All Uncertainties

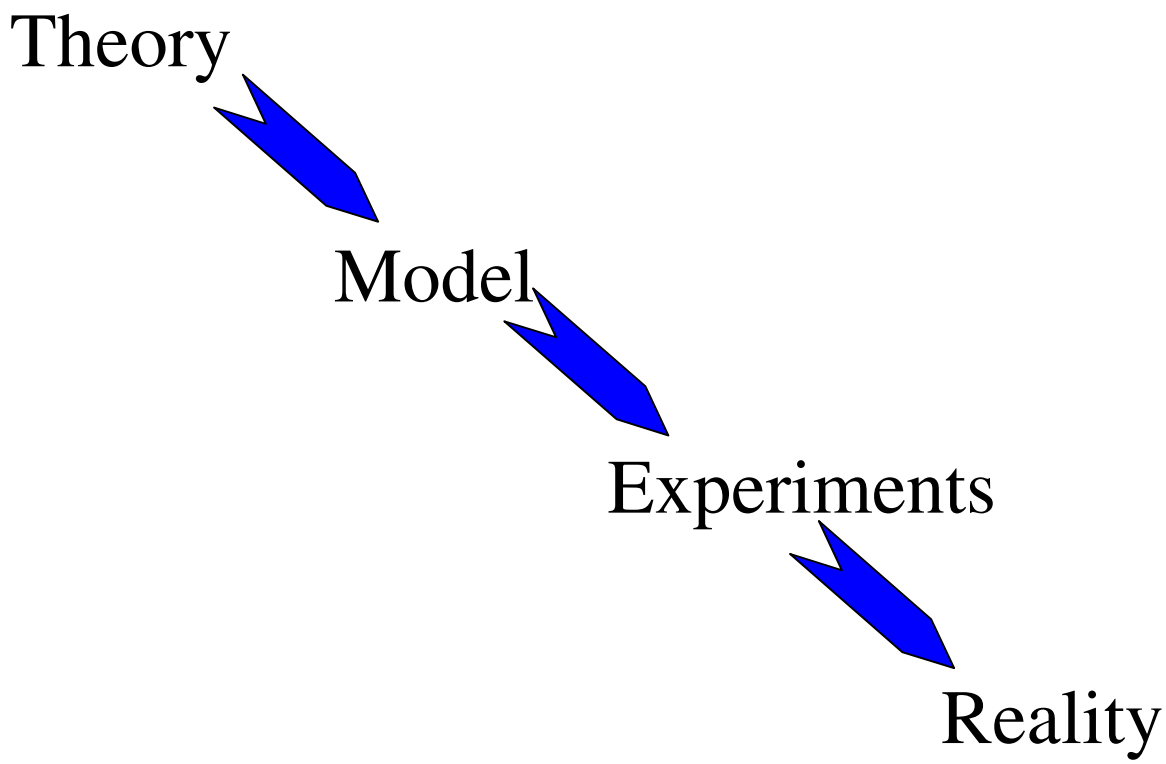
Uncertainties

Many meanings and connotations to different communities.

Propose a broad definition that includes:

- chance or randomness
- lack of knowledge or imprecise knowledge
- vagueness or ambiguity
- lack of precision (e.g., in measurements)
- approximation and inference (e.g., modeling)

Inference Continuum—Uncertainty



Uncertainties exist all along the continuum

Probability is Useful for Inference

Probability Uses — II

- Risk

$$Risk = Probability * Consequence$$

Probability is Useful for Risk

Probability Uses — III

- Performance / Reliability

Reliability = Probability {system performs according to specifications}

Probability is Useful for Reliability

Humans Are NOT Probabilistic Thinkers

- Studies have shown humans do not think well in terms of probability. {Difficult}
- They cannot estimate probability well {Miscalibrated}
- They underestimate uncertainty {Over confidence bias}

Probability is not recommended for elicitation

Probability Useful for Complex, Dynamic Problems

- Performance / Reliability
- Uncertainties
- Risk

Probability is a Useful Base For a Methodology that Integrates All Available Information for Decision Making

Probabilistic Information Integration Technology (IIT) Methods

- For sparse data problems, combine everything we know and how well we know it (uncertainty)
- Provide the capability for continuous evaluation of effectiveness/performance as the system changes and/or as new information becomes available.
- Include formal use of expert judgment elicitation and analysis
- Estimate and integrate uncertainties in all sources of information
- Provide guidance for test planning, design improvements, alternate environments, and other decisions.

Probabilistic Information Integration

We have developed and successfully applied a set of formal techniques to predict effectiveness and/or performance by mathematically combining all sources of data/information into an overarching process for decision making.

NOT a piece of software—
It's a methodology

Probabilistic Information Integration

These formal techniques have their origins in multiple disciplines:

- **Statistics / Probability**
- **Reliability**
- **Anthropology**
- **Knowledge Acquisition**
- **Computer Science**
- **Rule-based (Fuzzy) Logic**

PREDICT—1999 R&D 100 Award

Developers: Mary Meyer, Jane Booker, Tom Bement

PREDICT—Performance and Reliability Evaluation with Diverse Information Combination and Tracking.

Two successful applications with sparse data:

Delphi Automotive Systems—birth to death development of new auto system designs

Los Alamos Nuclear Weapons Program—performance estimation of the aging nuclear physics package

Beyond Probability

Theories for Combining and Specifying Uncertainties

- Calculus of probability
- Fuzzy Logic [Zadeh (1965)]
- Possibility Theory [Dubois and Prade (1988)]
- Jeffrey's Rule of combination [Jeffrey (1983)]
- Upper and Lower Probabilities [Smith (1961)]
- Belief Functions [Dempster (1968)]

Fuzzy Set Theory: A Calculus for Imprecision

- Introduced by Lotfi Zadeh in 1965
- A mathematical construct in set theory—that enhances classical set theory
- Useful for quantification: turning rules into numerical functions
- Designed for capturing a vagueness type of uncertainty.

Fuzzy Set Theory: A Calculus for Imprecision

Consider the set of integers $X=\{\mathbf{1, 2, \ldots, 10}\}$.
Define a subset, of X, where
A = $\{x : x \in X$ and x is "medium"$\}$
Defining A implies a precision in defining what is "medium".

Most agree that 5 is a "medium" integer. What about 7? Is it "medium" or is it "large"? We are uncertain about the classification of 7. Because of this vagueness, we are unable to define the subset .

Fuzzy Sets and Membership Functions

Membership functions are a way of dealing with the above vagueness (or uncertainty).

$\mu_A(x)$ = membership function of A and is (almost always, but not necessarily) a number between 0 and 1 that reflects the extent to which $x \in$ A.

The expert assigns to each $x \in X$ a number, $\mu_A(x)$, and this is done for all subsets of the type that are of interest. The set is called a *fuzzy set*.

Fuzzy sets reject the law of the excluded middle.

For crisp (our usual) sets; all $x \in X$, $\mu_A(x) = 0$ or 1.

Fuzzy Sets and Probability

Suppose we have new information (say from experts) that can best be elicited using membership functions (fuzzy space).

However, our performance is a reliability (probability space) and our “prior” existing knowledge is a probability distribution function.

It can be shown that *membership functions* are *likelihoods*. Then Bayes Theorem provides the bridge between fuzzy and probability.

Beyond Probability

- Calculus of probability
- Fuzzy Logic [Zadeh (1965)]
- Possibility Theory (Dubois and Prade, 1988)
- Jeffrey's Rule of combination [Jeffrey (1983)]
- Upper and Lower Probabilities [Smith (1961)]
- Belief Functions [Dempster (1968)]

Working on Connecting Probability to These Other Theories

Damage Prognosis Technology

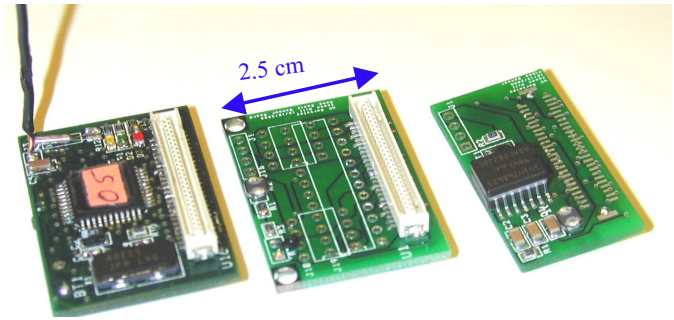
Preventing Catastrophic Failure

Predicting Remaining Life

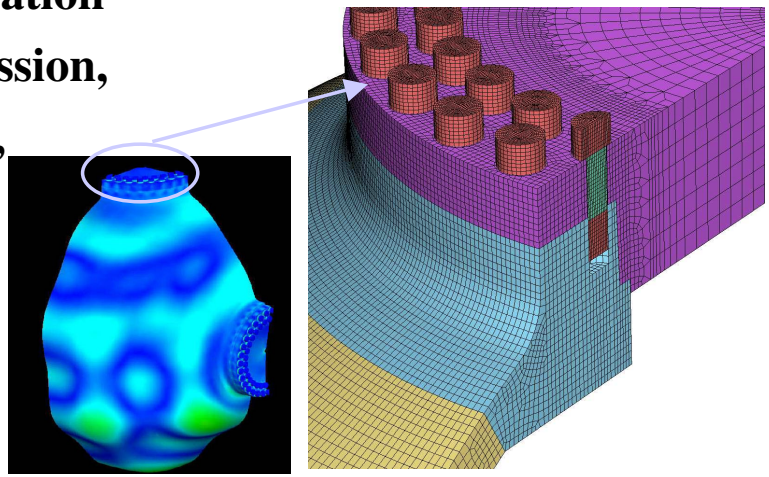
Advancing Damage Prognosis Technology

A coordinated, multidisciplinary effort is required to capitalize on recent revolutionary advances in:

- **Smart microelectronic sensing technology**
- **Tera-scale computer simulations**
- **of damage evolution**
- **Machine learning and information technology for model compression, large-scale data management,**
- **model correlation and**
- **probabilistic system life**
- **prediction**



A Smart Sensing System



Tera-Scale Simulation of a six-foot-diameter Steel Vessel Subject to Blast Loading

Damage Prognosis Technology Integrates

Smart Sensing and Computer Simulations to Diagnose and Forecast System Performance

1. Develops a Computational Model of the System
2. Measures Critical System Parameters and Identifies Damage
3. Updates the Computational Model of the System
4. Estimates the Future Loading Environments on the System
5. Simulates Updated System Response to Future Environments
6. Predicts the Remaining Useful Life of the System

Probabilistic Analysis of Gas Turbine Components Using the New ANSYS Probabilistic Design System

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Abstract - **The paper illustrates the capabilities of the new probabilistic design system (PDS) implemented and available in ANSYS 5.7. The individual probabilistic methods are illustrated and their use in the context of gas turbine engine design is illustrated. The post-processing capabilities of the ANSYS-PDS allow the engine designer and/or analyst to address the reliability and quality of the design.**

Index terms - **Finite elements (FE), Probabilistic analysis, Quality based Design, Reliability, Sensitivities**

I. INTRODUCTION

The manufacturing of structural components is generally associated with manufacturing imperfections that arise due to inherent physical reasons and financial constraints. In general, the geometry of a component cannot be reproduced with infinite accuracy, but only within certain finite tolerances. Also the material properties of a component are inherently subjected to scatter as can be observed in typical measurements of material properties. In general, the boundary conditions, such as environmental conditions and loads are uncertain as well.

In the following it is assumed that the behavior of the components of a gas turbine are assessed using Finite-Element methods, i.e. parameters describing this behavior are a result of a Finite-Element analysis such as stresses. As a direct consequence of the uncertainty of the input parameters the behavior of the component is subjected to scatter as well.

In this situation the new Probabilistic Design System (PDS) in ANSYS 5.7 [1] can be used to answer the following questions:

- How large is the scatter of the parameters describing the behavior of the component?
- What is the probability that by chance a performance criteria of the component is no longer met leading to either a certain scrap rate or to the failure of the component under operation conditions?
- What are the parameters on the input side that need to be tackled in order to achieve a robust and reliable design and minimize the failure probability and the scrap rate? The answer to this question automatically leads to measures that should be implemented during quality control in the manufacturing process.

II. PROBABILISTIC MODELLING AND METHODS

Based on their physical nature uncertainties are either random variables (constant in time and space), random fields (constant in time and random function of spatial coordinates), random processes (random function in time and constant in space) or combinations of these. This paper focuses on random variables for gas turbine components.

There are many probabilistic methods available in literature. This paper focuses on the Monte Carlo Simulation method and the Response Surface method. Both methods have been implemented in the ANSYS probabilistic design system [1,2].

III. PROBABILISTIC RESULTS

The ANSYS 5.7 program has been used to assess the temperatures, stresses and lifetime of a turbine blade (see Figures 1) influenced by uncertainties in geometry, material properties and boundary conditions. Histogram charts (see Figure 2) describe the amount of uncertainty that is induced on the result parameters. The failure probabilities and scrap rate can be illustrated by the cumulative distribution functions of the behavioral properties of the blade such as stresses (see Figure 3). Measures to increase the quality and reliability of the design can be directly derived from and illustrated by sensitivity charts (see Figure 4).

REFERENCES

[1] S. Reh, The ANSYS Probabilistic Design System, ANSYS Solutions, Vol. 3, No. 1, 2001

[2] S. Reh, et al., Quality based Design and Design for Reliability of Micro Electro Mechanical Systems (MEMS) Using Probabilistic Methods, Proceedings of the 3rd Int. Conference on Modeling and Simulation of Microsystems, San Diego

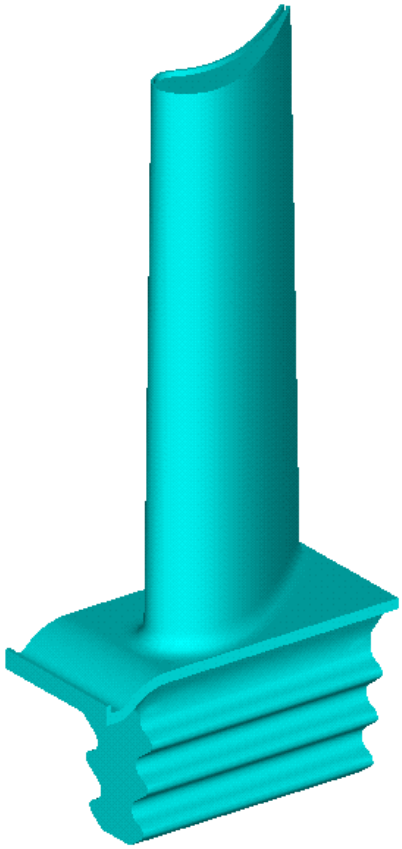


Figure 1 Gas Turbine Blade

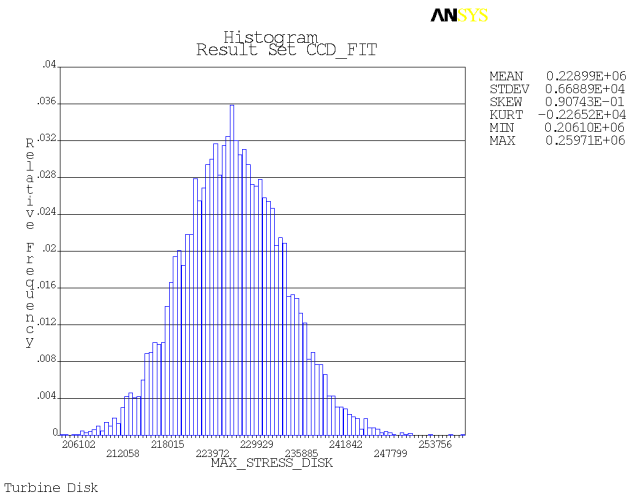


Figure 2 Histogram of Blade Stresses

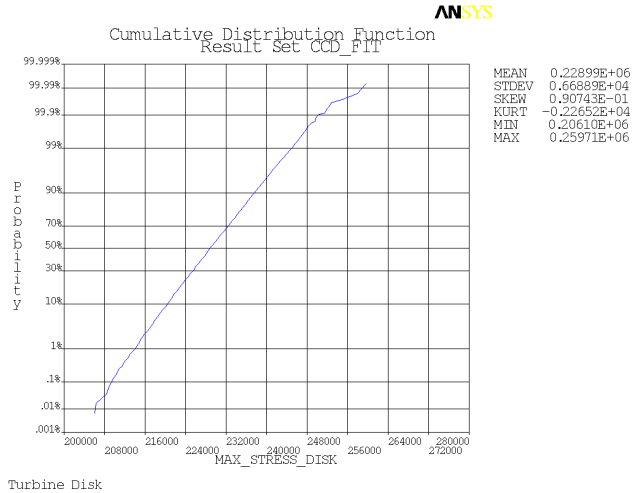


Figure 3 Probability of Blade Stresses

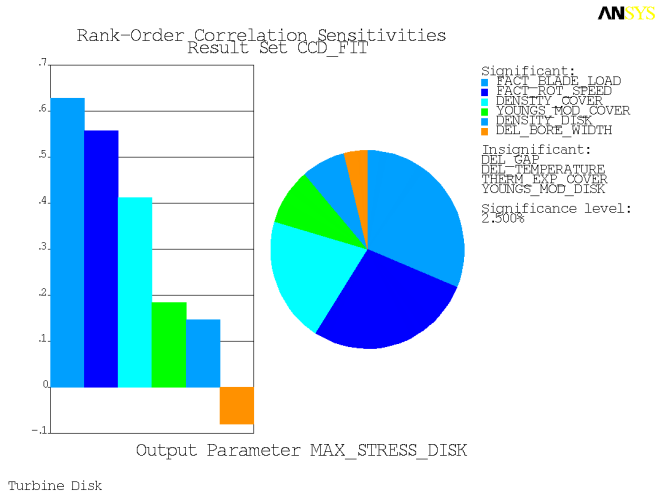
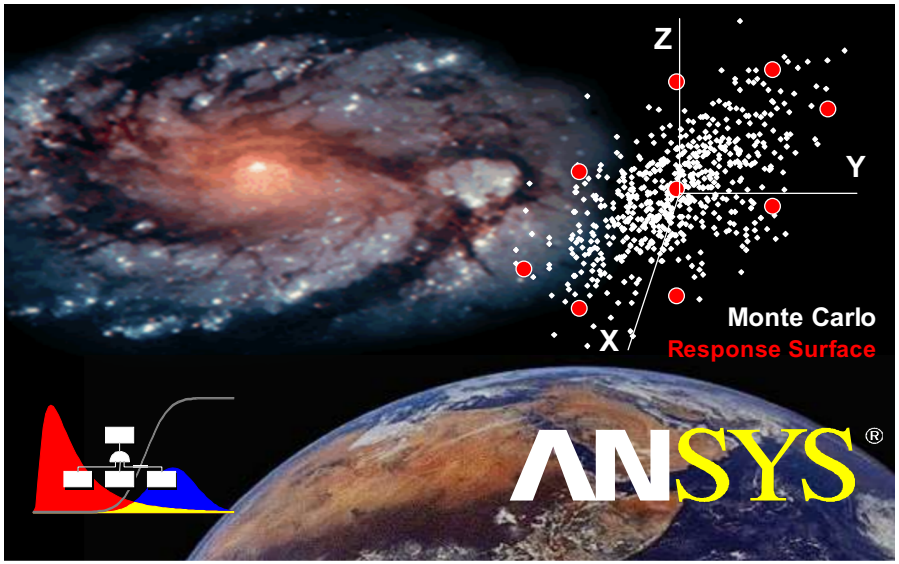


Figure 4 Sensitivities of Blade Stresses

Probabilistic Analysis of Gas Turbine Components using the New ANSYS Probabilistic Design System

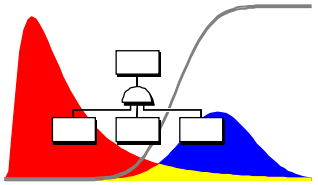
Dr. Stefan Reh

Team Leader and Sen. Development Engineer, ANSYS Inc.



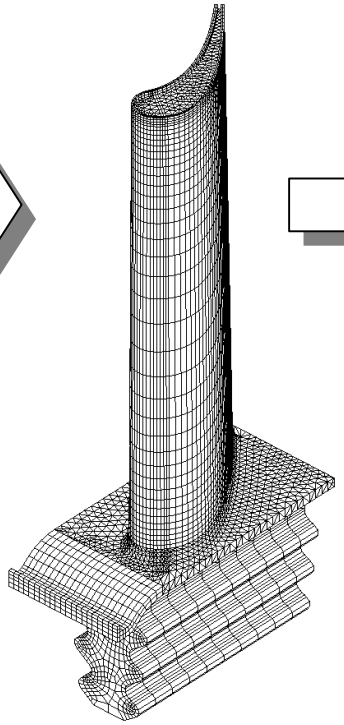
Probabilistic Design: Bringing CAE closer to REALITY!

ANSYS Probabilistic Design System:
Introduction



Component description

→ Material
→ Geometry
→ Loads
→ Boundary Condition

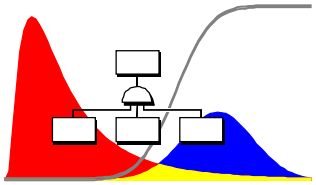


Component behavior

→ Deformations
→ Stresses
→ Lifetime (LCF,...)

Uncertainties → As a consequence of the uncertainties of the input parameters there will be also uncertainties of the results → **Uncertainties**

ANSYS Probabilistic Design System: *Features*



- The ANSYS/PDS is FREE for every ANSYS customer
- It works with *any* ANSYS model (static, dynamic, linear, non-linear, thermal, Structural, Electro-magnetic, CFD …)
- It allows for a large number of random input and output parameters
- It has 10 statistical distributions for random input variables
- The random input variables can be correlated
- Probabilistic methods:
  - Monte Carlo - Direct & Latin Hypercube Sampling
  - Response Surface - Central Composite & Box-Behnken Designs
- Sophisticated regression analysis capabilities for response surface fitting (automatic transformation functions for a “more than quadratic” fit, automatic filtering of insignificant regression terms to avoid “over-fitting” problem)
- Use of distributed, parallel computing techniques for drastically reduced wall clock time of the analysis
- Comprehensive probabilistic results (convergence plots, histogram, probabilities, scatter plots, sensitivities, ...)
- State-of-the art statistical procedures to analyze and visualize probabilistic results

ANSYS Probabilistic Design System: *Customer Base*

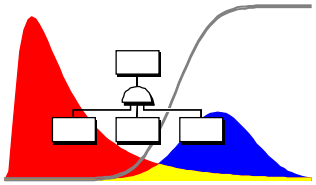
ANSYS Customer Base

- All "Top 10" Fortune 100 Industrial companies
- 73 of the Fortune 100 Industrial companies
- Over 5,700 commercial companies
- Over 40,000 commercial customer seats
- Over 100,000 university licenses

Probabilistic Design

- Available in ANSYS 5.7
- Used by 35 companies worldwide

Reliability of Gas Turbine Components: *Example Turbine Blade*



17 Random Variables for input variables

Geometry parameters

- Cooling channel shift (Circumference) UNIF(-0. 6,0.6)
- Cooling channel shift (Axial) UNIF(-0. 6,0.6)
- Thickness of oxidation protection LOG(0.3,0.03)

Material parameters

- Young's Modulus (*) NORM(1.0,0.04)
- Density (*) NORM(1.0,0.05)
- Therm. Expansion (*) NORM(1.0,0.05)
- Heat conduction (*) NORM(1.0,0.05)
- Heat capacity (*) NORM(1.0,0.04)
- Oxidation depletion rate (*) LOG(1.0,0.05)

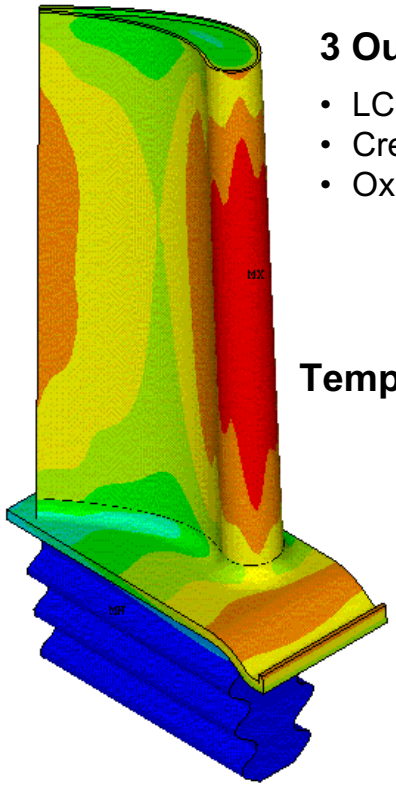
Strength related material parameters

- LCF curve (*) LOG(1.0,0.15)
- Creep rupture curve (*) LOG(1.0,0.10)

Thermal Boundary Conditions

- Hot gas temperature NORM(0.0,25.0)
- Hot gas heat transfer coefficient (*) LOG(1.0,0.2)
- Cooling air temperature NORM(0.0,10.0)
- Cooling air heat transfer coeff. (*) LOG(1.0,0.1)
- Hot gas mass flow (*) NORM(1.0,0.03)
- Cooling air mass flow (*) NORM(1.0,0.05)

(*) Factor relative to nominal value or curve



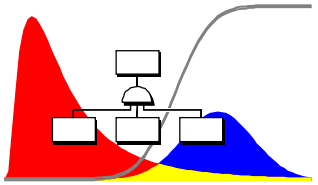
3 Output parameters

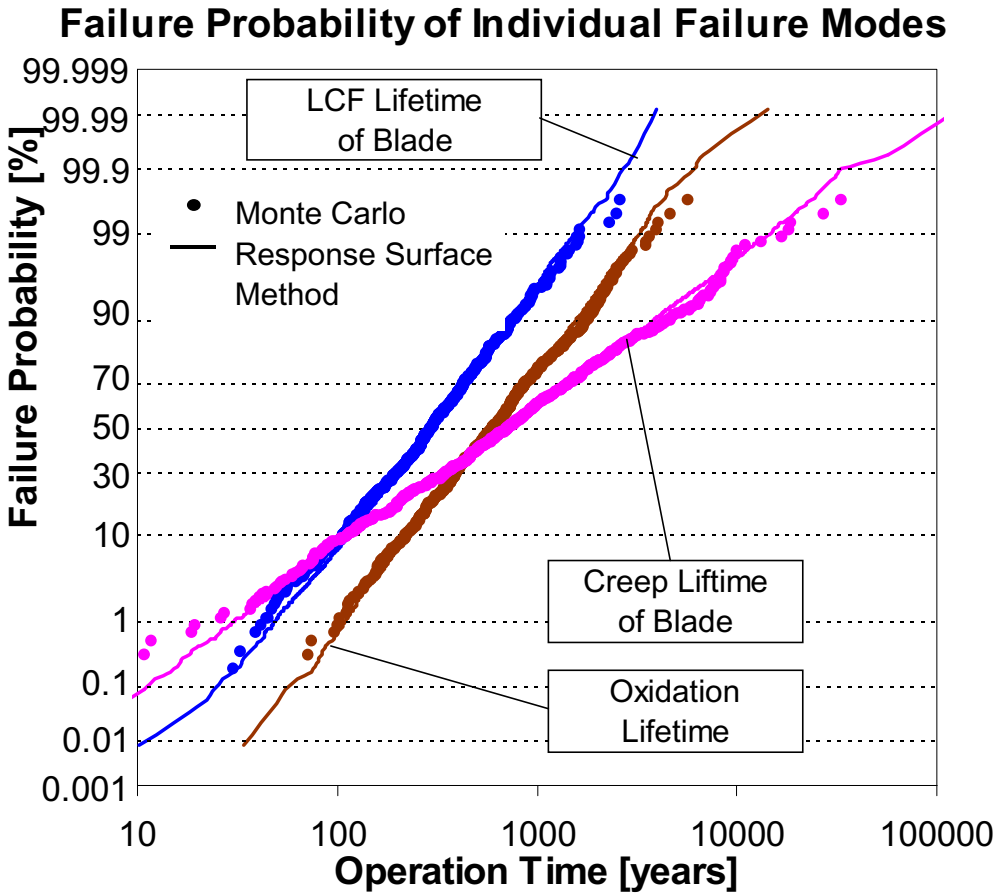
- LCF lifetime
- Creep lifetime
- Oxidation lifetime

Temperatures

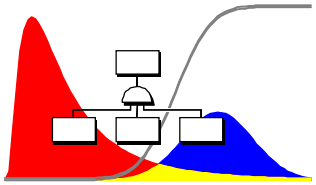
Thermo-mechanical analysis
60'000 Elements (quadratic)
180'000 Nodes
2 h of CPU time per analysis

Reliability of Gas Turbine Components:
Failure Probability of Turbine Blade

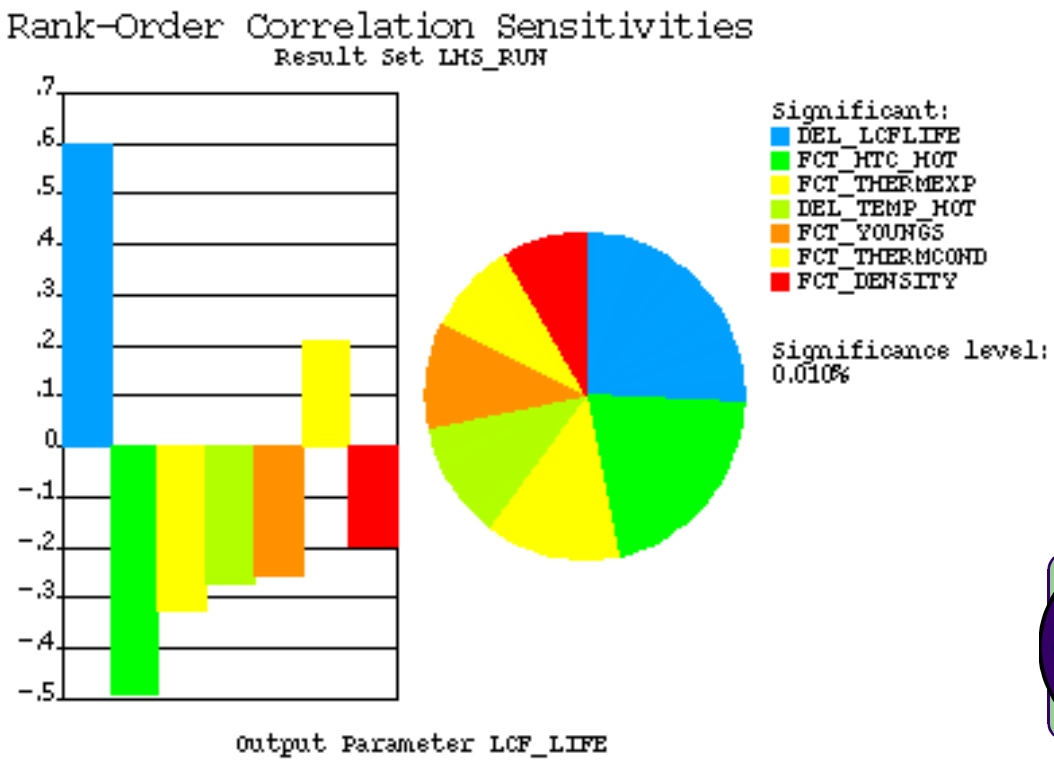




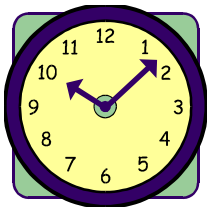
Reliability of Gas Turbine Components: *Sensitivities for Turbine Blade*



Sensitivities of the output parameters with respect to the random input variables



- **Improve the design efficiently if needed**
- **Justify spending to improve knowledge about the input parameters (lab tests)**
- **Save money without sacrificing reliability/quality**



Reliability of Gas Turbine Systems: *Example Turbine Stage*

Turbine Stage

100 Turbine blades on circumference
1 Turbine disk

Random input variables for turbine blades

- Geometry parameters (as described above)
- Material parameters (as described above)
- Strength parameters (as described above)

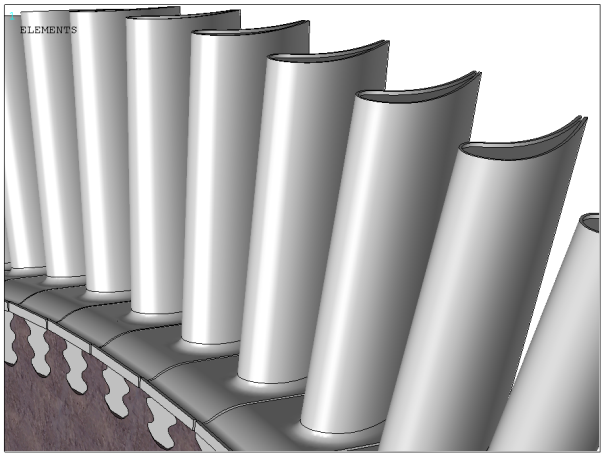
Random input variables for turbine disk
Cyclic crack growth of an existing crack in disk center that is just not detectable in non-destructive inspection

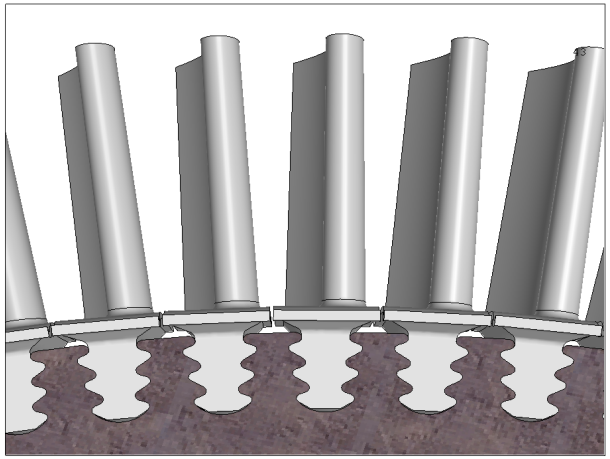
Fracture Mechanical Lifetime => Paris Law

- Initial crack size a_{init}
- Fracture toughness K_{Ic}
- Crack growth parameters A and n

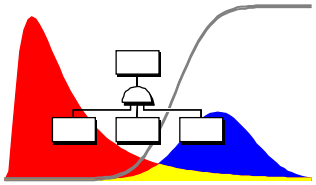
Random input variables for entire stage

- Thermal boundary conditions (as described above)





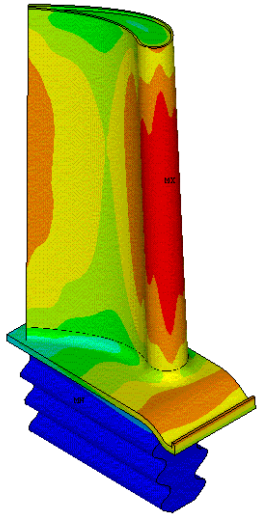
Reliability of Gas Turbine Systems:
Elements of the Turbine Stage

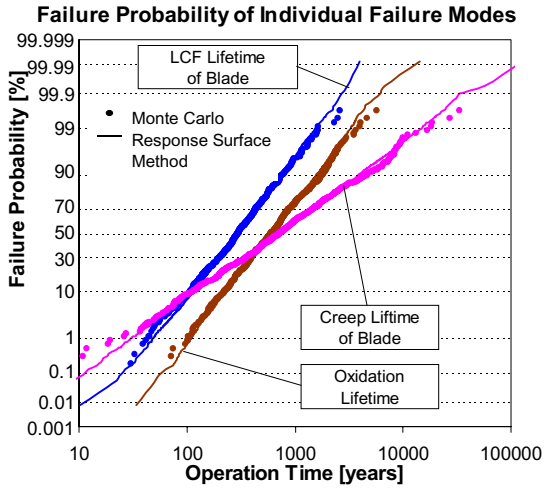


Entire Turbine Stage

100 Turbine Blades

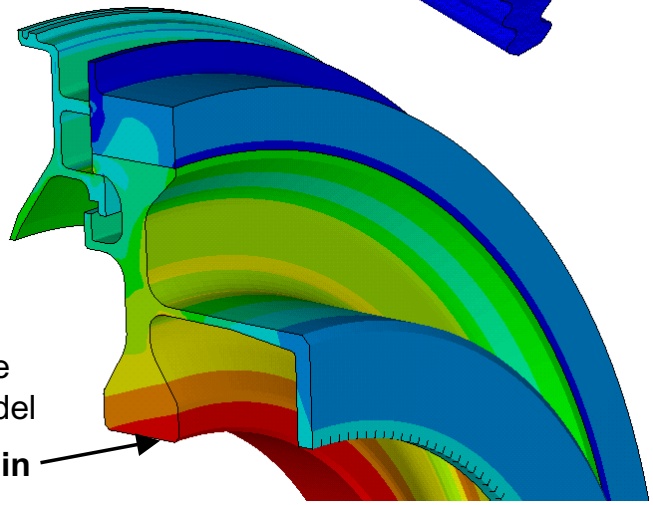
Temperatures





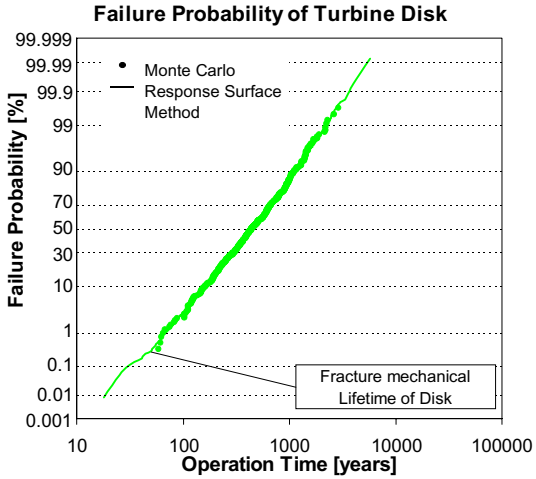
1 Turbine Disk

Stresses (*)



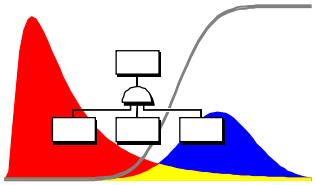
(*) Grooves for blade root attachment are not included in model

potential crack origin

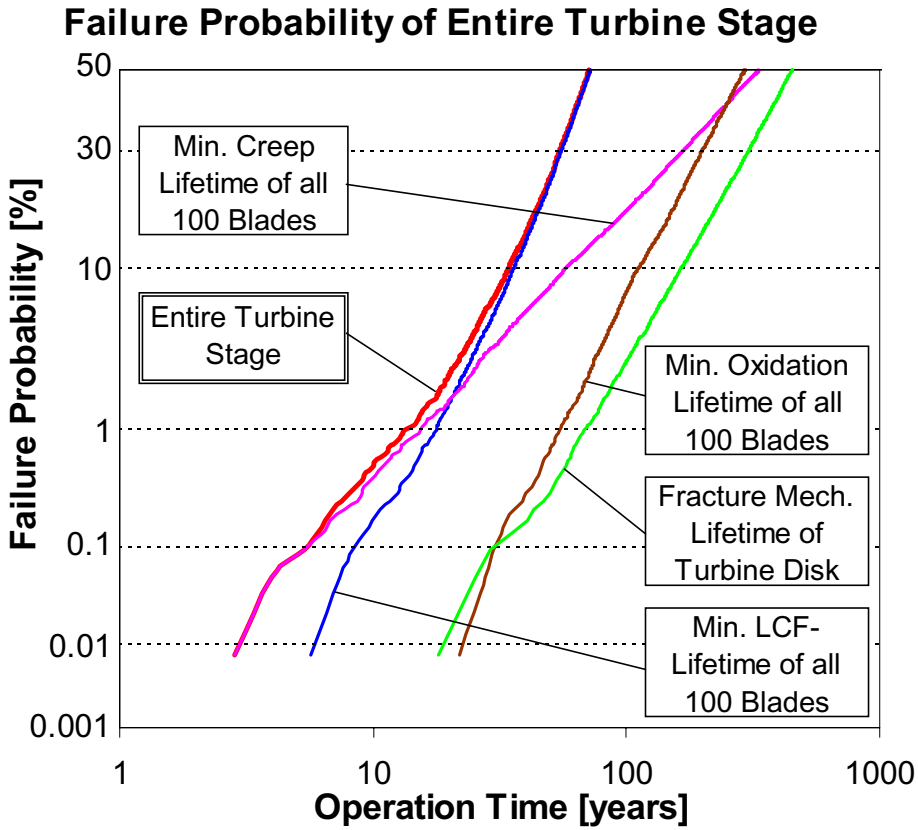


Probabilistic Analysis of Gas Turbine Engines using the ANSYS Probabilistic Design System

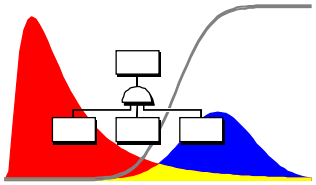
Reliability of Gas Turbine Systems:
Failure Probability for Turbine Stage



Probabilistic Analysis of the Turbine Stage using the Response Surface Method



ANSYS Probabilistic Design System: *Summary*



- **The ANSYS/PDS is FREE for every ANSYS customer**
- **It works with *any* ANSYS model (static, dynamic, linear, non-linear, thermal, Structural, Electro-magnetic, CFD …)**
- **Uses well accepted and robust probabilistic methods**
- **Sophisticated regression analysis capabilities for response surface fitting**
- **Use of distributed, parallel computing techniques**
- **Together with the standard ANSYS Finite-Element capabilities the ANSYS probabilistic design system is well suited for the analysis of gas turbine components**

Probabilistic Analysis of a Stator Ladder Using ProFES

Mark A. Cesare
Applied Research Associates, Inc.
Raleigh, North Carolina

Alan C. Pentz
Naval Air Systems Command
Propulsion and Power Engineering Department
Patuxent River, Maryland

ABSTRACT

The purpose of this investigation was to apply probabilistic methods to determine the probability of failure associated with torque loads and sensitivity to model variable/inputs on the stage 3 compressor stator vane ladder configuration used in the F405-RR-401 Adour engine. The analysis was performed using ProFES. ProFES is a probabilistic finite element analysis system that allows engineers to perform probabilistic finite element analysis in a 3D environment that is completely familiar and similar to modern deterministic FEA. A deterministic approach was used previously using a commercial FEA package called ANSYS. An underlying purpose of this investigation was to gauge the accuracy and timesaving that a probabilistic approach could provide to this problem versus a deterministic approach.

NASA/CP—2002-211682

Probabilistic Analysis of a Stator Ladder Using ProFES

Alan C. Pentz

Mark A. Cesare

June 11, 2001

Introduction

- Background
- Approach
  - What the Navy was looking for out of ProFES
- Problem Definition
  - Input Variables
  - Probabilistic Methods Used
- Analysis/Steps
- Results

Background

- HPC stator ladder originally analyzed deterministically
- Purpose of the investigation was to determine the stresses associated with various torque loads on several HPC stator vane ladder configurations
- Investigation was conducted by the engine manufacturer where the different configurations were physically cycled until failure
  - This provided torque and displacement vs. load cycle charts; however, material stresses for the design were not associated with specific torques or deflections
- All models were constructed and run within ANSYS
- Three different design configurations were modeled
  - Production Standard, Modified Production Standard, New Design

Background (cont.)

- Production Standard
  - model generated with zero radius to serve as a worse-case production scenario and to achieve an upper stress boundary
- Modified Production Standard
  - model incorporated a radius of .2 mm
  - model was re-analyzed using different radii (.1mm, .4mm, .5mm) to account for various radii generated by different manufacturing methods
- New Design
  - a proposed design aimed at decreasing the stresses associated with torque loads
  - model incorporated an increased radius of .5mm at the ladder and beam intersections and was re-analyzed using a .2mm radius to understand the sensitivity of the design change to radius change
  - incorporated a design change in the beam cross-section from a funnel to a rectangular shape

Approach

- Take a typical/reasonable Navy engine problem and conduct a probabilistic analysis
- Validate the probabilistic analysis with conventional deterministic analysis and test data
- Evaluate available commercial codes
- ProFES
  - Ease of Use, Speed, Output, etc.
- Underlying approach was to bring this analysis tool in-house to determine its merits when approached with "real world" problems

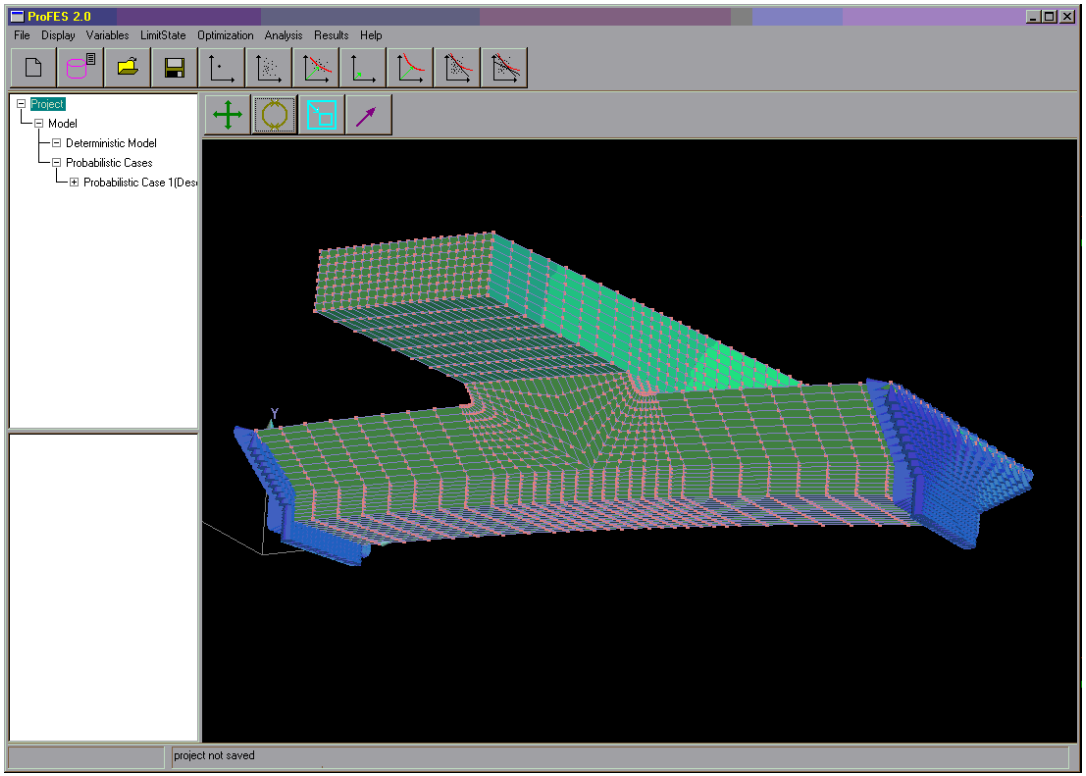
Problem Definitions and Analysis

- Key Input Variables/Uncertainties
  - Fatigue Limit
  - Fillet Radius
  - Torque
- Probabilistic Methods Used
  - FORM
  - Monte Carlo

Importing FEM Model

- FEM model in ProFES
- Loads, Boundary Conditions, Material properties can be random

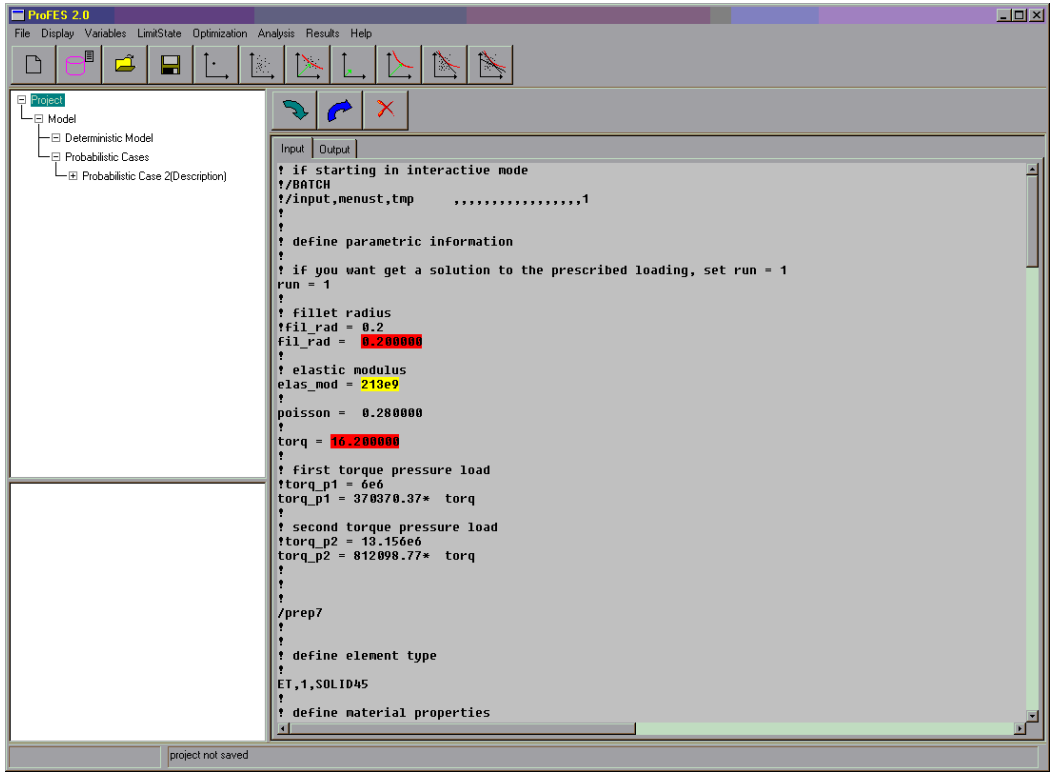
- Fillet radius can not be changed



File Mode Import of Model

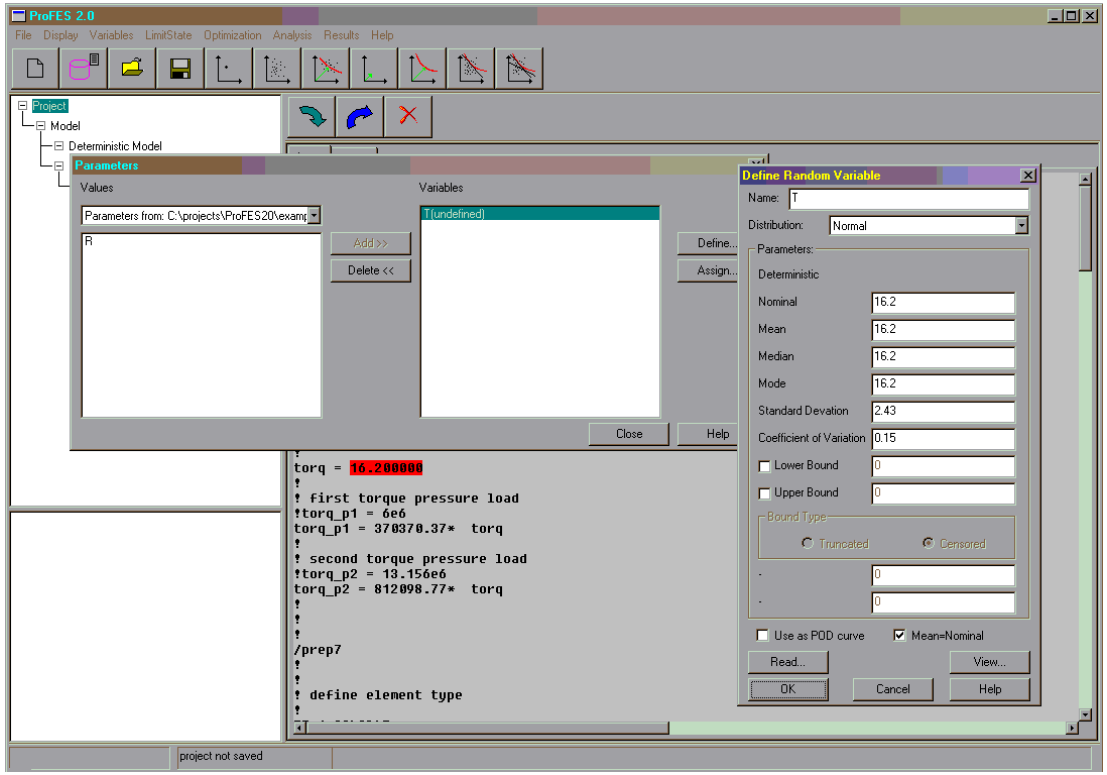
- Any ANSYS parameter can be random
- Results written to file in ADPL

- Fillet radius can be made random in this mode



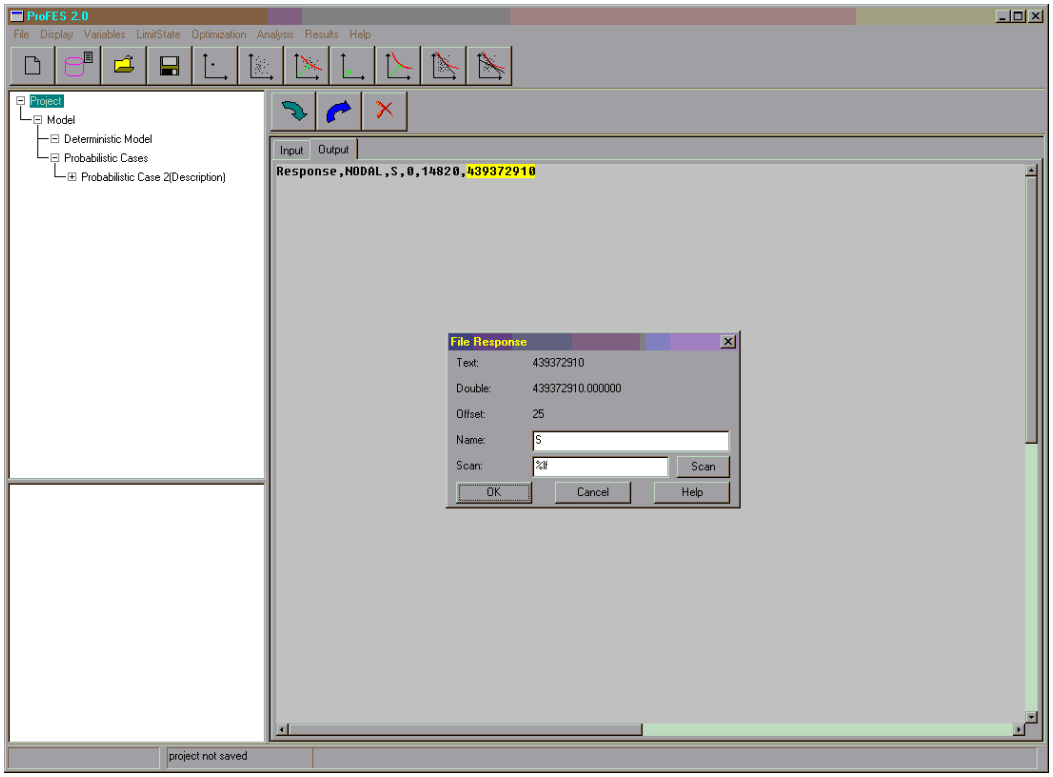
Defining Random Variables

- Highlighted text becomes a ProFES Parameter
- Parameters can be made a random variables
- Random Variable given a distribution



Selecting Response Variables

- Highlighted text becomes a response variable
- Response variables used in limit-states or post processing functions



Results

- The Deterministic Model
  - Setup time, run time, analysis of results, and presentation of results was on the order of three weeks.
- The Probabilistic Model
  - Setup time, run time, analysis of results, and presentation of results was on the order of two days.
  - Provided sensitivities to random variables allowing a user to modify the analysis accordingly.

NASA/CP—2002-211682

Workshop on Probabilistic Design Validation

June 11-13

5th Annual FAA/AIR Force/NASA/Navy Workshop on the Application of Probabilistic Methods to Gas Turbine Engines

Jeffrey M Brown

Turbine Engine Division

Propulsion Directorate

Air Force Research Laboratory

Panel Members

- Johnny Adamson, Pratt & Whitney
- Dr. Paul Roth, GEAE,
- Dr. Tom Cruse, Consultant
- Academic representative

Question

Panel Member

Question

Challenge

Available Data

Validation

Key Validation Issues

How do you validate a Probabilistic Design?

Challenges

Panel Member

Question

Challenge

Available Data

Validation

Key Validation Issues

You will never have enough data.

Available Data

Panel Member
Question
Challenge
Available Data
Validation
Key Validation Issues

- Development program
  - Lots of response data
  - Little failure data
- Fleet experience
  - Little response data
  - Lots of failure data (relatively)

Validation

Panel Member
Question
Challenge
Available Data
Validation
Key Validation Issues

- Validation is required to give confidence/assurance that a prediction or design life is accurate
- We lack confidence/assurance in predictions because of uncertainty
  - physical model uncertainty
  - parameter variation uncertainty
  - statistical/probabilistic modeling uncertainty
- Uncertainty has been accounted for by use of safety factors and design margins based on historical evidence
- Application of probabilistics requires new validation methodology

Key Validation Issues

Panel Member
Question
Challenge
Available Data
Validation
Key Validation Issues

- How many tests do I have to run?
- What types of tests do I have to run?
- In absence of test data, how do I validate?
- What else is required?

Verification and Validation

Tom Cruse
Consultant to AFRL/PRTC
Pagosa Springs, CO

Overview of V&V issues

- Verification & Validation standards required by the Defense Modeling and Simulation Office (DMSO)
- Verification & Validation process is required by DOE for the weapons certification program
- Verification & Validation standards development
  - AIAA Committee for CFD complete (AIAA G-077-1998)
  - USACM/ASME for FEM (in process)
  - No one is currently working probabilistics

Standard definitions for V&V

- Verification is the process of determining that a computational software implementation correctly represents a defined model of a physical process.
- Validation is the process of determining the degree to which a computer model is an accurate representation of the real world from the perspective of the intended model applications
- V&V applies to both deterministic and probabilistic elements of the modeling

What is V&V process?

- Applies to all model development and software implementations
- Defines a step-wise assurance process including the following elements
  - Well-defined engineering model
  - Verify that codes that work for the model
  - Validate the physical process models[1]
  - Quantify uncertainties in the models[1]

[1] Sandia Report SAND2001-0312, May 2001

Probabilistic HCF program recommendations

- Establish a V&V process for p-HCF design certification support
  - Consistent with past FAA lifing certification process
  - Supported by ongoing deterministic efforts
- Achieve V&V consensus on design software
- Define V&V requirements for probabilistics
- Incorporate V&V process and requirements in a future generation of ENSIP

Probabilistic Fatigue: Computational Simulation

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Glenn Research Center
Cleveland, Ohio 44135
Ph: 216–433–3252
Email: christos.c.chamis@grc.nasa.gov

ABSTRACT

Fatigue is a primary consideration in the design of aerospace structures for long term durability and reliability. There are several types of fatigue that must be considered in the design. These include low cycle, high cycle, combined for different cyclic loading conditions – for example, mechanical, thermal, erosion, etc.

The traditional approach to evaluate fatigue has been to conduct many tests in the various service-environment conditions that the component will be subjected to in a specific design. This approach is reasonable and robust for that specific design. However, it is time consuming, costly and needs to be repeated for designs in different operating conditions in general.

Recent research has demonstrated that fatigue of structural components/structures can be evaluated by computational simulation based on a novel paradigm. Main features in this novel paradigm are progressive telescoping scale mechanics, progressive scale substructuring and progressive structural fracture, encompassed with probabilistic simulation. These generic features of this approach are to probabilistically telescope scale local material point damage all the way up to the structural component and to probabilistically scale decompose structural loads and boundary conditions all the way down to material point. Additional features include a multi-factor interaction model that probabilistically describes material properties evolution, any changes due to various cyclic load and other mutually interacting effects. The objective of the proposed paper is to describe this novel paradigm of computational simulation and present typical fatigue results for structural components. Additionally, advantages, versatility and inclusiveness of computational simulation versus testing are discussed. Guidelines for complementing simulated results with strategic testing are outlined. Typical results are shown for computational simulation of fatigue in metallic composite structures to demonstrate the versatility of this novel paradigm in predicting a priori fatigue life.

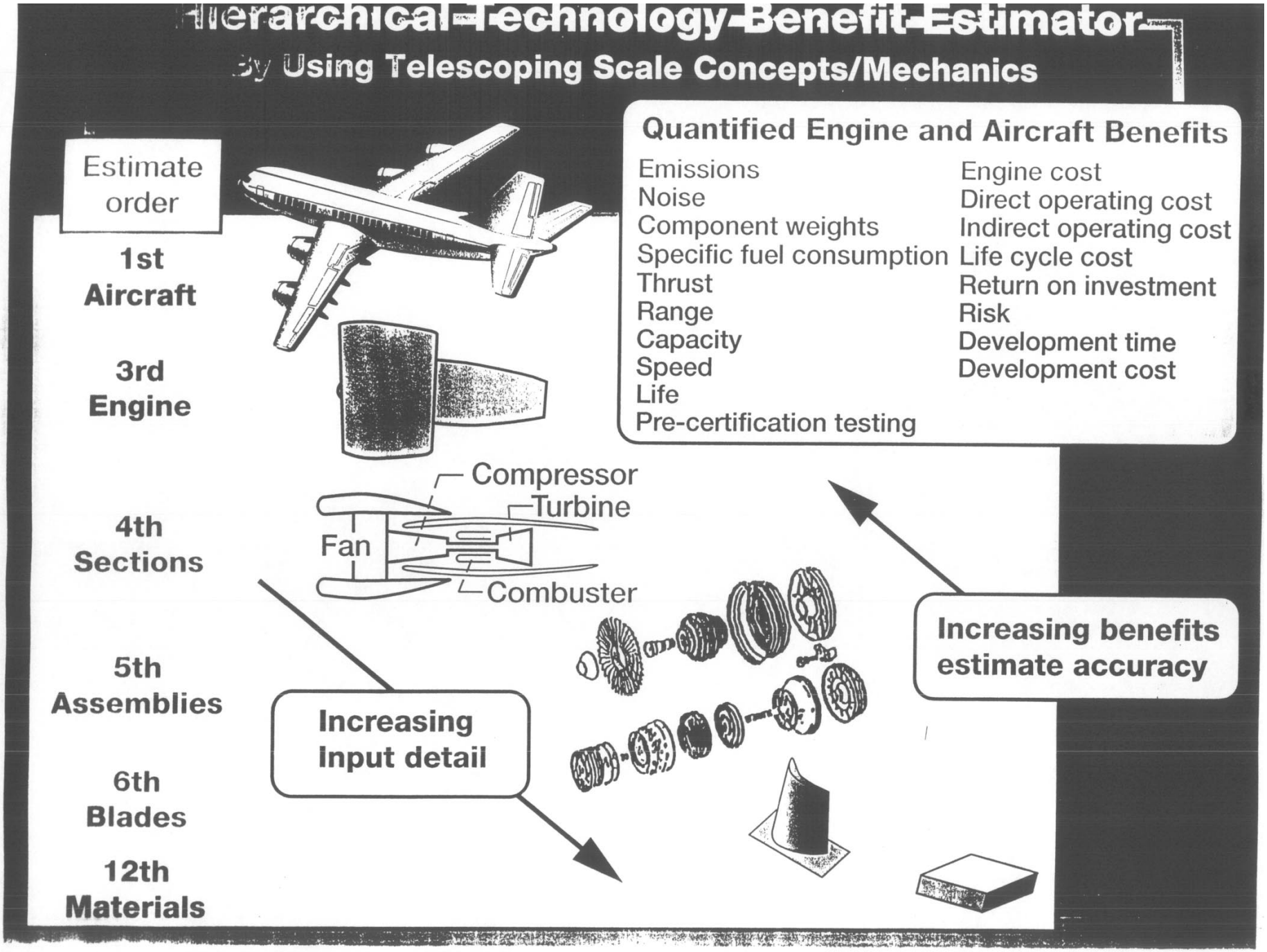
PROBABILISTIC FATIGUE: COMPUTATIONAL SIMULATION

Christos C. Chamis
NASA Glenn Research Center
Cleveland, OH 44135

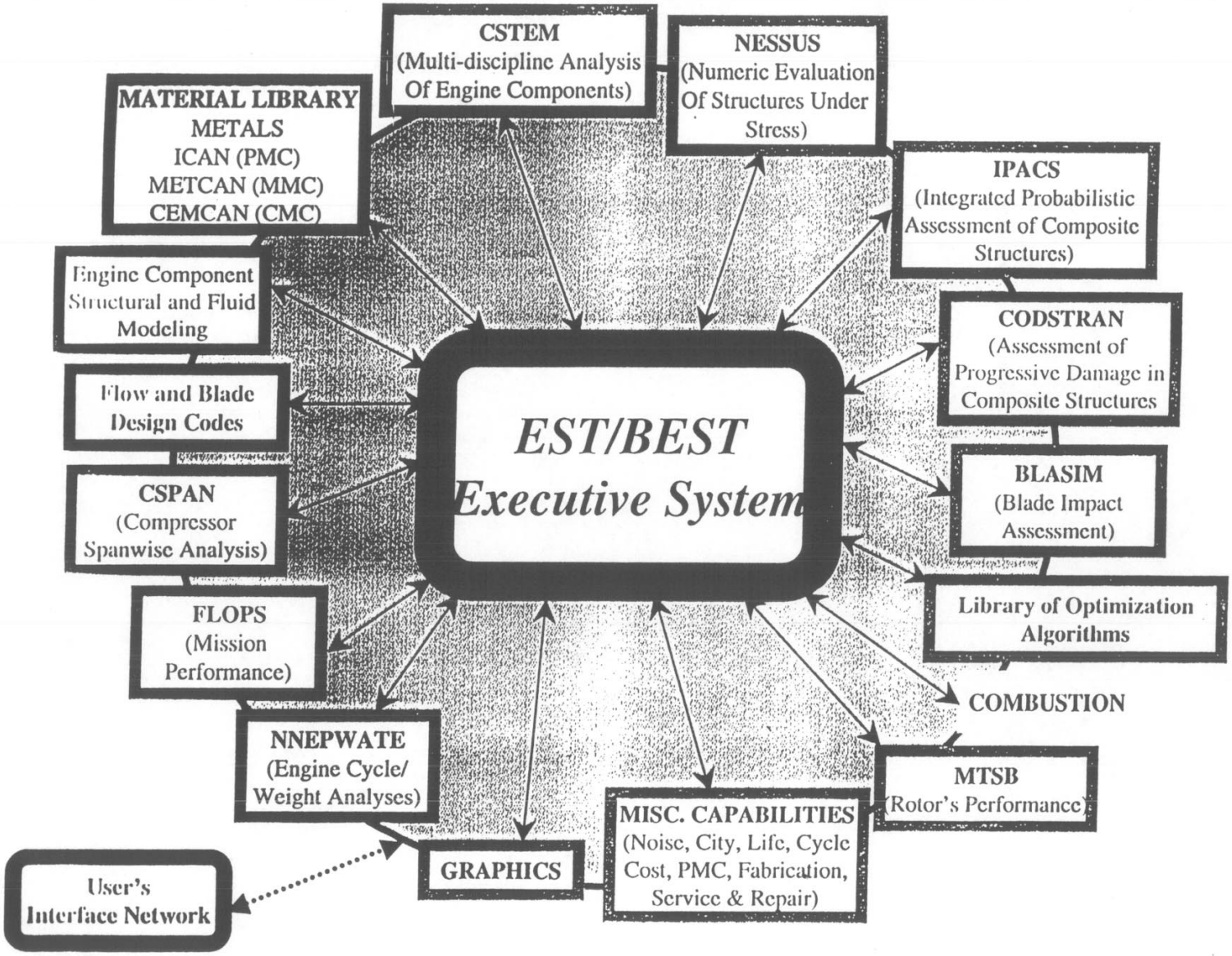
Presented at:
The 5th Annual FAA/AFIN/NASA/NAVY Workshop
on the Application of Probabilistic Methods to Gas Turbine Engines
Holiday Inn, Westlake, OH – June 11-13, 2001

BACKGROUND:

- Fatigue is a primary consideration in the design of aerospace structures for long-term durability and reliability.
- There are several types of fatigue that must be considered in the design, such as: low cycle, high cycle, combined for different cyclic loading conditions – for example, mechanical, thermal, erosion, etc.
- The traditional approach to evaluate fatigue has been to conduct many tests in the various service-environment conditions that the component will be subjected to in a specific design.
- This approach is reasonable and robust for that specific design.
- However, it is time consuming, costly and needs to be repeated for designs in different operating conditions in general.


Hierarchical Technology Benefit Estimator
By Using Telescoping Scale Concepts/Mechanics
Estimate order
1st Aircraft
3rd Engine
4th Sections
5th Assemblies
6th Blades
12th Materials
Compressor
Turbine
Fan
Combuster
Quantified Engine and Aircraft Benefits
Emissions
Noise
Component weights
Specific fuel consumption
Thrust
Range
Capacity
Speed
Life
Pre-certification testing
Engine cost
Direct operating cost
Indirect operating cost
Life cycle cost
Return on investment
Risk
Development time
Development cost
Increasing Input detail
Increasing benefits estimate accuracy

EST/BEST ENGINE STRUCTURES TECHNOLOGY BENEFIT ESTIMATOR



NEED:

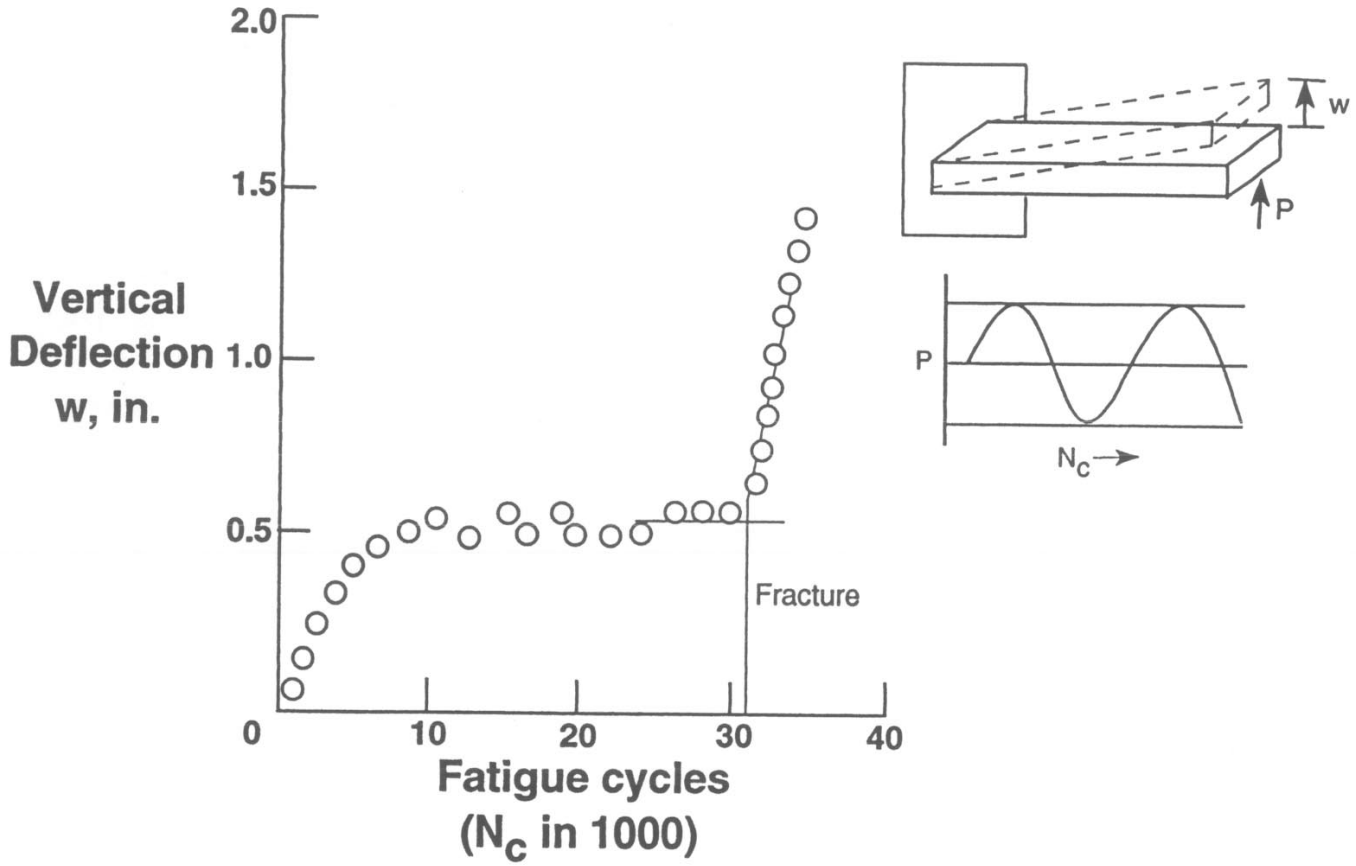
- There is a continuing need to develop a method to reduce cost in long-life fatigue evaluations.

- Recent research has demonstrated that fatigue of structural components/ structures can be evaluated by computational simulation based on a novel paradigm.

OBJECTIVE:

- Describe the novel paradigm and present structural component results that illustrate versatility, inclusiveness and that - YES IT CAN BE DONE!

Progressive Fracture Under Cyclic Load
(Experimental data: Mandel, et al)

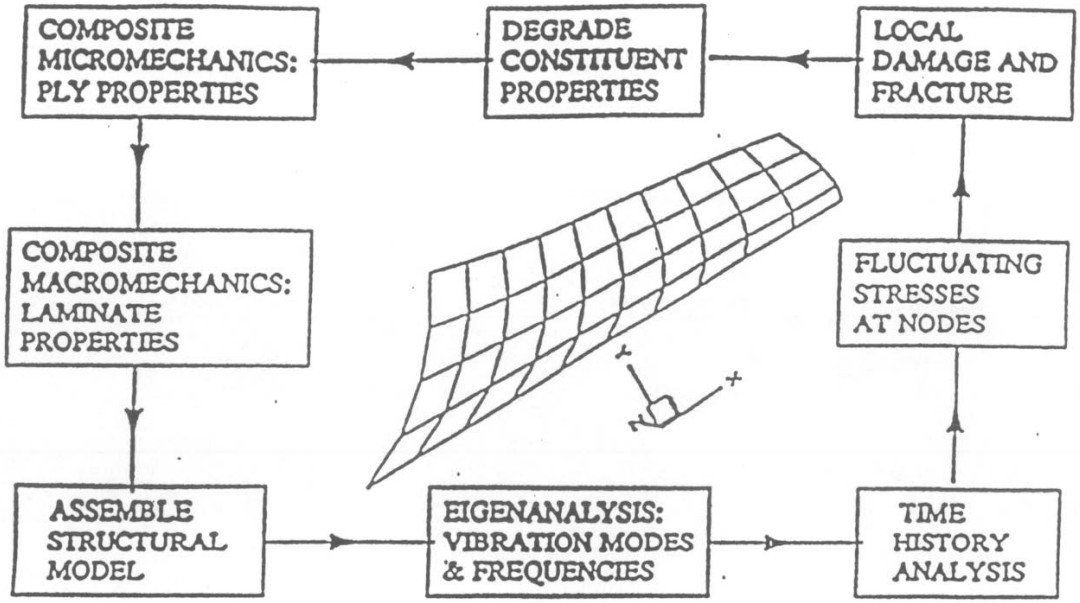


APPROACH:

MAIN FEATURES IN THIS NEW PARADIGM ARE:

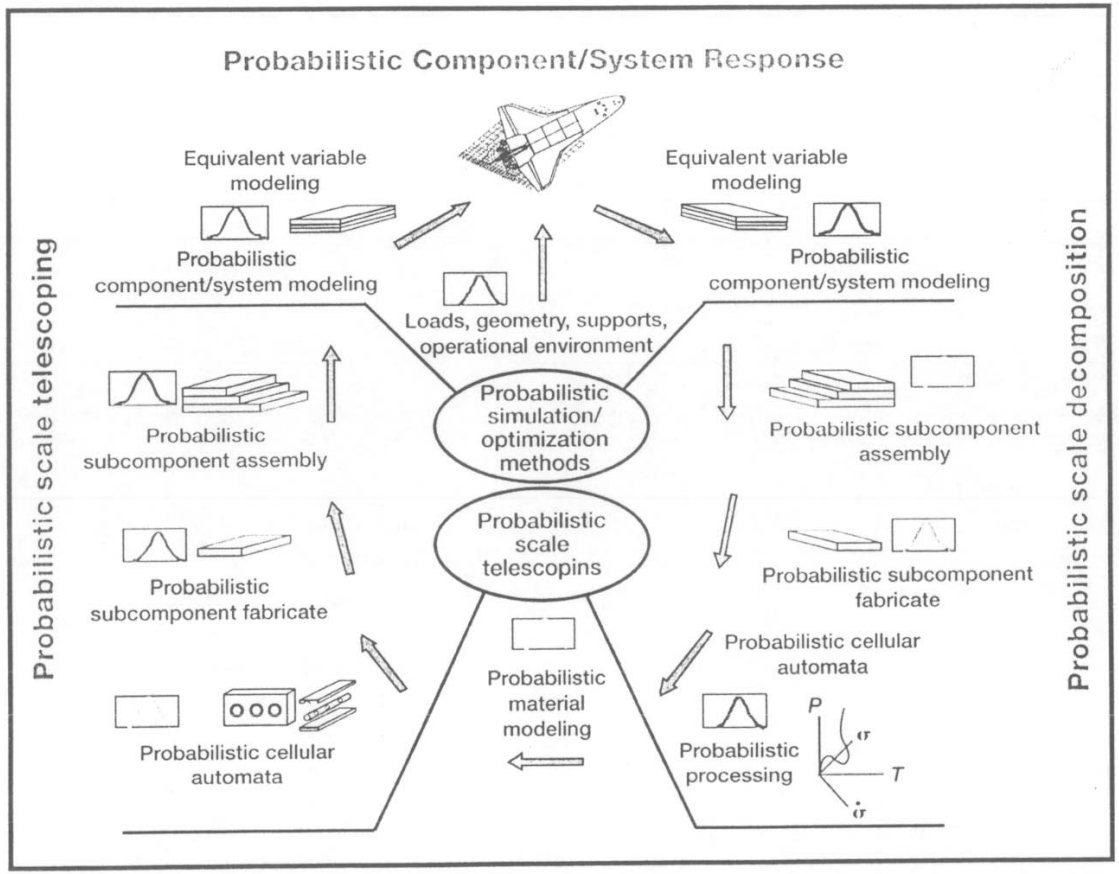
- Progressive Structural Fracture
- MFIM for Material Behavior
- Telescopic Scale Mechanics

COMPUTATIONAL SIMULATION CYCLE



Non-Deterministic/Non-Traditional (ND/NT) Methods for Design to Cost in the Presence of Uncertainties

(Simulation Iterative Cycle)



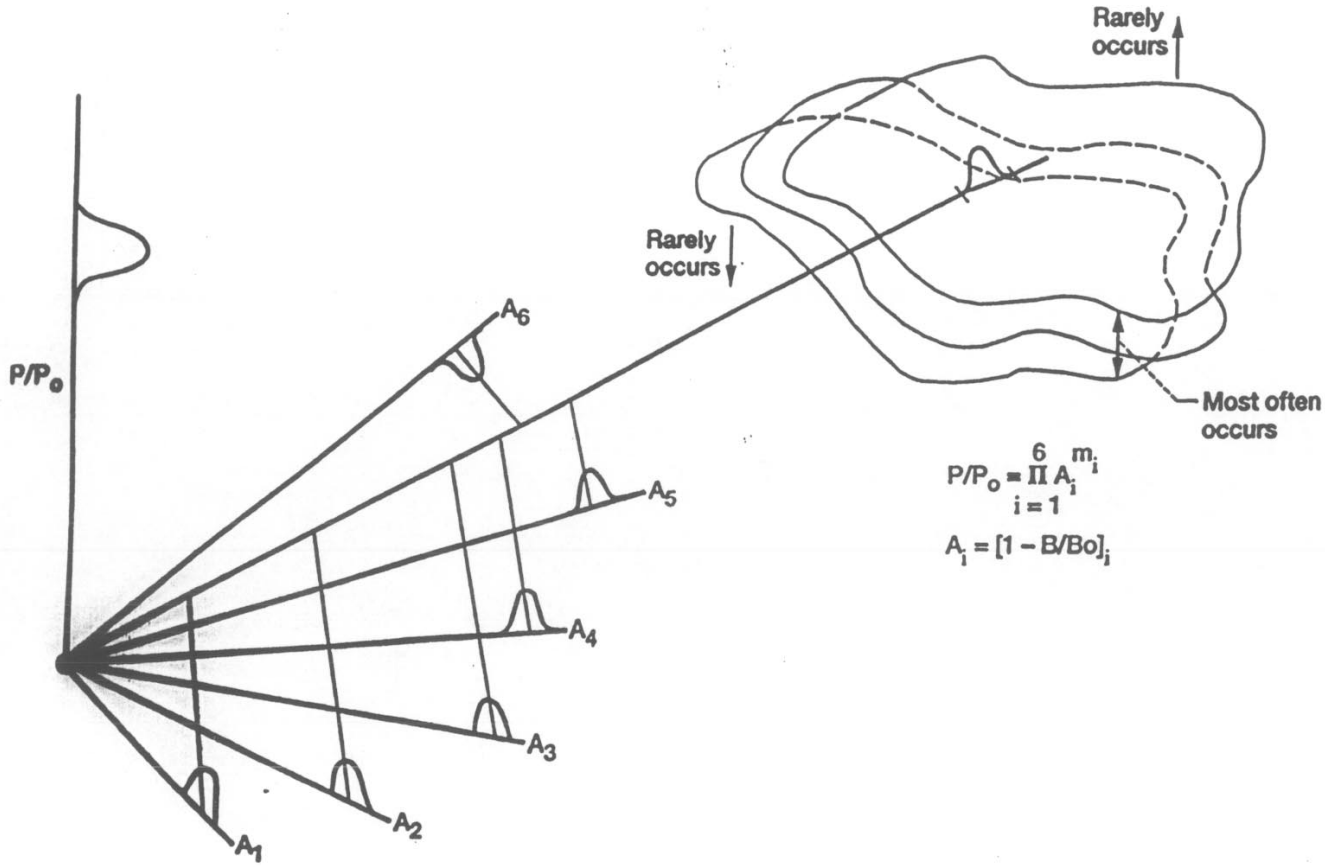
CD-01-81190

C.C. Chamis
NASA/GRC

TYPICAL RESULTS:

- MFIM – Behavior Illustration
- Blade Thermomechanical Fatigue – GRC Simulation
- Two-Stage Rotor Fatigue – GRC Simulation
- Tank Fatigue – SWRI Simulation
- Large Shell Fatigue – GRC Simulation

MULTI-FACTO-INTERACTION MODEL WITH SUBSTRUCTURING



Time dependent Multi-Factor Interaction Equation (MFIE):

$$\frac{P}{P_o} = \left(\frac{T_{gw}-T}{T_{gw}-T_o}\right)^m \left(1-\frac{\sigma}{S_f}\right)^n \left(1-\frac{\sigma t}{S_f t_f}\right)^q \left(1-\frac{\sigma_M N_M}{S_f N_{fM}}\right)^r \left(1-\frac{\sigma_T N_T}{S_f N_{fT}}\right)^u$$

where:

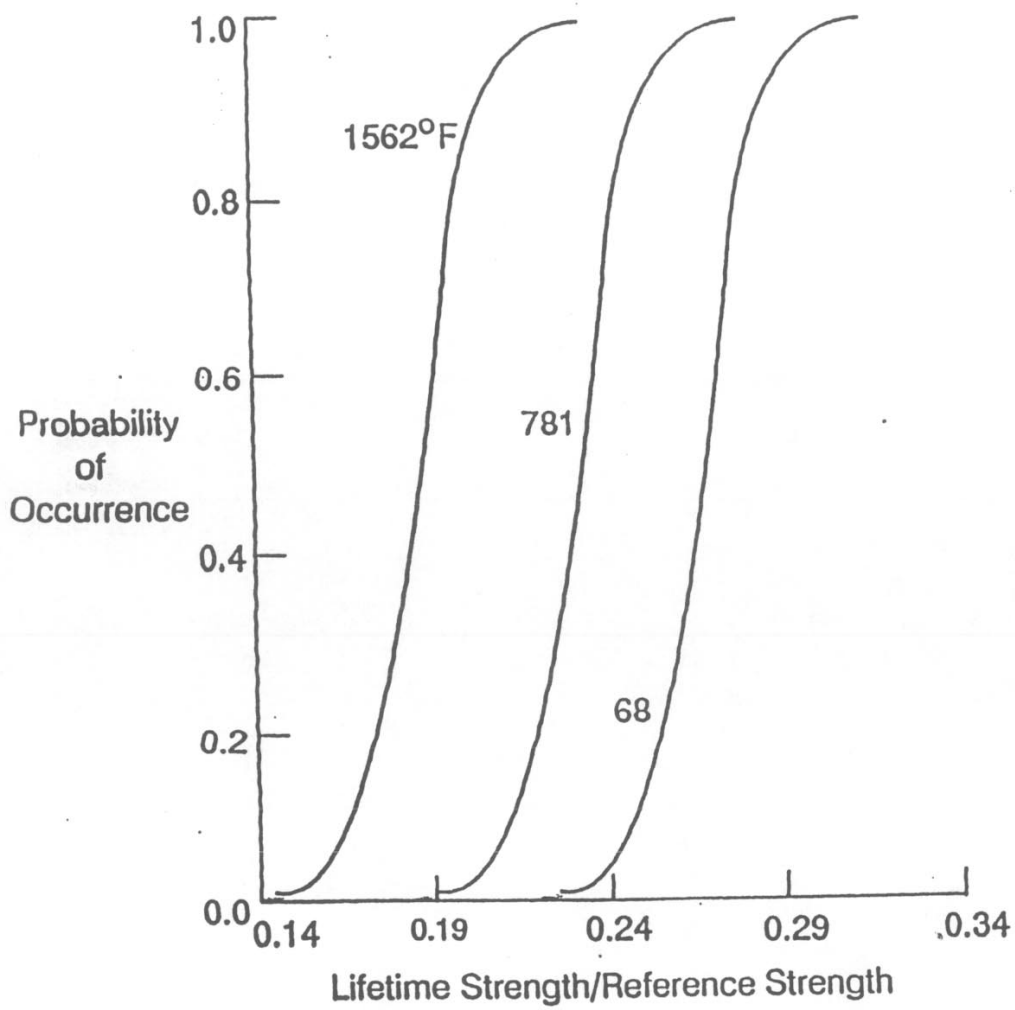
P - Property
T - temperature
S - strength
σ - stress
N - number of cycles
t - time

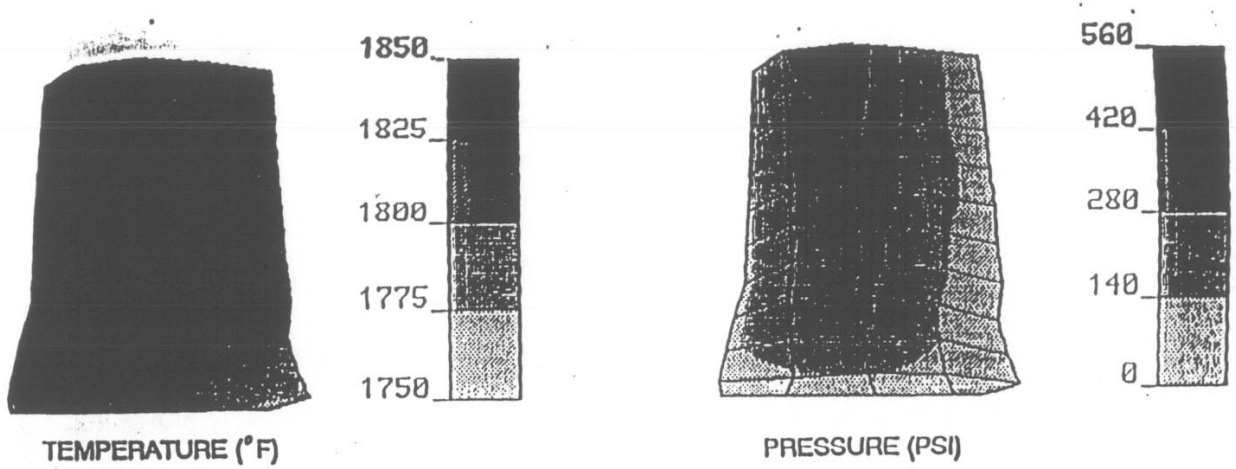
subscripts:

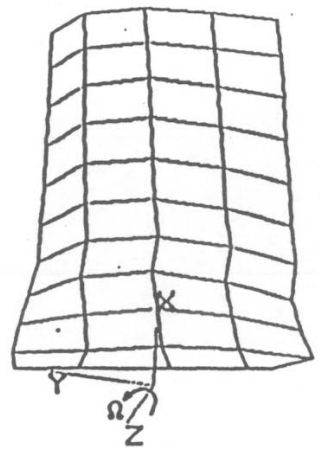
gw - wet glass temperature
o - reference condition
f - final condition
M - mechanical load
T - thermal cyclic load.

superscripts: m, n, q r and u are exponents for the material that describe the behavior path from the reference to the final values

PMBM-SIMULATED LIFETIME STRENGTH FOR A NICKEL-BASED SUPERALLOY SUBJECTED TO 3162 STRESS CYCLES AND 100 HOURS OF CREEP





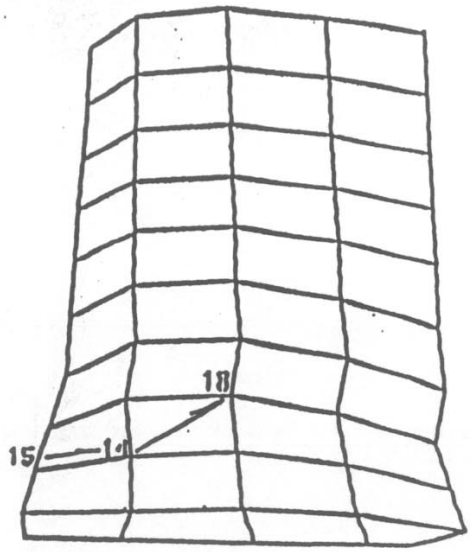


CENTRIFUGAL LOADS

Ω = ROTATIONAL SPEED
= 40,000 RPM

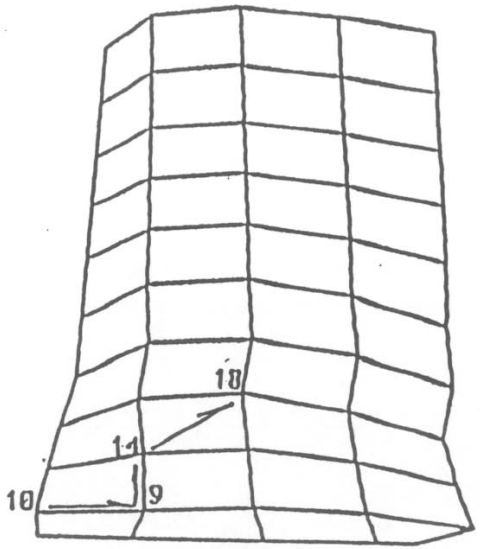
THERMAL MECHANICAL LOADS ON SSME BLADE

PROBABILITY OF COMPONENT DAMAGE PROPAGATION PATH CAUSED BY 100,000 FATIGUE CYCLES



PATH A

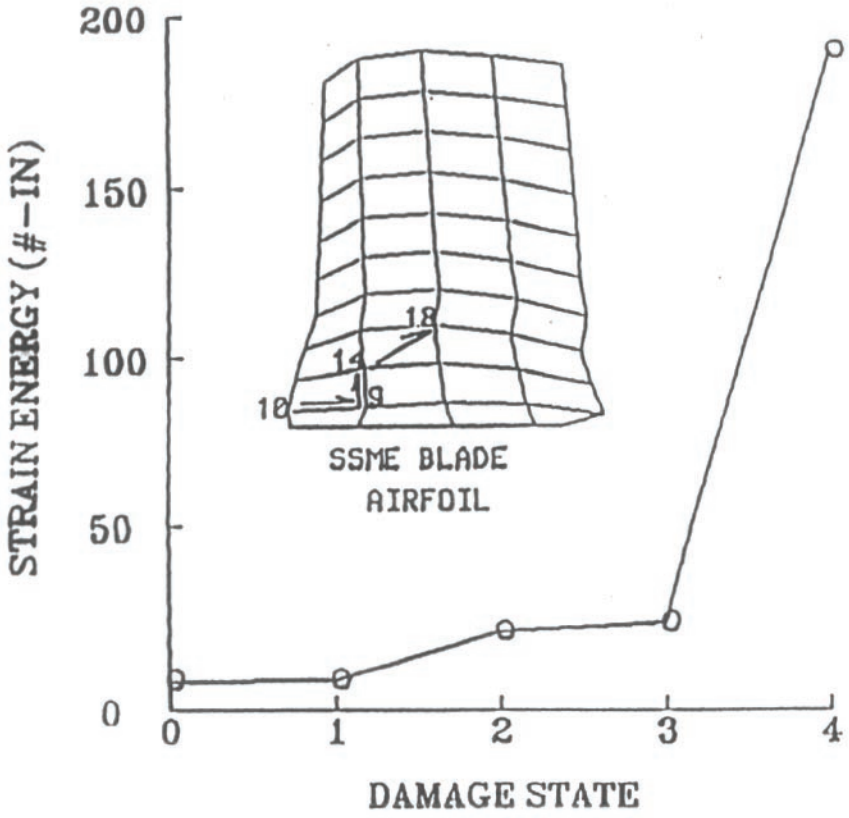
PROBABILITY OF
PATH A OCCURS
= 0.00001



PATH B

PROBABILITY OF
PATH B OCCURS
= 0.0002

STRAIN ENERGY INCREASES AS THE DAMAGE PROGRESSES



STATE 0
UNDAMAGED STRUCTURE

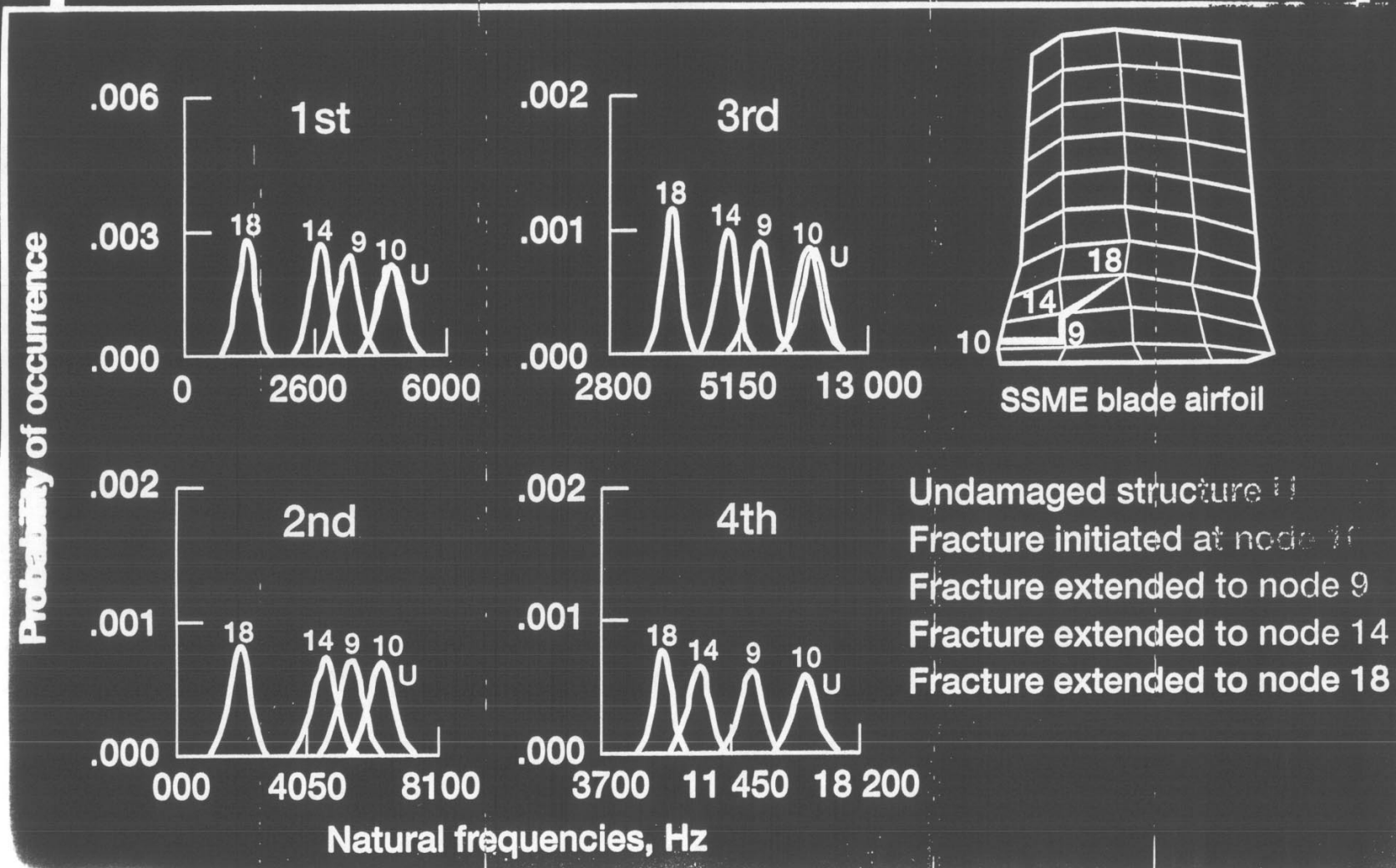
STATE 1
DAMAGE INITIATED AT NODE 10

STATE 2
DAMAGE EXTENDED TO NODE 9

STATE 3
DAMAGE EXTENDED TO NODE 14

STATE 4
DAMAGE EXTENDED TO NODE 1(

Natural Frequencies Decreases as Fracture Progresses



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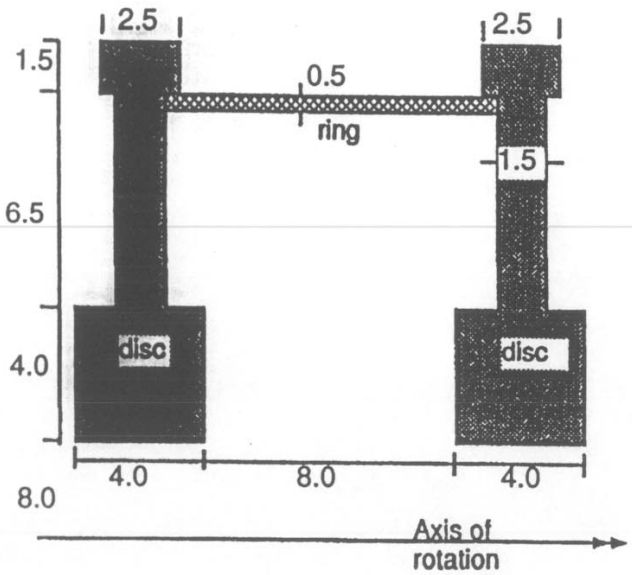
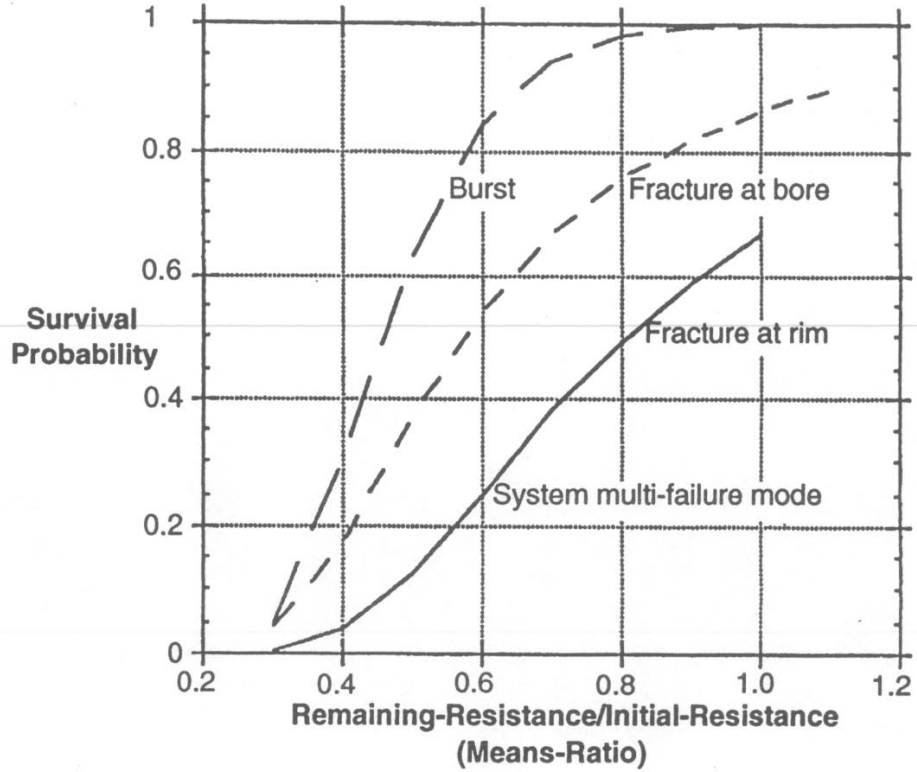
Rotor System Survival Probability Under Multiple Failure Modes



(Dimensions in inches)



Failure Mode	S	R
1. Disc burst	Average stress	Burst strength
2. Fracture at bore	Fracture life	10,000 cycles
3. Fracture at rim	Fracture life	10,000 cycles
4. Progressive damage	Yielding of the ring	Yield strength

Note: Yielding of ring affects all other modes through mutual interaction.

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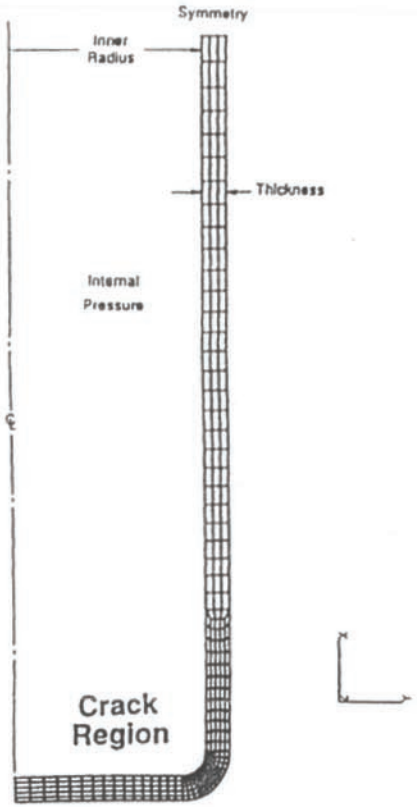
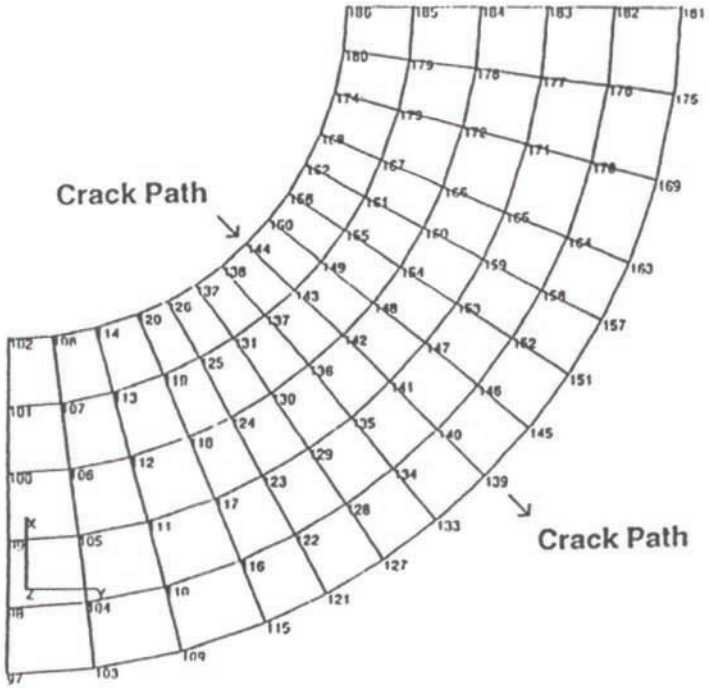
Sensitivity Factors of Rotor System Failure Probability

Name	In u(i) Space
E_ROT	0.016011
E_RIN	-0.002698
ROTOR DENS	0.438499
RING DENS	-0.000386
SPEED	0.850827
TEMPE	0.170793
BURST	-0.011983
RINGY	0.073086
RK1C	-0.061872
AO	0.057976
C	0.133702
NI	-0.000008
Kt	0.060917
A_LCF	-0.005132
TOLER	0.0

STRUCTURAL SYSTEM RELIABILITY CONSIDERING PROGRESSIVE FRACTURE EXAMPLE



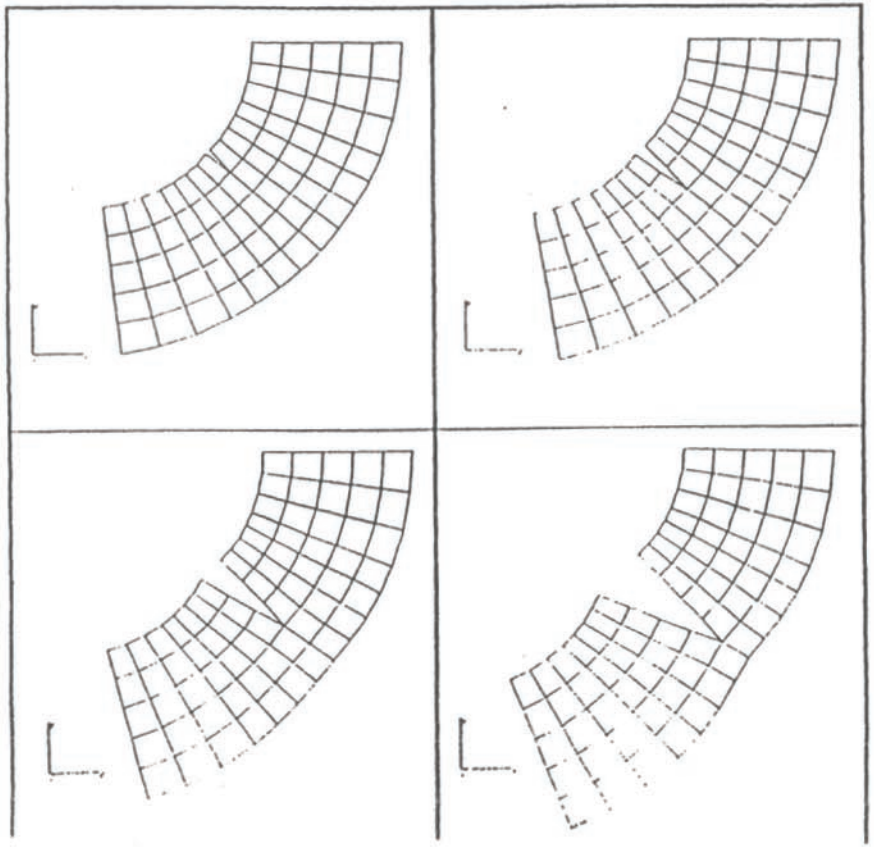
Finite Element Model of Axisymmetric Structure Under Internal Pressure



Crack Path Region

STRUCTURAL SYSTEM RELIABILITY CONSIDERING PROGRESSIVE FRACTURE EXAMPLE

Crack Growth: Bottom Events Modeled through Node Unzipping. Each Bottom Event Corresponds to Crack Initiation or a Crack Growth Increment



STRUCTURAL SYSTEM RELIABILITY CONSIDERING PROGRESSIVE FRACTURE EXAMPLE

Fatigue Calculations

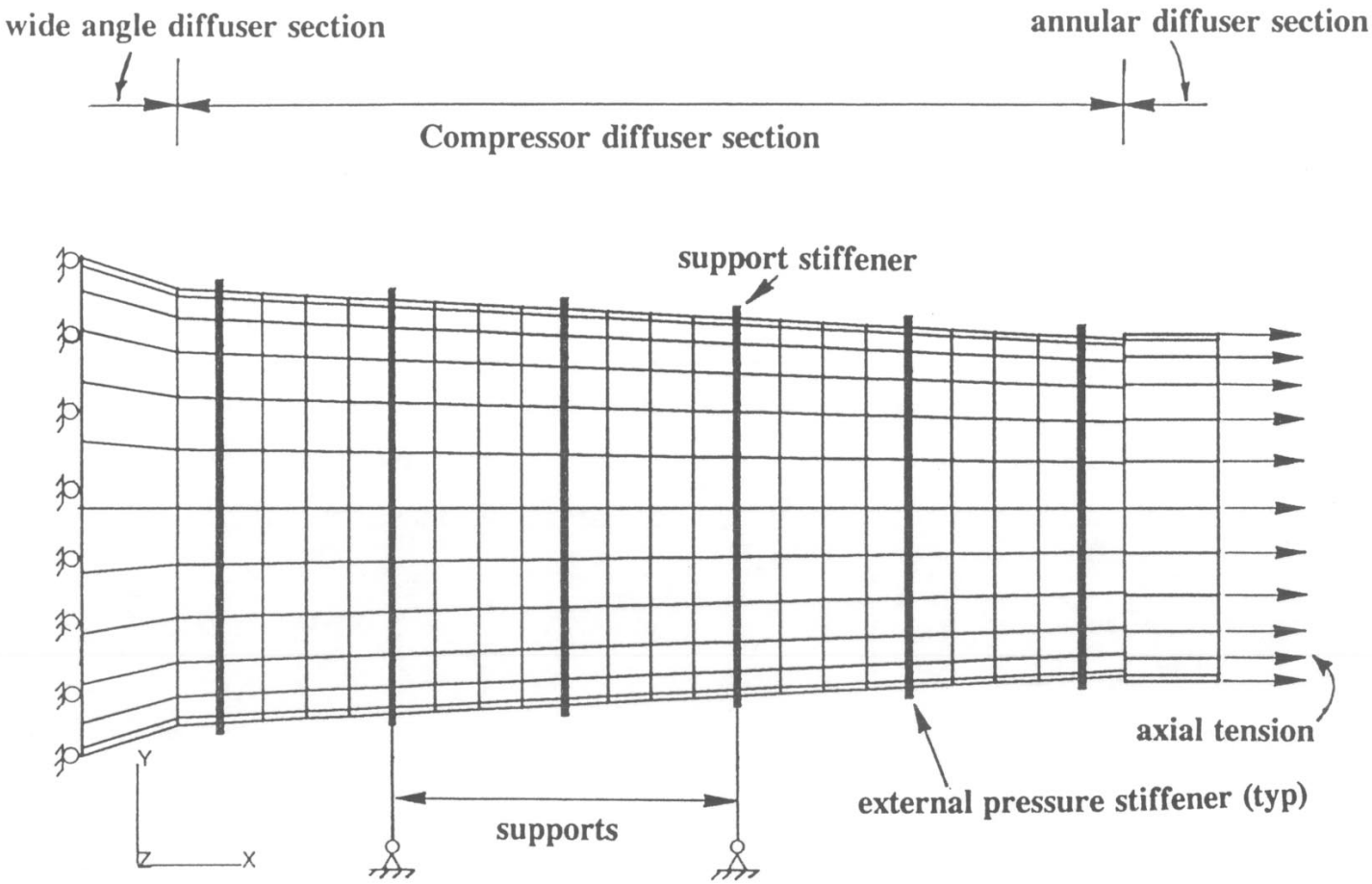
Number of Cycles to Grow Crack Computed Using Crack Growth Law Given Crack Increment

Cycles to Failure Results	
Event	# Cycles
Crack Initiation at node 144	$1.00 * 10^{+4}$
Fracture, N 144 → N 143	$1.80 * 10^{+4}$
Fracture, N 143 → N 142	$5.99 * 10^{+3}$
Fracture, N 142 → N 141	$2.99 * 10^{+3}$
Total	$3.70 * 10^{+4}$

Paris Crack Growth Law

$$\frac{da}{dn} = C\,(\Delta\, k)^m$$

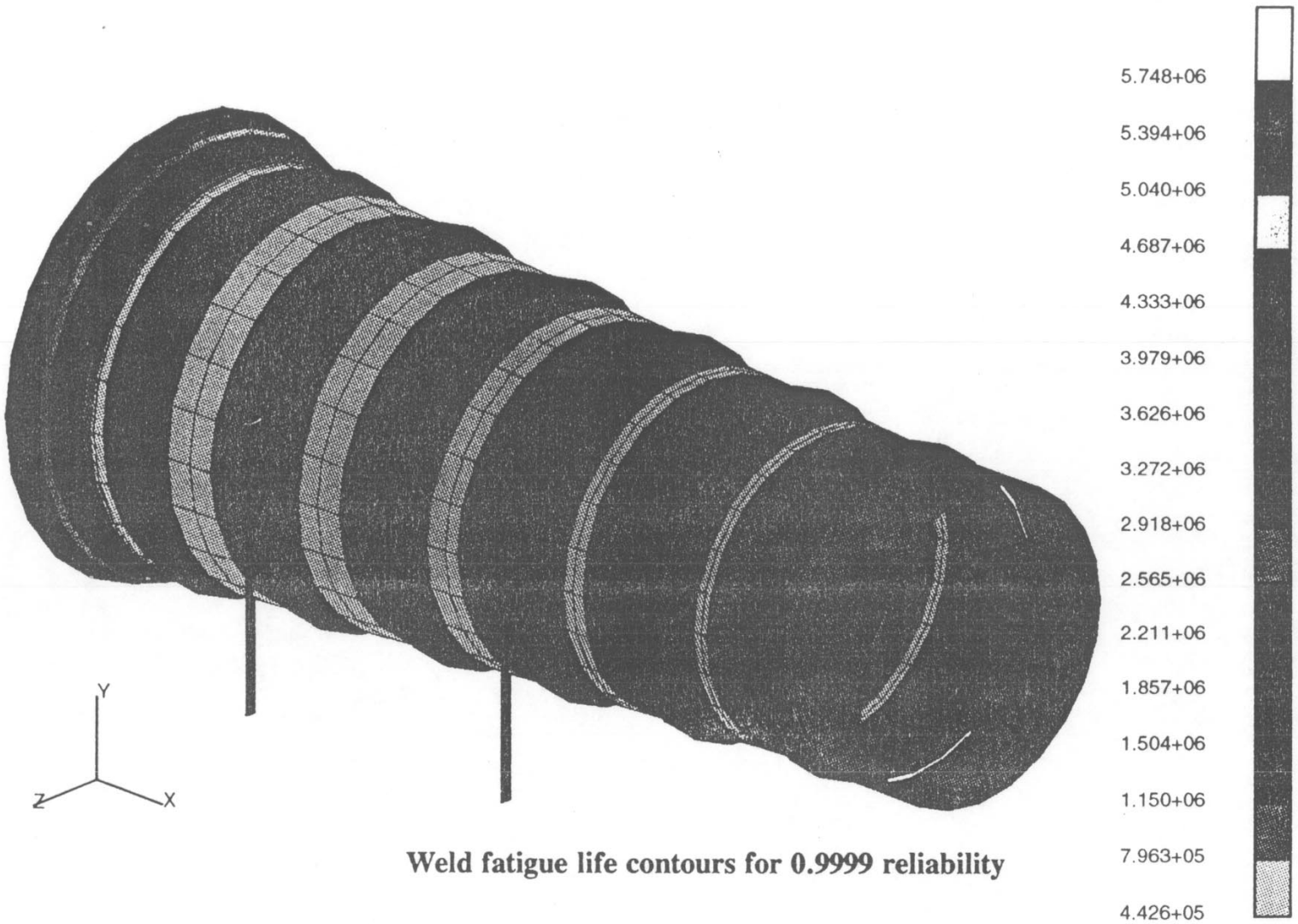
$$N_f = \frac{2[a_f^{(1-n/2)} - a_i^{(1-n/2)}]}{C\,(2-n)\,(Y\,\sigma_{max}\sqrt{\pi})^n} \qquad n \neq 2$$



National Wind Tunnel - structure and components

National Wind Tunnel Details:

- **Dimensions:**
  - Length = 133 ft.
  - Diameter at wide angle diffuser end = 51.67 ft
  - Diameter at annular diffuser end = 41.25 ft
- **Material A516 Grade 70 steel**
- **Load: Internal pressure = 5 atm (73.0 psi)**



Weld fatigue life contours for 0.9999 reliability

SUMMARY:

- Probabilistic fatigue by computational simulation is doable and can be adapted throughout the design practice.
- One way to enhance its implementation is to identify appropriate staff and task them to do it.
- The method constitutes a "virtual" statistical desk-top laboratory applicable at all stages of the design, development and service life cycle.
- Probabilistic fatigue evaluations rely on computational simulation results while statistic methods rely on experimental data.

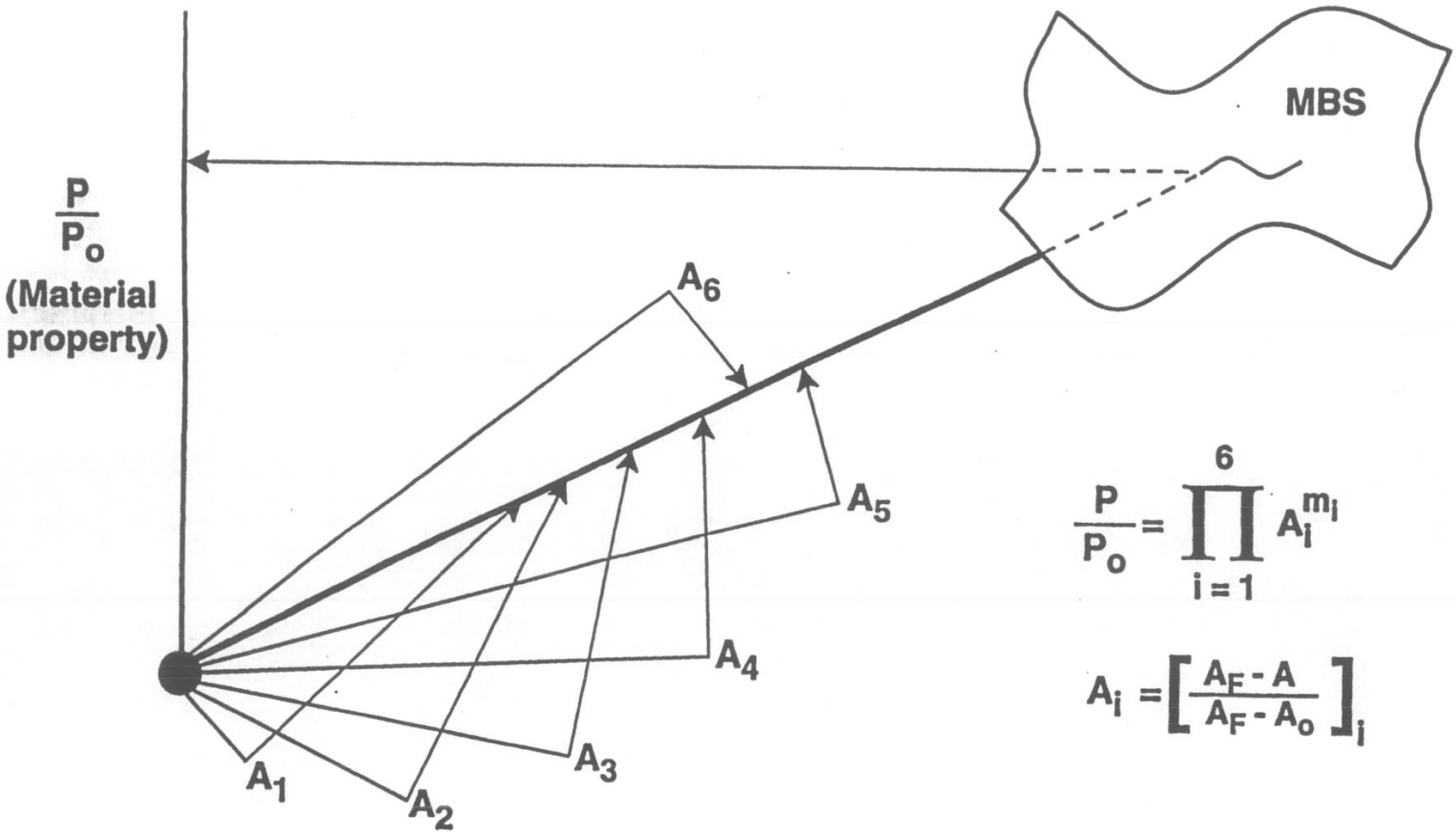
WHAT IS THE FUTURE OF PROBABILISTIC FATIGUE METHODS?

- The future is an exponential use of Probabilistic Fatigue Methods because the drive for Better-Cheaper-Faster engines necessitates quantification of risk for the utilization of unproven:

  -- Design Concepts
  -- Material
  -- Processes
  -- Etc.

- Probabilistic Fatigue Simulation is the most effective formal method to quantify risk and justify commitment of required resources.

Multi-Factor Interaction Model for Material Behavior Space (MBS)



$$\frac{P}{P_o} = \prod_{i=1}^{6} A_i^{m_i}$$

$$A_i = \left[\frac{A_F - A}{A_F - A_o}\right]_i$$

Factors influencing material behavior

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The Prediction of Fatigue Life for Arbitrary Geometries From the Statistical Analysis of Plain Specimen Data

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Engine manufacturers are under constant commercial pressure to produce engines with improved performance, with increased reliability and at lower cost. As a result, the materials from which fracture critical components are made are increasingly being pushed to the limit of their capability. To ensure that uncontained failures of these components are reduced below current levels, it is critically important to understand the behaviour of these materials under the extremes of stress and temperature they are now expected to endure in service. However, since practical understanding of materials derives largely from laboratory specimen studies, it is necessary to know how the observed properties are reflected in full scale components. The current paper introduces a statistical model for the size effect in fatigue, which, when combined with fully non-linear stress analysis, advanced materials models and fracture mechanics calculations, provides a means of predicting fatigue life distributions for arbitrary geometries and loadings. The model is applied to an extensive fatigue database for a modern engine alloy, which contains both notched specimen and full scale component results. It is demonstrated that the model can predict both types of results accurately, which is important because they represent the relative extremes in terms of both stress and volume.

NASA/CP—2002-211682

The Prediction of Fatigue Life for Arbitrary Geometries from the Statistical Analysis of Plain Specimen Data

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5th Annual FAA/Air Force/NASA/Navy
Workshop on the Application of Probabilistic
Methods to Gas Turbine Engines

Westlake, Ohio

June 11-13 2001

Issues for current LCF life prediction methodologies

- Current predictions show commercial air traffic increasing
- Requirements for improved performance mean design margins reduced
- New manufacturing and fabrication techniques are being introduced
  - Surface treatments
  - Blisks
  - Processing routes

Implications for lifing methods - 1

- Materials are operating closer to the limit of their capability
- Creep behaviour increasingly becoming significant factor
- As the fatigue life process becomes more refined, so the number of parameters which need to be accounted for increases

- Stress analysis needs to be as accurate as possible
- Combined plastic/creep analysis required
- Utilise improved understanding of materials behaviour, both in initiation and propagation

Implications for lifing methods - 2

- Further complication arises because materials models developed from laboratory specimen testing
- Material volume known to have a significant effect on LCF behaviour
- Moreover, the material volume will influence the distribution of fatigue lives, not just mean behaviour
- Requirement for statistical model of the ‘size effect’ to establish safe component lives

Requirement for new lifing methodology

- Traditional safe life approach increasingly unable to cope with complexities introduced by modern design
- Databank methods have difficulty dealing with parameters which have been demonstrated to display very different effects in the initiation and propagation regimes
- Difficulties with damage tolerance methods in developing NDI procedures capable of detecting small enough crack sizes to give acceptable lives

New Lifing Methodology

- New lifing methodology aims to meet demands placed by current generation of component designs
- Non-linear 3-dimensional stress analysis techniques employed, using combined plasticity/creep constitutive equations
- Includes separate models for both crack initiation and crack propagation
- Statistics of the size effect modelled explicitly
- The inclusion of the size effect model means that all the parameters can be obtained purely from plain specimen results

Stress analysis procedures

- Conventional isotropic and kinematic constitutive laws not flexible enough to model reverse yielding behaviour correctly
- Use Mroz multilayer hardening rule, and shakedown to stabilised loop is modelled iteratively
- Mainly used Rolls-Royce CT07 creep law, but sometimes Norton-Bailey
- Creep and plasticity are uncoupled
- Creep rupture analysis is also performed

Fatigue life model

- Walker strain parameter used to model crack initiation, effect of temperature and R-ratio is included

$$\varepsilon_W = \left(\frac{\sigma_{\max}}{E} \right) \left(\frac{\Delta\varepsilon . E}{\sigma_{\max}} \right)^m$$

- Use conventional S-N relationship
- Crack propagation model uses conventional LEFM, with appropriate stress intensity solutions
- Only the tensile part of the stress range is used

Size effect model - 1

- Standard theory for the size effect in materials is based on the ‘weak link’ hypothesis

$$P_s(v_1 + v_2) = P_s(v_1)P_s(v_2)$$

- From this, it can be shown that the

$$F(N; v, \varepsilon_W(\boldsymbol{x})) = 1 - \exp\left(-\frac{1}{v_0} \int_v \left(\frac{N\varepsilon_W^{\alpha}(\boldsymbol{x})}{c_\eta^{-1}} \right)^{\beta} d\boldsymbol{x} \right)$$

Size effect model - 2

- Fundamental problem is that this equation does not provide adequate fit the data
- However 3-parameter Weibull distribution provides a much better fit

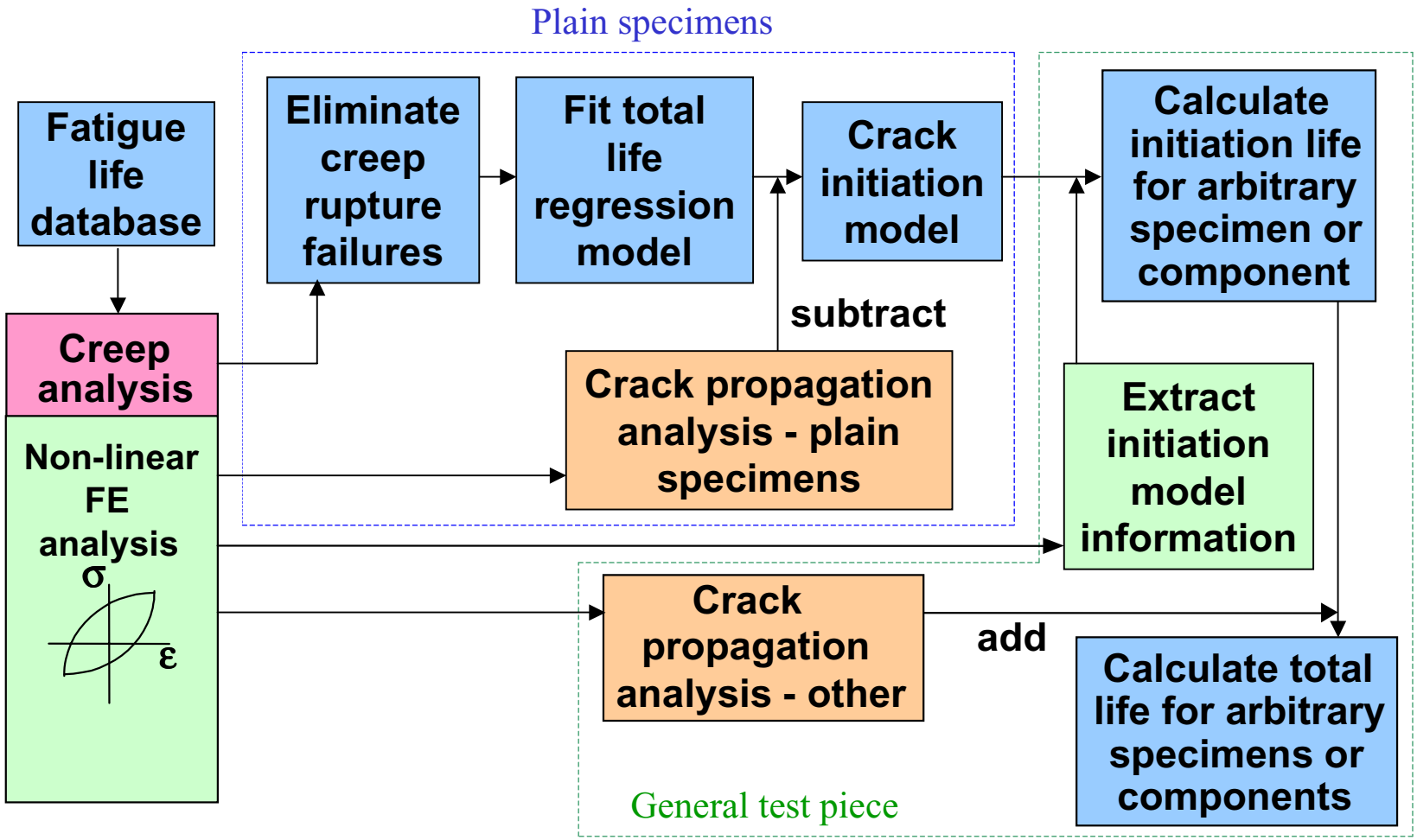
$$F_N(N) = 1 - \exp\left(-\frac{1}{V_r} \int_V \left(\frac{N - N_0(\varepsilon_W(\boldsymbol{x}))}{N_\eta(\varepsilon_W(\boldsymbol{x}))} \right)^\beta d\boldsymbol{x} \right)$$

$$N_\eta(\varepsilon_W(\boldsymbol{x})) = \frac{\varepsilon_W^{-\alpha}(\boldsymbol{x})}{c_\eta}, \quad N_0(\varepsilon_W(\boldsymbol{x})) = \frac{\varepsilon_W^{-\gamma}(\boldsymbol{x})}{c_0},$$

Data

- The Rolls-Royce Waspaloy database has been used to validate the methodology
- Extensive set of results, including in excess of 1500 plain specimen tests over a wide range of conditions
- Also includes a range of notched specimen results with different stress concentration factors, as well as component tests

New lifing methodology process



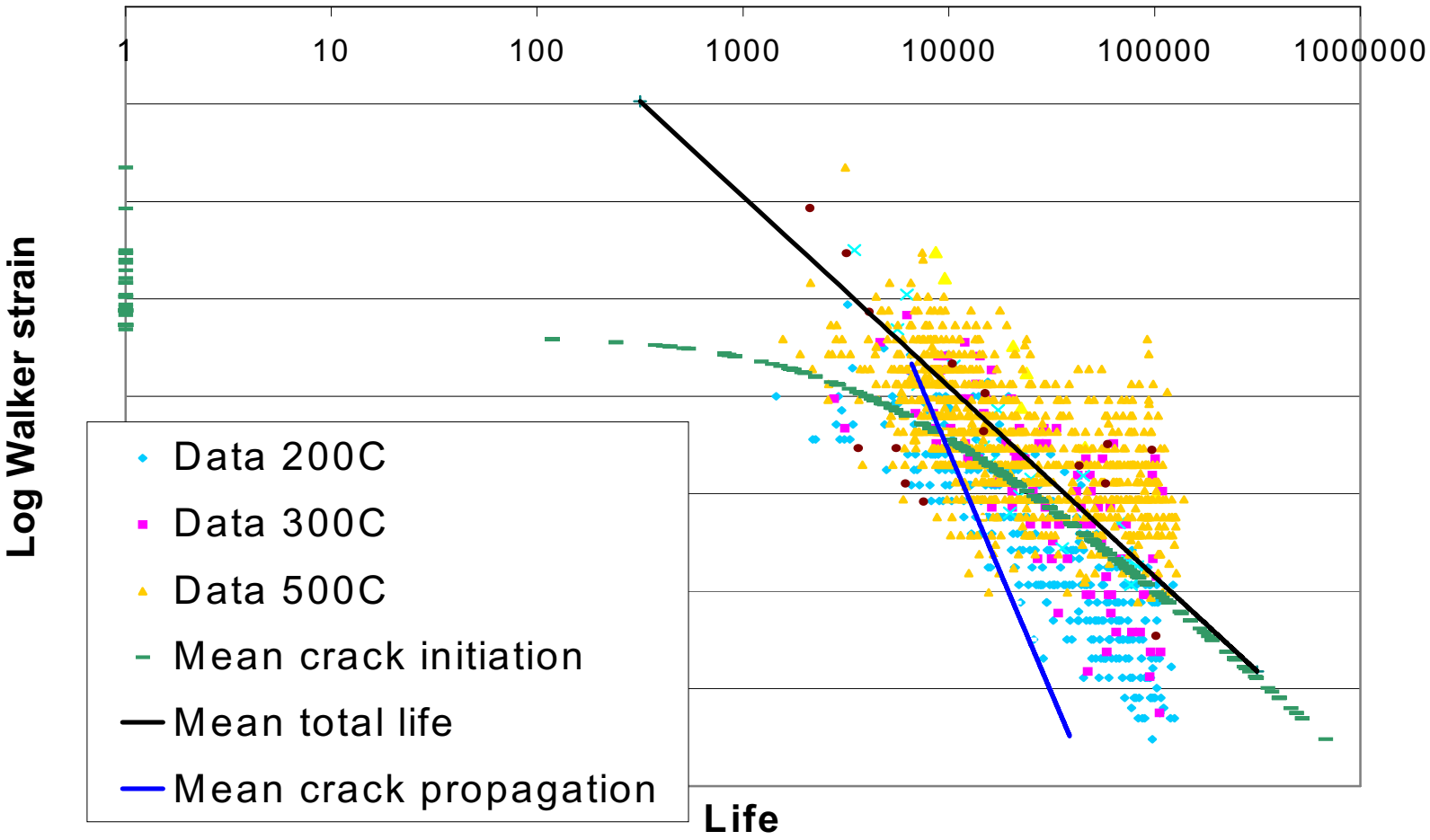
Implementation - 1

- Since Waspaloy is a surface sensitive material, it is appropriate to consider the integral taken over the surface area of the geometry
- However, this gives lives which are too short
- Since the initiation process actually involves a finite volume of material, the integral is evaluated over a 3-dimensional surface layer, the thickness of the layer appearing as an additional parameter in the model
- Depth used in current study was 0.4mm, approximately equal to conventional ‘engineering crack size’

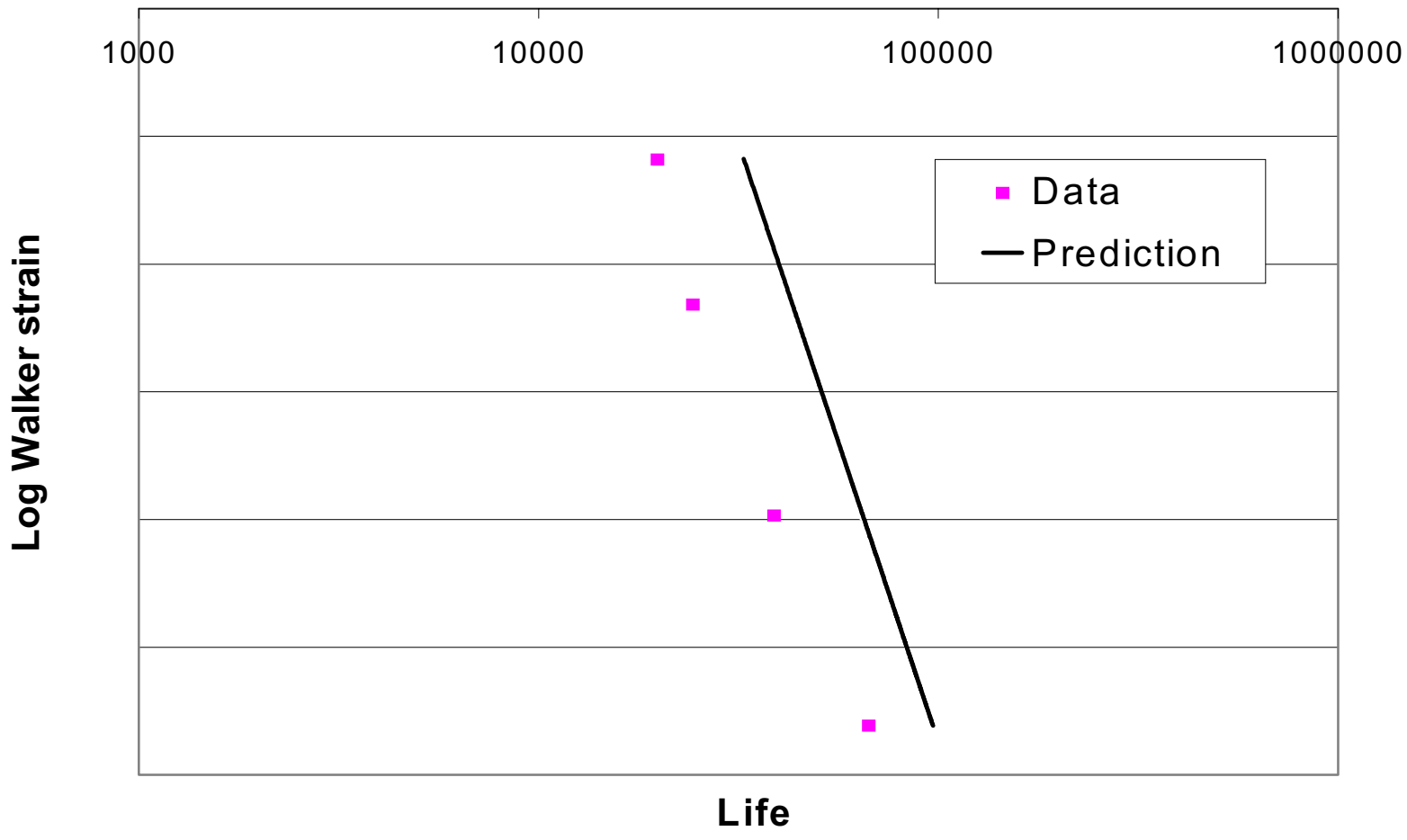
Implementation - 2

- Since the model involves separate crack initiation and propagation models, need to define the interface between the two
- This involves defining the crack size at which propagation is assumed to begin appearing as an additional parameter to be optimised within the analysis
- Current study gave value of 0.3mm, close to value of surface depth parameter
- Suggests that they could be considered as a single parameter, reducing complexity of the model

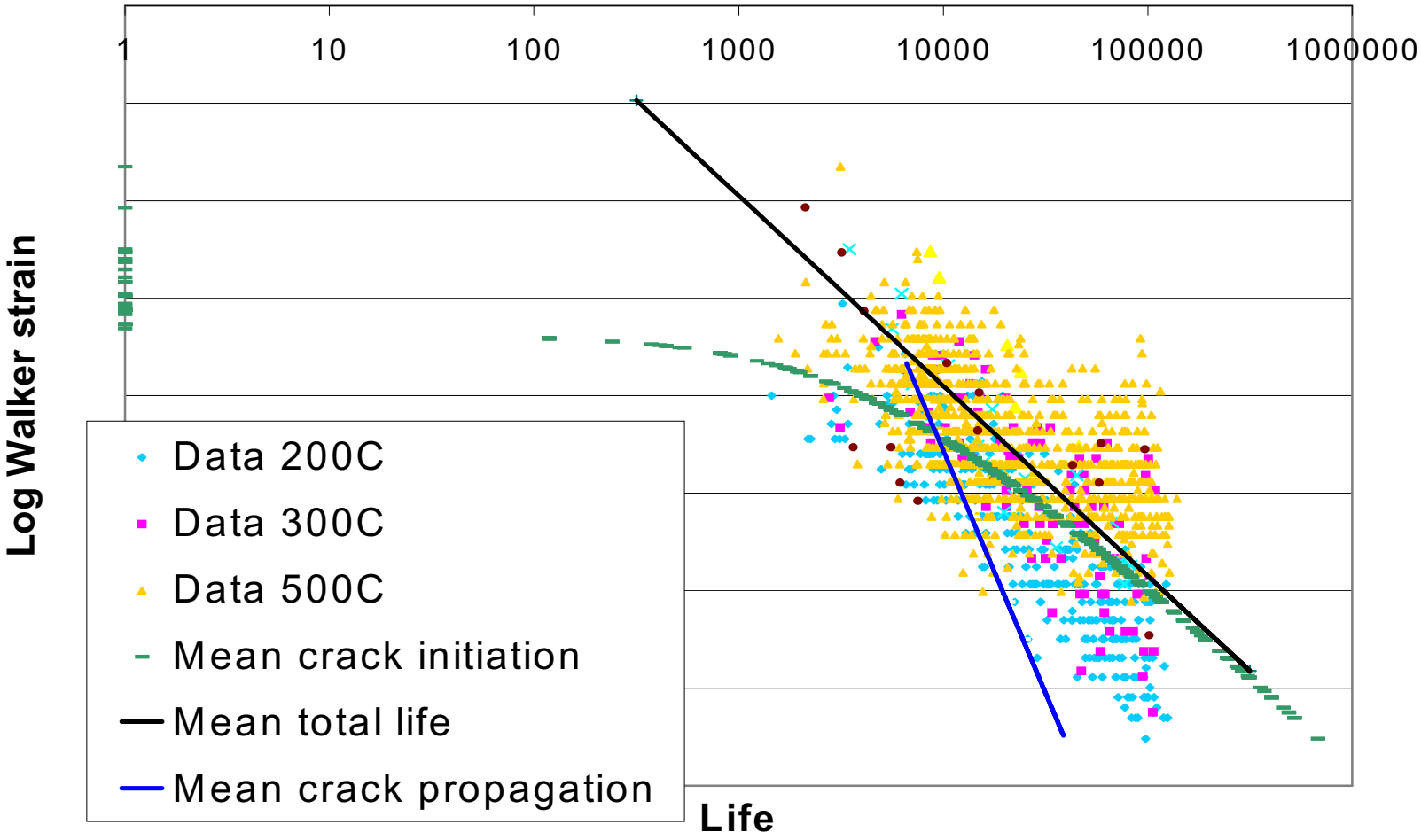
Crack initiation model

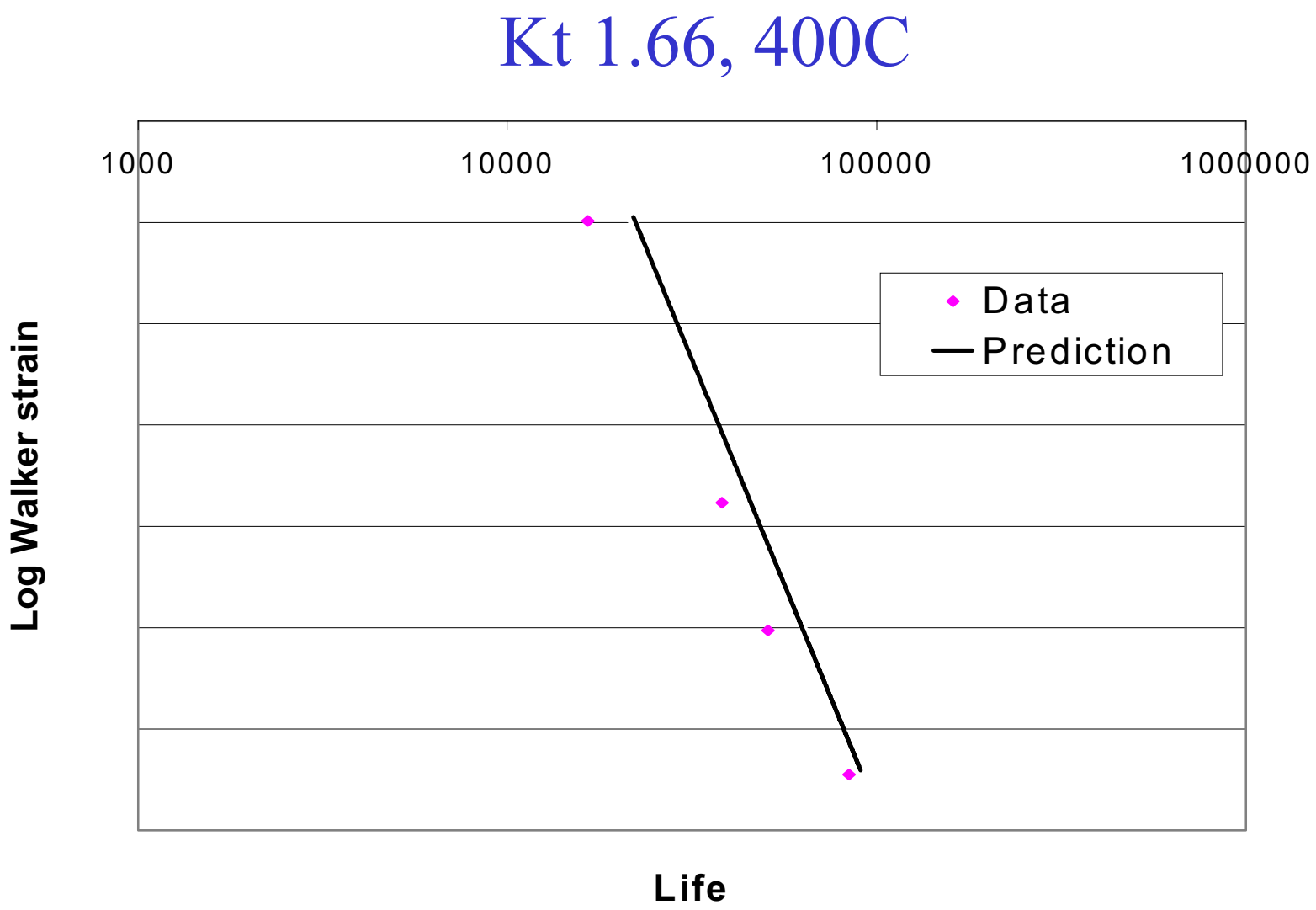


Kt 1.66, 200C


1000
10000
100000
1000000
Data
Prediction
Log Walker strain
Life

Crack initiation model

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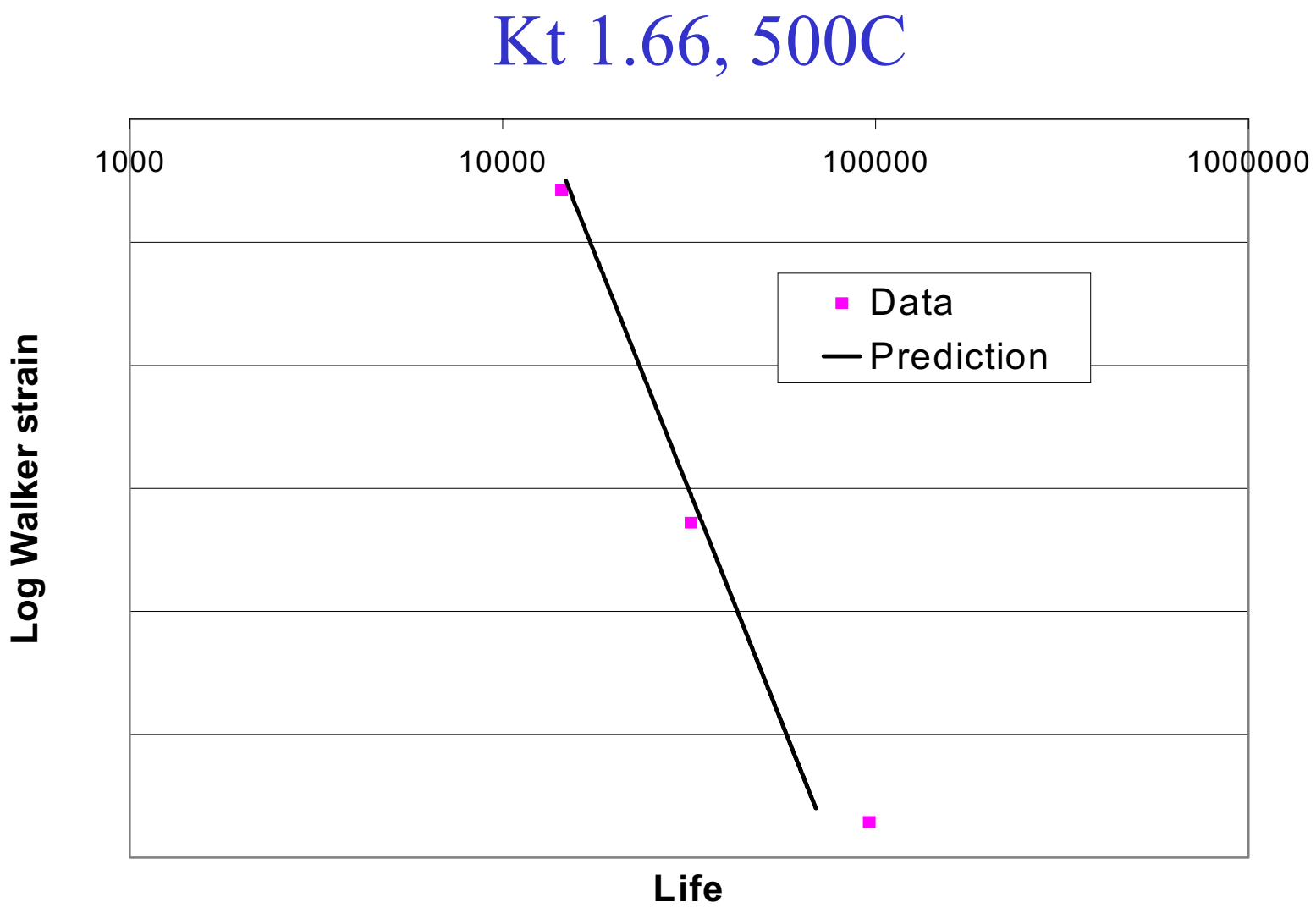
Data
Prediction
Log Walker strain
Life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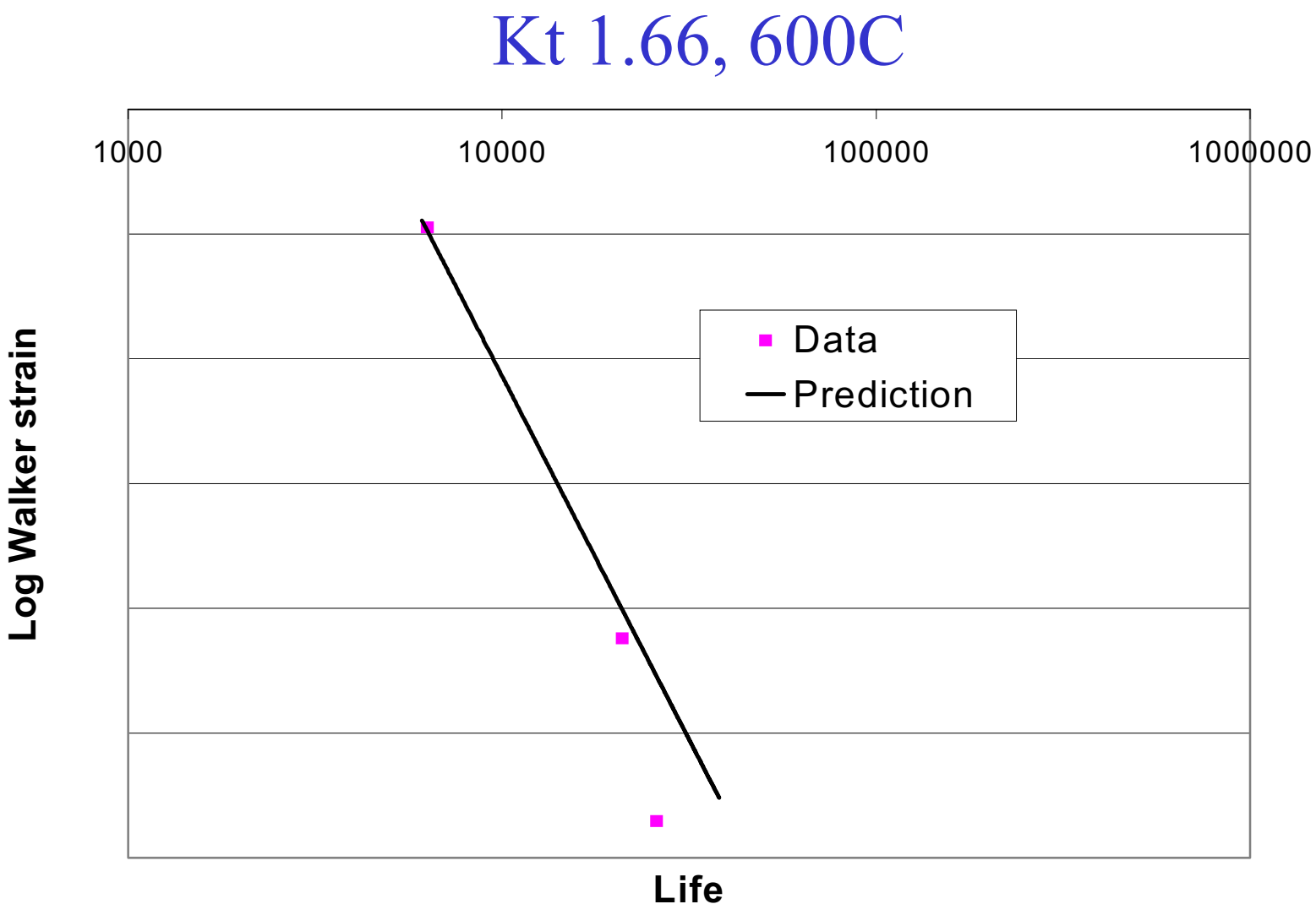
Log Walker strain
Life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Log Walker strain
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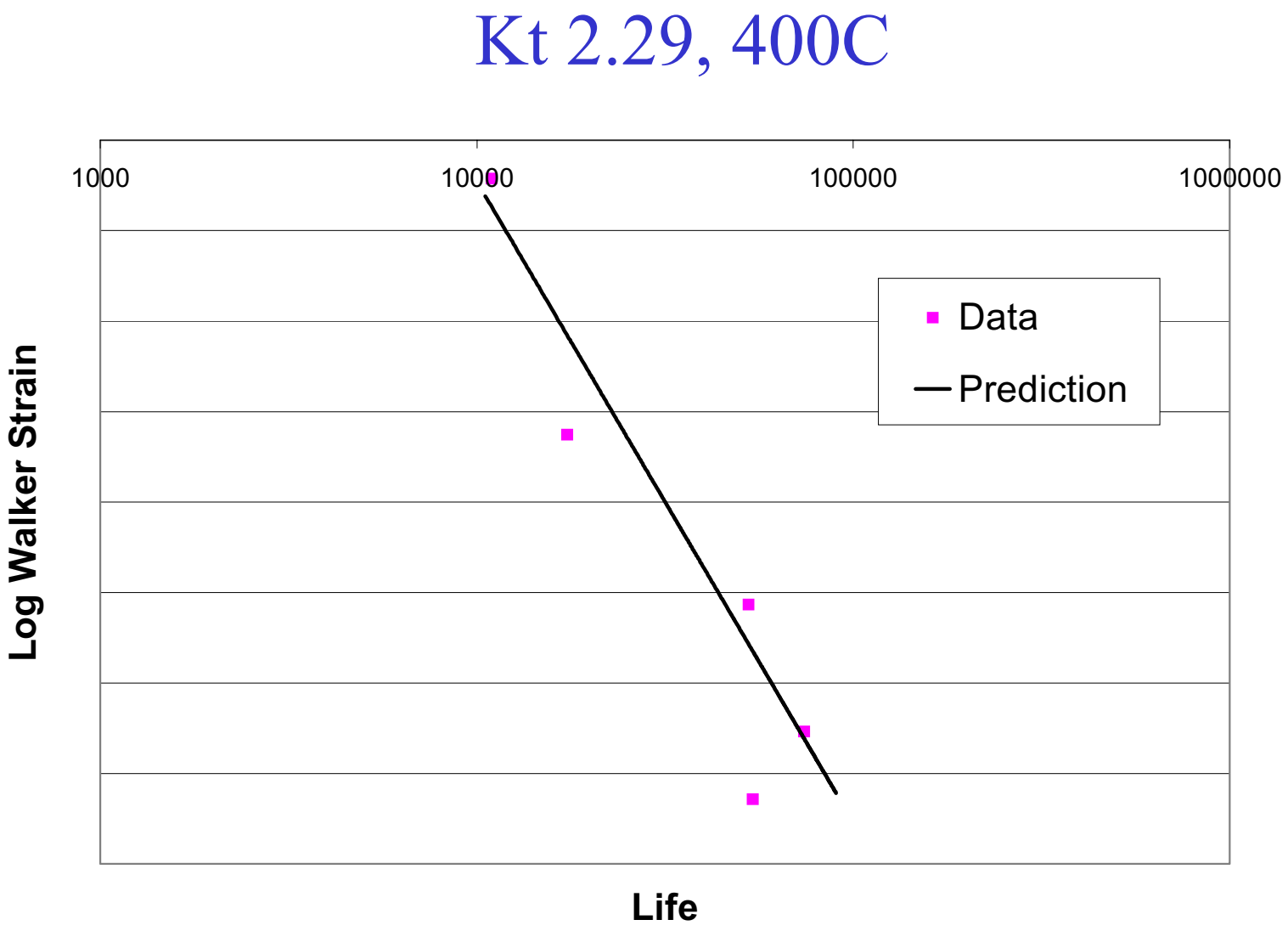
Data
Prediction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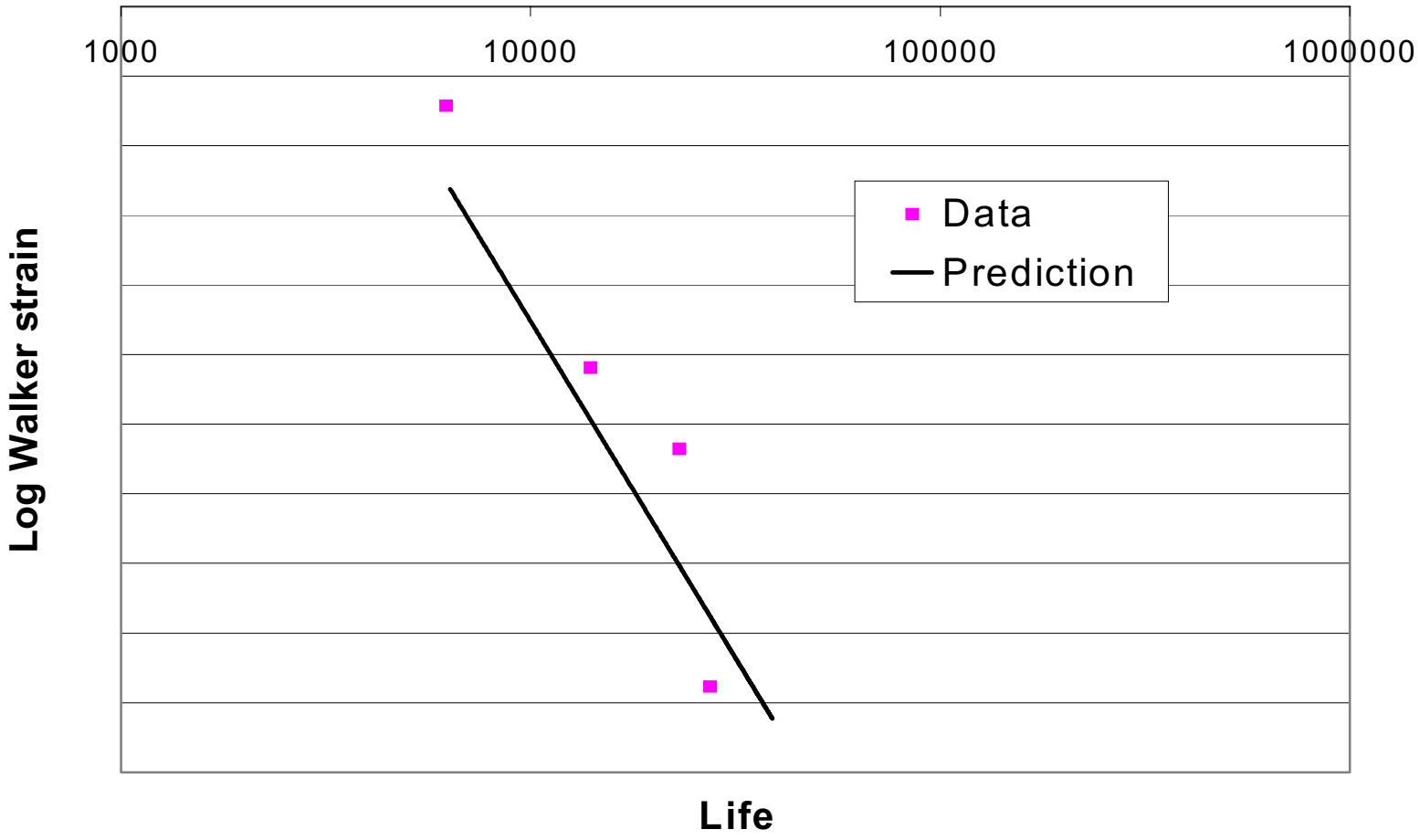
Data
Prediction
Log Walker Strain
Life

Kt 2.29, 500C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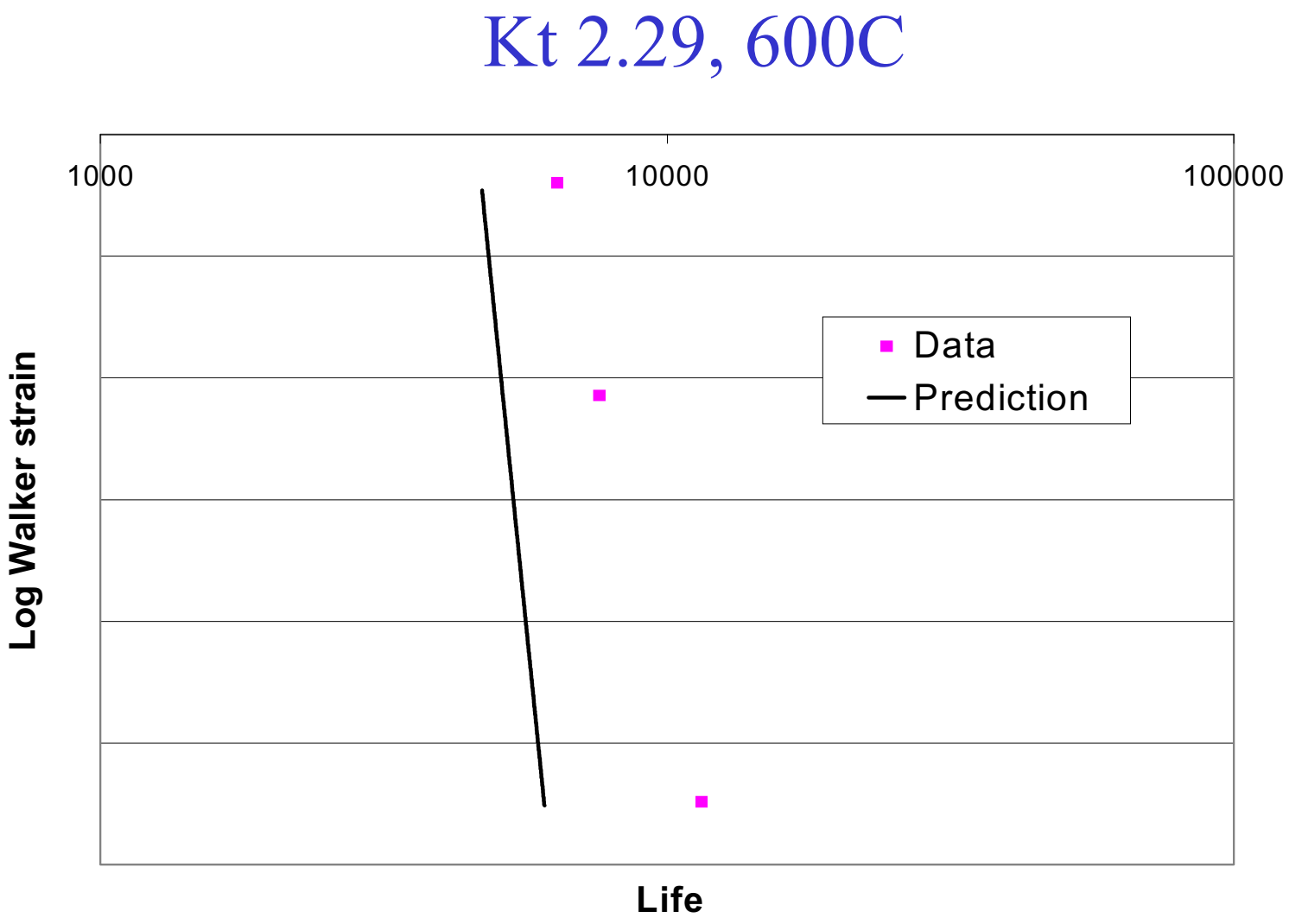
Prediction
Log Walker strain
Life


Kt 2.29, 600C
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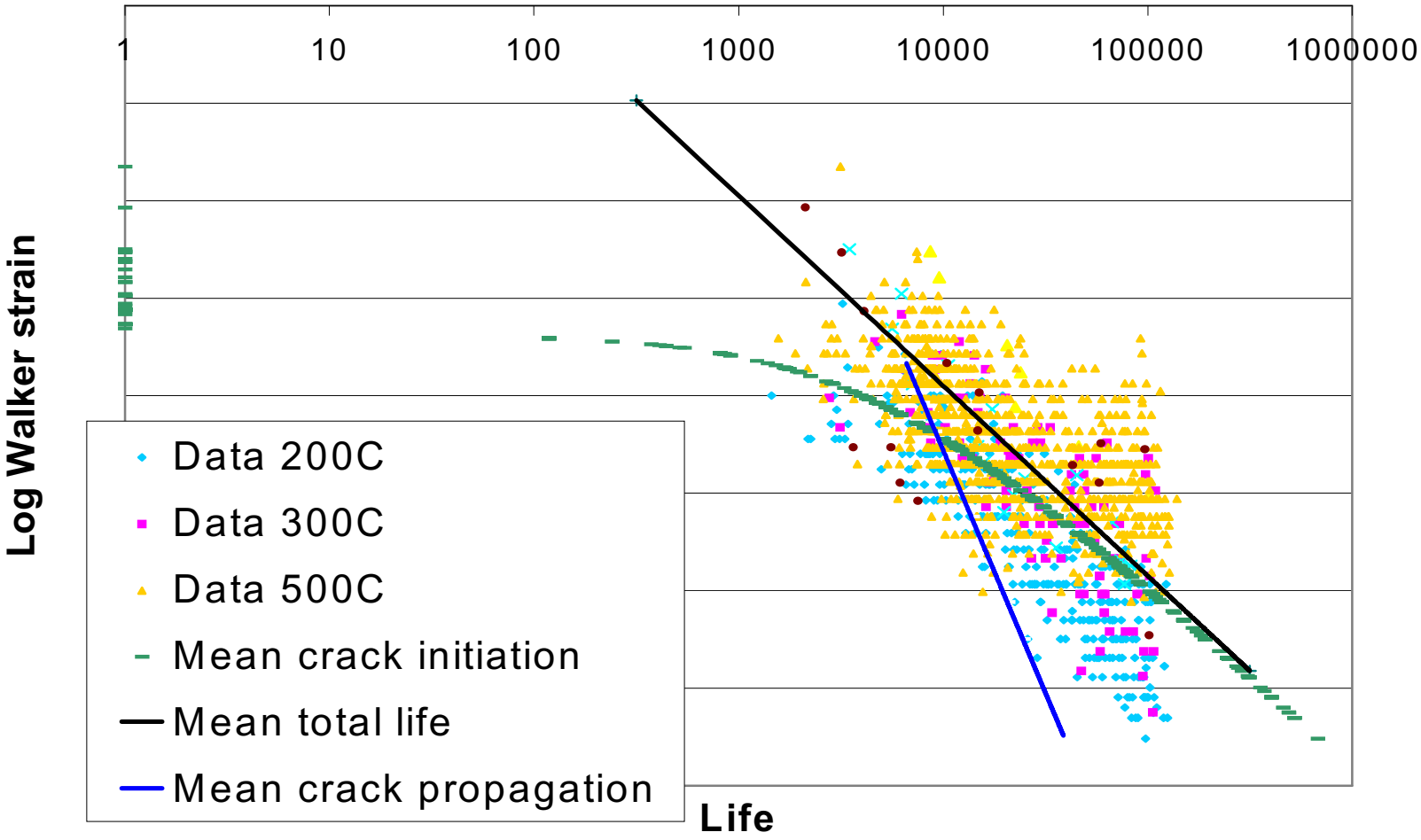
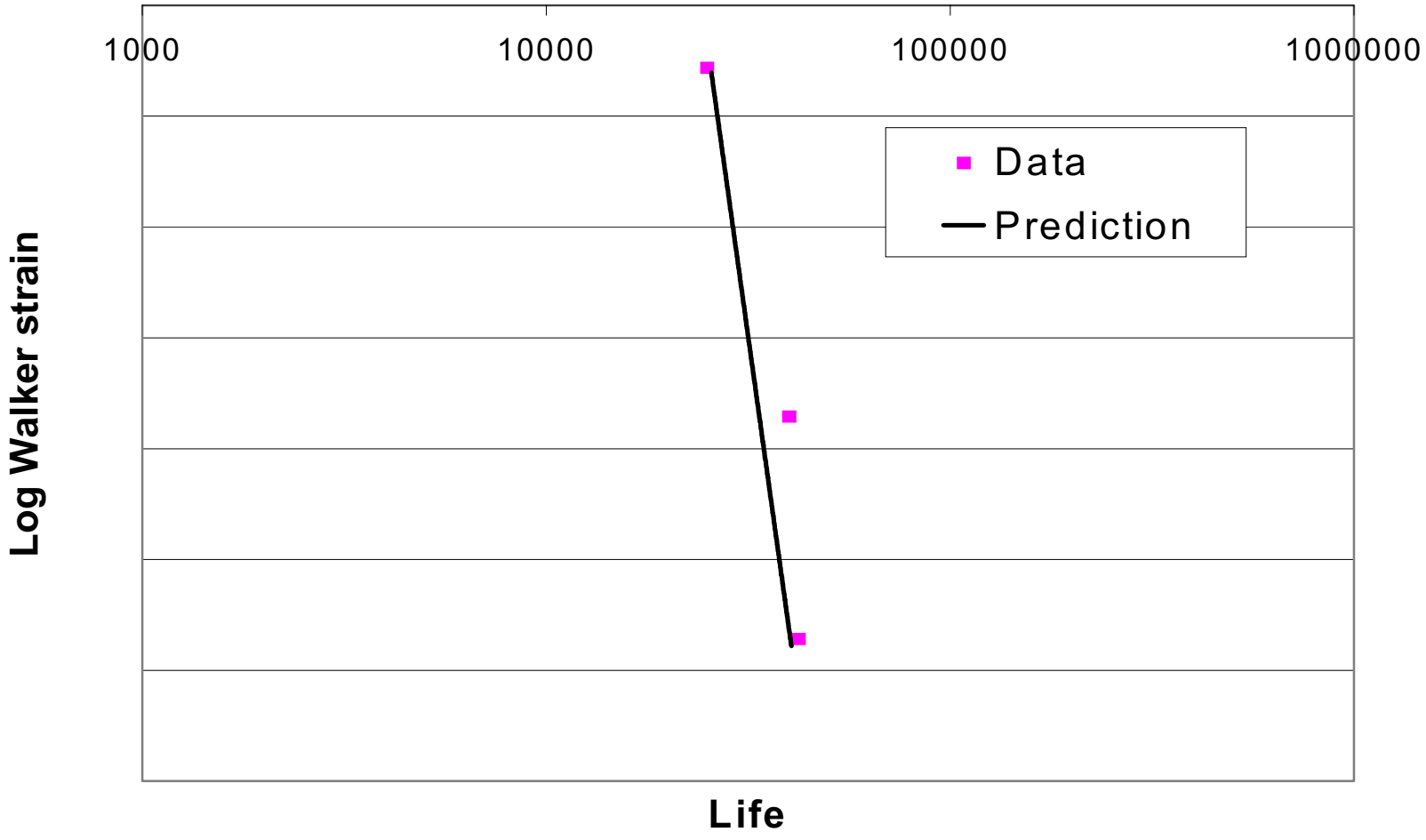
Log Walker strain
Life
Data
Prediction

Crack initiation model



Component bore tests



Conclusions

- Can predict both specimen and component behaviour, based on analysis of plain specimen data
- This provides a strong validation of the methodology, since the component bore and specimen results represent extremes in terms of both strain and volume
- Method is very flexible, in that alternative initiation/propagation models can be substituted into the basic framework, allowing all relevant features to be described

Further work

- Work remains to fully optimise the current analysis
- Develop the method to provide predictions of the distribution of lives for arbitrary test pieces
- Analyse remaining specimens and component results in database
- Further validate the method against other materials

Durability and Fatigue of Composite Structures in Acoustic Environment

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Power Spectral Density (PSD) of base acceleration is used to describe the frequency content and intensity of random forced vibration of a composite structure in an acoustic environment. Structural degradation is represented by the reduction of natural frequency during the application of PSD loading. A computational tool is developed to simulate the degradation response. Quantitative predictions of damage initiation, damage progression and propagation to fracture are monitored. The degradation of frequency is plotted out with the increment of time steps. The Excitation level-Time curve is predicted from the output of several simulations at different PSD levels. There are three computational modules in the program as follows: (1) damage progression module, (2) composite mechanics module, and (3) structural analysis module. The composite mechanics module conducts a **time domain cyclic durability analysis**. However, the structural analysis module conducts a **frequency domain FEM analysis** under PSD fatigue loading. Output from the structural analysis module is in the form of mean square stress responses. To combine the frequency domain structural analysis module and the time domain composite mechanics module, a new program block, named the PSD block, has been developed. The function of the PSD block is to retrieve the upper and lower bound and the representative period of cyclic stress responses from the frequency domain output and submit them to the composite mechanics module. Probabilistic analysis of response taking into account uncertainties in the primitive design variables will be considered. Methods will be demonstrated via the analysis of a composite airfoil under three different PSD load intensities.

Durability and Fatigue of Composite Structures in Acoustic Environment

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ABSTRACT

Engine structures are designed to function in acoustic fatigue environments where excitation levels can only be defined non-deterministically. Power Spectral Density (PSD) is used to describe the frequency contents and intensities of random vibrations. Random excitations can be applied in the form of accelerations, pressures or forces. Degradation of a structure is usually represented by reduction of the natural frequency during the application of PSD loading. A computational tool is developed to simulate the degradation response of composite structures under a PSD type fatigue loading condition. Quantitative predictions of damage initiation, damage progression and propagation to fracture are monitored. Iteration of the program is based on a step-by-step update of time during damage progression under PSD loading. For each equilibrium point natural frequencies of the structure are computed. The degradation of frequency response is determined with the increment of time steps. The Excitation level-Time relationship is predicted from the output of several simulations at different PSD levels. An adhesively bonded PMC test coupon is simulated on a dynamic shaker by imposing the PSD of base accelerations. Failure mechanisms and their locations are identified.

KEY WORDS: Acoustic Fatigue, Computational Simulation, PSD Loading, Random Excitation

INTRODUCTION

Components of airframe and engine structures are usually subject to stochastic loads. Accordingly, the behavior of a composite structure under such loading conditions is of considerable interest to design engineers. In this paper, a new computational simulation strategy under power spectral density (PSD) fatigue loading condition is discussed. Assumptions and methodologies used in evaluating structures subjected to PSD loading are examined. To validate the new computational tool, an adhesively bonded tee-shaped specimen excited by base accelerations on a shaker table is simulated. Different excitation levels of the PSD loading are investigated in the simulation. Damage progression in specimens subjected to different PSD levels are compared and discussed. The developed method is general and applicable to complex

structural systems, as well as simple shaker coupon specimens. The response degradation of the structure and the detailed failure mechanisms are quantified.

METHODOLOGY

Computational simulation is implemented via three modules as follows: (1) damage progression module, (2) composite mechanics module, and (3) structural analysis module (Minnetyan et al 1998). The steps in the evaluation of a composite structure are as follows:

1. Compute the constituent properties of each node using the composite mechanics module.
2. Set the initial time increment.
3. Do the analysis under PSD fatigue loading condition via the structural analysis module.
4. Call the PSD block to retrieve the upper and lower bounds of the stress response and equivalent period at each node.
5. Check the failure criteria and assess the failure modes via the composite mechanics module.
6. Keep an account of the degradation in each lamina at each structural node.
7. Update the structural model using the degraded properties.
8. Delete fractured nodes to allow simulation of the progress of fracture across the laminate.
9. If equilibrium is reached, increase the time.
10. If equilibrium is not reached due to additional damage, make the necessary material property adjustments and reanalyze.

The iterations are based on increasing the duration of time. The composite mechanics module conducts a time domain cyclic durability analysis. However, the structural analysis module conducts a frequency domain FEM analysis under PSD fatigue loading instead of a time history analysis. Under the PSD fatigue loading, output from the structural analysis module is in the form of mean square stress responses. To combine the frequency domain structural analysis module and the time domain composite mechanics module, a new program block, named the PSD block, has been developed (Li 2000). The function of the PSD block is to retrieve the upper and lower bounds and the representative period of cyclic stress responses from the frequency domain output and submit them to the composite mechanics module. Figure 1 shows a schematic of the computational simulation cycle under PSD cyclic fatigue loading.

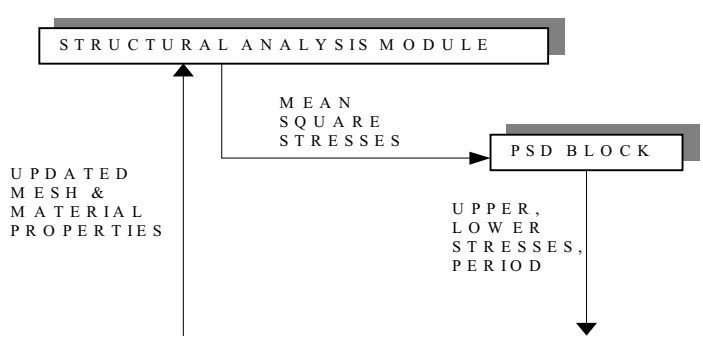


Figure 1 Schematic of Simulation Cycle under PSD fatigue loading

With the PSD block, the program has the ability to include the frequency domain finite element analysis as a module. In other words, the PSD block works as a bridge between the structural analysis module and the other components of the simulation method. The PSD block mainly carries out three jobs:

1. Determines the average upper bound, average lower bound of the nodal stresses.
2. Determines the dominant periods of stress responses of nodes.
3. Rearranges the stresses and period information and stores them in a file, so that the composite mechanics module can take them as input.

The FEM program is called three times in order to achieve all the tasks enumerated. The PSD block is run after calling the structural analysis module and before calling the composite mechanics module. The position of it in the computational simulation cycle is shown in Figure 1.

Implementation of the PSD block is based on the following assumptions:

I. There exists an equivalent cyclic harmonic response to the PSD fatigue loading that satisfies the following three conditions:
   1. The response has a unique frequency of ω, $(\omega_1<\omega<\omega_2)$, where ω_1, ω_2 are the lower bound and upper bound of the loading frequency band.
   2. The upper stress V_u, lower stress $V_l = -V_u$ of the response give rise to the Mean Square Stresses $E(V^2)$, which is the Mean Square Response computed by FEM.
   3. The equivalent cyclic harmonic response has the same effects on the structure as the actual PSD response of the structure, which has multi-frequency content.

II. The frequency ω corresponding to the largest stress response of the structure is the dominant response frequency of that node.

III. A cyclic response with the dominant frequency as its only frequency content will have equivalent effects on the structure as the actual PSD response of the structure. Thus using the dominant frequency as the pseudo-response will be able to estimate the structural behavior.

In a computational simulation cycle under PSD loading, FEM module is called three times.

- On the first time, FEM is called to determine the upper and lower bounds of cyclic stresses.
- On the second and third times, FEM is called to determine the dominant response frequencies.

The FEM input file is rewritten for different purposes every time the structural analysis module is called.

Computation of Upper and Lower Stresses of The Representative Cyclic Loading To construct the representative harmonic response, i.e. to determine the equivalent cyclic response for computation of failure analysis in the composite mechanics module, we need to find out the upper and lower stresses as well as the dominant frequency. The upper and lower bounds of cyclic stresses are determined using the following method:

Assume that the cyclic response with the dominant frequency is a sine curve as in Figure 2, $V = V_u \sin(\omega t)$, in the case of harmonic loading $V_u = |V_l|$

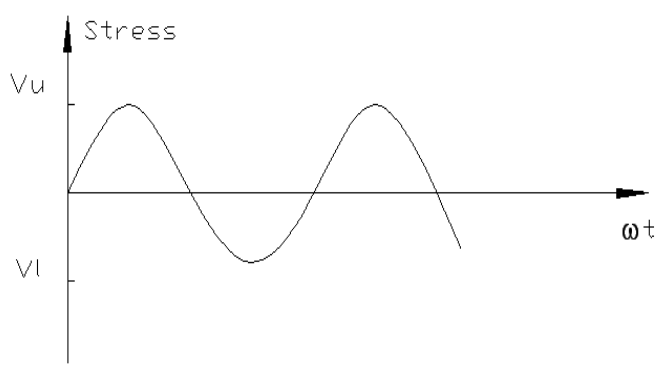
Then the mean square of the stress response will be:

$$
\begin{aligned}
E(V^2) = E[V_u^2 \sin^2(\omega t)] &= V_u^2 E[\sin^2(\omega t)] \\
&= V_u^2 \frac{1}{\pi} \int_0^{\pi} \sin^2(\omega t) d(\omega t) \\
&= V_u^2 \frac{1}{\pi} \int_0^{\pi} \frac{1-\cos(2x)}{2} dx \\
&= V_u^2 \frac{1}{\pi} \times \frac{\pi}{2} \\
&= \frac{1}{2} V_u^2
\end{aligned}
\tag{1}
$$

A sample mean square representation of the cyclic response is shown in figure 3.

Therefore from (1) it follows that:

$$
V_u = \sqrt{2E(V^2)}\ ,\ V_l = -\sqrt{2E(V^2)} \tag{2}
$$



V_l, lower stress of the harmonic PSD stress response
V_u, upper stress of the harmonic PSD stress response
t, time
ω, frequency of the harmonic PSD stress response

Figure 2 Response of Structure to Harmonic Loading

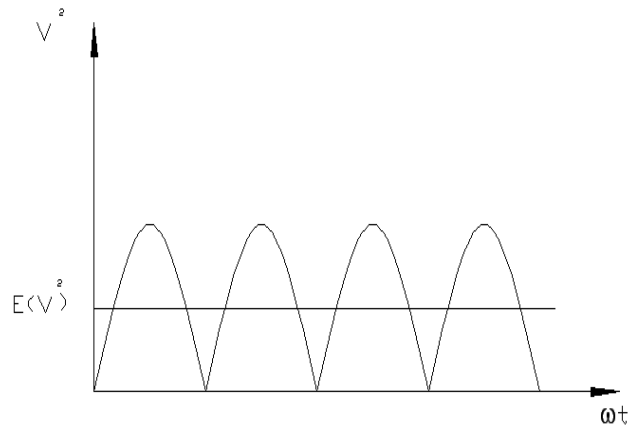


Figure 3 Mean Square Harmonic Responses

To obtain the upper and lower stresses of the equivalent cyclic response of the structure, first the FEM input file is prepared for PSD loading analysis. Since the stress response of the structure to PSD loading is required, only one frequency band, the loading frequency band**,** is used when the FEM input file is written. The FEM module carries out a Gaussian quadrature over the PSD loading frequency range, and outputs the mean square response $E(V^2)$ of each node. Based on assumption (2), the mean square stresses are output $E(V^2)$ with equation (2) and the V_u and V_l values are determined. Thus the upper and lower stresses of the objective harmonic response are obtained.

Search and Calculation of the Dominant Frequency After determination of the upper and lower stresses of the representative cyclic response in the last section, the remaining problem is obtaining the dominant frequency. The search for the dominant frequency of the Structural Cyclic Response can be divided into two steps. In the first step, the frequency band is subdivided into 10 intervals and the interval that gives rise to largest stresses is identified. If the user doesn't require high precision in the simulation, the result of the first step can be used and the simulation will jump out of the PSD block and proceed to the composite mechanics module, thus the time of computation will be reduced. If higher precision simulation is required, the program will go to the more refined second stage of the period computation. In the second step, the frequency interval found out by the first step is again divided into 10 smaller subintervals, whose bandwidth is of 1/100 of the original frequency band. The dominant frequency search procedure as in step one is repeated here. The resulting frequency becomes the dominant frequency.

COMPOSITE TEST SPECIMEN

Adhesively Bonded PMC tee shaped test coupon had a height of 2.8 inches, a horizontal wing that measured 6.0 inches in length and 2.0 inch at its widest point. Figure 4 contains a finite element model of the "tee" shaped coupon geometry definition. The top skin consisted of 24 layers of IM7/5250-4 BMI tape and the tee rib consisted of 8 layer of IM7/5250-4 BMI fabric. Composite specimen on a dynamic shaker were simulated by imposing the PSD of base accelerations. Simulations were conducted at room temperature. The ply layup and ply

properties are given in table 1. At the junction of the vertical and horizontal members, the "noodle" consisted of IM7/5250-4 BMI tape rolled into a cylindrical shape and placed in the tee section. The purpose of the noodle was to fill the void in the structure where the eight layers of the vertical tee divided, formed a radius, and became the lower four layers of the horizontal tee section. These four layers when joined with the upper layers of the horizontal tee brought the total thickness back to eight layers. The vertical legs of the specimens were clamped in a vice-like manner to the shaker table, with the fixed portion of the model 1.0 inch from the top surface of the top (horizontal) skin. This clamping distance indicated where the fixed boundary conditions and accelerations should be applied. The coupons were simulated at various input levels over a frequency band that was approximately ±10% of the coupon's resonant frequency. The PSD spectrum was flat in this frequency band. A 4.68-gram weight was mounted on one wing of the coupon. The location of this weight was to produce some eccentricity in the symmetric mode so that shaking the specimen symmetrically would excite this asymmetric mode. Failure was defined as 5% decrease in the resonant frequency. The result of the simulations was S-N curve for this tee coupon configuration. The failure mechanism(s) and location(s) were identified.

Finite Element Model for Tee Specimen The finite element model for the Tee Specimen had 1217 nodes and 1200 elements (Figure 4). The structure was constrained in 1,3,4,5,6 directions at the bottom nodes, and excited also on the base nodes in the 2 direction. The material properties used were calibrated according to the modulus given by test data, and the material was IM-7/5250. The laminate configuration in the web was fabric of 8 ply layup $(45,0,-45,45)_s$, while the laminate configuration in the top skin was tape of 24 ply layup$(45,0,-45,90)_{3s}$. The 4.68 gram weight was simulated by adding the mass at all three directions at node 788. Frequency shifted eigenanalysis was used to extract the natural frequencies from 5 rad/sec to 5000 rad/sec. The damping ratio of 0.001 was adopted for the carbon fiber composite. Six different laminate types were used to simulate the laminate structure of the tee shaped specimen. The laminate type 1 was the typical laminate configuration used for the top skin. Type 2 was the typical laminate configuration used for the stem. Type 3 and type 6 were the parts of the top skin that combined with the stem. Type 5 represented the laminate where the stem split into two at the junction with the top skin. Duplicate nodes were used in the nodes where the laminate configuration changed.

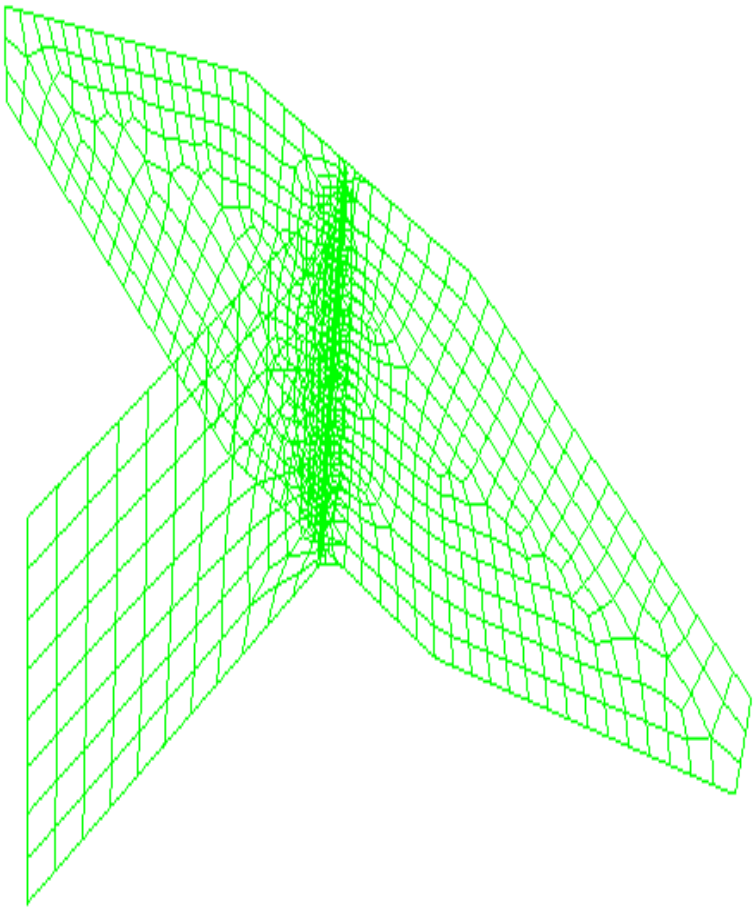


Figure 4 Finite Element Model for Tee Specimen

Table 1 Laminate Types used in the Model

Type	Laminate Configuration	Number of Plies
1	$[45/0/-45/90]_{3s}$	24
2	$[45/-45/0/90/-45/45/45/-45]_s$	16
3	$[45/0/-45/90]_{3s}[45/-45/0/90/-45/45/45/-45]_s$	40
4	$[45/0/-45/90]_{3s}[45/-45/0/90/-45/45/45/-45]$	32
5	[45/-45/-45/45/0/90/45/-45]	8
6	$[45/-45/0/90/-45/45/45/-45]_s[45/0/-45/90]_{3s}$	40

Modal Analysis of the Specimen The frequency range was defined by taking the ±10% value of the structural natural frequency. Therefore in the simulation, the natural frequency of the structure had to be determined before defining the test frequency range. The first two dominant natural modes of the coupons were asymmetric and symmetric modes. The resulting natural

frequency for the first asymmetric mode was 110.8Hz. The loading frequency band was calculated as:

Upper Bound = 110.8 * 110% = 121.88 Hz
Lower Bound = 110.8 * 90% = 99.72 Hz

Ply Layup and Ply Properties The composite mechanics package ICAN (Murthy and Chamis 1986) was used to compute the structural properties from the constituent fiber and matrix properties for the tape layup and woven fabric, assuming a fiber volume ratio of 0.60, Void Volume Ratio of 0.01, and curing temperature of 177°C (350 F°).

IM-7 FIBER properties for specimen(tape):
Number of fibers per end = 12000
Fiber diameter = 0.00508 mm (0.200E-3 in)
Fiber Density = 4.14E-7 Kg/m^3 (0.0645 lb/in^3)
Longitudinal normal modulus = 255 GPa (36.90E+6 psi)
Transverse normal modulus = 14.7 GPa (2.13E+6 psi)
Poisson's ratio (ν_{12}) = 0.320
Poisson's ratio (ν_{23}) = 0.355
Shear modulus (G_{12}) = 24.8 GPa (3.60E+6 psi)
Shear modulus (G_{23}) = 11.04 GPa (1.60E+6 psi)
Longitudinal thermal expansion coefficient = -2.29E-6/°C (-1.27E-6 /°F)
Transverse thermal expansion coefficient = 0.92E-5/°C (0.51E-5 /°F)
Longitudinal heat conductivity = 0.301 J-m/hr/m^2/°C (4.03 BTU-in/hr/in^2/°F)
Transverse heat conductivity = 0.0301 J-m/hr/m^2/°C (0.403 BTU-in/hr/in^2/°F)
Heat capacity = 0.712 KJ/Kg/°C (0.17 BTU/lb/°F)
Tensile strength = 3.45 GPa (500 ksi)
Compressive strength = 1.724 GPa (250 ksi)

WIM-7 FIBER properties for specimen(fabric):
Number of fibers per end = 12000
Fiber diameter = 0.00508 mm (0.200E-3 in)
Fiber Density = 4.14E-7 Kg/m^3 (0.0645 lb/in^3)
Longitudinal normal modulus = 225 GPa (32.50E+6 psi)
Transverse normal modulus = 13.8 GPa (2.00E+6 psi)
Poisson's ratio (ν_{12}) = 0.350
Poisson's ratio (ν_{23}) = 0.355
Shear modulus (G_{12}) = 51.7 GPa (7.50E+6 psi)
Shear modulus (G_{23}) = 6.21 GPa (0.90E+6 psi)
Longitudinal thermal expansion coefficient = -2.29E-6/°C (-1.27E-6 /°F)
Transverse thermal expansion coefficient = 0.92E-5/°C (0.51E-5 /°F)
Longitudinal heat conductivity = 0.301 J-m/hr/m^2/°C (4.03 BTU-in/hr/in^2/°F)
Transverse heat conductivity = 0.0301 J-m/hr/m^2/°C (0.403 BTU-in/hr/in^2/°F)
Heat capacity = 0.712 KJ/Kg/°C (0.17 BTU/lb/°F)
Tensile strength = 2.62 GPa (380 ksi)
Compressive strength = 1.310 GPa (190 ksi)

5250 INTERMEDIATE MODULUS INTERMEDIATE STRENGTH MATRIX.(tape):
Matrix density = 3.50E-7 Kg/m^3 (0.0470 lb/in^3)
Normal modulus = 4.34 GPa (630 ksi)
Poisson's ratio = 0.320
Coefficient of thermal expansion = 0.518E-4/°C (0.288E-4 /°F)
Heat conductivity = 0.654E-3 J-m/hr/m^2/°C (0.868E-2 BTU-in/hr/in^2/°F)
Heat capacity = 1.047 KJ/Kg/°C (0.25 BTU/lb/°F)
Tensile strength = 90.3 MPa (13.1 ksi)
Compressive strength = 283 MPa (41.0 ksi)
Shear strength = 138 MPa (20.0 ksi)
Allowable tensile strain = 0.02
Allowable compressive strain = 0.05
Allowable shear strain = 0.04
Allowable torsional strain = 0.04
Void conductivity = 16.8 J-m/hr/m^2/°C (0.225 BTU-in/hr/in^2/°F)
Glass transition temperature = 300°C (572°F)

W5250 INTERMEDIATE MODULUS INTERMEDIATE STRENGTH MATRIX(fabric):
Matrix density = 3.50E-7 Kg/m^3 (0.0470 lb/in^3)
Normal modulus =3.24 GPa (470 ksi)
Poisson's ratio = 0.350
Coefficient of thermal expansion = 0.518E-4/°C (0.288E-4 /°F)
Heat conductivity = 0.654E-3 J-m/hr/m^2/°C (0.868E-2 BTU-in/hr/in^2/°F)
Heat capacity = 1.047 KJ/Kg/°C (0.25 BTU/lb/°F)
Tensile strength = 90.3 MPa (13.1 ksi)
Compressive strength = 283 MPa (41.0 ksi)
Shear strength = 138 MPa (20.0 ksi)
Allowable tensile strain = 0.02
Allowable compressive strain = 0.05
Allowable shear strain = 0.04
Allowable torsional strain = 0.04
Void conductivity = 16.8 J-m/hr/m^2/°C (0.225 BTU-in/hr/in^2/°F)
Glass transition temperature = 300°C (572°F)

SIMULATION CASES

To determine the PSD level—time relation of the asymmetric mode, simulations were conducted using five PSD levels. In this section the details of damage progression for each case is discussed. The Frequency-time curve is constructed. The running result of five cases are examined and compared, and the PSD level-time relation is computed.

Simulation Case 1: PSD Level 27 G^2/Hz The structure was simulated in asymmetric mode with PSD level of 27G^2/Hz. The structure failed immediately within the first second after loading. The natural frequency of the structure dropped to 98.9Hz, which was about 89.3% of the initial value. In this case, the structure failed at the same iteration step as the damage initialization. Most of

the failure occurred in the junction of the top skin and the web. The damage was spread to almost all nodes on the left side of junction where the 4.68 gram weight was mounted. On the other side of the junction most of nodes were also damaged. The damages in the junction were mainly in the form of ply transverse tensile failure σ_{l22T}. Some of the plies also showed longitudinal tensile failures σ_{l11T}. A large number of nodes on the web were also damaged.

Simulation Case 2: PSD Level 16.5 G^2/Hz The structure failed in 100 seconds. As soon as the load was applied, damage initiated on the left side of the junction part and some of the web nodes. At this time, all the damage occurred due to transverse tensile failures σ_{l22T}, and the damage volume was 0.41% of the structure. As the time reached 10 sec, the damage spread to more nodes on the web, and the damage volume was 1.39% of the total structural volume. The structure failed at the time of 100 sec and the frequency was degraded to 94.11 Hz, which was 84.9% of the initial value. The damage occurred due to not only transverse tensile failures σ_{l22T} but also longitudinal tensile failures σ_{l11T}. Most of the nodes on both sides of the junction and in the web part were damaged and the damage volume increased to 3.37% of the total structure.

Simulation Case3: PSD Level 10.5 G^2/Hz The structure failed in 1000 seconds. Damage initiated on the left side of the junction part at the first second of loading. All the damage occurred due to transverse tensile failures σ_{l22T}, and the damage volume was 0.00438% of the structure. As the time reached 10 sec, the damage spread to several nodes on the web, and the damage volume was 0.1127% of the total volume. The damage form was still transverse tensile failure σ_{l22T}. At the time of 100sec, the frequency was degraded to 109.9 Hz and damage spread to more nodes on the web. Almost all the nodes on the left side of the junction were damaged. The structure failed as the time reached 1000 sec and the natural frequency degraded to 97.07 Hz, which was about 87.6% of the original frequency. Damage occurred due to not only transverse tensile failures σ_{l22T} but also due to longitudinal tensile failures σ_{l11T}. Most of the nodes on both sides of the junction part and in the web part were failed and the damage volume increased to 3.107% of the total structure.

Simulation Case4: PSD Level 5.5 G^2/Hz The damage initiated at 100 seconds on the left side in the junction part. All damage occurred due to the transverse tensile failures σ_{l22T}, and the damage volume was 0.003607% of the structure. As the time reached 1000 sec, damage spread to 4 other

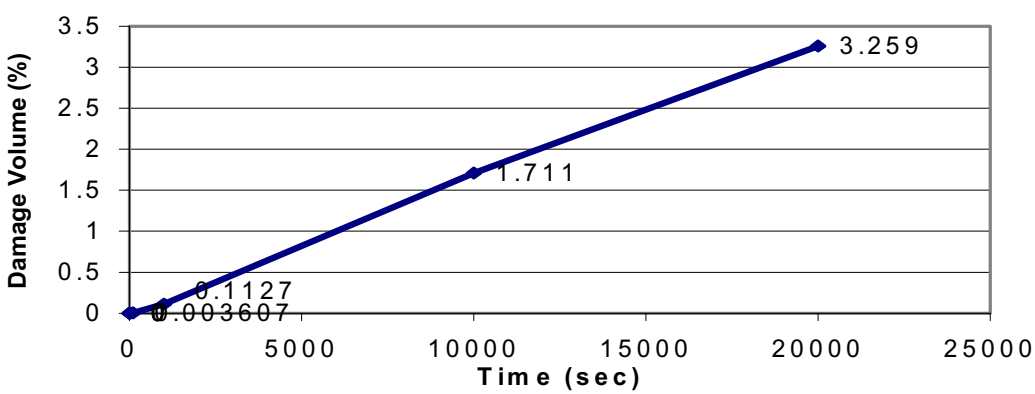


Figure 5. Case 4 Damage Progression with Time

nodes on the web, and the damage volume was 0.1127% of the total volume. The damage mode was still transverse tensile failure $\sigma_{l22T.}$ At the time step of 10000sec, the frequency was degraded to 109.3 Hz and the damage spread to more nodes on the web and the nodes on the other side of the junction. Almost all the nodes on the left side of the junction were damaged and some of them showed the new damage type of longitudinal tensile failure σ_{l11T}. The structure failed at the time of 20000sec when the natural frequency degraded to 95.85 Hz, which was 86.5 % of the initial value. The damage occurred due to not only the transverse tensile failures σ_{l22T} but also the longitudinal tensile failures σ_{l11T}. Most of the nodes on both sides in the junction part and in the web part were failed and the damage volume increased to 3.259% of the total structure. The damage progression of the structure for case 4 is in Figure 5. The degradation of the natural frequency with time is in Figure 6.

Simulation Case5: PSD Level 2.3 G^2/Hz The damage initiated at 10000 seconds on the left side of the nodes in the junction part. All the damage occurred due to the transverse tensile failure σ_{l22T}, and the damage volume was 0.005887% of the structure. As the time reached 20000 sec, the damage spread to 8 other nodes on the web, and the damage volume was 0.1557% of the total volume. The damage mode was still transverse tensile failure $\sigma_{l22T.}$ The same σ_{l22T} damage kept spreading to more nodes and plies on the web and on the other side of the junction until the new damage mode of σ_{l11T} occurred at 60000sec. The structure failed at time of 100000sec when the natural frequency degraded to 99.39 Hz, which was 89.7 % of the initial value. The damage occurred due to not only the transverse tensile failures σ_{l22T} but also longitudinal tensile failure σ_{l11T}. Most of the nodes on both sides in the junction part and in the web part were failed and damage volume increased to 1.6850% of the total structure.

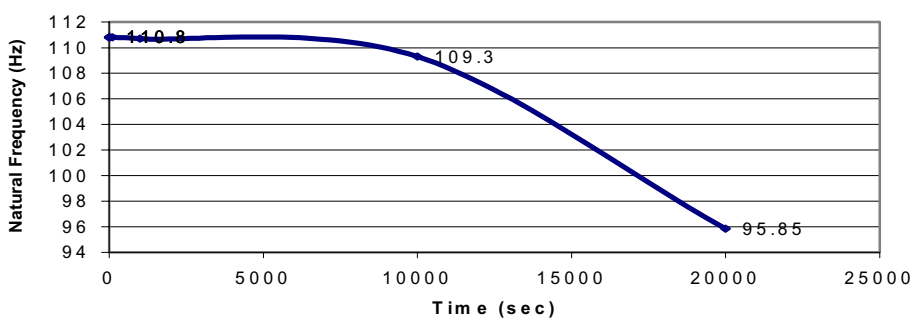


Figure 6. Case 4 Degradation of Natural Frequency with Time

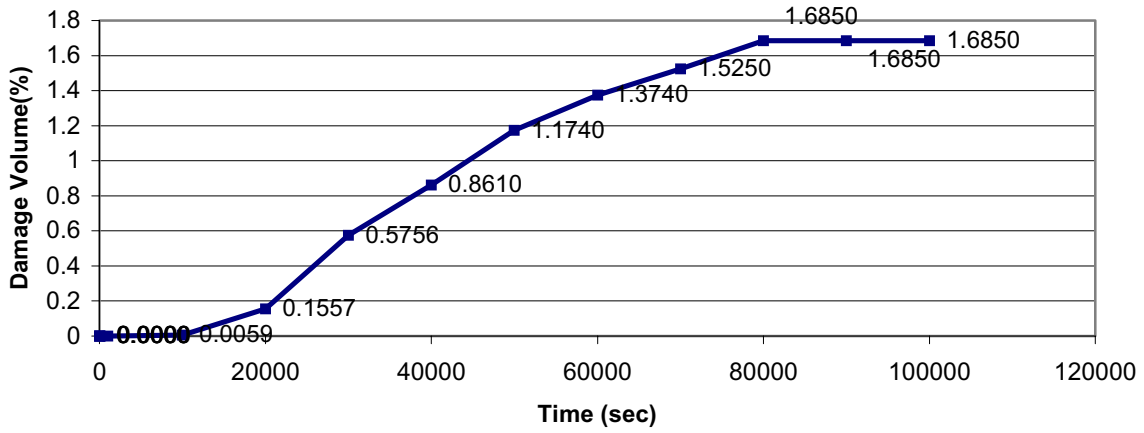


Figure 7. Case 5 Damage Progression with Time

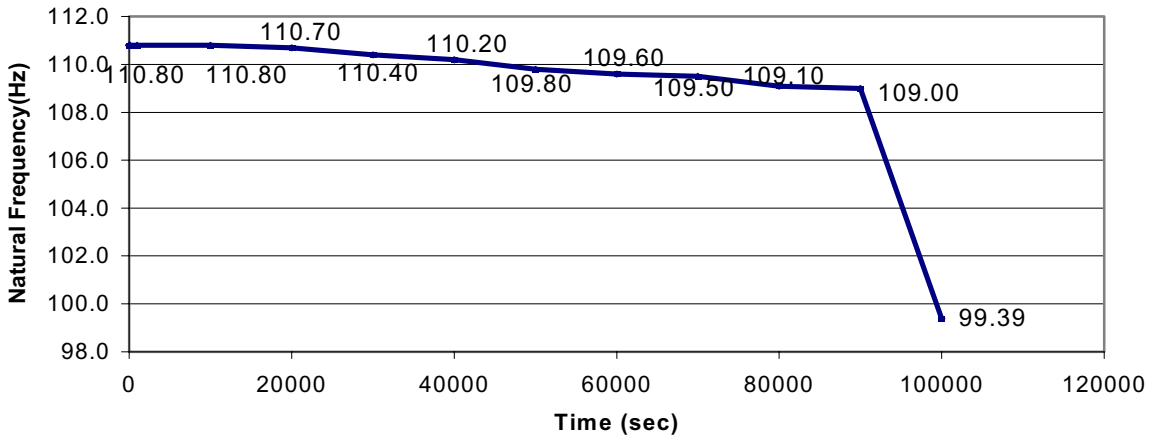


Figure 8. Case 5 Natural Frequency Degradation with Time

Table 2. PSD Level vs. Time Duration for All the 5 Cases

	Time (sec)	FEM Cycles
27	1	10
16.5	100	11
10.5	1000	12
5.5	20000	15
2.3	100000	51

Note: In simulations, the time was logarithmically increased to 10000 sec, and then increased by 10000sec every time increment.

PSD Level --- The excitation level of the structure.
Time --- The time duration for the structure to fail.
FEM Cycle --- The total number of FEM cycle used when the structure fails.

Comparison of the Five Cases The time duration for the structure to fail increased as the PSD level decreased in the five cases. The test with the PSD level of 27 G^2/Hz failed as soon as the load was applied, while for the test with the PSD level of 2.3 G^2/Hz it took almost 28 hours for the structure to fail.

If the results are plotted as a PSDlevel-hours to failure curve, the structural response to different PSD levels will be more clearly outlined (Figure 9). For all five cases, damage increased incrementally. The natural frequency showed a significant decrease when damage reached a certain level. The higher the damage volume, the more degradation of the natural frequency was shown by the structure. Coupling of the damage volume and degradation of natural frequency for all the five cases is shown in Figure 10. Since the time incrementation is rather large in this simulation, the results in figure 10 may not be precise enough. However, the correlation between damage volume and degradation of natural frequency is evident.

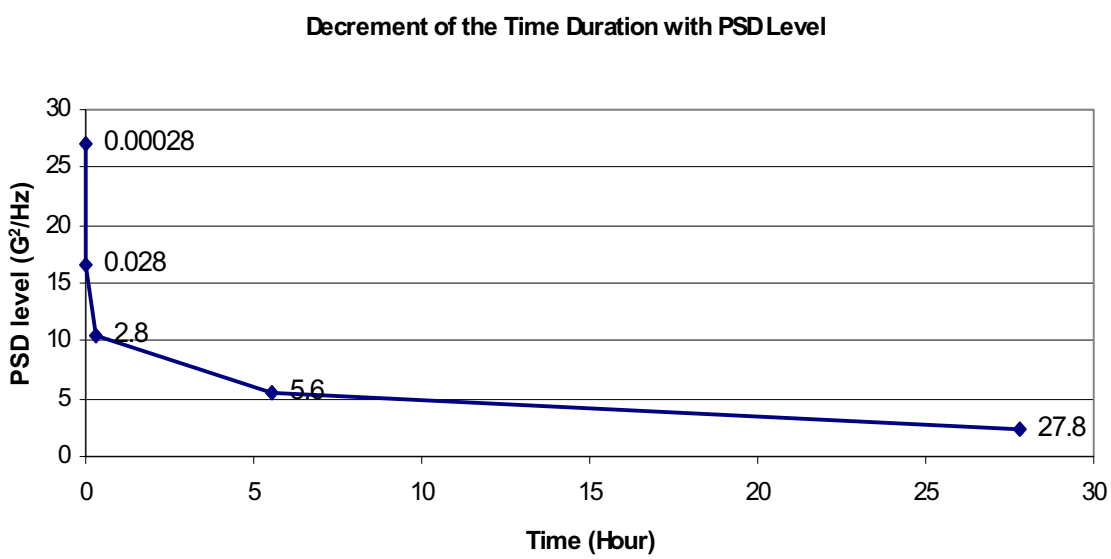


Figure 9 Decrement of Time Duration with PSD Level

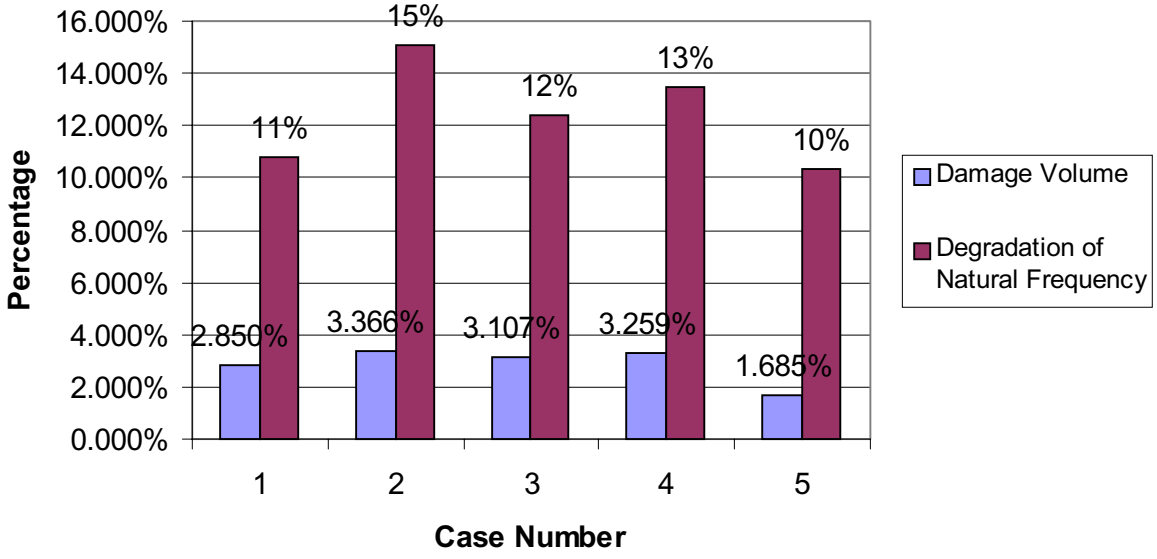


Figure 10 Damage Volume and Frequency Reduction of All the Five Cases.

CONCLUSIONS

A computational tool has been developed for the simulation of composite fatigue under PSD loading. It has been demonstrated by the simulation of a dynamic specimen subjected to base accelerations. The significant conclusions of this paper are the following:

1) Computational simulation, with the use of established composite mechanics and structural analysis modules, can be used to predict the progressive damage, safety, and durability of a composite structure under PSD loading.
2) Computational simulation under PSD loading can be used to track damage initiation, growth, and subsequent propagation to fracture for composite structures.
3) The availability of a computational simulation tool under PSD loading will increase the effectiveness and productivity of testing by improving the identification of damage progression processes.
4) Computational simulation under PSD loading facilitates composite structural design and certification in high-cycle acoustic load environments.
5) PSD simulation provides a significant new feature of computational simulation by extending the analysis capability into the frequency domain.

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1. L. Minnetyan, D. Huang, C.C. Chamis, and F. Abdi (1998) "Cyclic Fatigue of Composite Airfoil Structures," Paper No. AIAA-98-1876, Proc. 39th SDM Conference, April 20-23, Long Beach, California, pp. 1505-1514.

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BIOGRAPHIES

Dr. Levon Minnetyan is a professor of structural engineering at Clarkson University in the Department of Civil and Environmental Engineering. His primary research activities are directed toward the assessment of progressive damage and fracture in structures made of composite materials such as graphite/epoxy laminated, woven, and braided composites.

Ms. Qiuzhan Li is a computational simulation engineer for structural durability and damage tolerance evaluation at AlphaStar Corporation. She received her B.S. degree in 1998 from Tongji University in China and her M.S. degree in 2000 from Clarkson University. Her M.S. thesis topic was computational simulation of structures subjected to PSD loading.

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Transient Reliability of Ceramic Structures For Heat Engine Applications

Noel N. Nemeth

Osama M. Jadaan

5th Annual FAA/Air Force/NASA/Navy
Workshop on the Application of Probabilistic Methods to Gas Turbine Engines
June 13, 2001

Glenn Research Center
at Lewis Field

Outline

- Objective
- Background
- Theory
- Example
- Conclusions

Objective

Develop a methodology to predict the time-dependent reliability (probability of failure) of brittle material components subjected to transient thermomechanical loading, taking into account the change in material response with time.

-- Transient reliability analysis

Fully Transient Component Life Prediction

MOTIVATION:

To be able predict brittle material component integrity over a simulated engine operating cycle

REQUIRES:

- Life prediction models that account for:
  - transient mechanical & temperature loads
  - transient Weibull and fatigue parameters (temperature)
- Interface codes that transfer transient analysis finite element results into life prediction codes (CARES/Life)

CARES/*Life* (Ceramics Analysis and Reliability Evaluation of Structures)

Software For Designing With Brittle Material Structures

- CARES/*Life* – Predicts the instantaneous and time-dependent probability of failure of advanced ceramic components under thermomechanical loading
- Couples to ANSYS, ABAQUS, MARC, NASTRAN

Impact & Applications

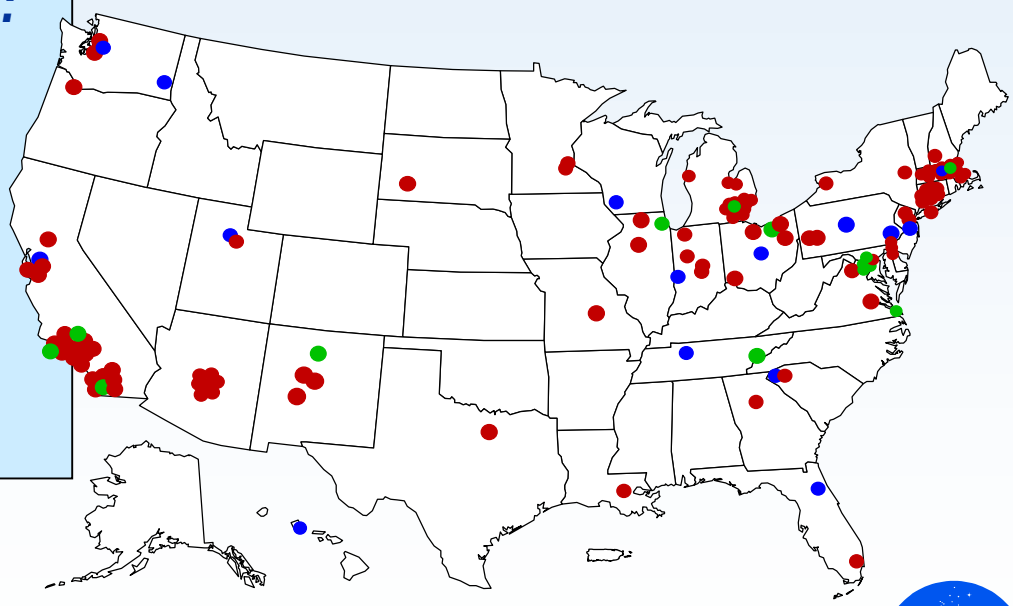
Hundreds of customers worldwide utilize CARES for life prediction of brittle material components.

CARES Users - United States

- ***Industry***
- ***University***
- ***Government Agency***

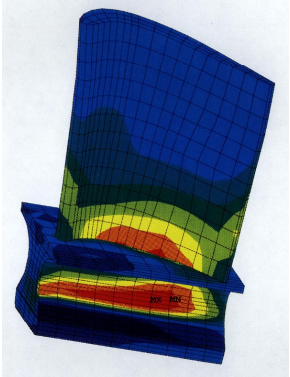
U.S. Industries:

- Aerospace
- Automotive
- Electronic
- Energy
- Glass
- Medical
- Power

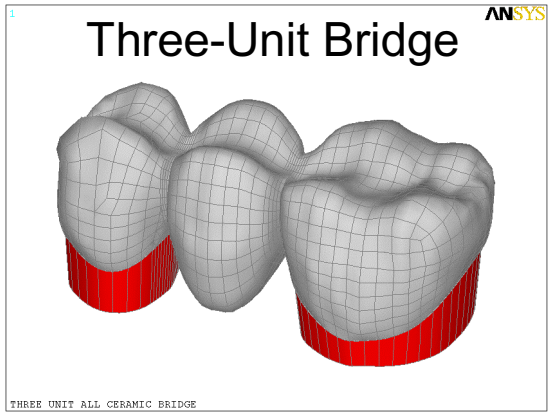


“Dual-Use” Ceramics Design Examples

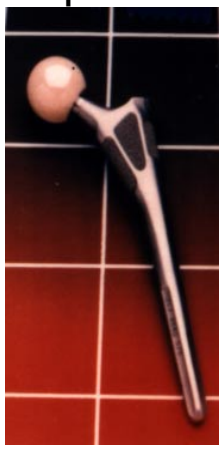
Turbine Blade



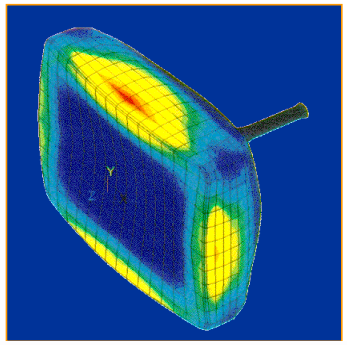
Three-Unit Bridge



Hip Joint

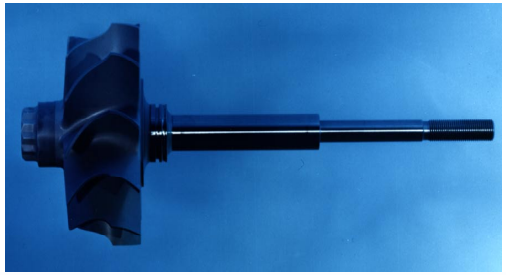


TV Picture Tube



MEMS Microturbine

Turbocharger Rotor

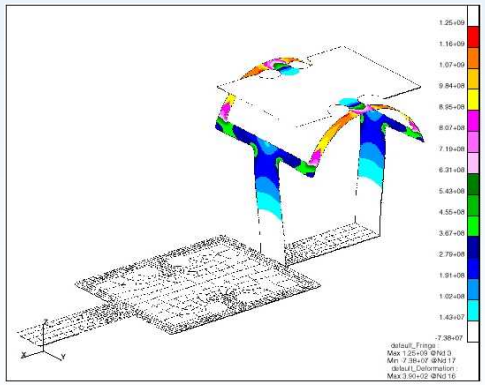


Technology Transfer – About 25 Requests per Year

Technology Transfer Activities for FY00:

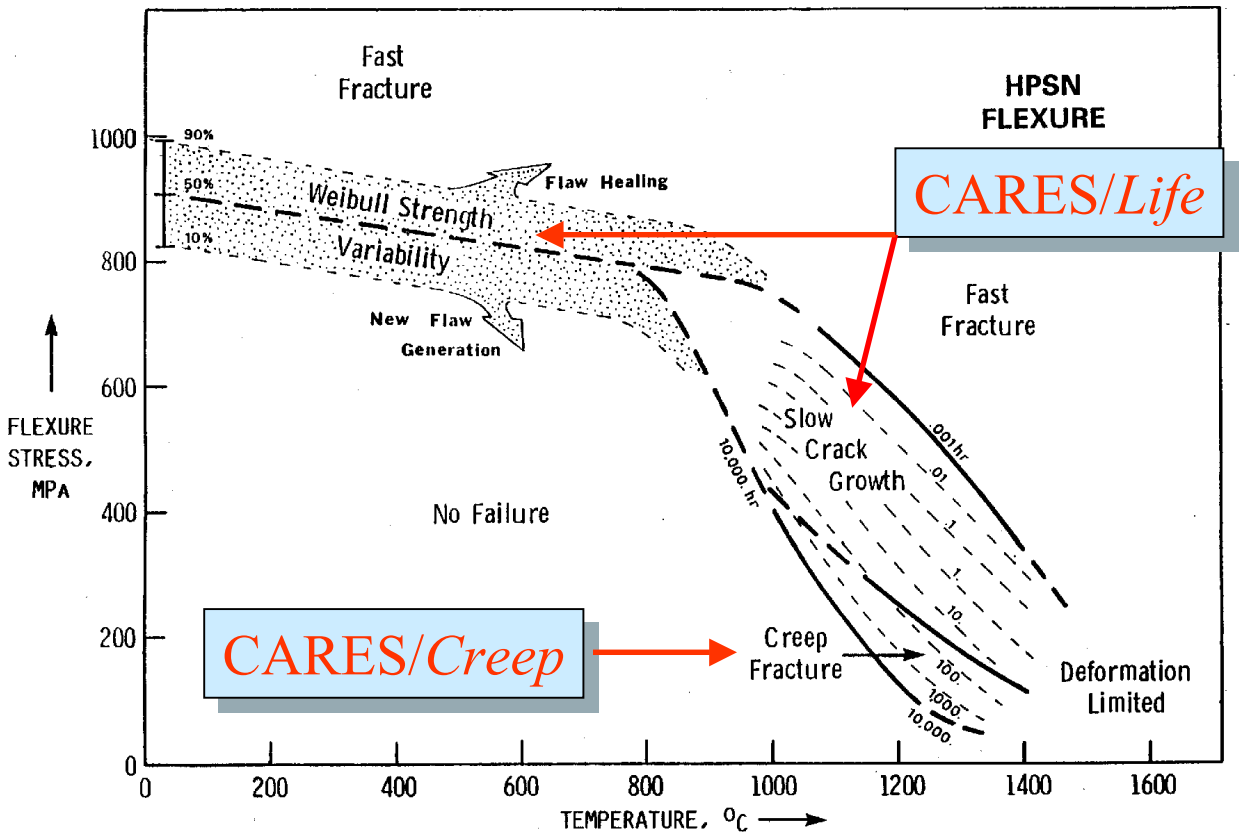
University of Alaska Fairbanks – DOE program
BP AMOCO – **Ceramic membranes** for various reactor and separation applications
HSG-IMIT - **MEMS sensors**
Alenia – **SiC mirrors**
FEV Engine Technology – Automotive ceramic components
Sest – Evaluation/training
University of Technology Aachen – Department of Dental Prosthetics – Bio ceramics
Texas A&M – Baylor College of Dentistry – **Dental prosthetics**
Honeywell – Ceramic to metal Joining
MIT – **MEMS microturbine engines**, micro hydraulic transducers
Caterpillar – **Engine components**
Defense Science and Technology Organization – Australia – Evaluation for metals fatigue
Osram Sylvania – Fracture of glass vessels **(lighting applications)**
Borg Warner – Evaluation of CARES for powder metal parts
Sandia National Laboratories – **Feed-thru's, glass seals,** etc…
L3 Communication, Space and Navigation Div. – MEMS angular rate sensors
Science and Applied Technology Inc – Missile radomes
Dresden University of Technology – Gas turbine components
U.S. Army Dental Research Detachment – Evaluation of CARES for dental applications
Capstone Turbine Corporation – Ceramics for **Microturbine** designs (DOE program)
NAVY Warfare Division – China Lake – **Missile Radomes**
Washington State University – various uses, including **teaching** courses
STMicroelectronics – Ceramics for microelectronic components
Bettis Atomic Power Laboratory – For **silicon carbide device**

Mars microprobe aeroshell – NASA JPL



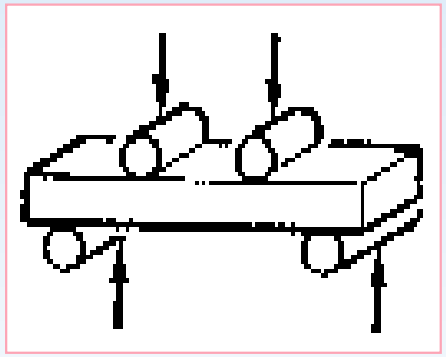
MEMS Pop-up pixel design with highly deformed and stressed support structure – NASA Goddard

Strength and Failure Mechanisms in Ceramics

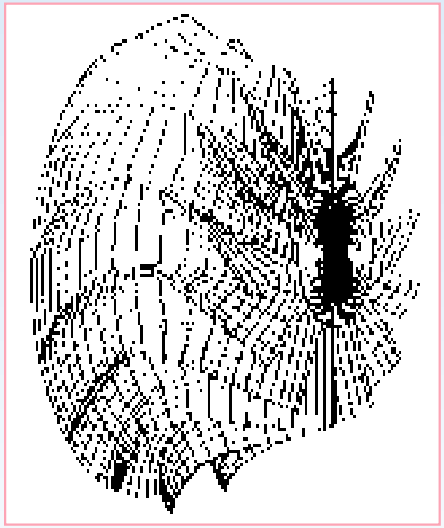


*G. D. Quinn, Journal of Material Science, 1990.

CARES/Life Probabilistic Design Procedure



Batdorf – Weibull
Stress-volume integral



Simple specimen tests

- Characterize material stochastic behavior in strength & fatigue

Complex component life predictions

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at Lewis Field

Component Reliability Evaluation

The incremental probability of failure under the applied state of stress Σ can be written as the product of two probabilities

$$d\,P_{f\,V}(\Sigma, \sigma_{cr}, dV) = d\,P_{1V}\,P_{2V}$$

dP_{1V} is the probability of the existence in dV of a crack having a critical stress between σ_{cr} and $\sigma_{cr} + d\sigma_{cr}$.

P_{2V} is the probability that a crack of critical stress σ_{cr} will be oriented in a direction such that an effective stress σ_e satisfies the condition $\sigma_e \geq \sigma_{cr}$

Integration over stress state and volume gives component failure probability

$$P_{fV} = 1 - \exp\left\{ -\int_V \left[\int_0^{\sigma_{c_{max}}} P_{2V}\, dP_{1V} \right] dV \right\}$$

CARES/*Life* Structure

Parameter Estimation
Weibull and fatigue parameter estimates generated from failure data

Finite Element Interface
Output from FEA codes (stresses, temperatures, volumes) read and printed to Neutral Data Base

Reliability Evaluation
Component reliability analysis determines "hot spots" and the *risk of rupture intensity* for each element

Current Capabilities

Parameter Estimation

- Weibull parameters
- Slow crack growth parameters
- Cyclic fatigue parameters

Specimen Types:

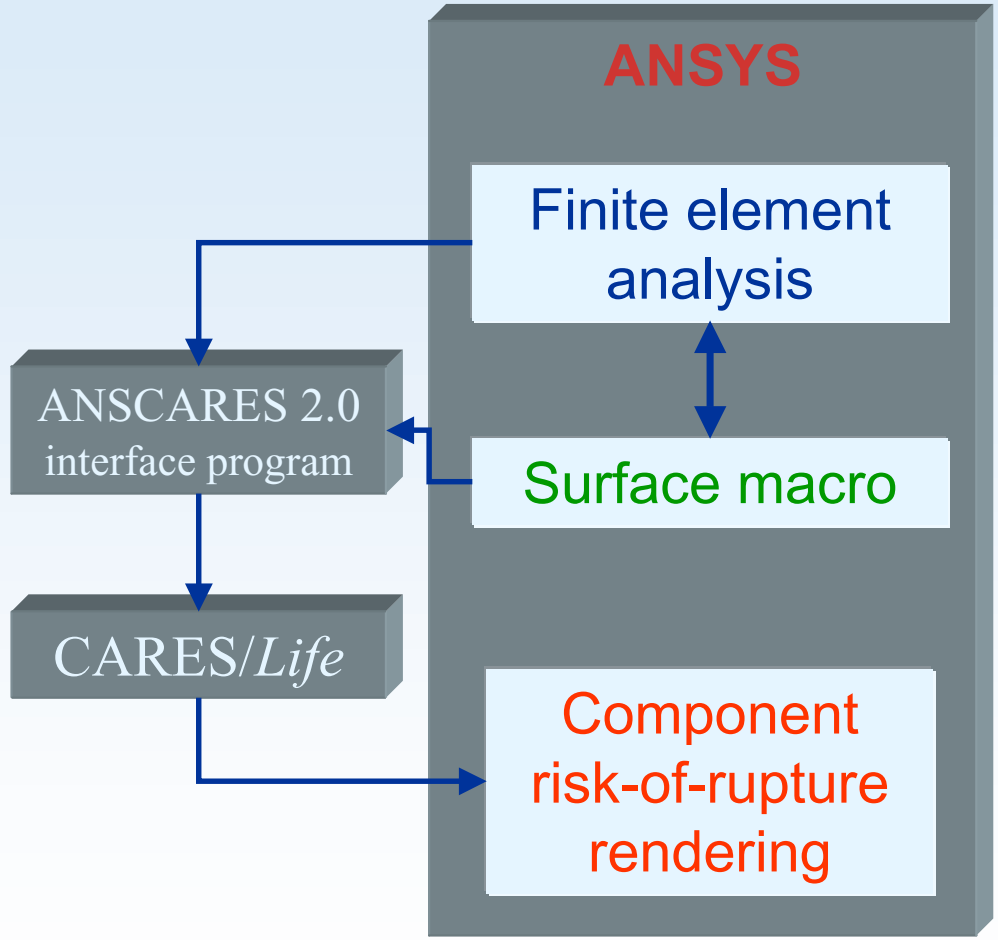
- Flexure
- Tensile
- User-defined (finite element model)

Component Life Prediction

- Volume flaw & surface flaw analysis
- PIA, Weibull NSA, and Batdorf multiaxial models
- Fast fracture reliability analysis
- Time-/Cycle-dependent reliability analysis (power law, Paris law, Walker law)
- Multiaxial proof testing (PIA and Batdorf theories)
- Flaw orientation anisotropy
  - Grinding Damage
  - Textured materials

ANSYS-CARES Interface

- **Automatic detection and modeling of component surfaces**
- **Graphical representation of risk-of-rupture intensity**
- **Robust element library (solid, shell, axisymmetric)**



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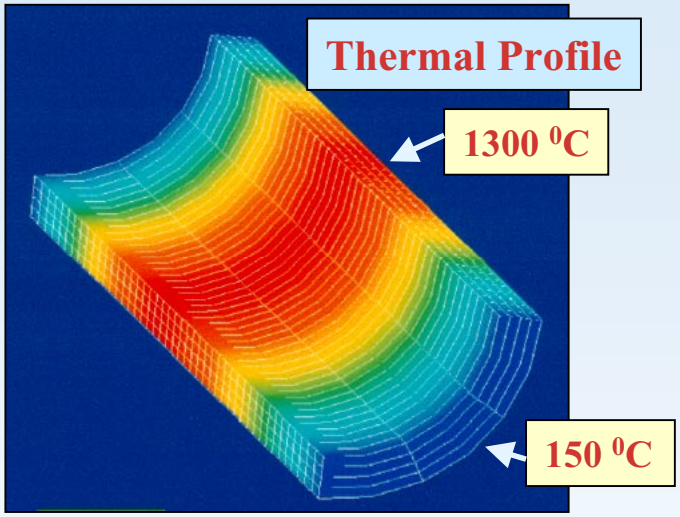
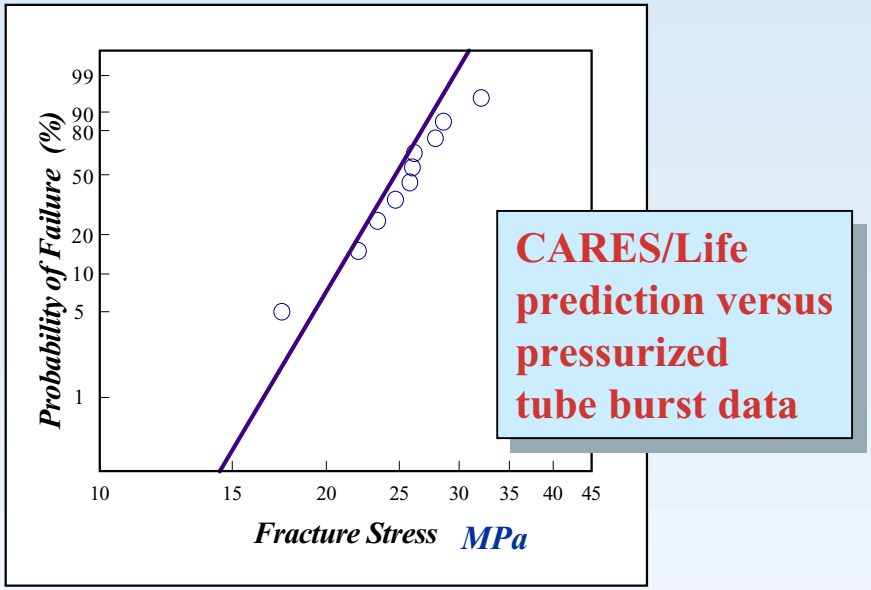
CARES/Life Benchmark Application

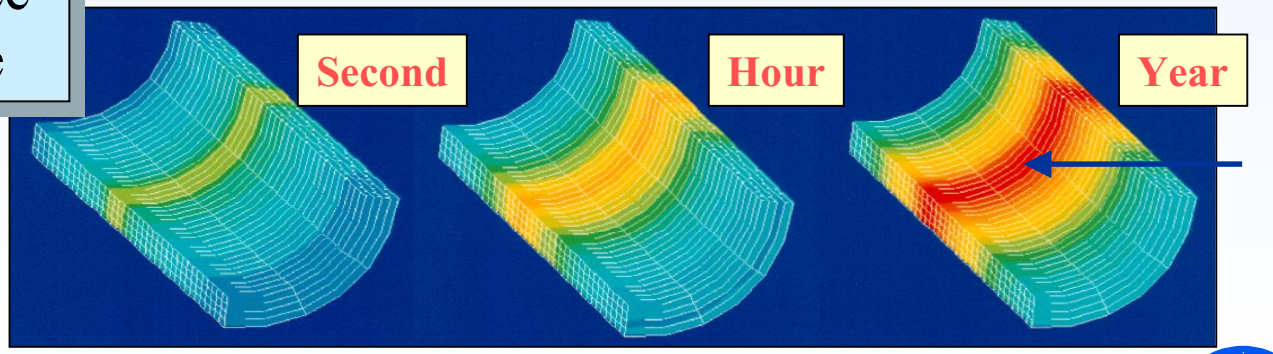
SASC Pressurized Tube





Service Time

Risk-of-rupture intensity map



Likelihood of failure

High

Low

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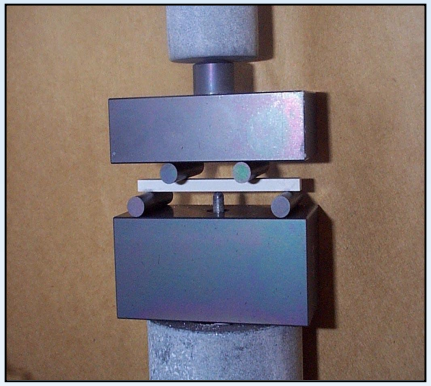
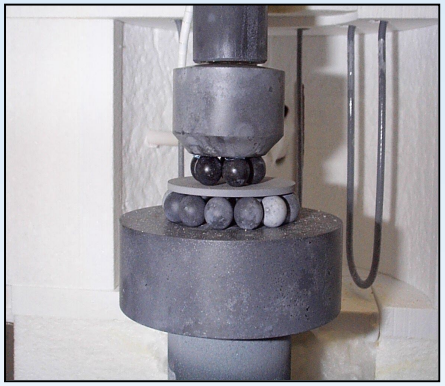
Experimental Facilities/Validation

High-Temperature Test rig



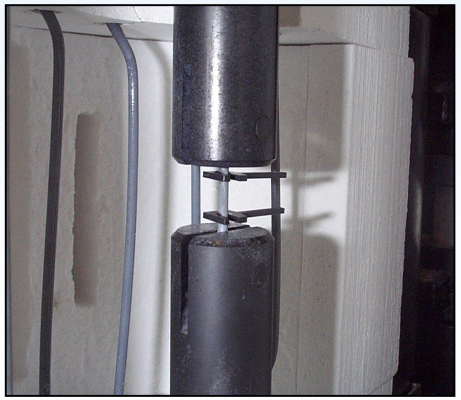
4-Point Flexure



Biaxial Flexure

Test Capabilities:

- 'Ultra-Fast'
- Static, Dynamic, & Cyclic Fatigue
- Creep
- Uniaxial & Multiaxial Testing
- High temperature material properties



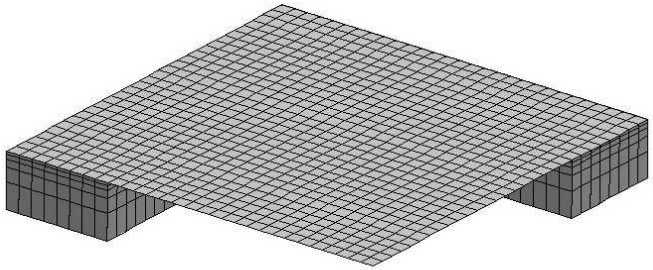
Tensile Creep

ANSYS Finite Element Modeling of MEMS Pressure Sensor Thin Film Membrane

- Determine the fracture strength of SiC and Si_3N_4 thin films

- Examine thin film stochastic strength response for different materials/processing conditions
- Characterize strength on a per-unit-area basis
- Demonstrate single crystal multiaxial strength model

- Account for device-to-device
- film thickness variations
- Account for residual stresses



¼ symmetry model
Of film and substrate

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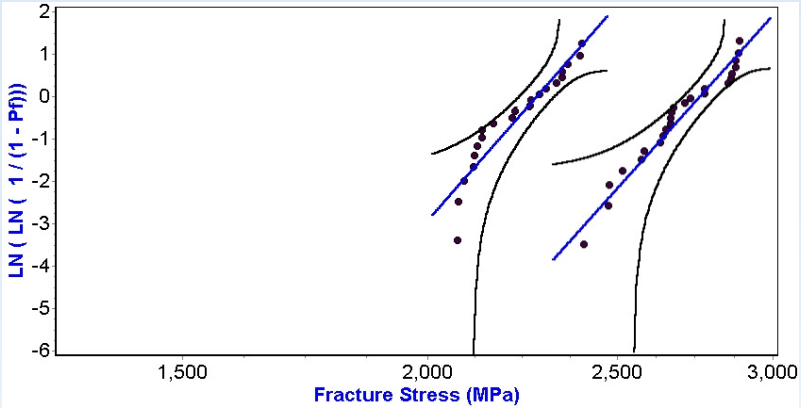
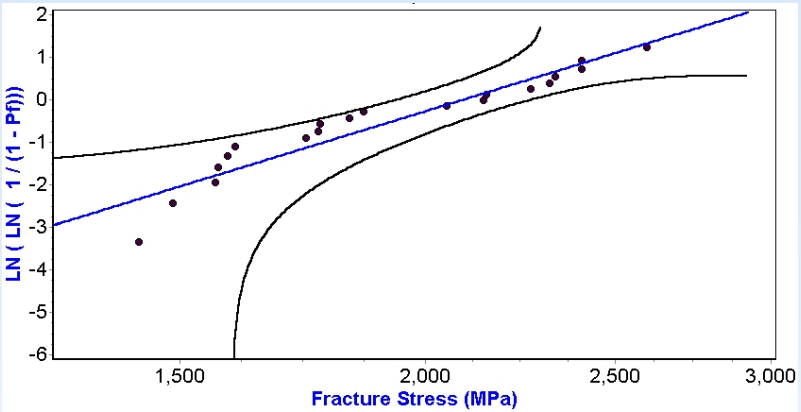
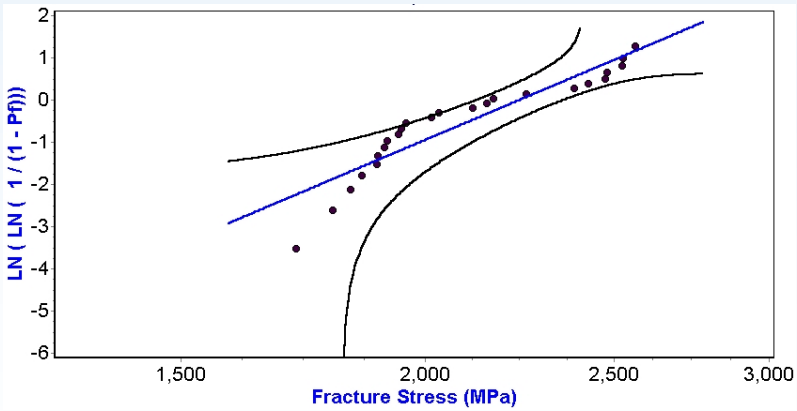
Weibull Plots



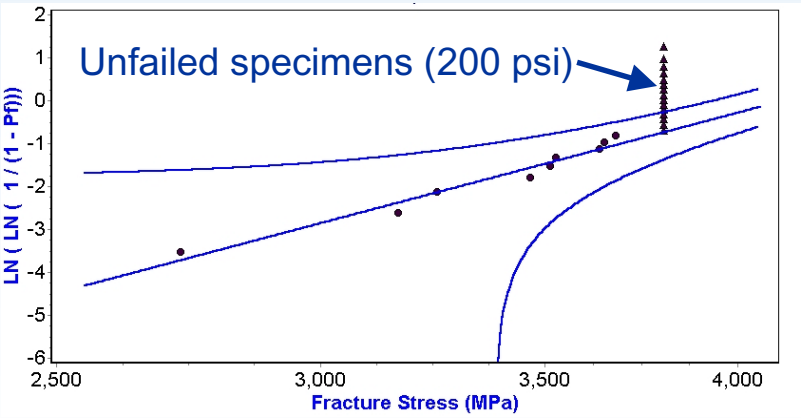
3C-SiC - Recipe 1a (left) & 1b (right) **(Suseptor)**



Amorphous Si_3N_4



3C-SiC - Recipe 2 **(Double growth rate)**



Polycrystalline SiC

Transient Life Prediction Theory For Slow Crack Growth

Assumptions:

- Component load and temperature history discretized into short time steps
- Material properties, loads, and temperature assumed constant over each time step
- Weibull and fatigue parameters allowed to vary over each time step – including *Weibull modulus*
- Failure probability at the end of a time step and the beginning of the next time step are equal

Transient Life Prediction Theory - Slow Crack Growth Modeled With Power Law

Power Law:

$$\frac{da(\Psi, t)}{dt} = A(t)\, K_{Ieq}^{N(t)}(\Psi, t)$$

Equivalent Mode I Stress Intensity Factor:

$$K_{Ieq}(\Psi, t) = \sigma_{Ieq}(\Psi, t)\, Y \sqrt{a(\Psi, t)}$$

Transient Life Prediction Theory
Slow Crack Growth and Power Law

General reliability formula for discrete time steps:

$$P_{SV}(t_k) = \exp\{-\sum_{i=1}^{n} \frac{V_i}{4\pi} [\int_{\Omega} [\ \ldots [\ \ [\ (\frac{\sigma_{Ieq,k,T\max}}{\sigma_{0BVk}})^{N_{Vk}-2} +$$

$$\frac{\sigma_{Ieq,k}^{N_{Vk}} \Delta t_k}{\sigma_{0BVk}^{N_{Vk}-2} B_{Vk}}]_k^{\frac{m_{Vk}(N_{Vj}-2)}{m_{Vj}(N_{Vk}-2)}} + \frac{\sigma_{Ieq,j}^{N_{Vj}} \Delta t_j}{\sigma_{0BVj}^{N_{Vj}-2} B_{Vj}}]_j^{\frac{m_{Vj}(N_{Vi}-2)}{m_{Vi}(N_{Vj}-2)}} + \ldots.$$

$$\ldots + \frac{\sigma_{Ieq,1}^{N_{V1}} \Delta t_1}{\sigma_{0BV1}^{N_{V1}-2} B_{V1}}]_1^{\frac{m_{V1}}{N_{V1}-2}} d\Omega]_i \}$$

Binomial Series Approximation Used to Derive Computationally Efficient Solution For Cyclic Loading

Binomial Series Expansion:

$$(x+y)^n = x^n + nx^{n-1}y + \frac{n(n-1)}{2!}x^{n-2}y^2 + \frac{n(n-1)(n-2)}{3!}x^{n-3}y^3 + \ldots$$

When x>>y the series can be approximated as a two term expression

$$(x + y)^n \approx x^n + nx^{n-1}\, y \quad , \text{ when } x >> y$$

Computationally efficient transient reliability formula For cyclic loading - full solution

$$Z_{Total} = \sum_{i=1}^{n} Z_i$$

$$P_{SV}(t_k) = \exp\{-\sum_{i=1}^{n} \frac{V_i}{4\pi}[\int_{\Omega}[X_1]_1^{\frac{m_{V1}}{N_{V1}-2}} d\Omega]_i\}$$

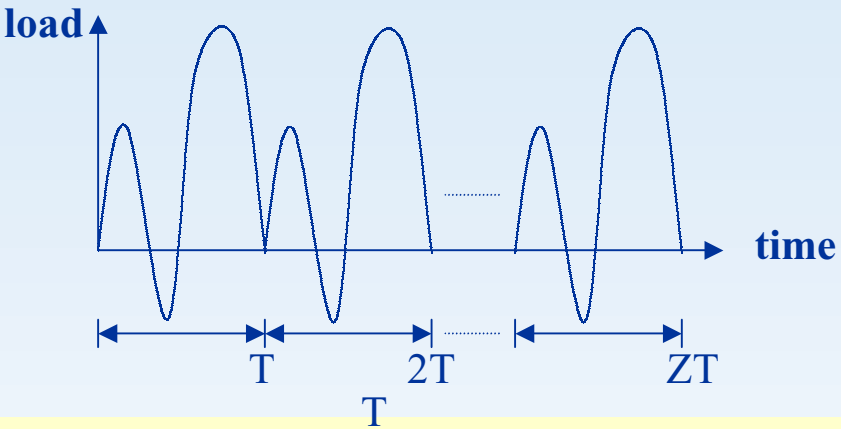
$$X_1 = \left\{[\ldots[[\ldots\left\{[\ldots[[\left\{[\ldots[[\left(\frac{\sigma_{Ieq,k,T\,max}}{\sigma_{0BVk}}\right)^{N_{Vk}-2} + \right.\right.\right.\right.$$

$$+\frac{\sigma_{Ieq,k}^{N_{Vk}} Z_1 \Delta t_k}{\sigma_{0BVk}^{N_{Vk}-2} B_{Vk}}]_k^{\frac{m_{Vk}(N_{V(k-1)}-2)}{m_{V(k-1)}(N_{Vk}-2)}} + \frac{\sigma_{Ieq,(k-1)}^{N_{V(k-1)}} Z_1 \Delta t_{(k-1)}}{\sigma_{0BV(k-1)}^{N_{V(k-1)}-2} B_{V(k-1)}}]_{k-1}^{\frac{m_{V(k-1)}(N_{V(k-2)}-2)}{m_{V(k-2)}(N_{V(k-1)}-2)}} + \ldots\ldots + \frac{\sigma_{Ieq,1}^{N_{V1}} Z_1 \Delta t_1}{\sigma_{0BV1}^{N_{V1}-2} B_{V1}}]_1^{\frac{m_{V1}(N_k-2)}{m_k(N_{V1}-2)}}\Bigg\} +$$

$$+\frac{\sigma_{Ieq,k}^{N_{Vk}} Z_2 \Delta t_k}{\sigma_{0BVk}^{N_{Vk}-2} B_{Vk}}]_k^{\frac{m_{Vk}(N_{V(k-1)}-2)}{m_{V(k-1)}(N_{Vk}-2)}} + \frac{\sigma_{Ieq,(k-1)}^{N_{V(k-1)}} Z_2 \Delta t_{(k-1)}}{\sigma_{0BV(k-1)}^{N_{V(k-1)}-2} B_{V(k-1)}}]_{k-1}^{\frac{m_{V(k-1)}(N_{V(k-2)}-2)}{m_{V(k-2)}(N_{V(k-1)}-2)}} + \ldots\ldots + \frac{\sigma_{Ieq,1}^{N_{V1}} Z_2 \Delta t_1}{\sigma_{0BV1}^{N_{V1}-2} B_{V1}}]_1^{\frac{m_{V1}(N_k-2)}{m_k(N_{V1}-2)}}\Bigg\} + \ldots$$

$$\ldots + \frac{\sigma_{Ieq,k}^{N_{Vk}} Z_n \Delta t_k}{\sigma_{0BVk}^{N_{Vk}-2} B_{Vk}}]_k^{\frac{m_{Vk}(N_{V(k-1)}-2)}{m_{V(k-1)}(N_{Vk}-2)}} + \frac{\sigma_{Ieq,(k-1)}^{N_{V(k-1)}} Z_n \Delta t_{(k-1)}}{\sigma_{0BV(k-1)}^{N_{V(k-1)}-2} B_{V(k-1)}}]_{k-1}^{\frac{m_{V(k-1)}(N_{V(k-2)}-2)}{m_{V(k-2)}(N_{V(k-1)}-2)}} + \ldots\ldots + \frac{\sigma_{Ieq,1}^{N_{V1}} Z_n \Delta t_1}{\sigma_{0BV1}^{N_{V1}-2} B_{V1}}]_1^{\frac{m_{V1}(N_k-2)}{m_k(N_{V1}-2)}}\Bigg\}$$

Transient Life Prediction Theory - Slow Crack Growth Modeled With Power Law



Computationally efficient transient reliability formula for cyclic loading
- simplified version

$$P_{SV}(t_k) = \exp\{-\sum_{i=1}^{n} \frac{V_i}{4\pi}[\int_{\Omega}[\ldots[[(\frac{\sigma_{Ieq,k,T\max}}{\sigma_{0BVk}})^{N_{Vk}-2} + \frac{\sigma_{Ieq,k}^{N_{Vk}} Z\Delta t_k}{\sigma_{0BVk}^{N_{Vk}-2} B_{Vk}}]_k^{\frac{m_{Vk}(N_{Vj}-2)}{m_{Vj}(N_{Vk}-2)}} + \frac{\sigma_{Ieq,j}^{N_{Vj}} Z\Delta t_j}{\sigma_{0BVj}^{N_{vj}-2} B_{Vj}}]_j^{\frac{m_{Vj}(N_{Vi}-2)}{m_{Vi}(N_{Vj}-2)}} + \ldots$$

$$\ldots + \frac{\sigma_{Ieq,1}^{N_{V1}} Z\Delta t_1}{\sigma_{0BV1}^{N_{V1}-2} B_{V1}}]_1^{\frac{m_{V1}}{N_{V1}-2}} d\Omega]_i\}$$

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Example Problem – Tradeoff between accuracy And computational efficiency for a cyclic load

10 step transient uniaxial loading for a single load block

Time step #	Time	σ_{leq}	Temp
1	25	100	100
2	50	90	200
3	75	80	300
4	100	70	400
5	125	60	500
6	150	70	600
7	175	80	700
8	200	90	800
9	225	95	900
10	250	100	1000

Temperature vs: material properties

Temp	m	σ_o	N	B
100	5	230	40	0.0021
500	9	226	36	0.021
1000	14	221	31	0.21

Exact solution versus the Z approximation method for one solution increment (n = 1).

- The results for one solution increment represent the least accurate but most computationally efficient answer.

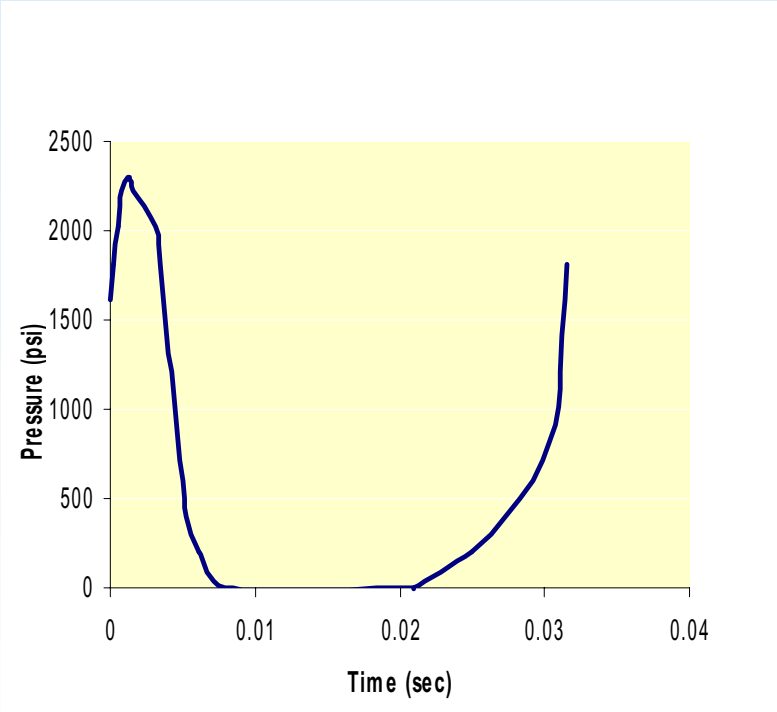
Number of load blocks	P_s Exact solution	P_s, Z method
1	0.83572	0.83572
10	0.78299	0.78429
100	0.71045	0.71963
1,000	0.58169	0.63003
10,000	0.29575	0.31670
100,000	0.030463	0.031499

Example of Z approximation method for various values of n.
The solution increments are equally spaced ($Z_i = Z_j = Z_n$).

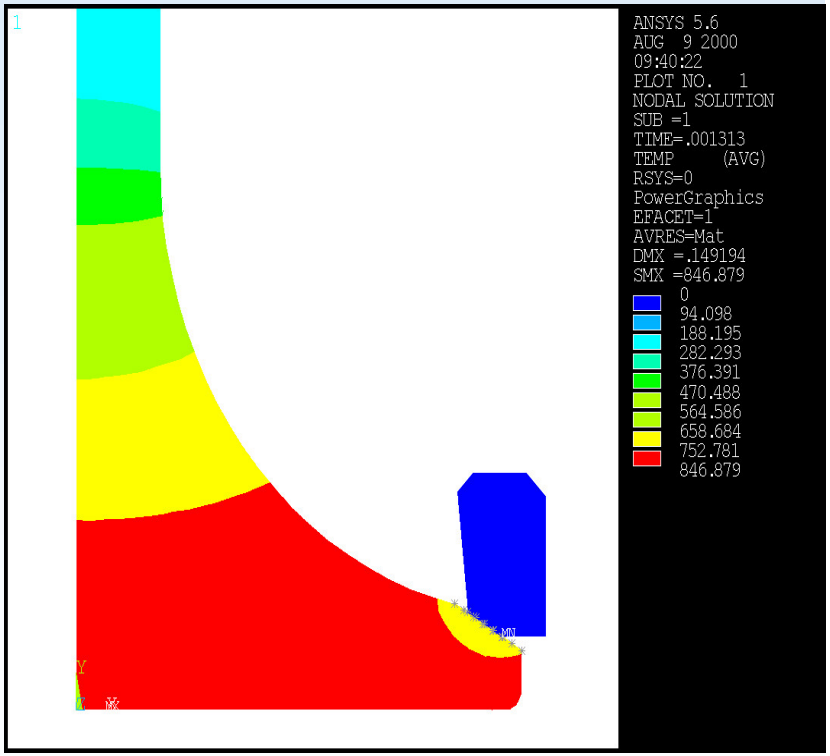
# of load blocks	P_s exact solution	P_s, n = 1	P_s, n = 2	P_s, n = 5	P_s, n = 10	P_s, n = 100	P_s, n = 500	P_s, n = 1000
1,000	0.58169	0.63003	0.60553	0.59042	0.58580	0.58204	0.58173	0.58169
100,000	0.030463	0.031499	0.031361	0.031230	0.031160	0.030765	0.030522	0.030491

Example

Diesel engine Si_3N_4 exhaust valve (ORNL/Detroit Diesel)



Pressure load applied to the face of a ceramic valve for combustion cycle.



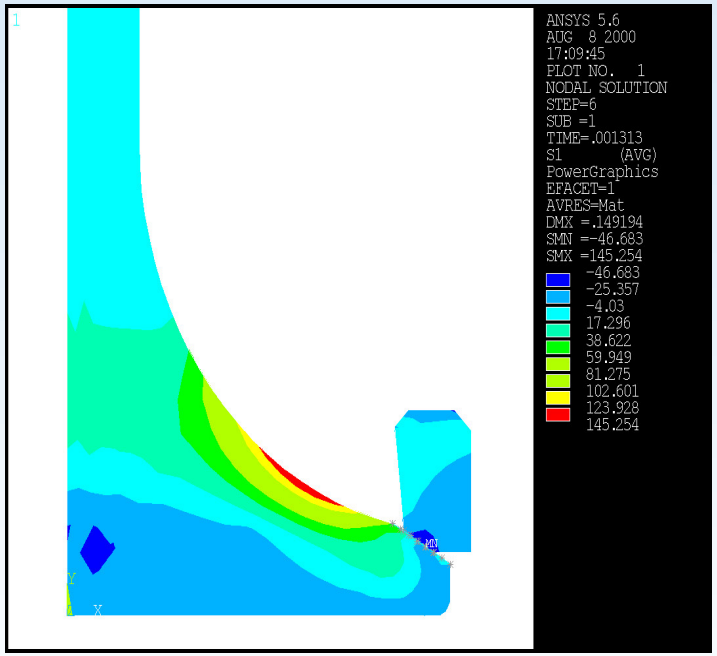
Thermal distribution

Example

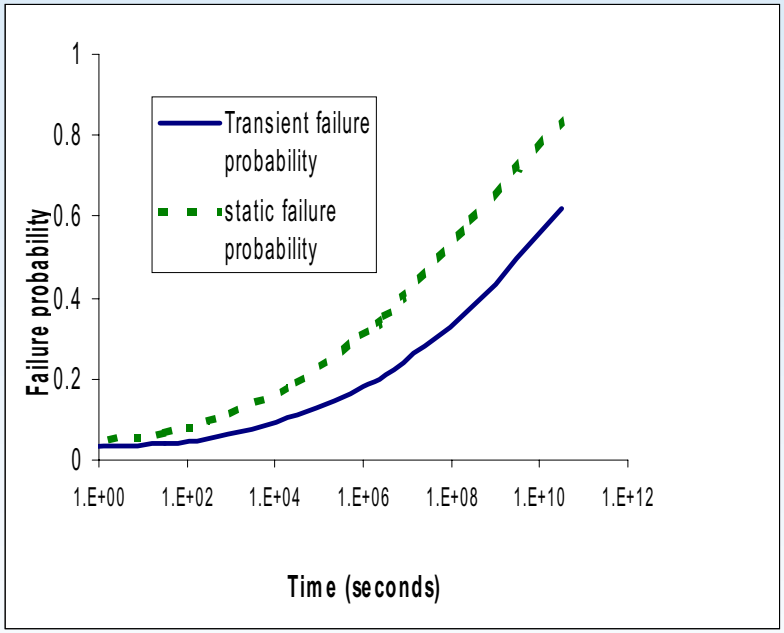
Silicon Nitride NT551 fast fracture and SCG material properties

T (^{0}C)	m	σ_{0V} (MPa.mm$^{3/m}$)	Average strength (MPa)	N	B (MPa^2.sec)
20	9.4	1054	806	31.6	5.44e5
700	9.6	773	593	87	1.12e4
850	8.4	790	577	19	1.13e6

Example



First principal stress at the instant of maximum applied pressure (MPa)



Transient and static probability of failure versus time
(cycles converted to time)

Conclusions

- A methodology for computing the transient reliability in ceramic components subjected to fluctuating thermomechanical loading was developed, assuming SCG as the delayed mode of failure.
- This methodology takes into account the effect of varying Weibull modulus and material properties with time.
- This methodology was coded into (a beta version of) NASA's CARES/*Life* code, and an example demonstrating its viability was presented.

Proposed Future Work Areas

- Cyclic fatigue models
- Investigate CARES working with ANSYS PDS
- CARES/Life for MEMS (CARES/MEMS)
- Probabilistic version of CARES/Creep
- Foreign object damage modeling

Structural Life and Reliability Metrics—Benchmarking and Verification of Probabilistic Life Prediction Codes

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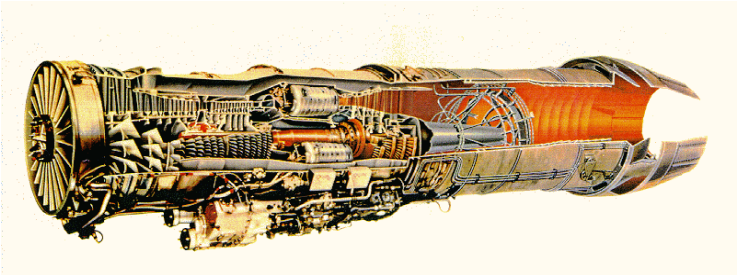
Over the past two decades there has been considerable effort by NASA Glenn and others to develop probabilistic codes to predict with reasonable engineering certainty the life and reliability of critical components in rotating machinery and, more specifically, in the rotating sections of airbreathing and rocket engines. These codes have, to a very limited extent, been verified with relatively small bench rig type specimens under uniaxial loading. Because of the small and very narrow database the acceptance of these codes within the aerospace community has been limited. An alternate approach to generating statistically significant data under complex loading and environments simulating aircraft and rocket engine conditions is to obtain, catalog and statistically analyze actual field data. End users of the engines, such as commercial airlines and the military, record and store operational and maintenance information. This presentation describes a cooperative program between the NASA GRC, United Airlines, USAF Wright Laboratory, U. S. Army Research Laboratory and Australian Aeronautical & Maritime Research Laboratory to obtain and analyze these airline data for selected components such as blades, disks and combustors. These airline data will be used to benchmark and compare existing life prediction codes.

5th Annual FAA/Air Force/NASA/Navy Workshop
On The Application of Probabilistic Methods for Gas Turbine Engines
June 11 – 13, 2001

STRUCTURAL LIFE AND RELIABILITY METRICS—BENCHMARKING AND VERIFICATION OF PROBABILISTIC LIFE PREDICTION CODES



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STATE OF THE ART

- Probabilistic life prediction codes are not verified with full-scale engine components
- Database is limited to simple rig specimens
- Lack of funds and time for full-scale engine component testing under controlled conditions
- Engine company data limited and proprietary
- Multiple codes do not correlate with each other and possibly not with limited data available

NEEDS

- Affordable and statistically significant database for critical engine components
- Ability to benchmark and verify existing reliability and life prediction codes with full-scale engine components
- Ability to develop reasonable engineering confidence in available analytical tools or modify the codes accordingly

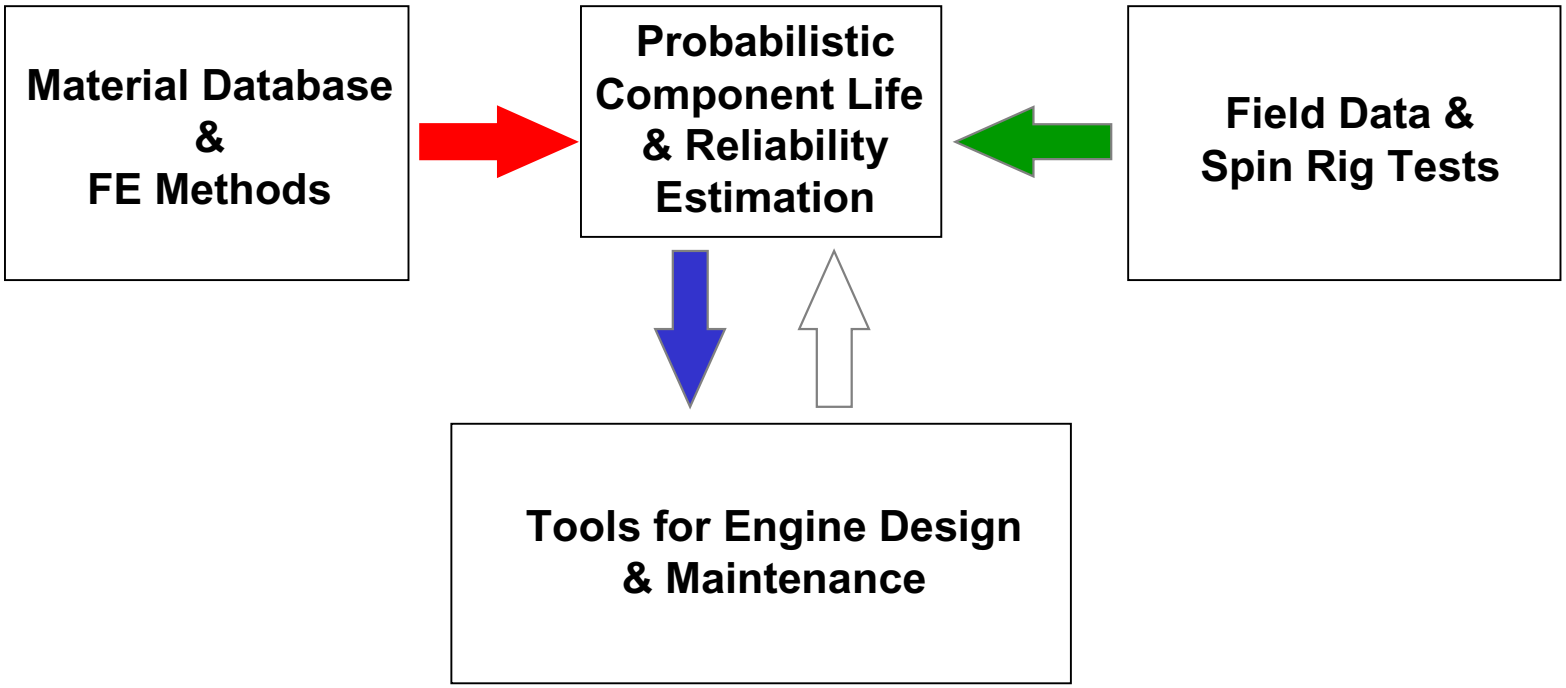
PROJECT OBJECTIVES

- Obtain from UAL reliability and life data for critical engine components and flight operating conditions information
- Develop a statistical database for each component selected for analysis
- Independent analysis by multiple participants of the life and reliability of the selected components
- Comparison of analysis with airline database

BENEFITS

- Enhanced aviation safety and accident prevention
- Low cost design and manufacturing for new production engines
- Reduced life-cycle and maintenance costs
- Reliable design for finite life
- Airline on-time performance, airport throughput
- Military readiness

Basic Philosophy of the Project



PARTICIPANTS

NASA GRC, Cleveland
UAL Maintenance, San Francisco
USAF Wright Labs, Dayton
NAVAIR, Pax River
Aeronautical & Maritime Research Laboratory (AMRL), Australia
Ohio Aerospace Institute (OAI), Cleveland

APPROACH

Obtain Statistical Maintenance Database on:

- Turbine Disk
- Fan Blade Hub
- Turbine Blade
- Combustor

Define Operating Profile for Each Component

Statistically Analyze Data

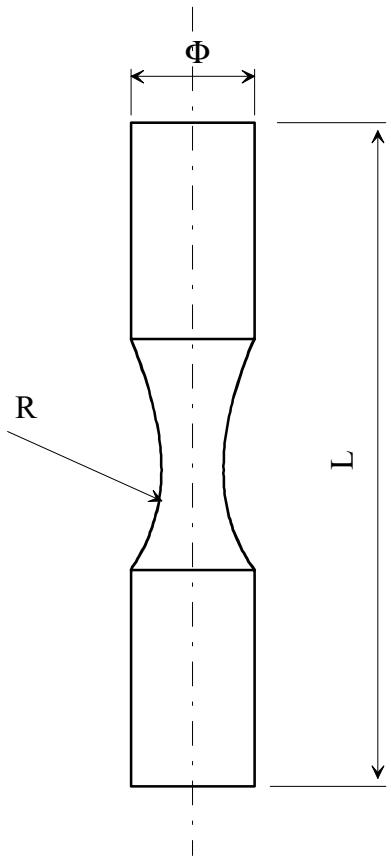
Independent Probabilistic Life Prediction of Each Component

Compare Prediction with Field Data

APPROACH—For Turbine Disks

- Test to Failure in Spin Rig
  - 10 Disks Retired for Time
- Develop Statistical Database for Disk Material For Life Prediction Purposes
- Apply Statistical Database to Disk Life Prediction

COUPON TESTING



Material: Disk material, IN 100

Static and Fatigue tests

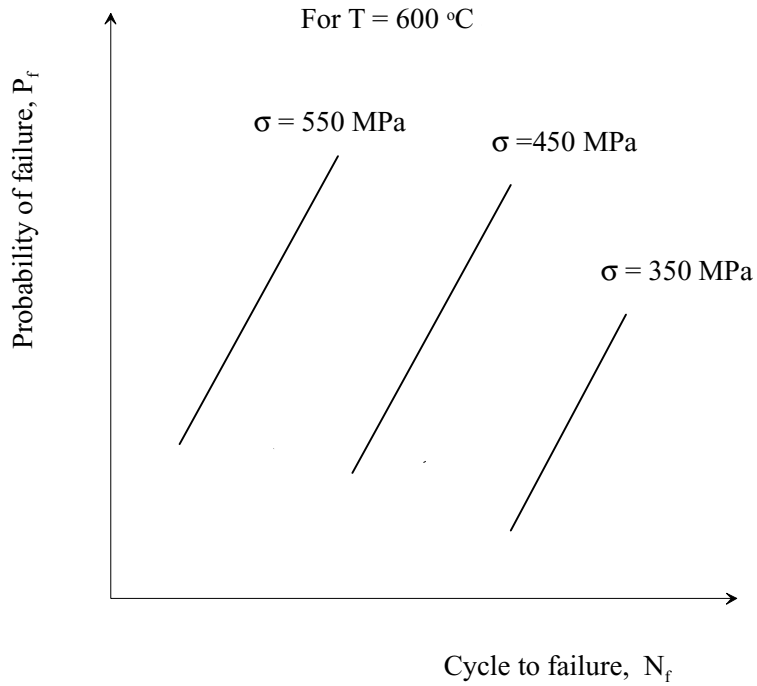
Fatigue test matrix:

- **Stress levels: 3-4 appropriate stress levels**
- **Temperature range: 3-4 appropriate temperatures 72 °F to ~1400 °F.**

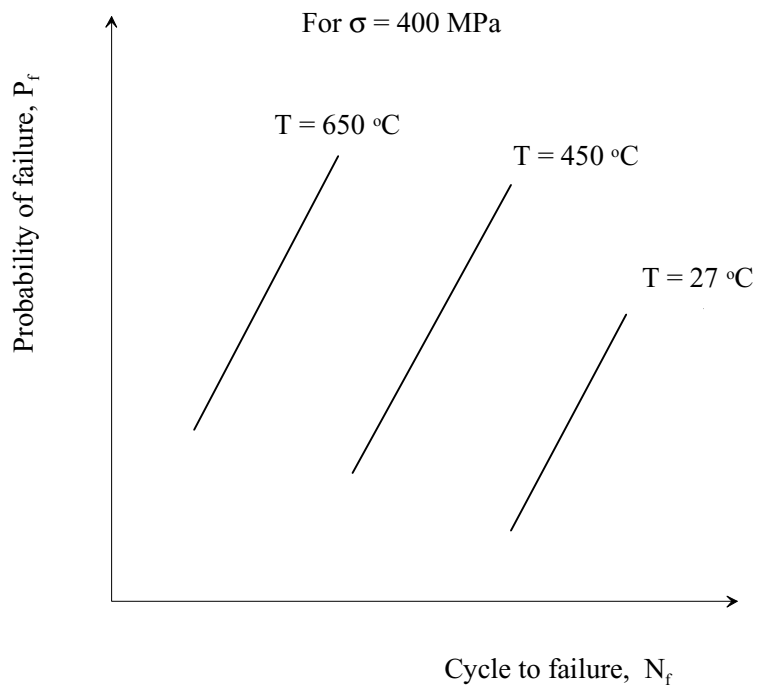
TEMPERATURE	STRESS			
	x_1	x_2	x_3	x_4
1. ROOM	✔	✔	✔	✔
2. 500° F		✔		
3. 1000° F		✔		
4. 1400° F		✔		

ANALYTICAL TOOLS

Sample: Weibull Analysis of Test Data

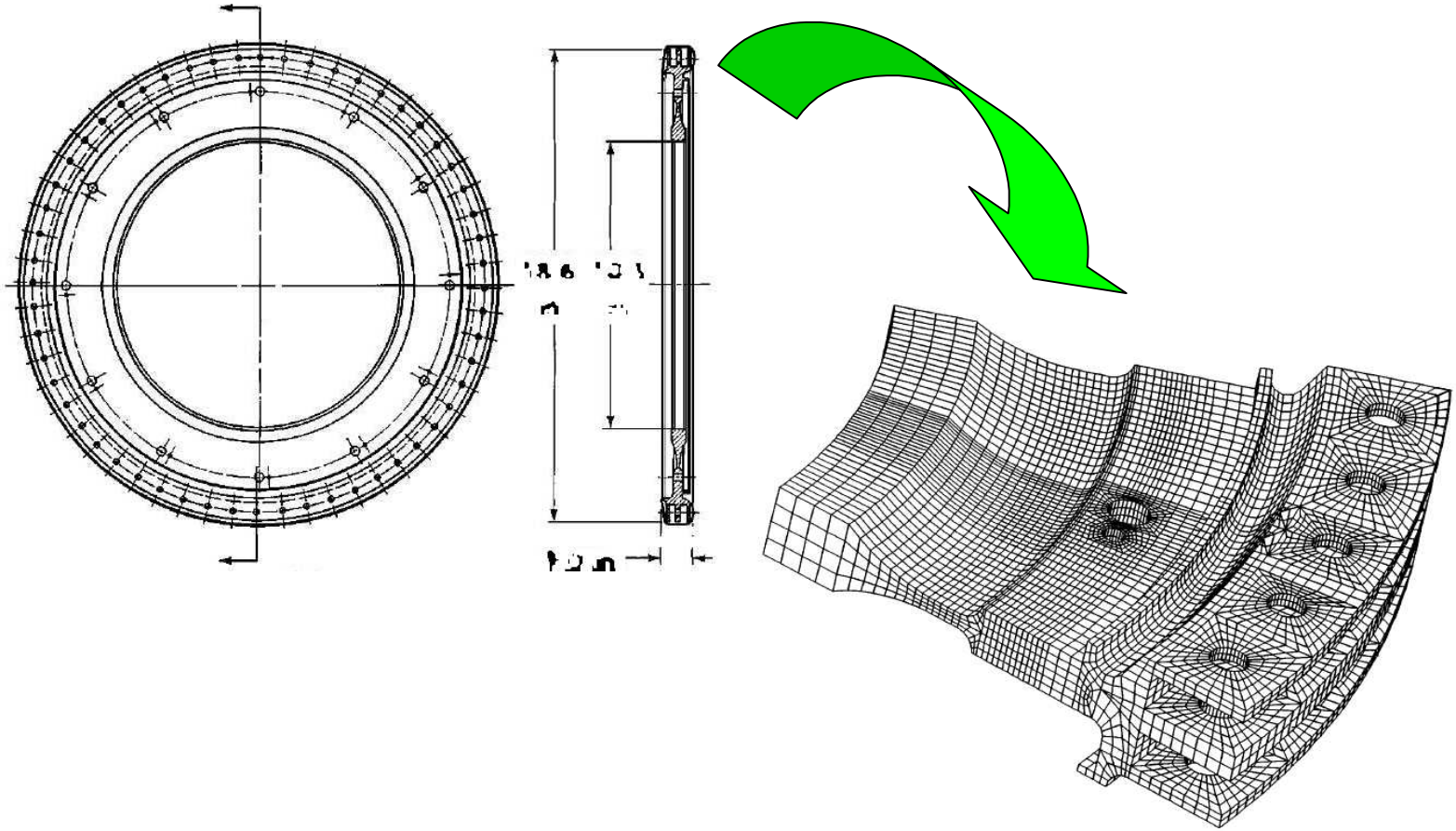


Effect of stress



Effect of temperature

Finite Element Analysis Of Selected Components



CURRENT STATUS

Field Data Collected and Statistically Analyzed

Retired Disks Collected for Spin Testing

Material Procured for Coupon Test Specimens

Perform Coupon Testing and Analyze Data

FEA and Component Life Prediction

Probabilistic Life Prediction and Compare with Field Data

Endurance Tests of 10 Turbine Disks

Probabilistic Life and Reliability Analysis of Model Gas Turbine Disk

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In 1939, W. Weibull developed what is now commonly known as the "Weibull Distribution Function" primarily to determine the cumulative strength distribution of small sample sizes of elemental fracture specimens. In 1947, G. Lundberg and A. Palmgren, using the Weibull Distribution Function developed a probabilistic lifing protocol for ball and roller bearings. In 1987, E. V. Zaretsky using the Weibull Distribution Function modified the Lundberg and Palmgren approach to life prediction. His method incorporates the results of coupon fatigue testing to compute the life of elemental stress volumes of a complex machine element to predict system life and reliability. This paper examines the Zaretsky method to determine the probabilistic life and reliability of a model gas turbine disk using experimental data from coupon specimens. The predicted results are compared to experimental disk endurance data.

Glenn Research Center

Probabilistic Life and Reliability Analysis of Model Gas Turbine Disk

Frederic A. Holland, Matthew E. Melis and Erwin V. Zaretsky

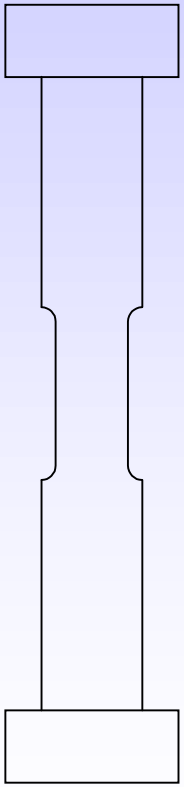
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

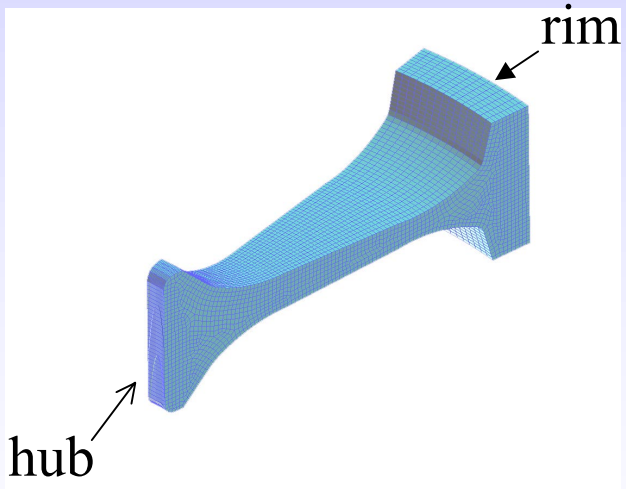
5th Annual FAA/Air Force/NASA/Navy Workshop
On The Application of Probabilistic Methods
for Gas Turbine Engines
June 13, 2001

Objective:

Predict Probabilistic Life and Reliability of
Model Turbine Disks From
A Statistical Material Database

Use Simple Specimen Data to Predict Disk Life





Weibull and Zaretsky Equations

From Weibull: $$\ln\frac{1}{S} = \int_V f(X)dV$$

From Zaretsky: $$f(x) = \tau^{ce}N^{e}$$

Zaretsky Modification of Weibull $$\ln\frac{1}{S} = \tau^{ce}N^{e}V$$

For A Given Probability Of Survival S: $$L = A\left(\frac{1}{\tau}\right)^{c}\left(\frac{1}{V}\right)^{\frac{1}{e}}$$

Material Life Factor $$A = L_{ref}\tau_{ref}^{c}V_{ref}^{1/e}$$

Where:

S = Probability of Survival

τ= Critical Shear Stress

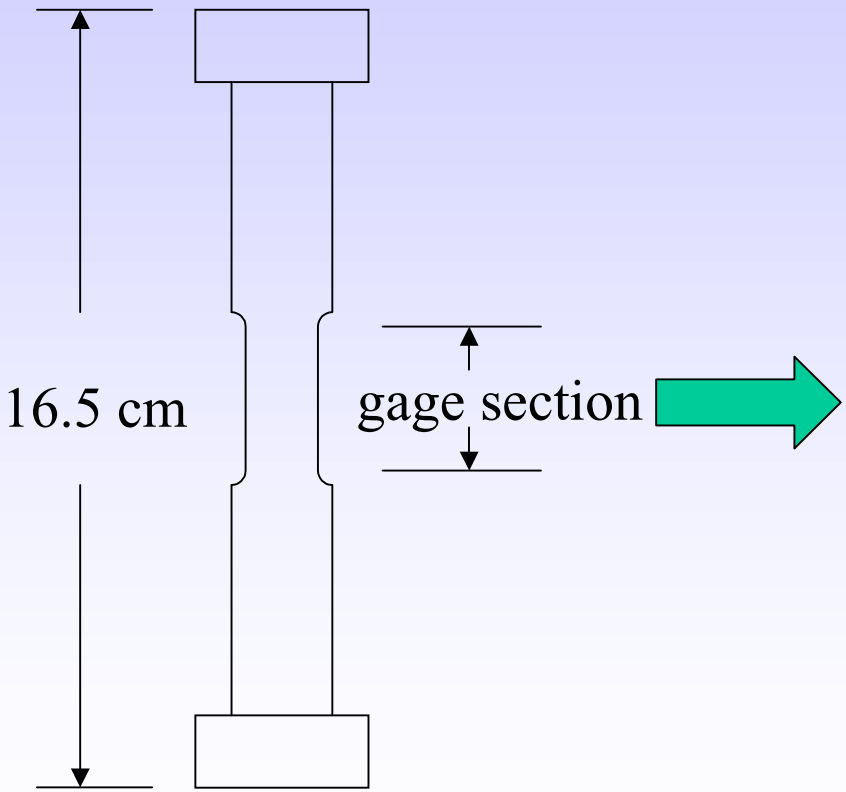
N = Life, stress cycles

V = Stressed Volume

c = Stress-Life Exponent

e = Weibull Slope

Rene' 88 LCF Specimen



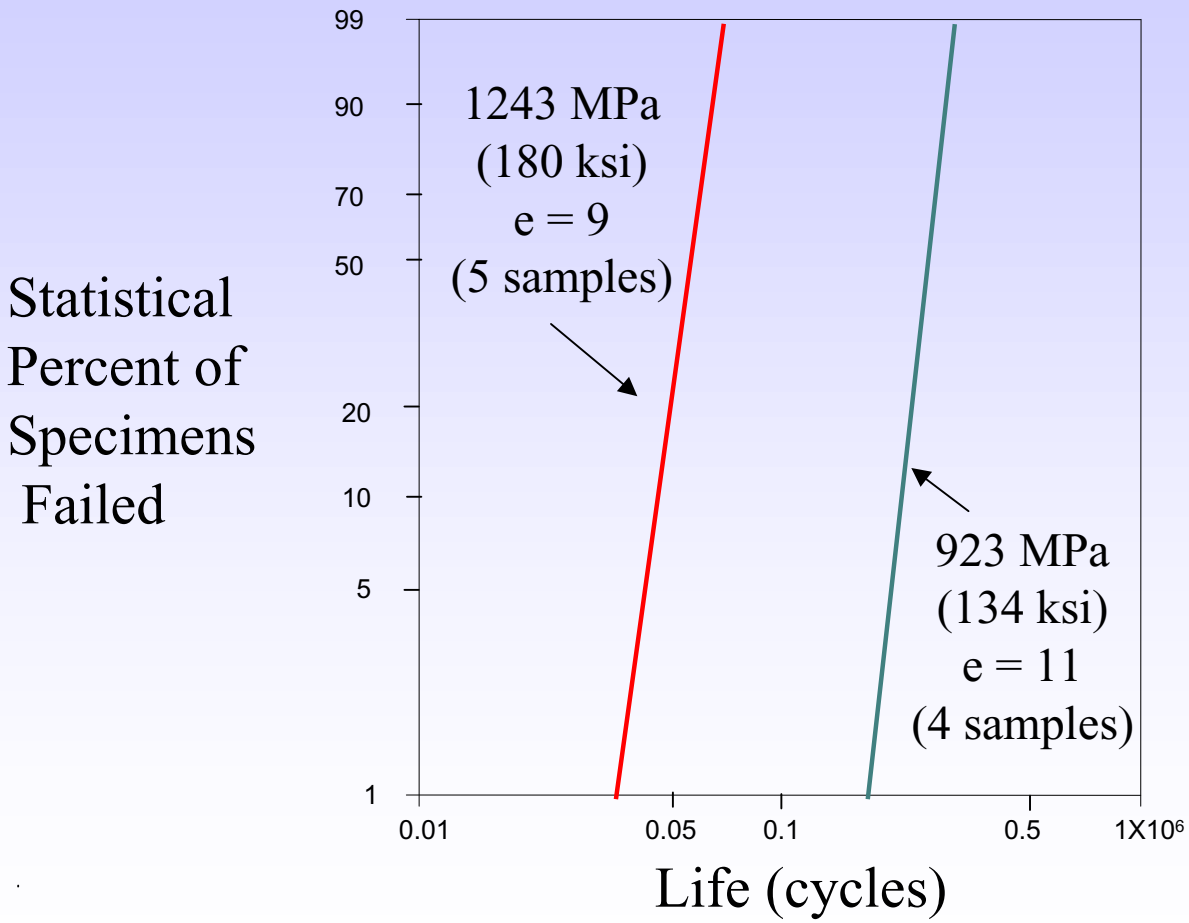
$$A = L_{ref} \tau_{ref}^{c} V_{ref}^{1/e}$$

$$\tau_{ref} = \tau_{45}$$

$$L_{ref} = L_{10}$$

ref. volume, $V_{ref} = 1544\ mm^3$

Rene' 88 Baseline Fatigue Data, 204°C (400°F)



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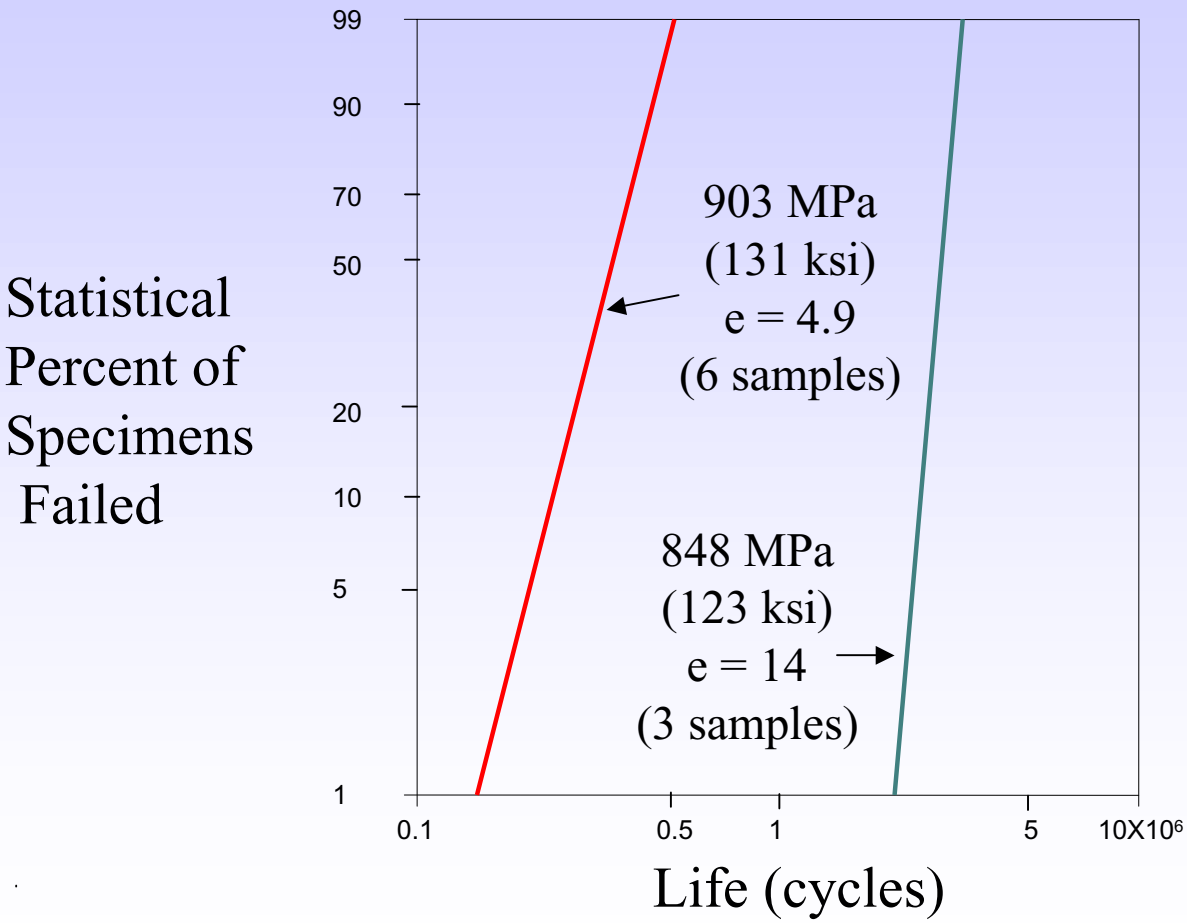
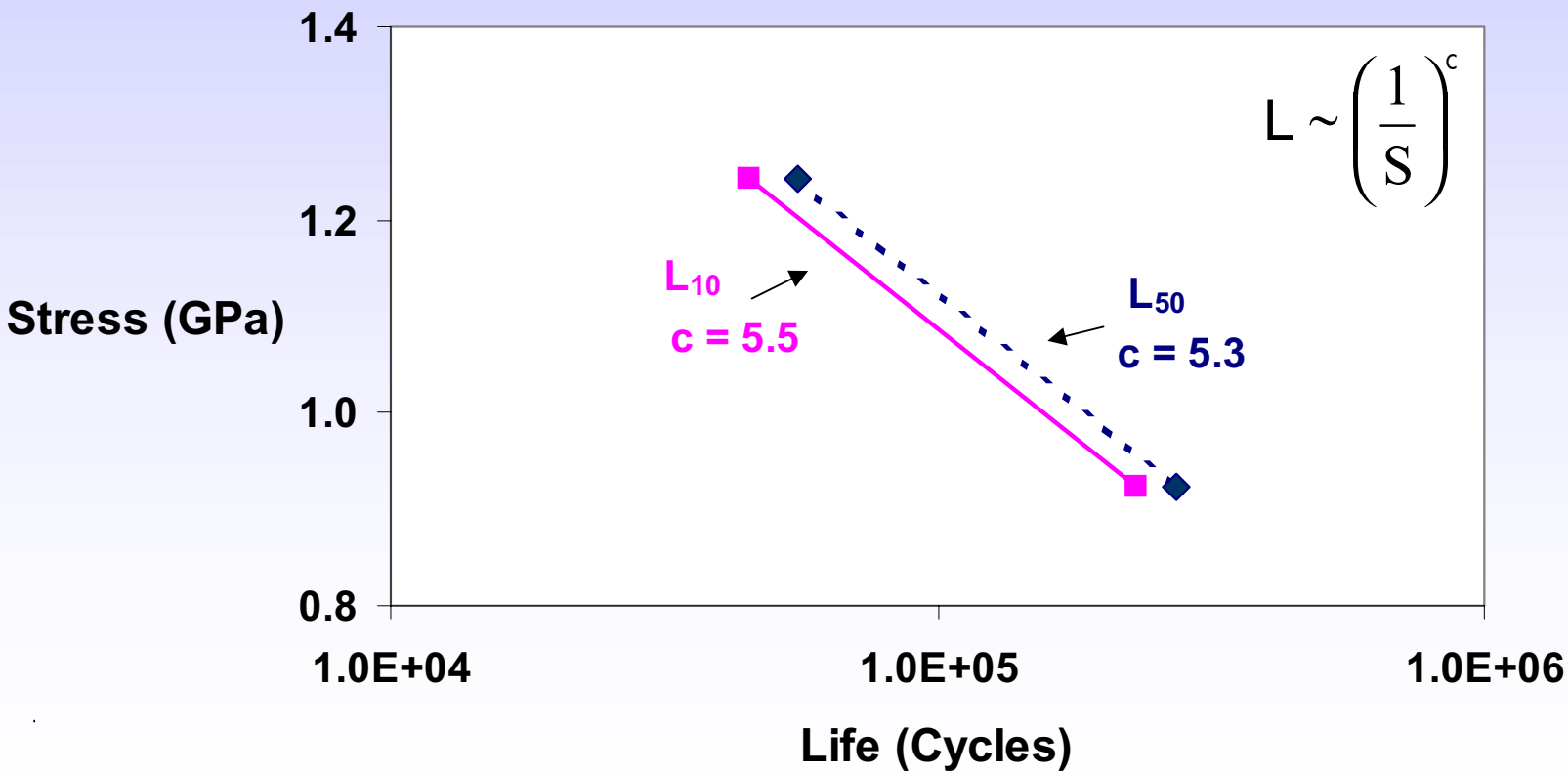
Rene' 88 Baseline Fatigue Data, 649°C (1200°F)

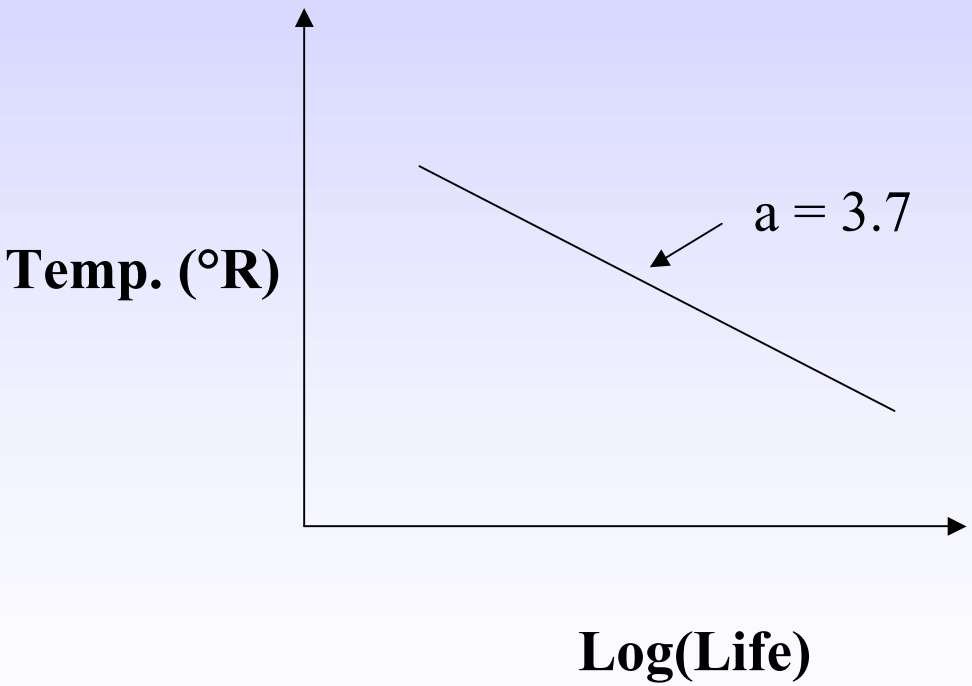


Rene' 88 Stress-Life Relation, 204°C (400°F)



Temperature-Life Relation

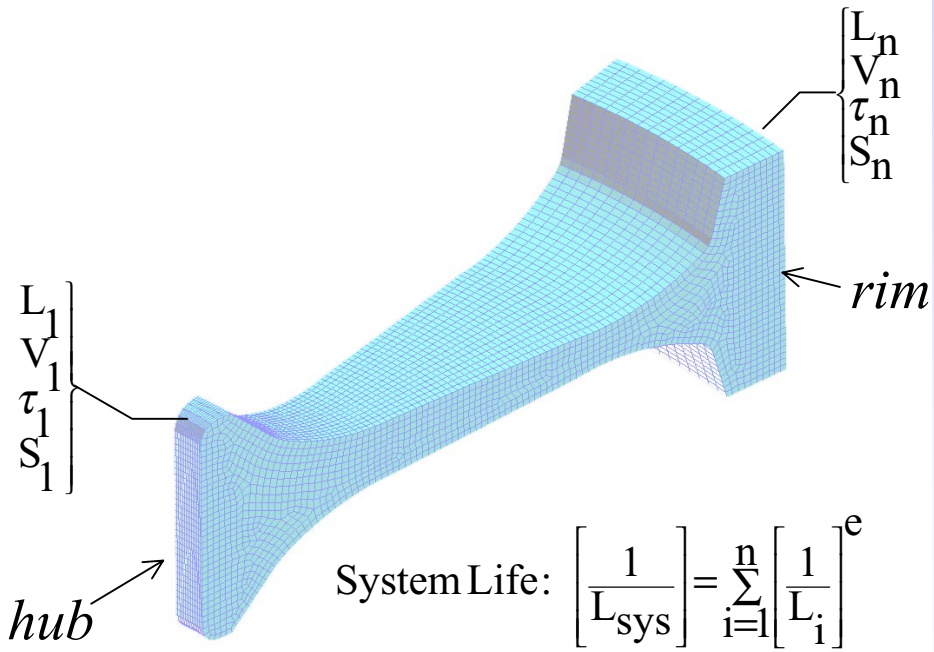
$$L \sim \left(\frac{1}{T}\right)^a$$



Material Parameters

Material:	Rene' 88
Elastic Modulus:	25,760 ksi
Poisson's Ratio:	0.323
Density:	0.78157×10^{-3} lbs/in.
Weibull Modulus, e	10
Stress-Life Exponent, c:	5.5
Ref. Stress, τ_{ref}:	0.129×10^{6} psi
Ref. Volume, V_{ref}:	1.427×10^{-6} in.^{3}
Ref. Life, L_{ref}:	1.2×10^{6} Cycles

Finite Element Model of Model Disk



System Life: $\left[\frac{1}{L_{sys}}\right] = \sum_{i=1}^{n}\left[\frac{1}{L_i}\right]^e$

Life Equations

Zaretsky Elemental Life:

$$L = L_{ref}\left[\frac{\tau_{ref}}{\tau}\right]^{c}\left[\frac{V_{ref}}{V}\right]^{\frac{1}{e}} \quad \text{or} \quad A\left[\frac{1}{\tau}\right]^{c}\left[\frac{1}{V}\right]^{\frac{1}{e}}$$

Where Material Life Factor:

$$A = L_{ref}\tau_{ref}^{c}V_{ref}^{1/e}$$

System Life:

$$\left[\frac{1}{L_{sys}}\right] = \sum_{i=1}^{n}\left[\frac{1}{L_i}\right]^{e}$$

Probability Equations

Elemental Probability of Survival:

$$S = S_{ref}^{\left(L_{ref}/L\right)^{e}}$$

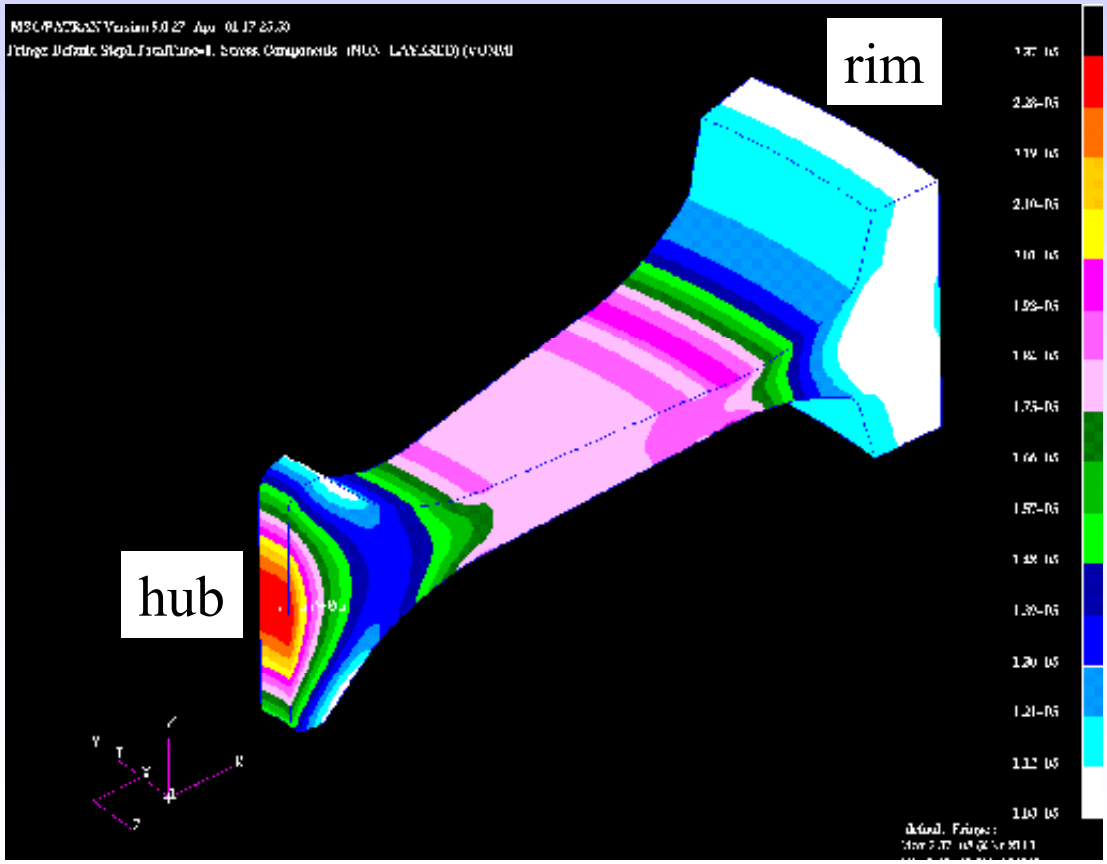
System Probability of Survival:

$$S_{sys} = S_1 \cdot S_2 \cdots S_n$$

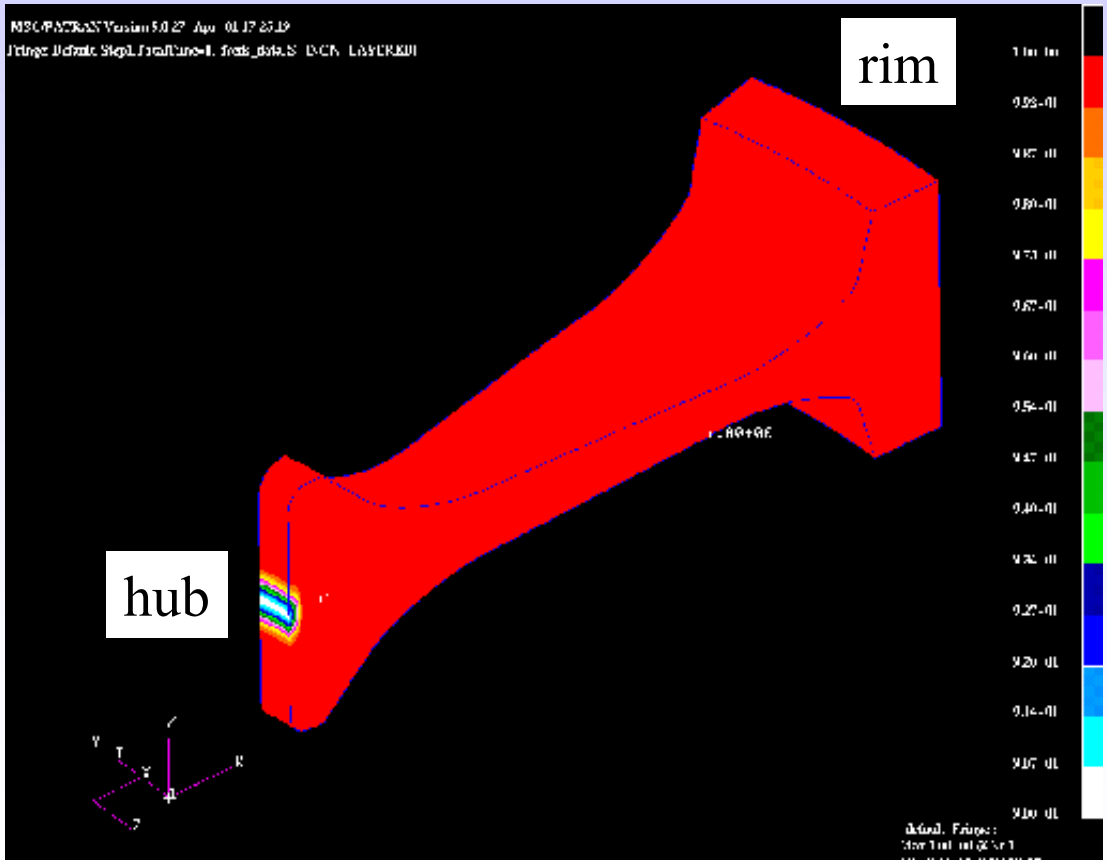
System Probability of Failure:

$$F_{sys} = 1 - S_{sys}$$

Max. Shear Stress Distribution of Model Disk, 48000 rpm

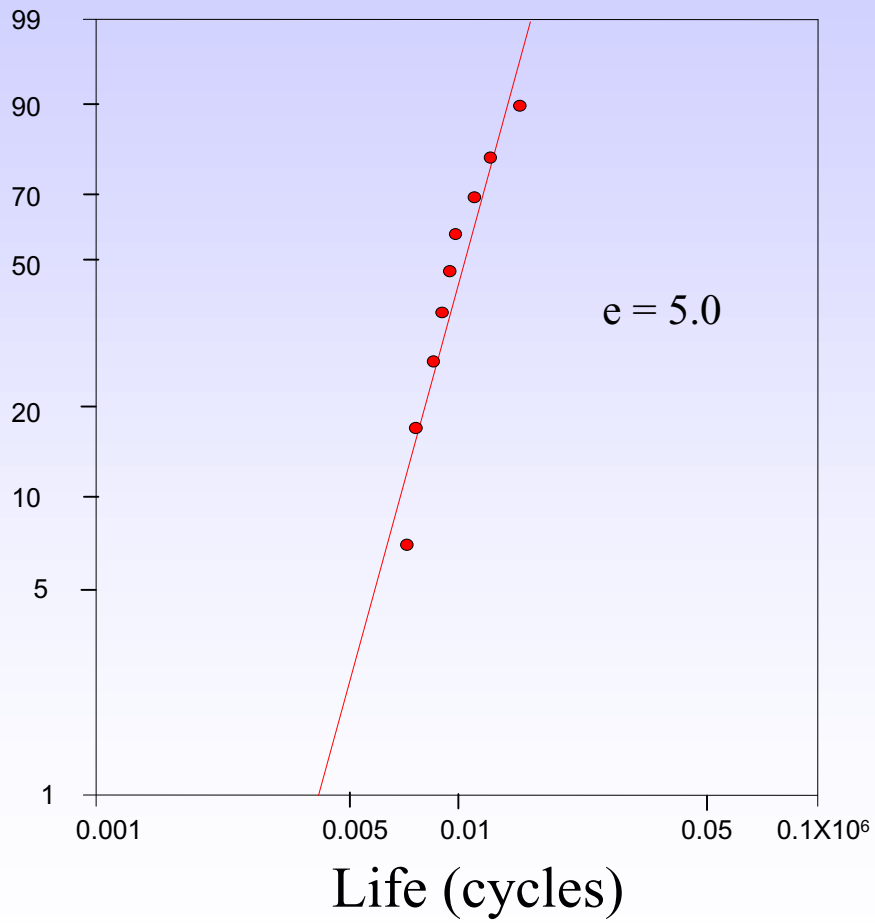


Probability of Survival of Model Disk, 48000 rpm



Rene' 88 Model Disk Test Data, 538°C (1000°F)

Statistical Percent of Specimens Failed



Speed: 48000 rpm

Comparison of Experimental and Predicted L_{10} Disk Life

Cycles To Failure	
Predicted	Experiment
6,358	7,196

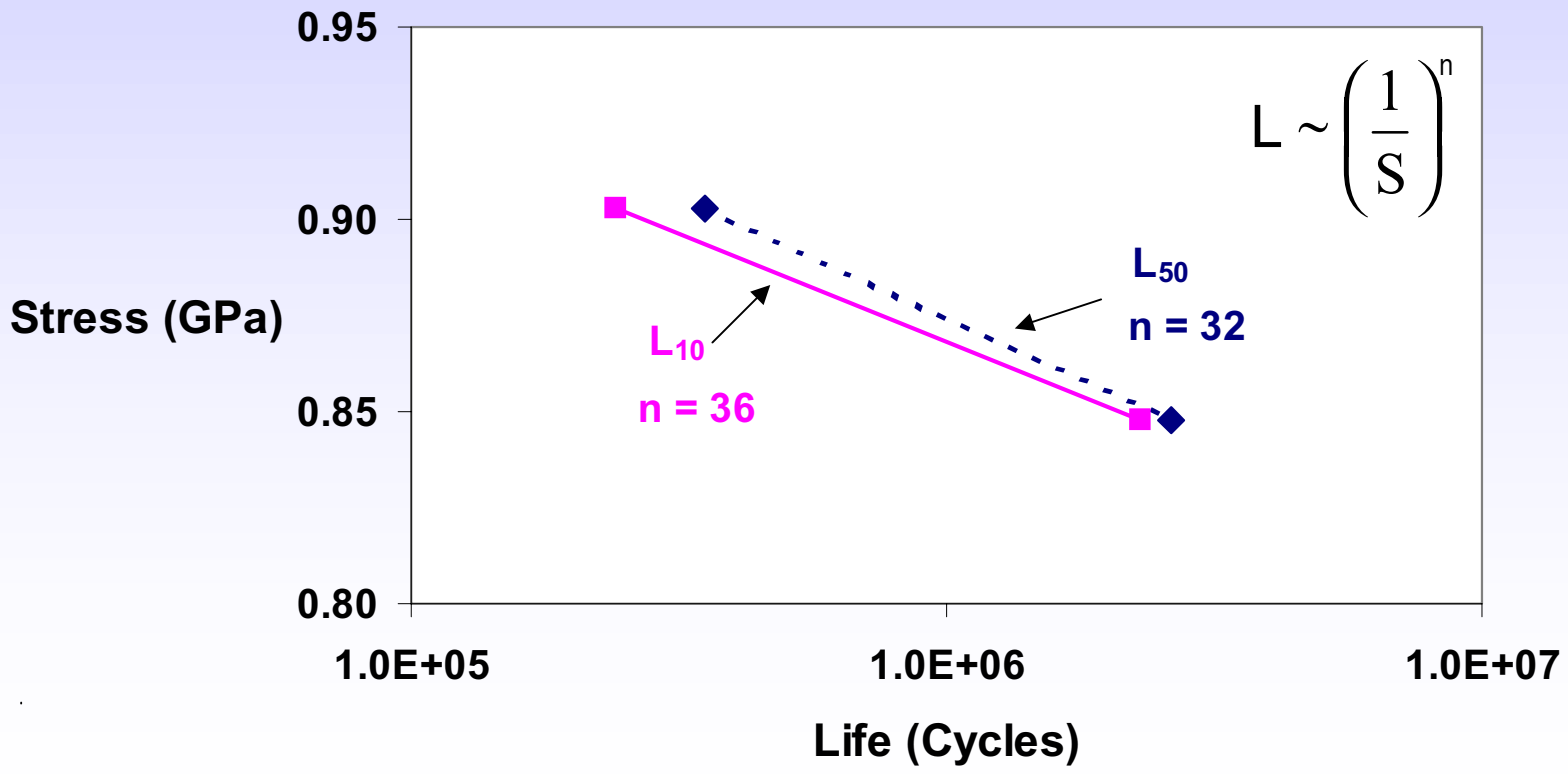
Summary

- Methodology gave a reasonably conservative prediction of L_{10} disk life from push-pull specimen data.

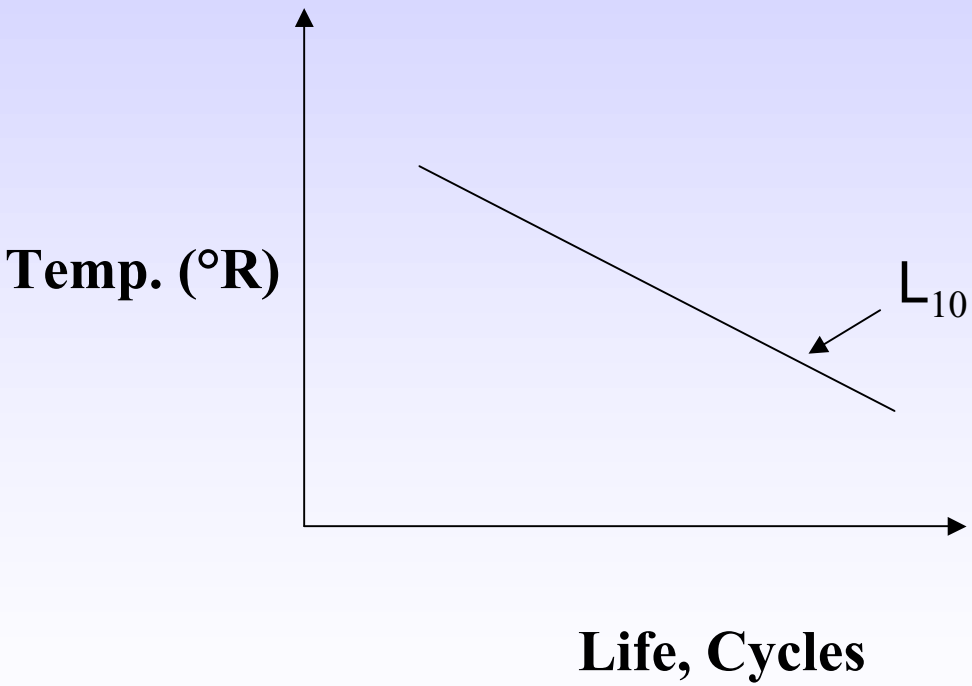
- Preliminary results suggest methodology is promising for accurately predicting fatigue life of metallic gas turbine disks.

- More verification needed.

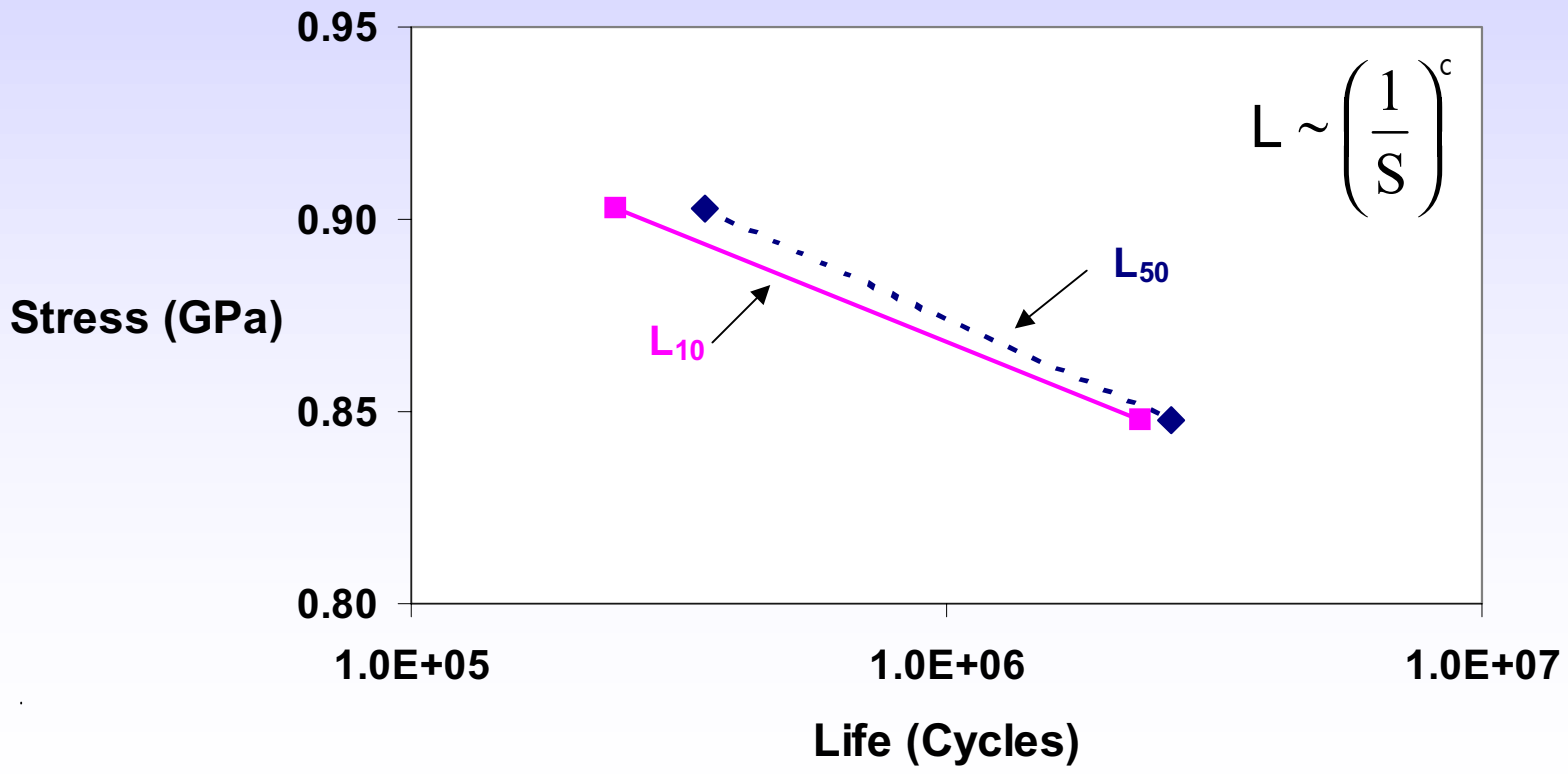
Rene' 88 Stress-Life Relation, 649°C (1200°F)



Temperature-Life Relation

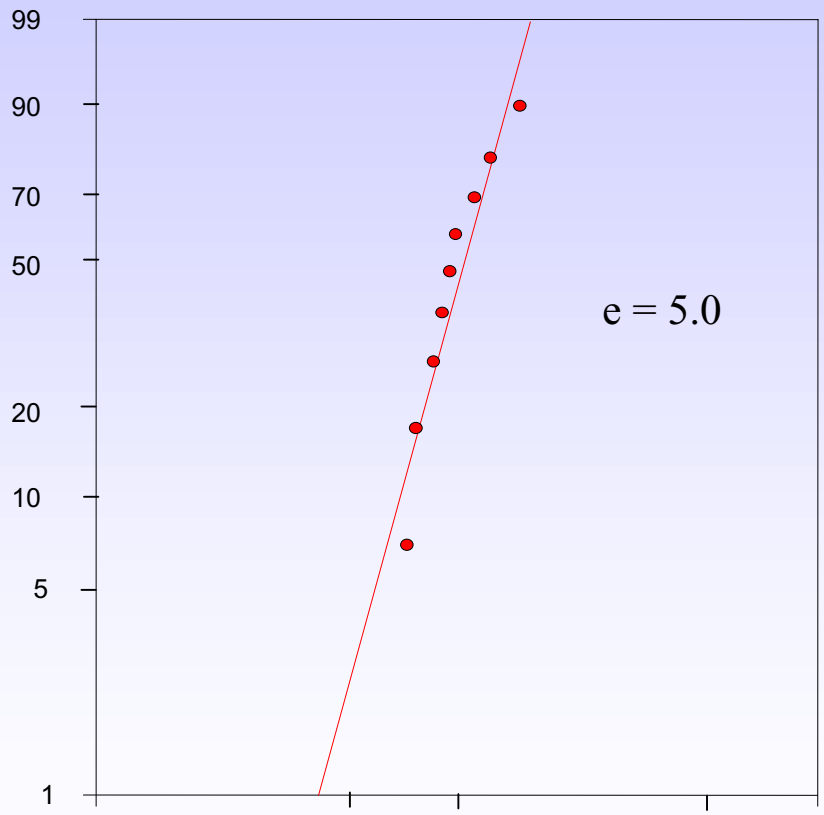


Rene' 88 Stress-Life Relation, 649°C (1200°F)



Rene' 88 Model Disk Test Data, 538°C (1000°F)

Statistical Percent of Specimens Failed



Speed: 48000 rpm

Life (cycles)

NASA GRC Fatigue Crack Initiation Life Prediction Models

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Glenn Research Center
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Metal fatigue has plagued structural components for centuries, and it remains a critical durability issue in today's aerospace hardware. This is true despite vastly improved and advanced materials, increased mechanistic understanding, and development of accurate structural analysis and advanced fatigue life prediction tools. Each advance is quickly taken advantage of to produce safer, more reliable, more cost effective, and better performing products. In other words, as the envelop is expanded, components are then designed to operate just as close to the newly expanded envelop as they were to the initial one. The problem is perennial.

The economic importance of addressing structural durability issues early in the design process is emphasized. Tradeoffs with performance, cost, and legislated restrictions are pointed out. Several aspects of structural durability of advanced systems, advanced materials and advanced fatigue life prediction methods are presented. Specific items include the basic elements of durability analysis, conventional designs, barriers to be overcome for advanced systems, high-temperature life prediction for both creep-fatigue and thermomechanical fatigue, mean stress effects, multiaxial stress-strain states, and cumulative fatigue damage accumulation assessment.

NASA/CP—2002-211682

NASA-GRC Fatigue Crack Initiation Life Prediction Models

Vinod K. Arya
University of Akron

Gary R. Halford
NASA Glenn Research Center

5th Annual FAA/Air Force/NASA/Navy Workshop on the Application of Probabilistic Methods to Gas Turbine Engines

Holiday Inn Cleveland West
Westlake, OH
June 11-13, 2001

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NASA-GRC Fatigue Crack Initiation Life Prediction Models

Abstract

Metal fatigue has plagued structural components for centuries, and it remains a critical durability issue in today's aerospace hardware. This is true despite (a) the development of vastly improved and advanced materials, (b) increased mechanistic understanding, and (c) development of accurate structural analysis and advanced fatigue life prediction tools. Each advance is quickly taken advantage of to produce safer, more reliable, more cost effective, and better performing products. In other words, as the envelop of capability expands, components are designed to operate just as close, or even closer, to the newly expanded limits as they did to the initial ones. The problem is perennial.

The economic importance of addressing structural durability issues early in the design process is emphasized. Durability tradeoffs with performance, cost, and legislated restrictions are pointed out. Several unique aspects of structural durability of advanced systems, advanced materials and advanced fatigue life prediction methods are presented. Specific items to be discussed include the basic elements of durability analysis, conventional designs, barriers to be overcome for advanced systems, high-temperature life prediction for both creep-fatigue and thermomechanical fatigue, mean stress effects, multiaxial stress-strain states, and cumulative fatigue damage accumulation assessment. While not classified as being truly mechanistic models with a micromechanistic basis, they do contain aspects traceable to macroscopic, cause-and-effect phenomena. In their present form, the models are deterministic. Some examples of their application is presented. The models are awaiting efforts to be recast into probabilistic interpretation.

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OUTLINE

0 - SETTING THE STAGE

- Cost of Elimination of Failure Modes
- Structural Durability - Vs. Performance - Vs. Cost
  - -- Durability, the poor step child
  - -- Life prediction - a perennial problem (local vs. global)
  - -- Prediction vs. Verification dilemma

0 - GLENN DURABILITY LIFING MODELS

- *Specific Material Models(for example, Oxidation, Coatings, Brittle Materials, etc.)*
- *Damage Mechanics Models*
- *Fatigue Crack Growth Models*
- *Multi-Factor Approach*
- Fatigue Crack Initiation/Early Growth Models
  - -- Estimating Fatigue Curves (LCF & HCF)
  - -- Modeling Effects of Variables
    - - Mean stresses
    - - Notches
    - - Multiaxiality
    - - Cumulative Fatigue Damage
    - - Creep-Fatigue
    - - Thermomechanical Fatigue
  - -- Probabilistic Assessment of Non-Linear Effects

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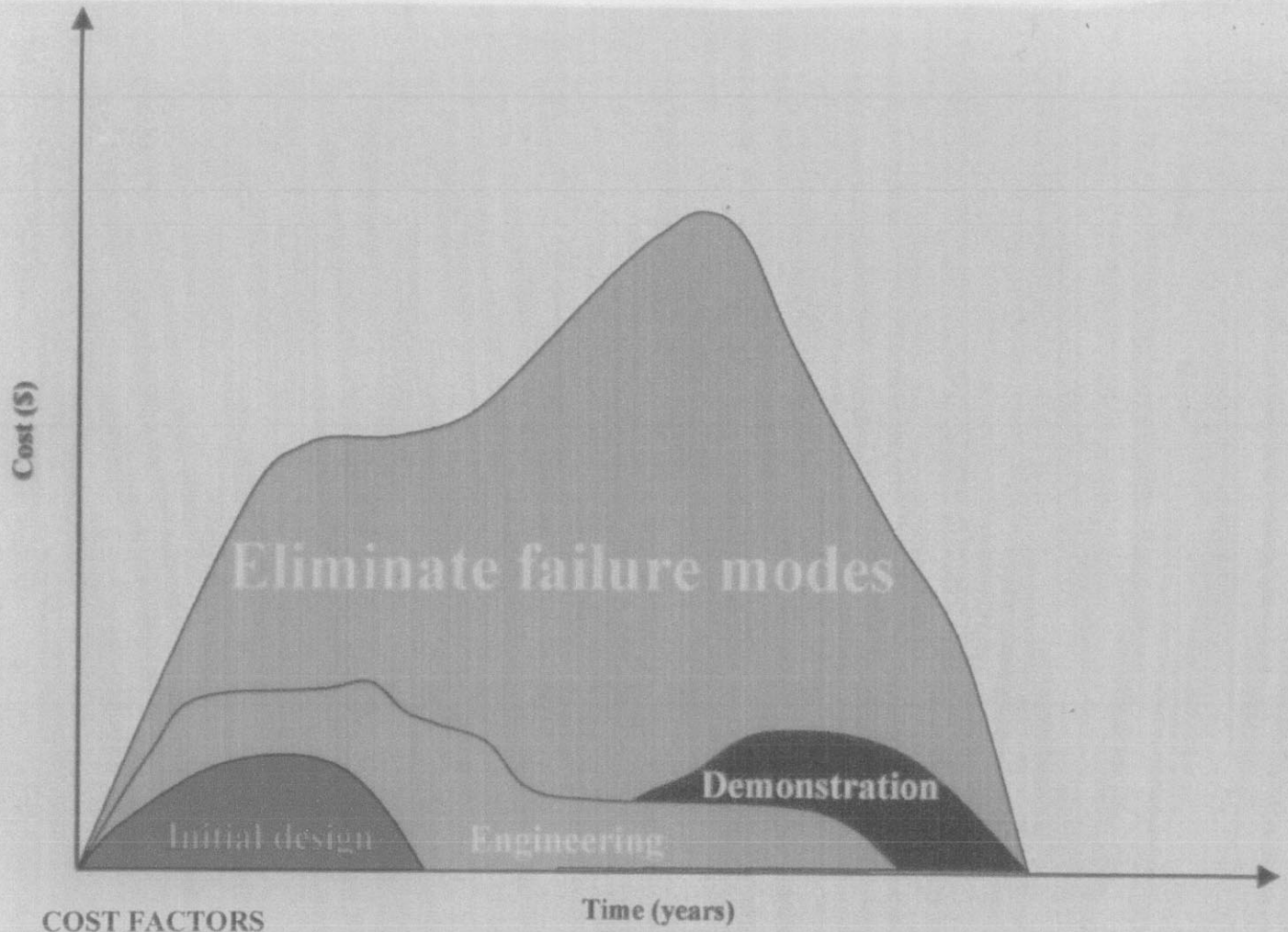
DEVELOPMENT COST DRIVEN BY FACTORS



COST FACTORS

Elimination Failure Modes	73%
Engineering	15%
Demonstration	10%
Initial Design	2%

Fig. Courtesy: Rockwell International

Primary Trade-off Troika Drivers

⇑

PERFORMANCE

DURABILITY ⇒

COST

⇓

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Overriding Requirements

Legislated / Public Outcry

⇑

SAFETY

ENVIRONMENTAL IMPACT

⇓

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Elements of Durability Analyses

0 - Mission and Environmental Loading Analysis

0 - Global Structural Response Analysis

0 - Local Stress-Strain-Temp-Time Material Response Analysis

0 - Durability Failure Modes Analysis

0 - Damage Accumulation and Life Prediction Analysis

0 - Coupon & Hardware Testing for Model Calib./Valid./Verif.

0 - Mfg Quality Analysis and Non-Destructive Evaluation (NDE)

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PEDESTRIAN DESIGNS

0 - Previous design experience

0 - Directly applicable rules of thumb

0 - Previous mission experience on similar hardware

0 - Extensive material property data bases

0 - Knowledge of all potential failure modes

0 - Knowledge of synergistic durability interactions

0 - Affordable 'build-em' and bust-em' prototypes

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BARRIERS TO ASSURED DURABILITY OF ADVANCED SYSTEMS

0 - Lack of previous direct experience/rules of thumb

0 - Limited material property data bases
-- long-term data bases unachievable in timely manner

0 - Ignorance of failure modes / synergistic interactions

0 - Low fidelity of damage accumulation/life models

0 - Prototypes too expensive to test or lead times too long

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SURMOUNTING THE BARRIERS

0 - Accept up-front costs of designed-in durability

0 - Require critical minimum data bases
- Early initiation of long-term testing

0 - Seek out failure modes & any synergism

0 - Capture the "physics" of damage accumulation

0 - Analytically model damage/life prediction

0 - Maximize durability information from each test
- Fewer tests, however, decrease assessment of probabilities of failure

0 - Continuously update analytic models

0 - Take advantage of probabilistic analyses where possible

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Glenn Program	Description
-PMUS	***Estimates Fatigue Resistance of Materials*** ***(Extensive use, e.g. Rocketdyne - SSME design)*** - Tensile Ductility & Tensile Strength - Cryogenic, Ambient, High Temperatures (10% Rule)
-LIFE	***Predicts Cyclic Life of Components Below Creep Regime*** - Multiaxiality via Triaxiality Factor - Mean Stress Correction
-PNOTCH	***Predicts Cyclic Life of Notched Components*** - Cyclic Stress-Strain Neuber Notch Analysis
-PDLDR	***Predicts Cumulative Damage Life of Components*** - Mission Loading History Analyzed - Predicts Crack Nucleation & Early Growth - Damage Curve Approach & Double Linear Damage Rule for Mission - Multiaxiality via Triaxiality Factor - Mean Stress Correction
-C-LIFE	***Predicts Cyclic Life of C-Section Components*** - Multiaxiality via Triaxiality Factor
-PSRPLIFE	***Predicts Cyclic Life of High-Temp Components*** ***(Adopted by FoMoCo - Manifold/Exhaust System Design)*** - Utilizes Raw Experimental Data. - Total Strain Version of Strainrange Partitioning (SRP) - Isothermal Creep-Fatigue Interaction Assessment - Thermomechanical Fatigue Life Prediction - Bithermal Characterization - Cyclic Stress-Strain-Time-Temperature Characterization - Multiaxiality via Triaxiality Factor - Thermal Mean Stress Correction

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Non-Linear Cumulative Fatigue Damage Code- PDLDR

0 - Why the Fuss?

- Example of Material Behavior

0 - Simple Models Developed

- Require no more than Linear Damage Rule

0 - Sample Calculations

- Idealized Space Shuttle Component

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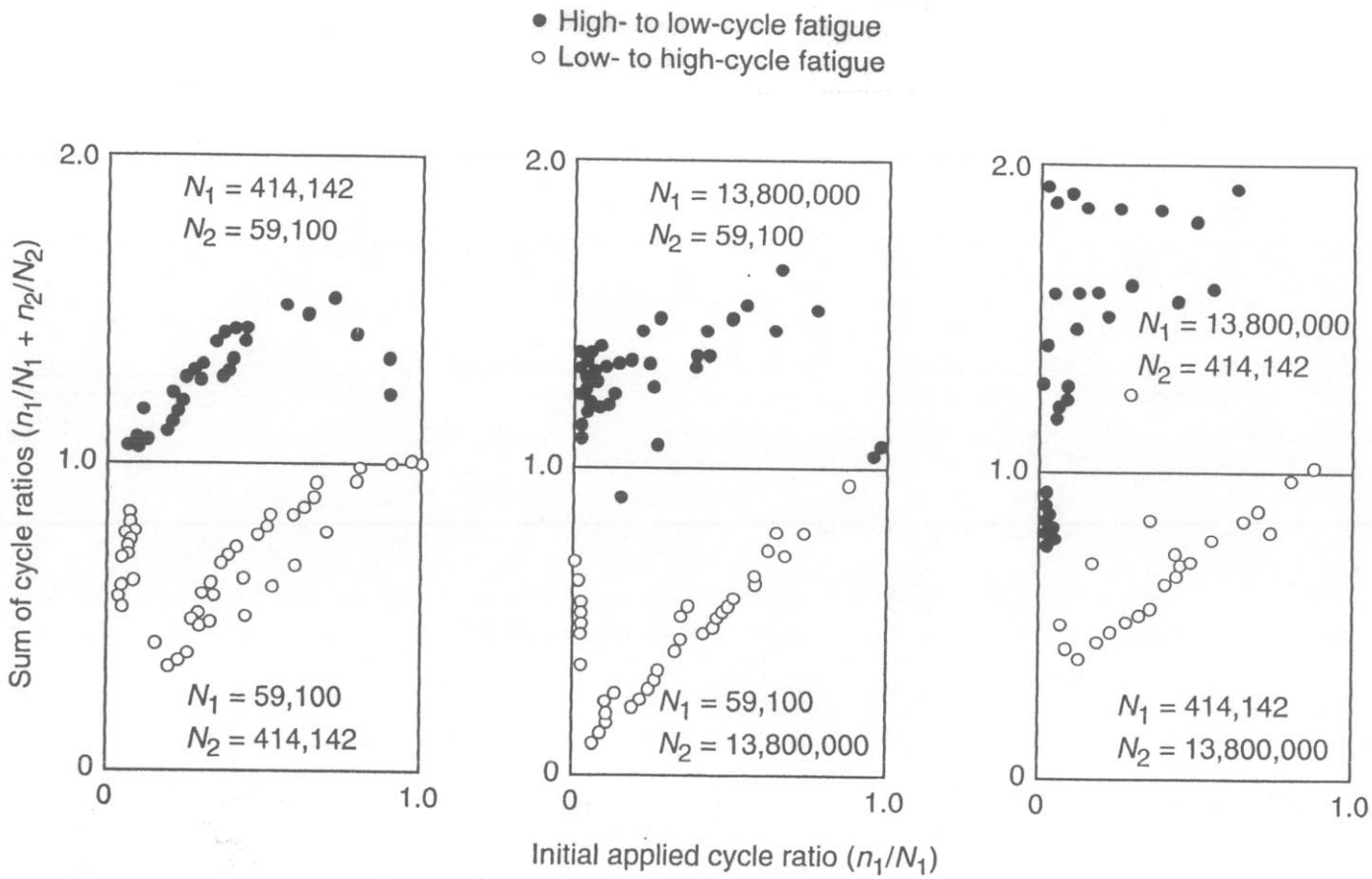
Why the Fuss?

Classic Loading Order Effect in Two Load Level Cumulative Fatigue Damage Tests
British Aluminum Alloy D.T.D. 683



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EXAMPLE APPLICATION - PDLDR

(Double Linear Damage Rule Vs. Linear Damage Rule)

Generic Space Shuttle Component using Haynes 188 Alloy, 705 °C

Loading Conditions Assumed:

0 - HCF Frequency 1000 Hz
0 - Mission Duration 500 sec
0 - HCF Life N_2 = 50,000,000 Cycles to Failure
0 - LCF Life N_1 = 500 Cycles to Failure

Mission consists of n_1 = 1 LCF Cycle
n_2 = 500,000 HCF Cycles

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LINEAR DAMAGE RULE (LDR)
PREDICTION OF NUMBER OF MISSIONS

$$\Sigma\left[\frac{n_1}{N_1}+\frac{n_2}{N_2}\right]=1.0$$

$$\Sigma\left[\frac{1}{500}+\frac{50{,}000}{50{,}000{,}000}\right]=\Sigma[0.002+0.010]=\Sigma 0.120=1.0$$

$$\frac{1}{0.012}=83$$

83 Number of Missions by LDR

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DOUBLE LINEAR DAMAGE RULE (DLDR) PREDICTION OF NUMBER OF MISSIONS

Two Linear Damage Rules Summed to 1.0, Sequentially, Where:

$$N_I + N_{II} = N_f$$

$$N_I = f(N_f, N_1/N_2)$$

$$N_{II} = N_f - N_I$$

PHASE I ("Initiation") = N_I:

$$\Sigma\left[\frac{n_1}{N_{I,1}} + \frac{n_2}{N_{I,2}}\right] = 1.0$$

Then,

PHASE II ("Propagation") = N_{II}:

$$\Sigma\left[\frac{n_1}{N_{II,1}} + \frac{n_2}{N_{II,2}}\right] = 1.0$$

Failure Occurs once Phase II reaches 1.0

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Based on DLDR for Haynes 188 at 705 °C:

$N_{I,1} = 10$	$N_{I,2} = 48{,}200{,}000$
$N_{II,1} = 490$	$N_{II,2} = 1{,}800{,}000$
$N_1 = 500$	$N_2 = 50{,}000{,}000$

PHASE I ("Initiation") = N_I:

$$\Sigma\left[\frac{n_1}{N_{I,1}} + \frac{n_2}{N_{I,2}}\right] = 1.0 = \Sigma\left[\frac{1}{10} + \frac{500{,}000}{48{,}200{,}000}\right] = \Sigma[0.1 + 0.013 = 0.113] = 1.0$$

$$\frac{1}{0..113} = \textbf{8.8 Missions to "Initiate"}$$

Then,

PHASE II ("Propagation") = N_{II}:

$$\Sigma\left[\frac{n_1}{N_{II,1}} + \frac{n_2}{N_{II,2}}\right] = 1.0 = \Sigma\left[\frac{1}{490} + \frac{500{,}000}{1{,}800{,}000}\right] = \Sigma[0.002 + 0.278 = 0.28 = 1.0] = 1.0$$

$$\frac{1}{0..28} = \textbf{3.6 Missions to "Propagate"}$$

$$8.8 + 3.6 = 12.4$$

≈ 12 Missions to Failure by DLDR vs. 83 Missions by LDR

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EFFECT ON MISSION LIFE OF IMPROVING FATIGUE RESISTANCE

Improvement	LDR (% increase)	DLDR (% increase)
Baseline Fatigue Curve	83 (--)	12 (--)
Increase LCF by X2	91 (10%)	23 (90%)
Increase HCF by X10	333 (300%)	25 (100%)
Increase HCF by X100	476 (475%)	97 (700%)
Increase LCF by X2 & HCF by X10	500 (500%)	37 (200%)

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PSRPLIFE

EXAMPLE APPLICATIONS

0 - StrainRange Partitioning (SRP)
- Compared to Linear Time- and Cycle Life Fraction Rule

0 - Schematic of Total Strain Version of StrainRange Partitioning (TS-SRP)

0 - Isothermal Total Strain Version of StrainRange Partitioning (TS-SRP)
- Applied to Inconel 718 at 650 °C

0 - Thermomechanical Fatigue Version of TS-SRP
- Applied to Haynes 188 & B-1900
- Applied to Automotive Exhaust System Alloy (Ferritic 409 SS)

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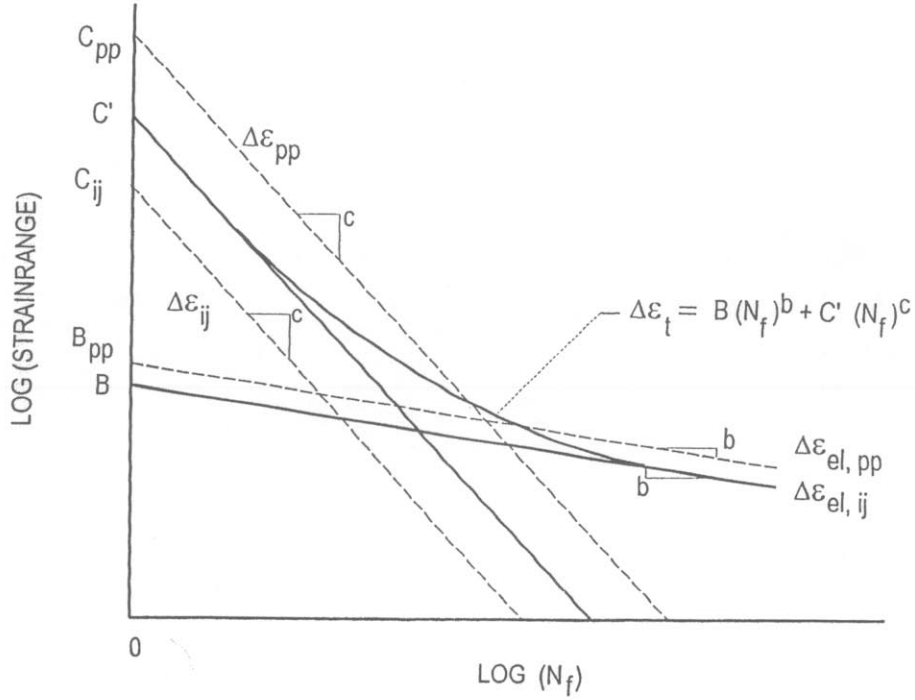
Schematic of Total Strain Version of StrainRange Partitioning (TS-SRP)



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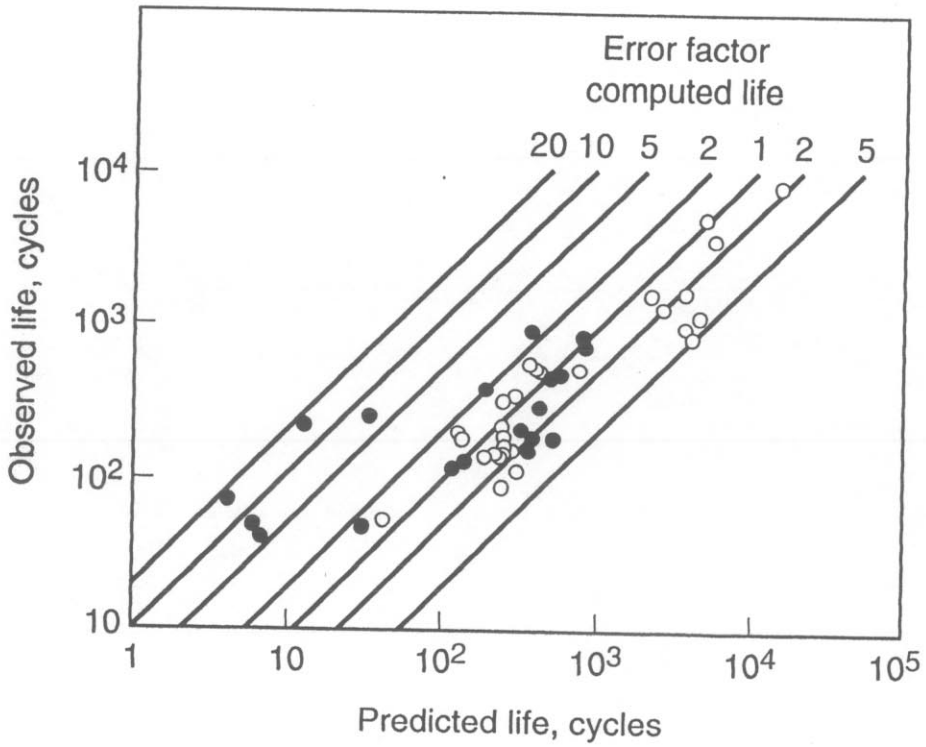
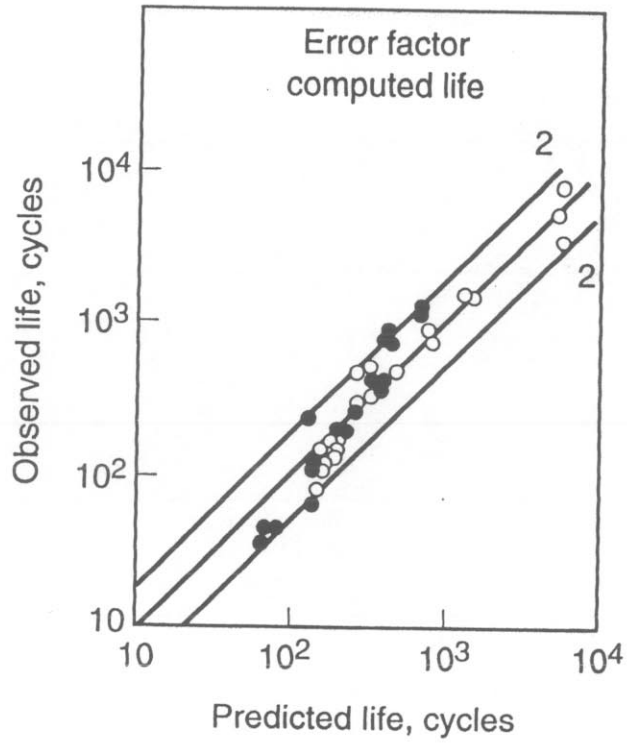
StrainRange Partitioning (SRP)

Prediction Capability Compared to Linear Time- and Cycle Life Fraction Rule

Creep-Fatigue Data for Incoloy 800 & 304 SS



Using predicted time and cycle fractions



Using strain range partitioning

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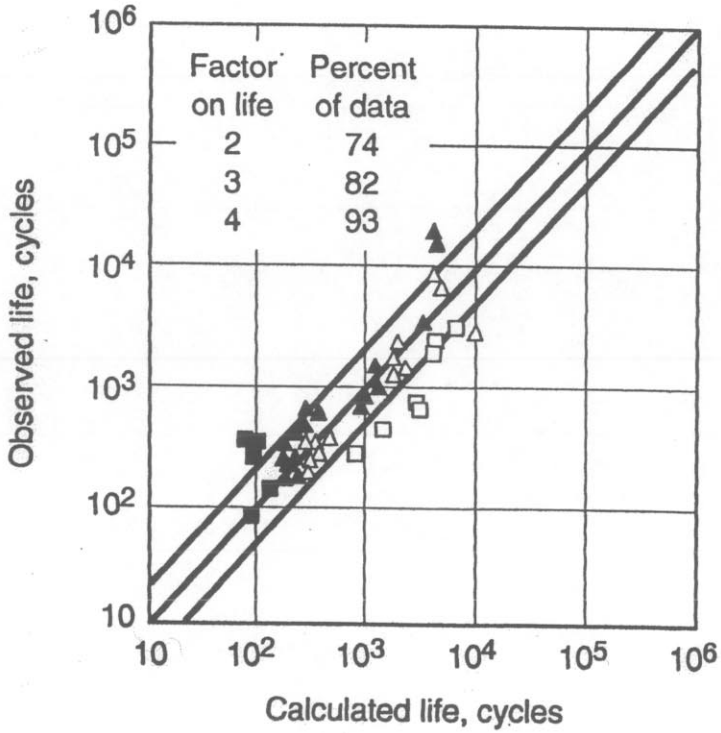
StrainRange Partitioning (SRP)

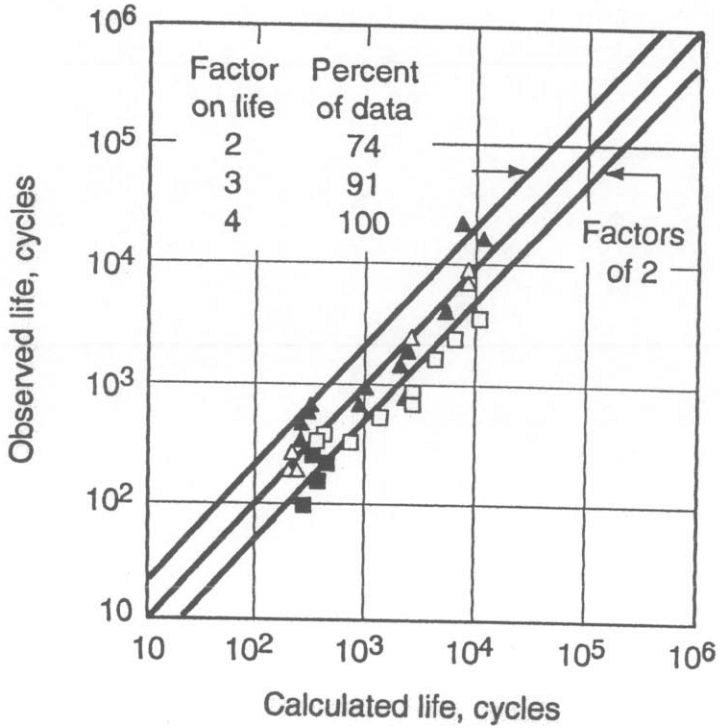
Isothermal Total Strain Version of StrainRange Partitioning (TS-SRP)

Predictability of Creep-Fatigue Data for Inconel 718 at 650 °C

Inelastic SRP



Total Strain Version



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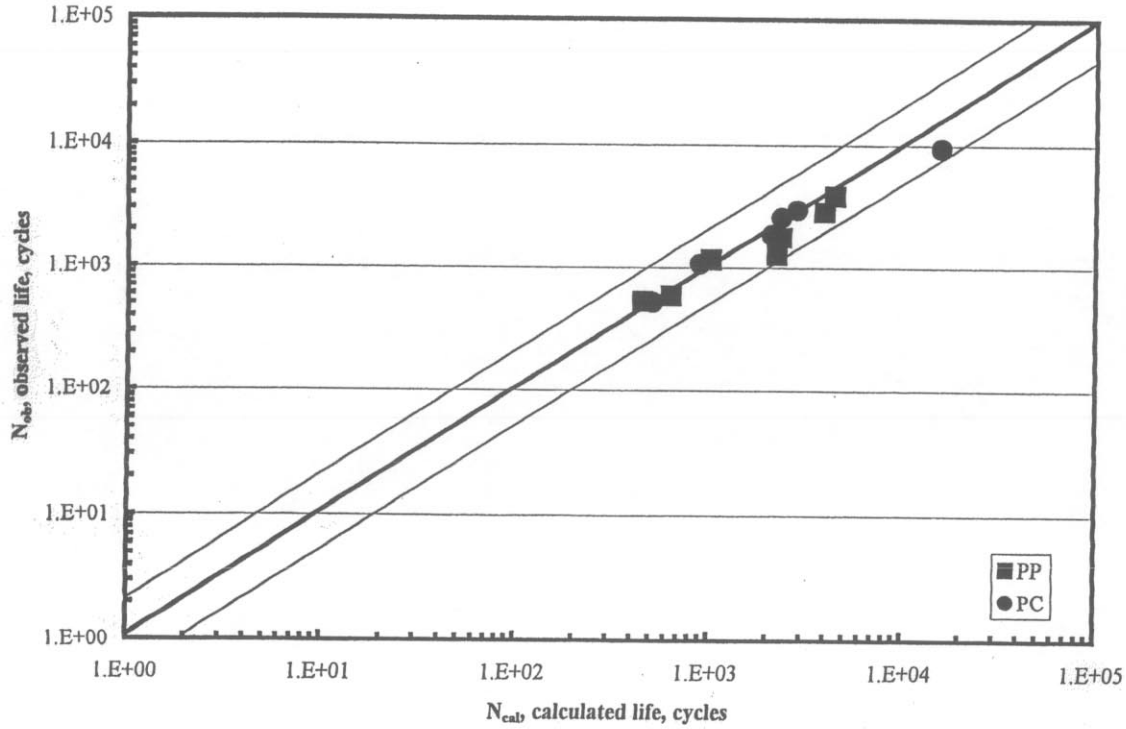
StrainRange Partitioning (SRP)

Thermomechanical Fatigue Version of SRP (TMF-SRP) Applied to Automotive Exhaust System Alloy (Ferritic 409 SS)

Correlation of calculated and observed lives of bithermal out-of-phase fatigue between 400 and 800 C



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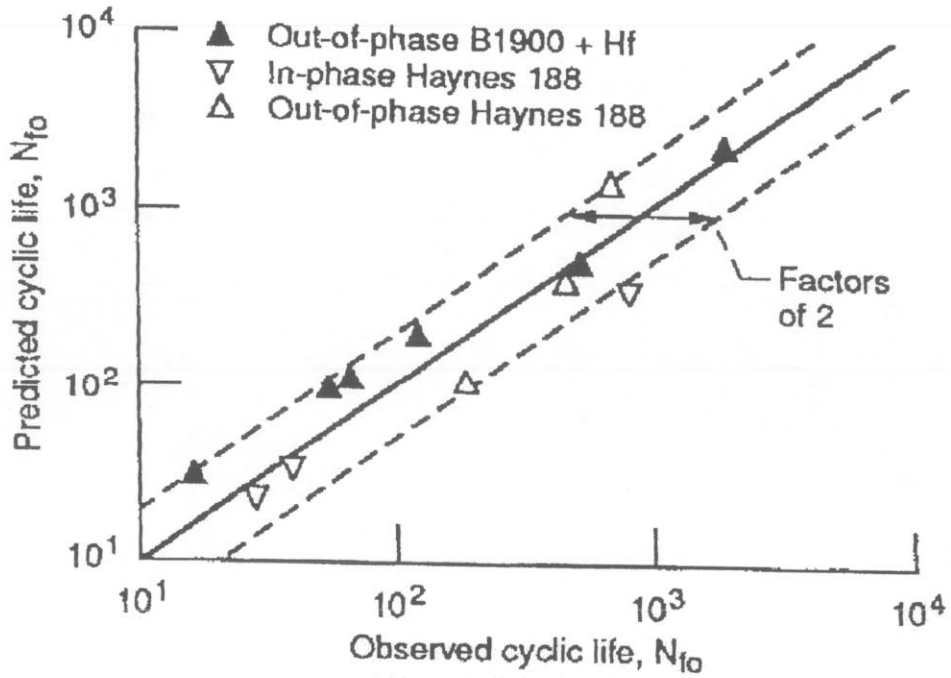
StrainRange Partitioning (SRP)

Thermomechanical Fatigue Version of SRP (TMF-SRP) Applied to Haynes 188 & B-1900



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Math Stats Results for Applied Probabilistics

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Did you know that "probability" and "statistics" are *not* synonymous terms? Did you know that probability has two *different* definitions, both part of mainstream statistical thought, yet fundamentally in conflict? Do you know what the likelihood function is, and where it comes from, and why you should care? Ever heard of the Fisher Information Matrix? Do you know what the Central Limit Theorem says and why it is central to successful Engineering Probabilistics? Were you aware that two variables can have a perfect functional relationship and yet have *zero* correlation? Do you know the difference between a condition distribution and a marginal distribution? Or a joint distribution? Or when you can get from one to another - and when you cannot?

If you have an analytically predicted stress of 50 KSI and a strain gage measurement that's different, which should you believe? How would you resolve the difference? (The common practice of adding the difference to the analytical result as a "correction" is dangerous. Do you know why?)

This paper will describe and discuss these and other interesting, important, and especially useful, results from Math Stats as they apply to Probabilistic Engineering Analysis.

Math Stats Results for Applied Probabilistics

Charles Annis, P.E.
Statistical Engineering

5th Annual FAA/Air Force/NASA/Navy Workshop on the Application of Probabilistic Methods to Gas Turbine Engines

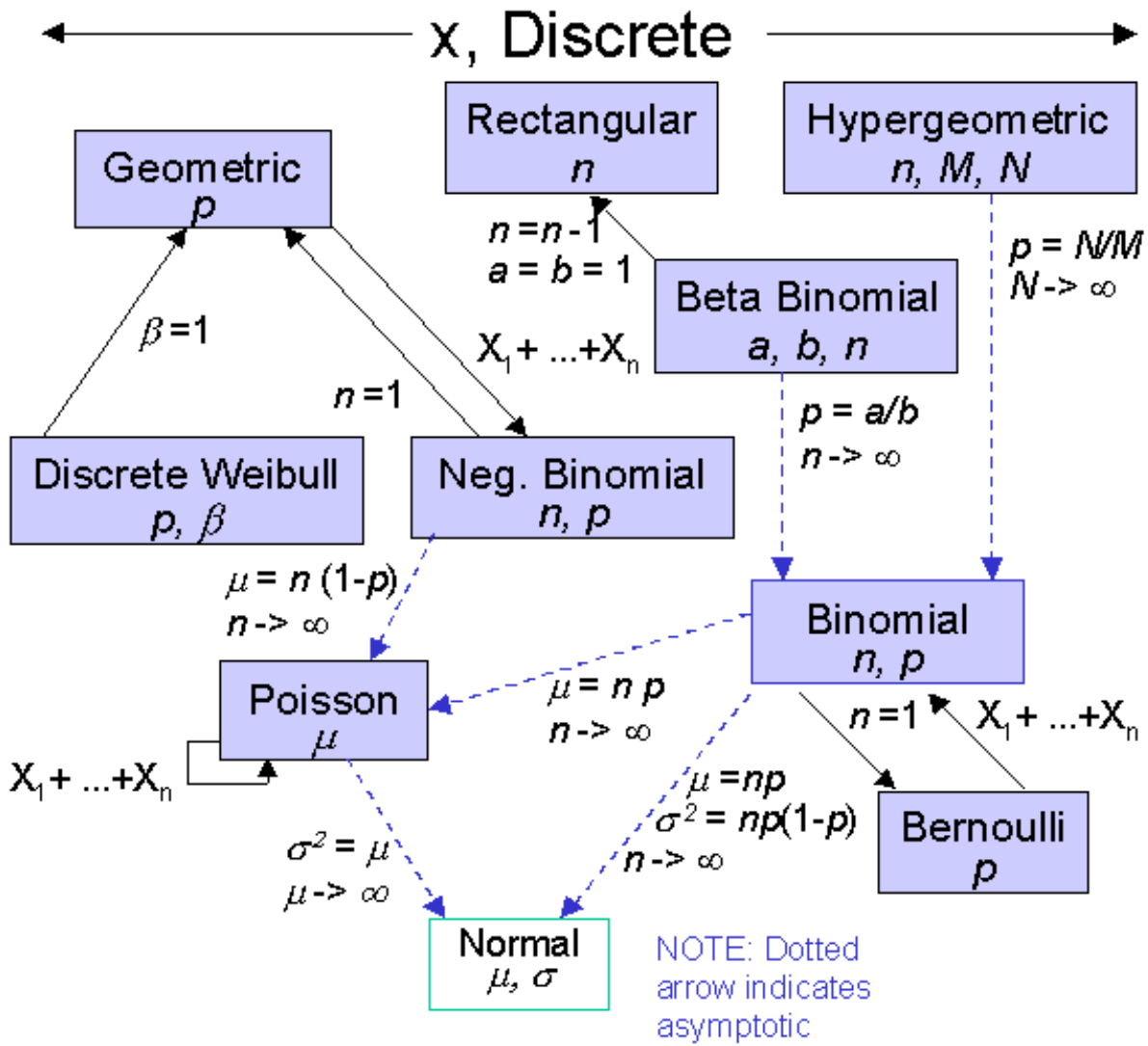
Holiday Inn Cleveland West Hotel in Westlake, Ohio

June 11- 13, 2001.

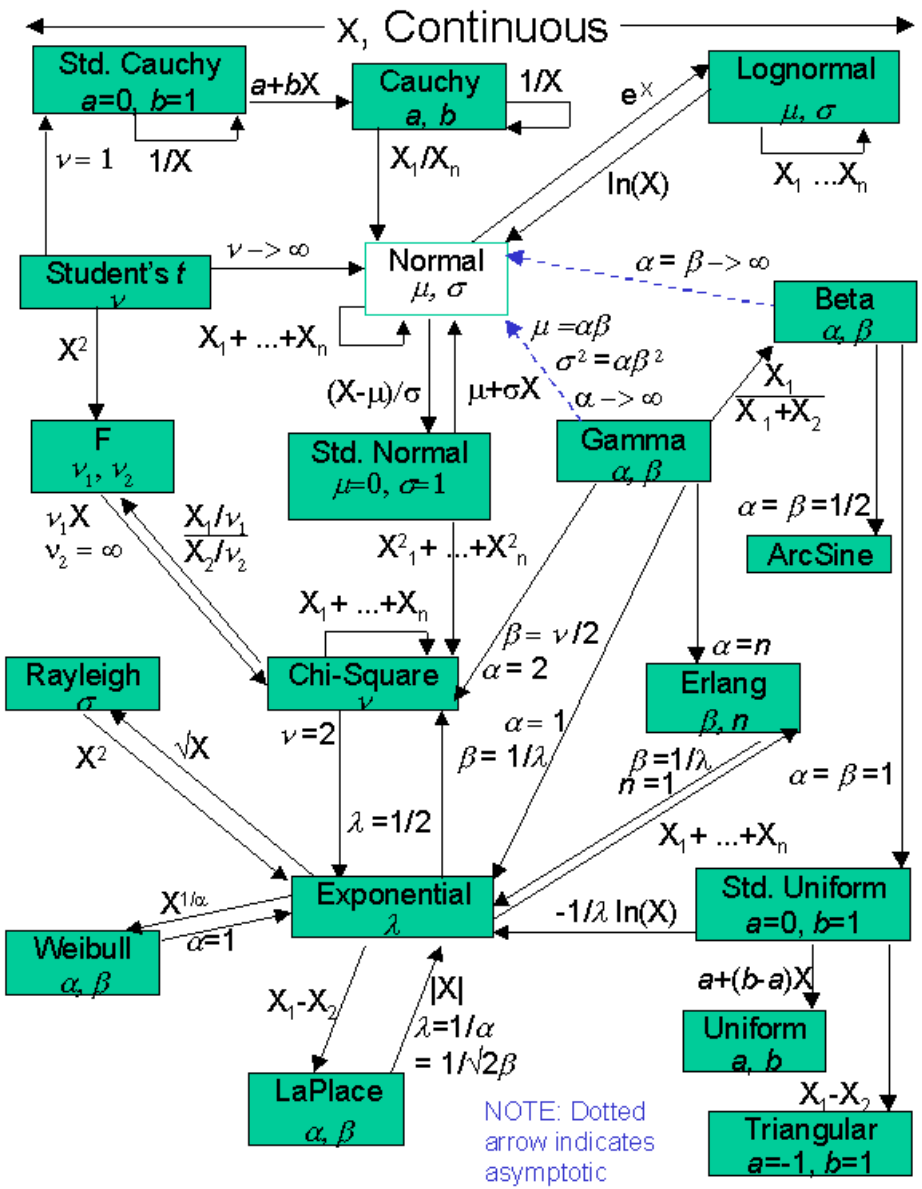
Math Stats Results for Applied Probabilistics

- Distributional interrelationships
- DOX
- Probability
- Statistics
- Joint, Marginal and Conditional Distributions
- Likelihood
- Fisher Information Matrix
- Central Limit Theorem
- Extreme Value Distributions
- Bayesian Philosophy

Did you know ...


x, Discrete
Rectangular
n
Hypergeometric
n, M, N
Geometric
p
n = n - 1
a = b = 1
Beta Binomial
a, b, n
p = N/M
N -> ∞
β = 1
X1 + ...+Xn
n = 1
p = a/b
n -> ∞
Discrete Weibull
p, β
Neg. Binomial
n, p
μ = n (1-p)
n -> ∞
Binomial
n, p
Poisson
μ
μ = n p
n -> ∞
n = 1
X1 + ...+Xn
X1 + ...+Xn
μ = np
σ2 = np(1-p)
n -> ∞
Bernoulli
p
σ2 = μ
μ -> ∞
Normal
μ, σ
NOTE: Dotted arrow indicates asymptotic

Did you know ...


x, Continuous
Std. Cauchy
a=0, b=1
a+bX
Cauchy
a, b
1/X
e^X
Lognormal
μ, σ
ν = 1
1/X
X1/Xn
ln(X)
X1 ...Xn
Student's t
ν
ν -> ∞
Normal
μ, σ
α = β -> ∞
Beta
α, β
X2
X1 + ...+Xn
μ =αβ
σ2 =αβ2
α -> ∞
X1
X1+X2
(X-μ)/σ
μ+σX
F
ν1, ν2
Std. Normal
μ=0, σ=1
Gamma
α, β
α = β =1/2
ν1X
ν2 = ∞
X1/ν1
X2/ν2
X21 + ...+X2n
ArcSine
X1 + ...+Xn
β = ν/2
α = 2
α =n
Rayleigh
σ
Chi-Square
ν
Erlang
β, n
X2
√X
ν =2
α = 1
β = 1/λ
β =1/λ
n =1
α = β =1
λ =1/2
X1 + ...+Xn
X1/α
Exponential
λ
-1/λ ln(X)
Std. Uniform
a=0, b=1
Weibull
α, β
α=1
a+(b-a)X
X1-X2
|X|
λ=1/α
= 1/√2β
Uniform
a, b
LaPlace
α, β
X1-X2
Triangular
a=-1, b=1
NOTE: Dotted arrow indicates asymptotic

Design Of eXperiments (DOX):

$$V(b) = V\begin{pmatrix} b_0 \\ b_1 \end{pmatrix} = \begin{bmatrix} V(b_0) & \operatorname{cov}(b_0, b_1) \\ \operatorname{cov}(b_0, b_1) & V(b_1) \end{bmatrix}$$

$$= \begin{bmatrix} \dfrac{\sigma^2 \sum X_i^2}{\sum (X_i - \overline{X})^2} & -\dfrac{\overline{X}\sigma^2}{\sum (X_i - \overline{X})^2} \\ -\dfrac{\overline{X}\sigma^2}{\sum (X_i - \overline{X})^2} & \dfrac{\sigma^2}{\sum (X_i - \overline{X})^2} \end{bmatrix}$$

$$V(b) = (X^T X)^{-1} \sigma^2$$ Big Deal Result!

"Probability" and "Statistics" ...

... are *not* synonymous terms.

- *Probability* describes the long-run frequency of occurrence (or a degree of belief, if you are a Bayesian)

- *Statistics* are functions of the data (observations) that do not contain any unknown parameters. Some statistics have interesting and useful properties, like the sample mean, a statistic, that *always* tends to a normal distribution.(*)

* (See **Central Limit Theorem** for the statistical fine-print.)

Probability has two different definitions:

- The *frequentist* definition sees probability as the long-run expected frequency of occurrence. P(A) = n/N, where *n* is the number of times event A occurs in N opportunities.

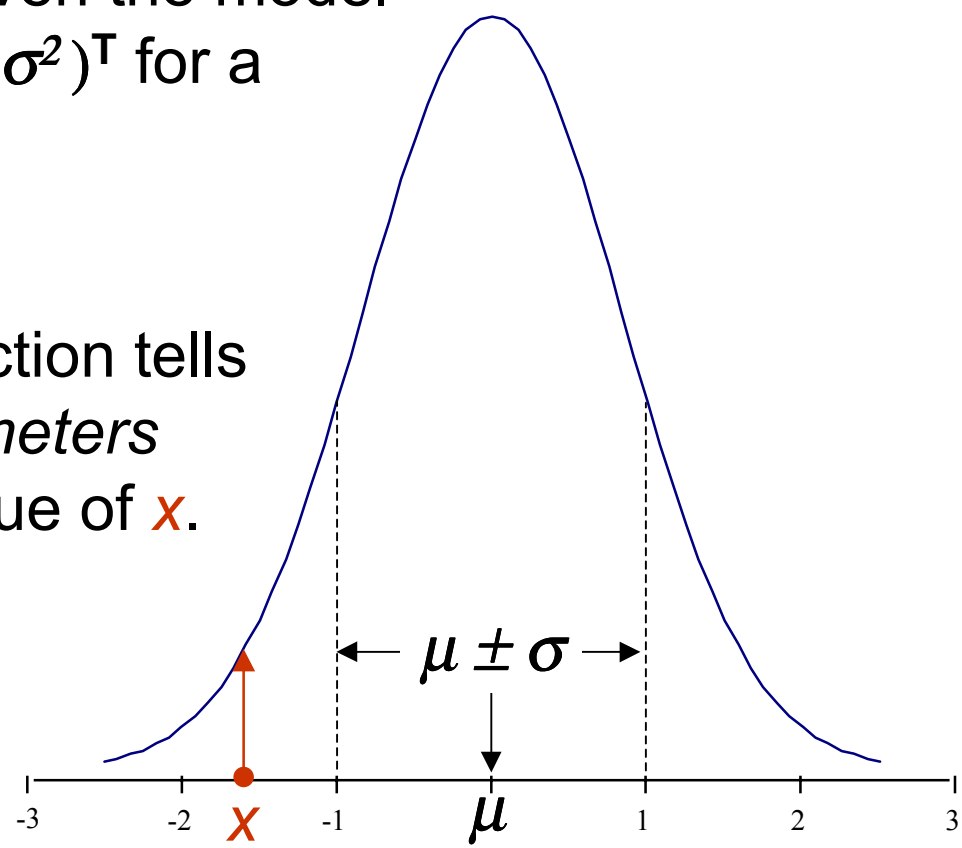
- The *Bayesian* view of probability is related to degree of belief. It is a measure of the plausibility of an event given incomplete knowledge.

(to be continued)

Probability and Likelihood

- **pdf**, probability density function, tells how **probable** a value of *x* is, given the model parameters, θ, *e.g.*: $\theta = (\mu, \sigma^2)^T$ for a Normal density.
  - Probabilities integrate to one.

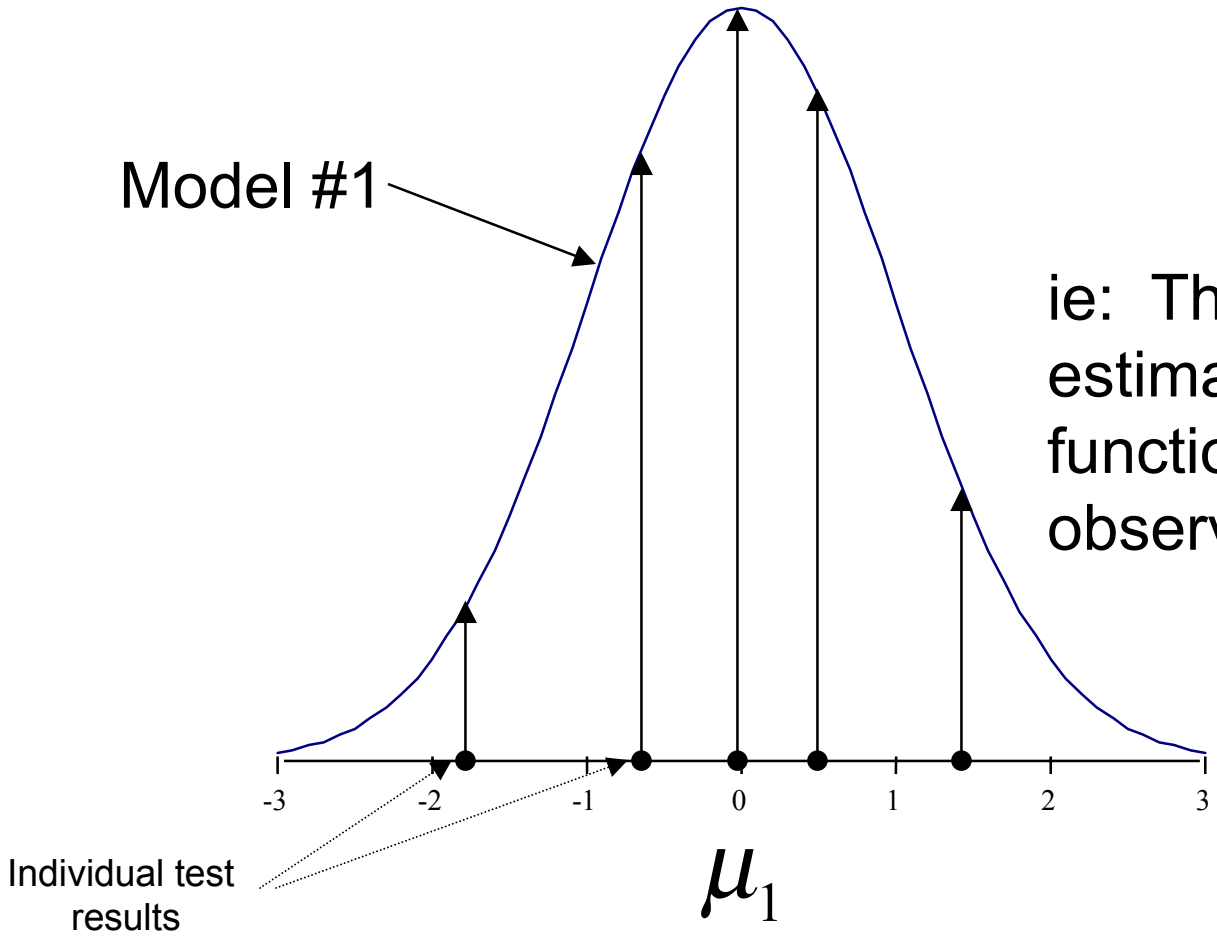
- **likelihood:** likelihood function tells how **likely** the model *parameters* are, given the observed value of *x*.
  - Likelihood can be defined for both censored and uncensored data. (Uncensored example shown here.)
  - Likelihoods *do not* necessarily integrate to one.



PDF Example

Likelihood ...

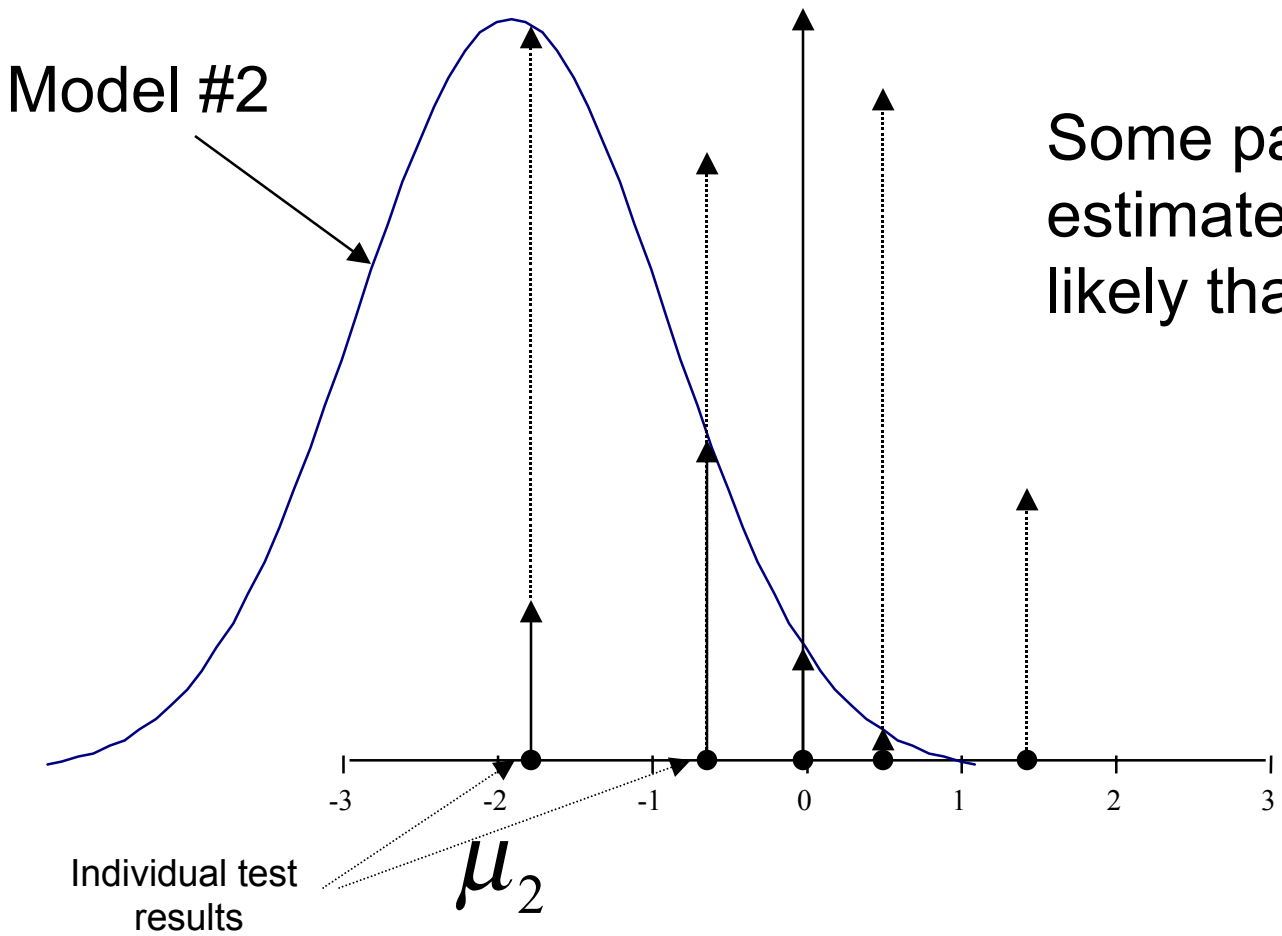
… describes the behavior (likelihood) of the population parameter estimates, given the data.



ie: The parameter estimates are a function of the observations.

Likelihood ...

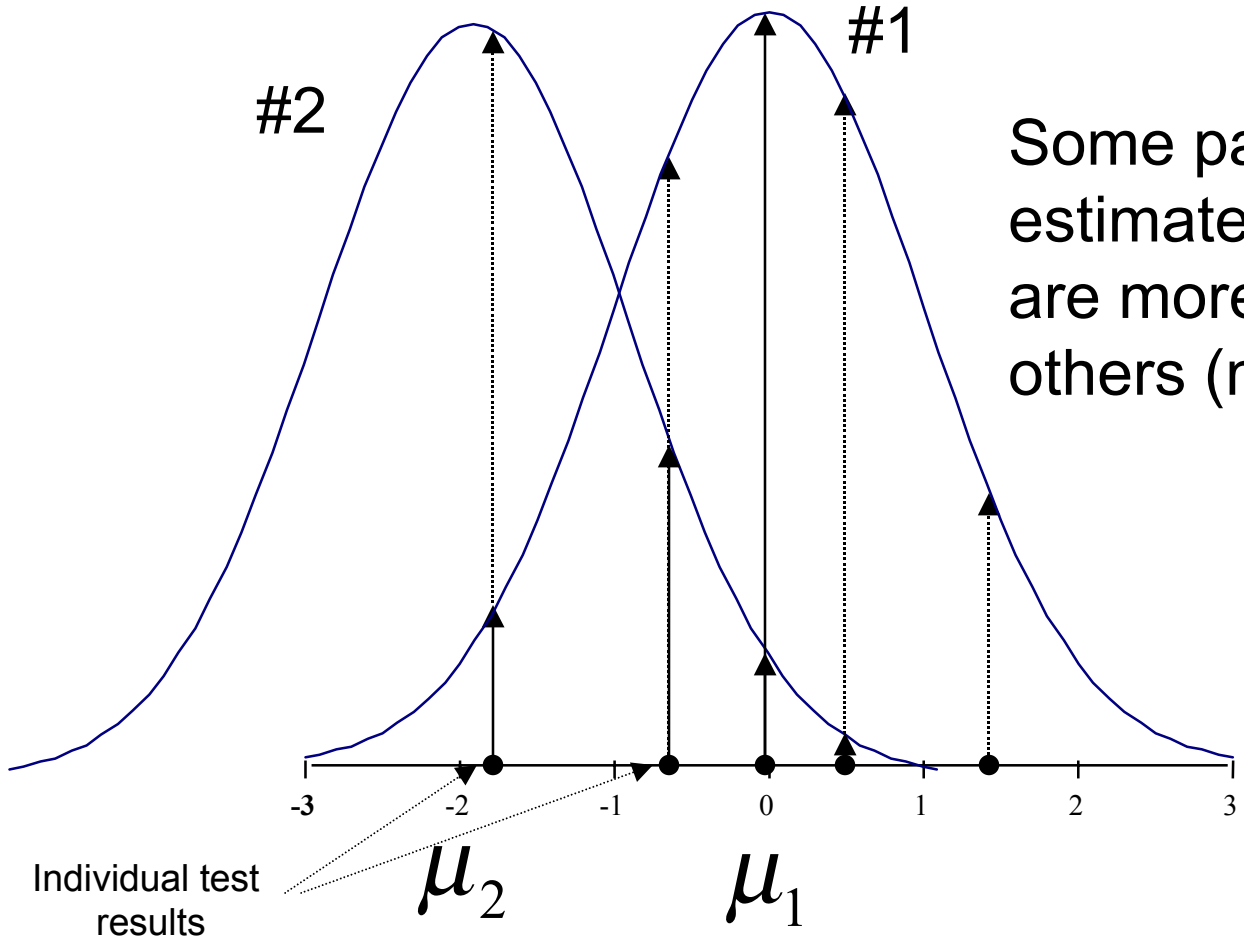
… describes the behavior (likelihood) of the population parameter estimates, given the data.



Some parameter estimates are more likely than others.

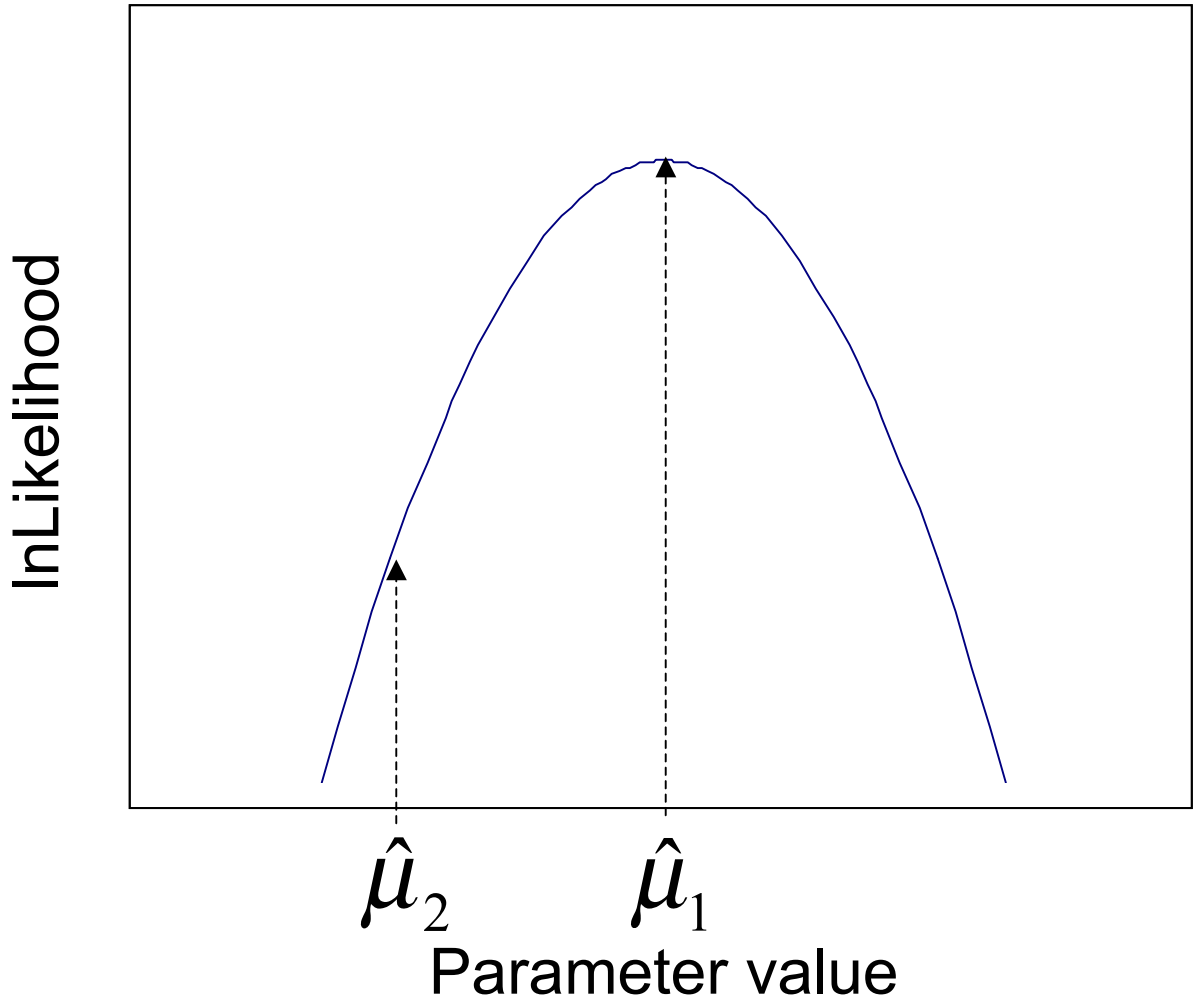
Likelihood ...

… describes the behavior (likelihood) of the population parameter estimates, given the data.



Some parameter estimates (model #1) are more likely than others (model #2).

Likelihood ratio can be used to compare models.



Central Limit Theorem

- The distribution of *averages* computed from repeated independent samples from *any* (*) distribution will tend toward Normal, *regardless of the form of the distribution from which the samples were drawn.*

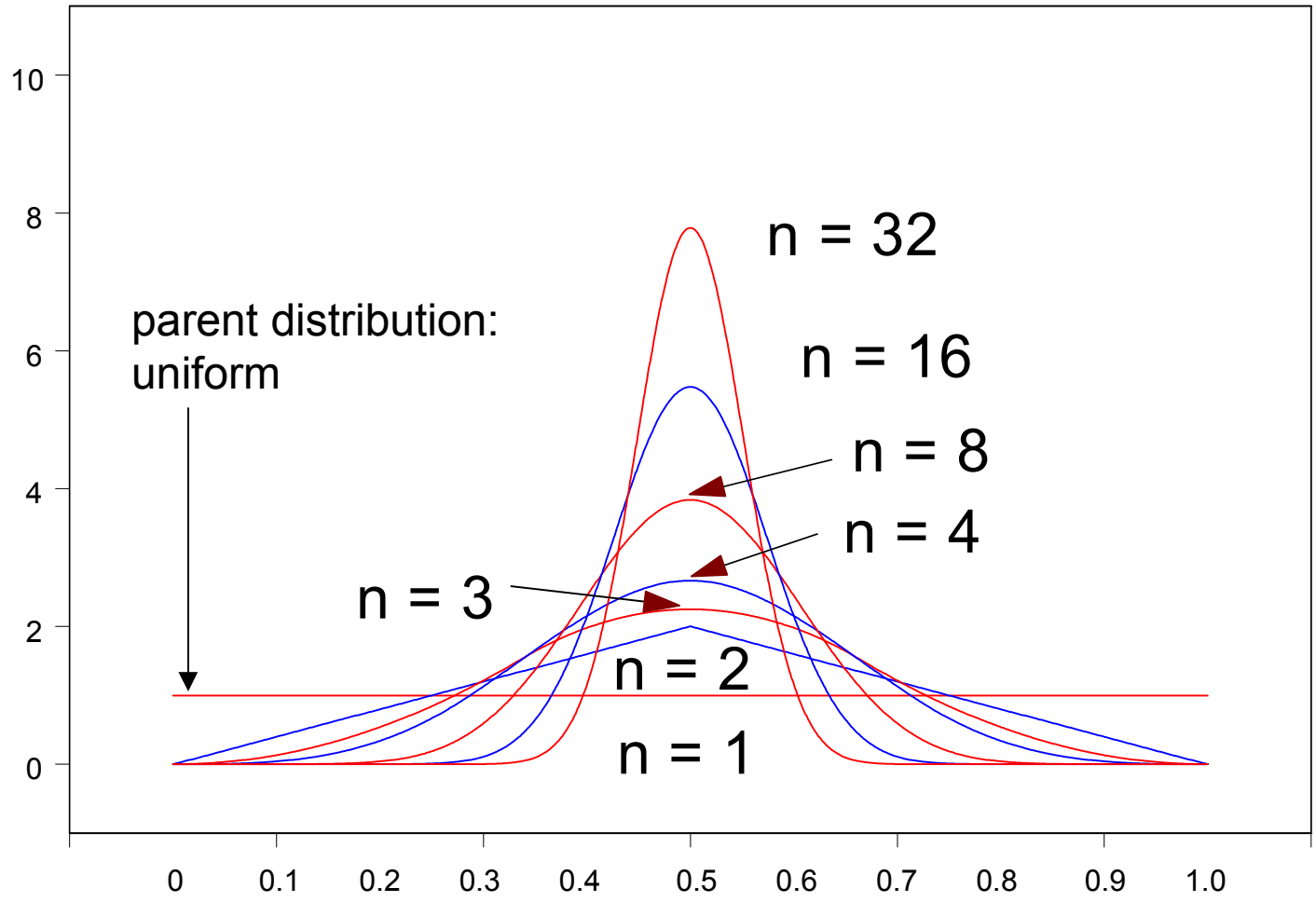
- Furthermore, this normal distribution will have the *same mean* as the parent distribution, and variance equal to the *variance of the parent divided by the sample size*.

- The sample average is a Maximum Likelihood Estimator (MLE). In fact for sufficiently large samples, **maximum likelihood estimators** are Normally distributed.

(*) Statistical fine print: The parent distribution must have a mean.

The Average of *n* samples tends to be Normal

... independent of the parent distribution.(*)



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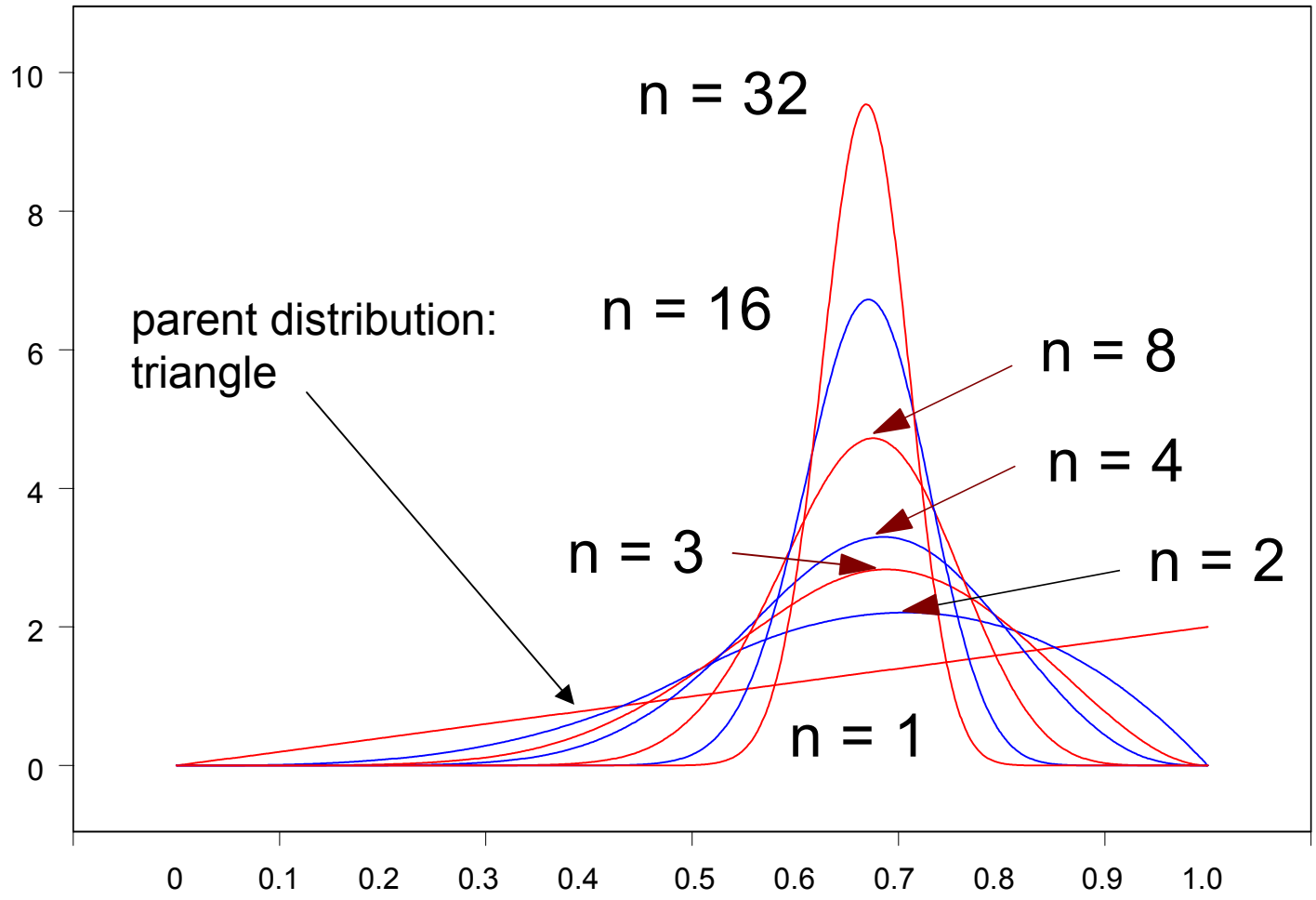


Central Limit Theorem - the fine print:

- Statistical fine print: The distribution of an average will tend to be Normal as the sample size increases, regardless of the distribution from which the average is taken *except when the moments of the parent distribution do not exist.*

- All practical distributions in statistical engineering have defined moments, and thus the CLT applies.

- The Cauchy is an example of a pathological distribution with nonexistent moments. Thus the mean (the first statistical moment) doesn't exist. If the mean doesn't exist, then we might expect some difficulties with an estimate of the mean like Xbar.

Central Limit Theorem

So what?

- This suggests methods for constructing *confidence limits*.
- *confidence limits, interval, or region* is said to contain the true parameter value with some stated long-run frequency, often 95%, meaning that the true value would be contained by the interval in 95% of future repeated realizations of the experiment. Bayesians have an analogous construct they call a **credibility interval.**
- The *parameters* underlying a statistical model (e.g.: Random Fatigue Limit model for HCF s-N data) are normally distributed (with caveats).
- That means that probability statements can be made about the behavior of a statistical HCF model, based on this known-to-be-Normal behavior.

Covariance ...

A measure of the *linear* relationship between two variables, computed as the average product of differences from the two means, .

$$\sigma_{x,y}^{2} = \frac{1}{n}\sum(x-\mu_x)(y-\mu_y)$$

Fisher Information Matrix

$$I(\theta) = -\begin{bmatrix} \dfrac{\partial^2 \ln L(\theta_1)}{\partial \theta_1^{\,2}} & \dfrac{\partial^2 \ln L(\theta_1)}{\partial \theta_1 \partial \theta_2} & \dfrac{\partial^2 \ln L(\theta_1)}{\partial \theta_1 \partial \theta_3} \\ \bullet & \dfrac{\partial^2 \ln L(\theta_2)}{\partial \theta_2^{\,2}} & \dfrac{\partial^2 \ln L(\theta_2)}{\partial \theta_2 \partial \theta_3} \\ symmetric & \bullet & \dfrac{\partial^2 \ln L(\theta_3)}{\partial \theta_3^{\,2}} \end{bmatrix}$$

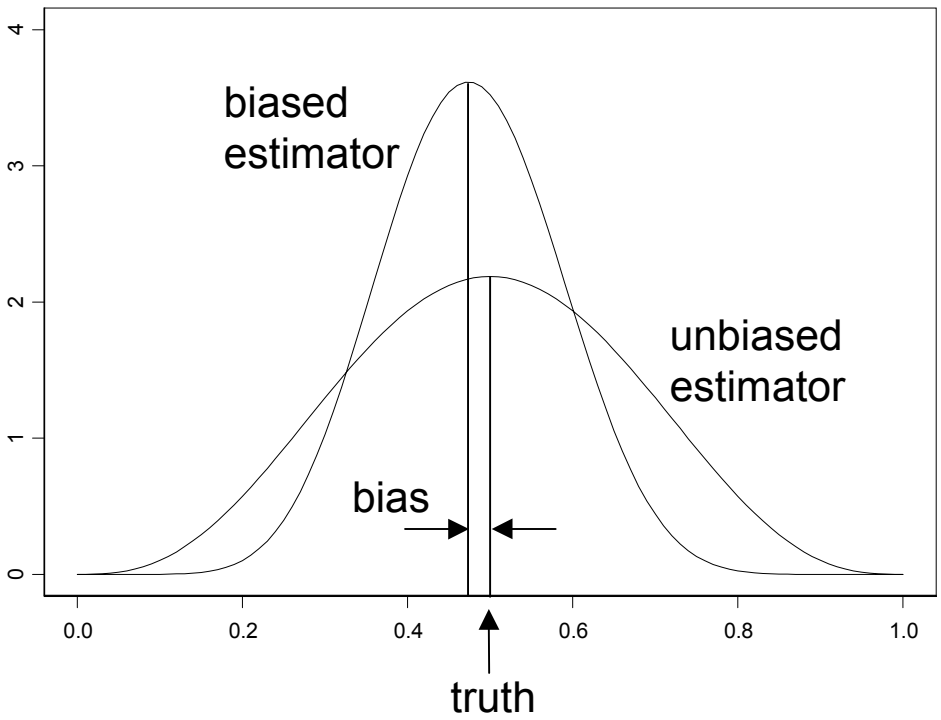
Important Result: $Cov(\boldsymbol{\theta}) = \boldsymbol{I}(\boldsymbol{\theta})^{-1}$

Fine Print: If the **regularity conditions** are satisfied and if the estimator is **unbiased**.

Bias, Precision ...

- *Bias* is the long-run difference between the average parameter estimate and the true value.
- *Precision* is the likely spread of estimates.

Quiz: Are unbiased estimators always better?



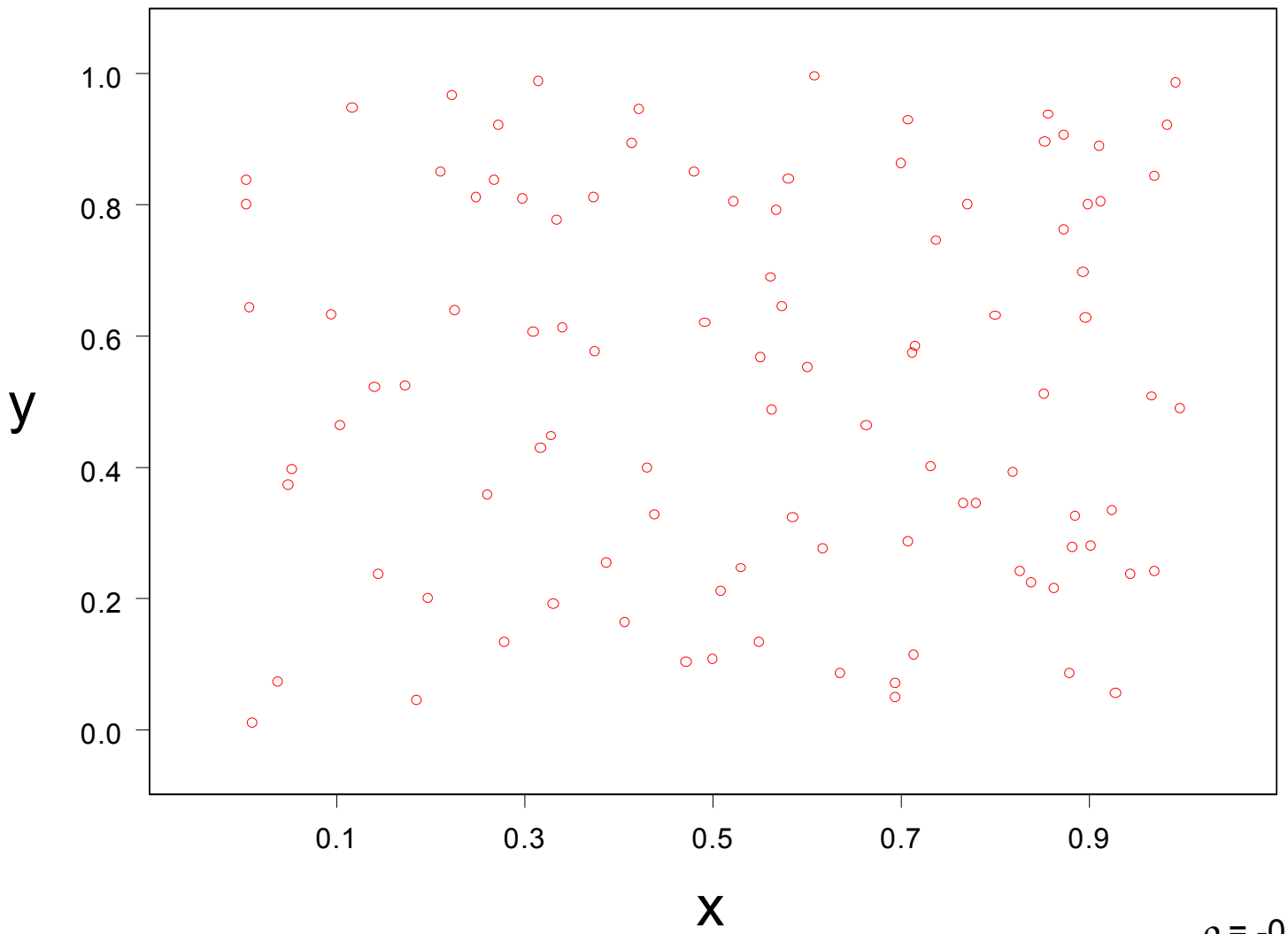
Correlation Coefficient ...

- **correlation coefficient:** The **covariance** scaled by the standard deviations so that: $0 \leq \rho \leq 1$

$$\rho = \frac{\mathrm{cov}(x, y)}{\sigma_x \sigma_y}$$

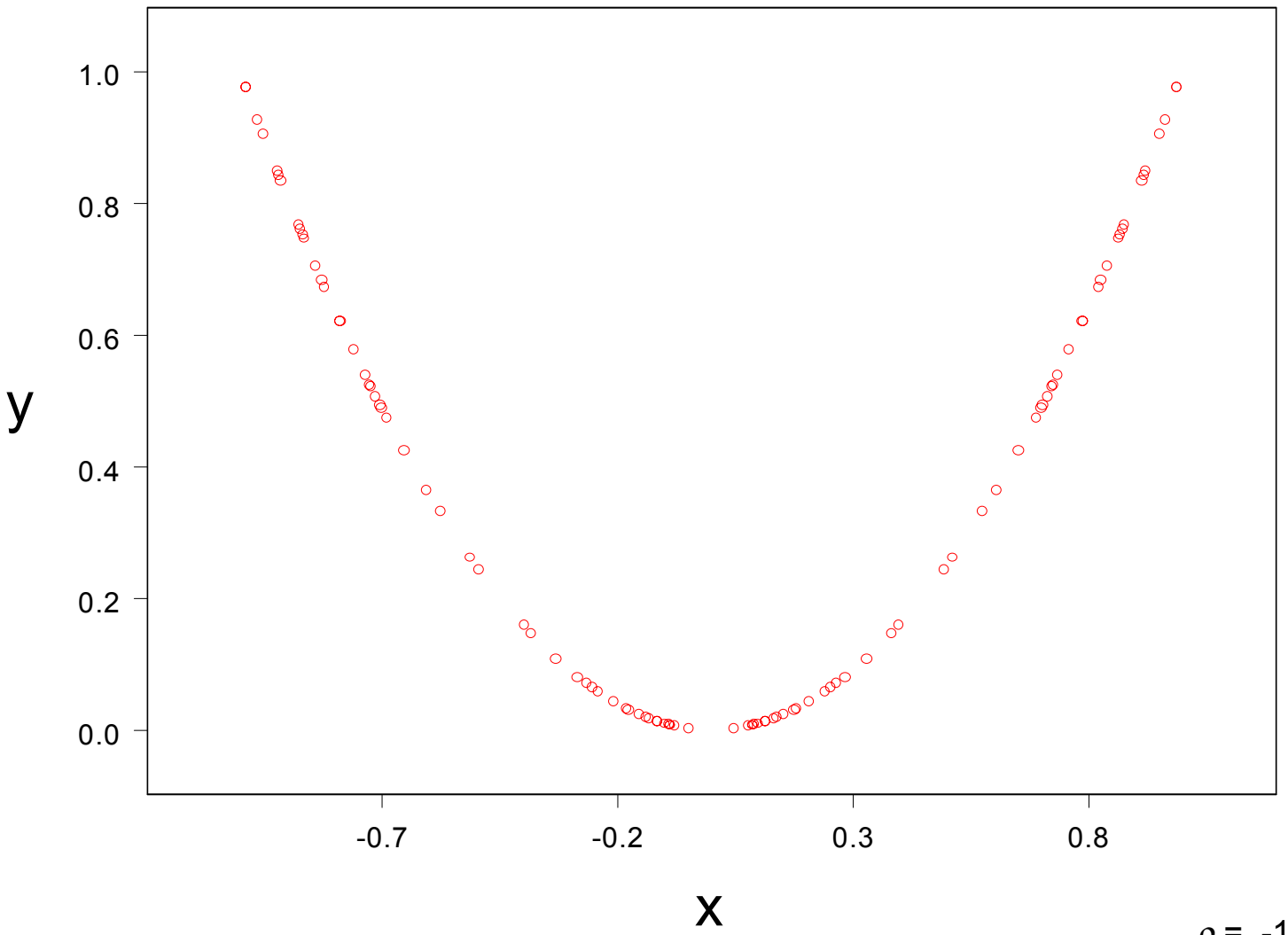
- Since correlation is a scaled covariance it only measures the *linear* relationship between two variables. If two variables are **independent**, then their correlation coefficient is zero. But a correlation of zero does *not* imply that two variables are independent.

These points have zero correlation.



ρ = -0.00278117

These points have zero correlation.



ρ = -1.144748e-017

Extreme Value Distributions

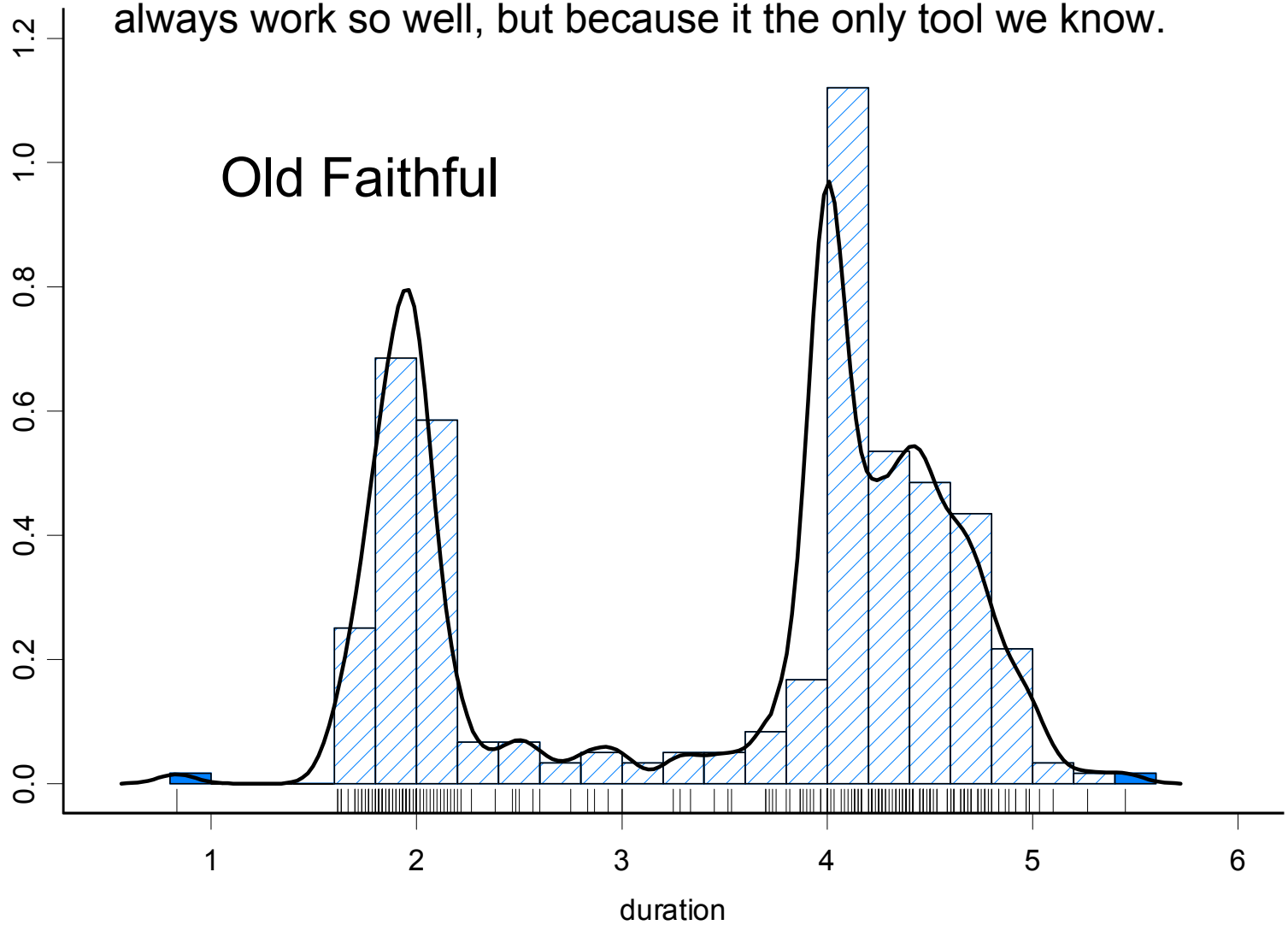
- The the extreme value (smallest or largest) of a sample taken from a normal distribution has a limiting distribution (SEV or LEV) as the sample size increases. And that this limiting form does NOT require that the parent distribution be normal.

- In other words, the distribution of the smallest (largest) value from a sample of size *n*, tends toward the same limiting distribution, *regardless* (*) of the distribution from which the samples were drawn.

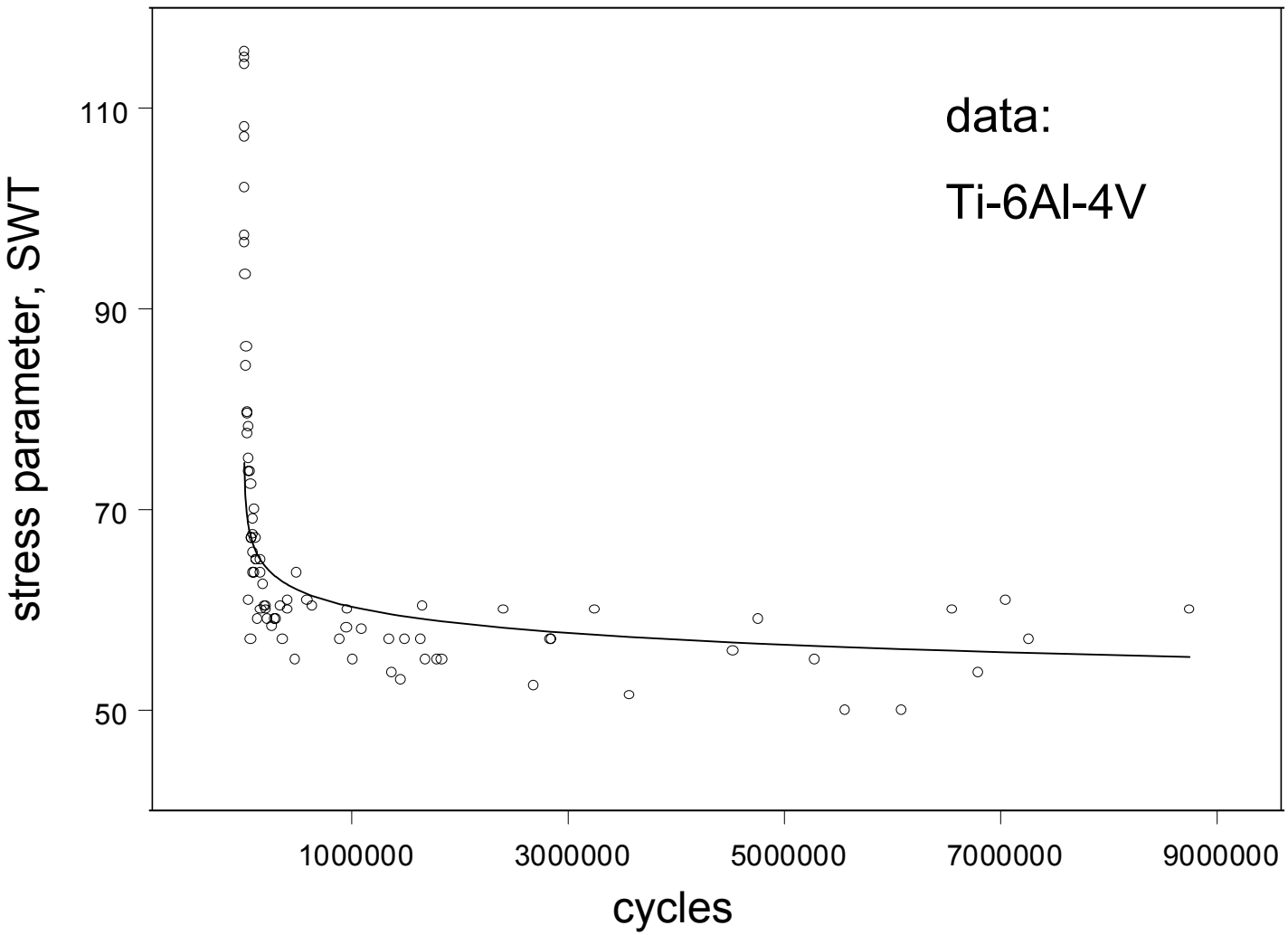
(*) Statistical fine print: The tails of the parent must be exponential.

Most real distributions are *not* standard.

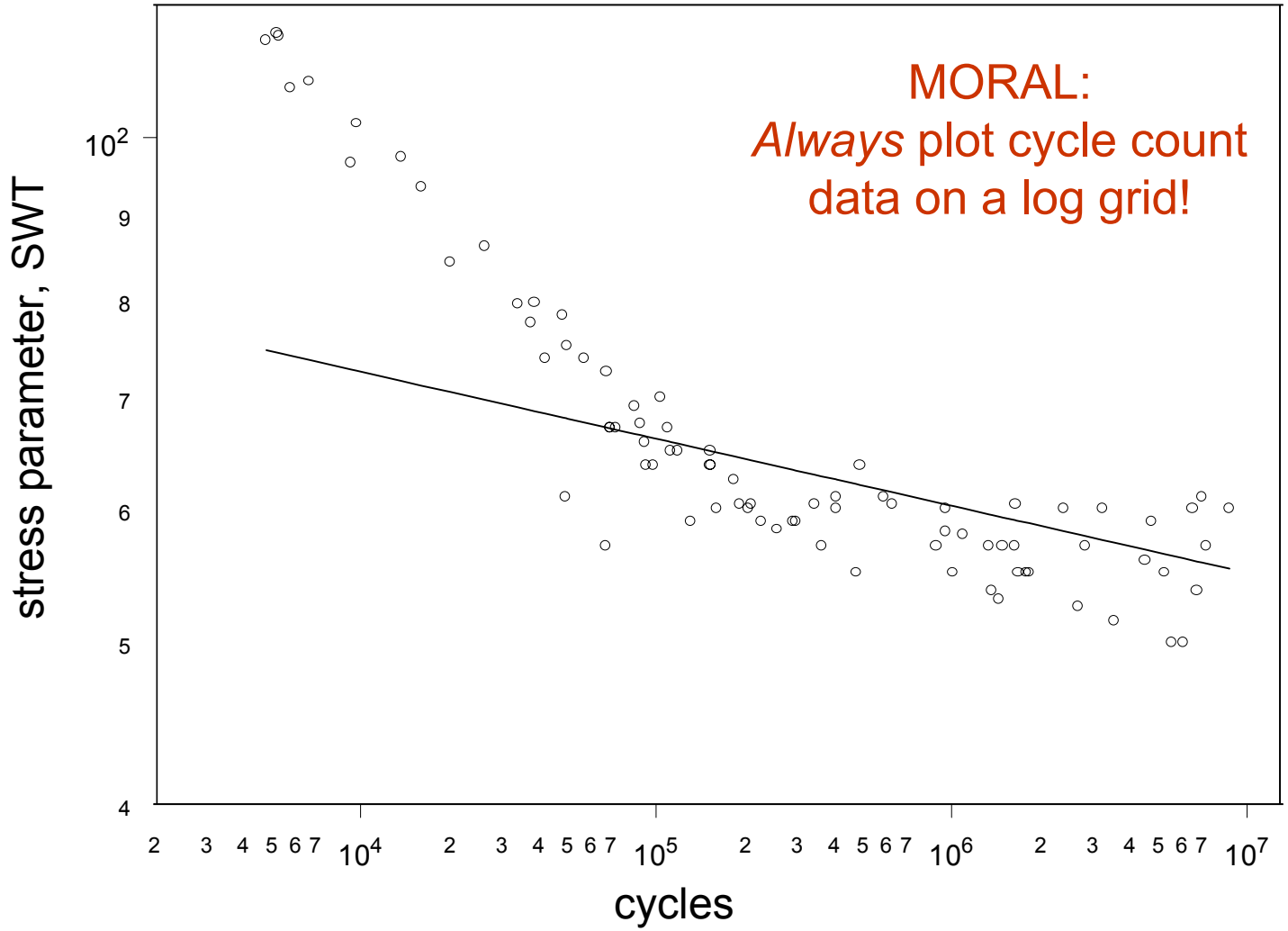
We use standard distributions to model reality, not because they always work so well, but because it the only tool we know.



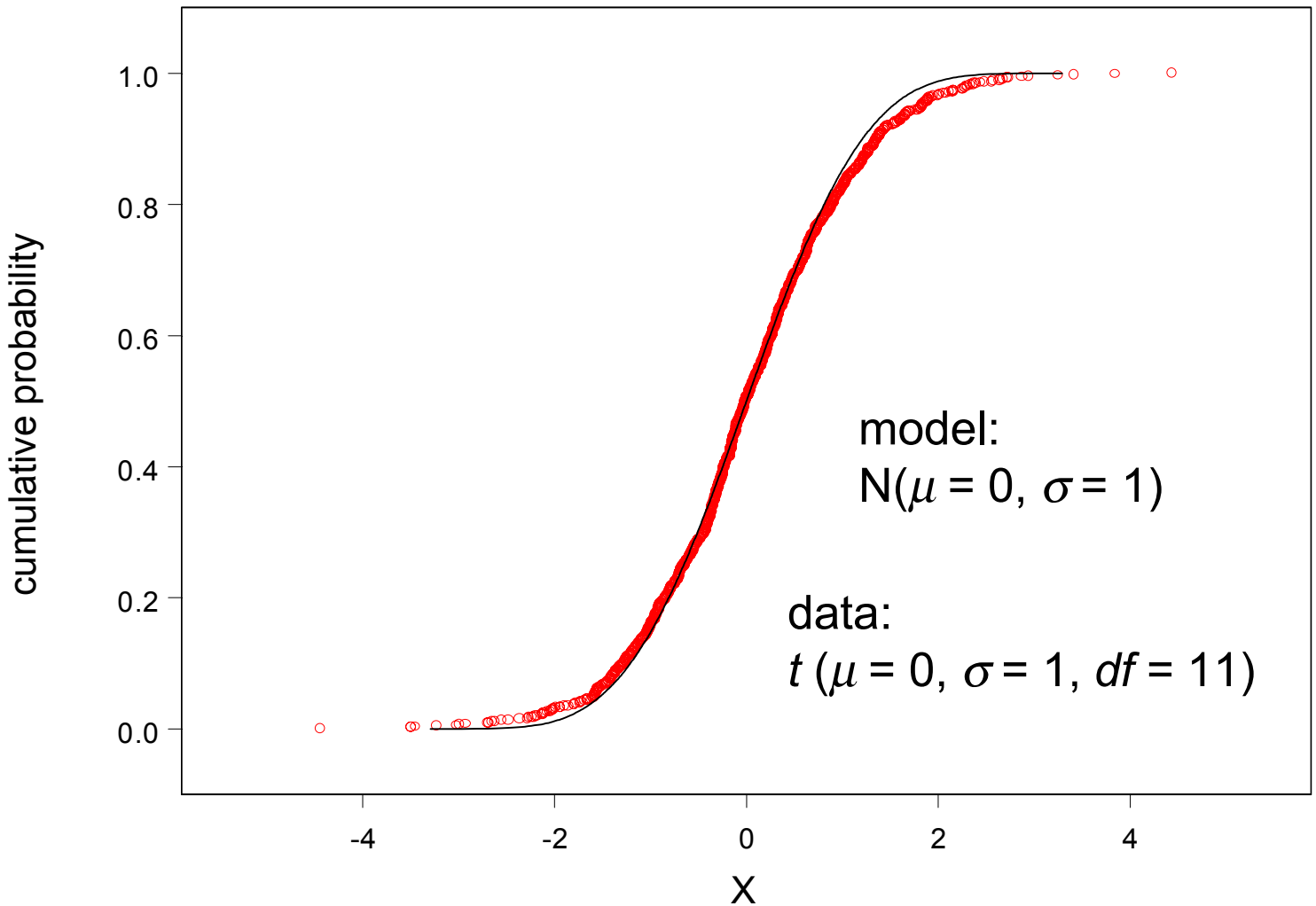
Model performance can be obscured by choice of grid.



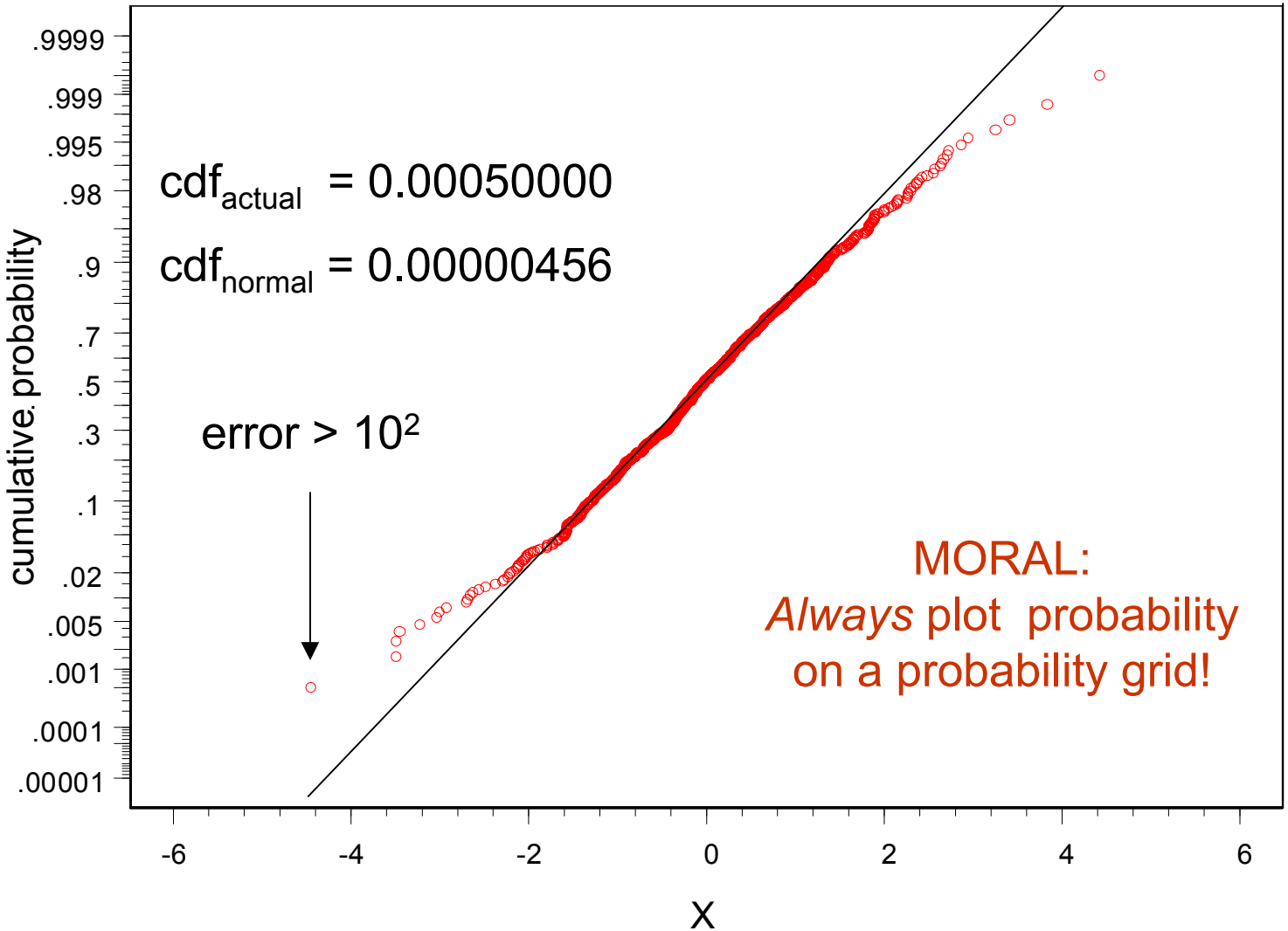
Model performance can be elucidated by choice of grid.



Probability can be obscured by choice of grid.



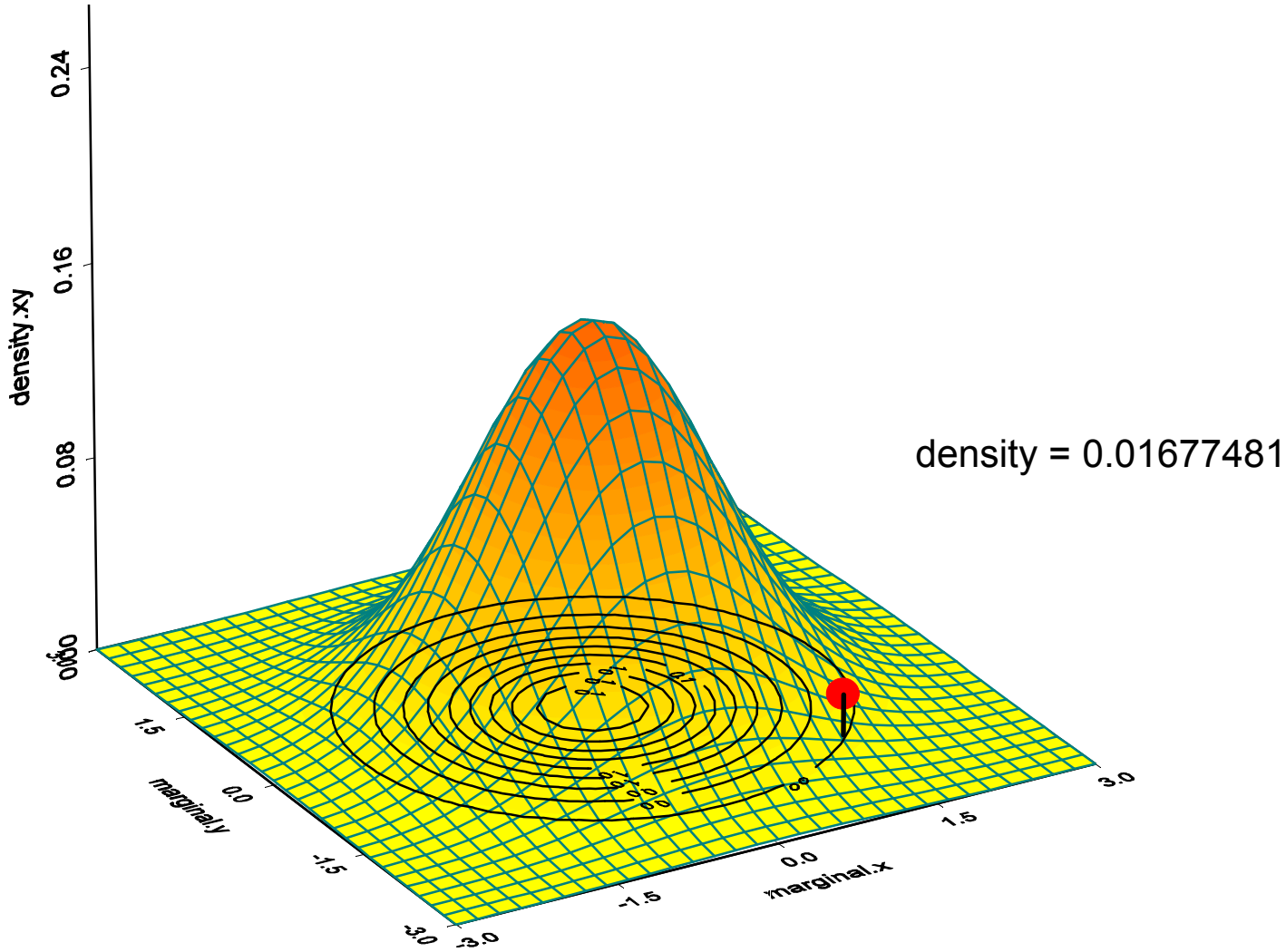
Probability can be elucidated by choice of grid.



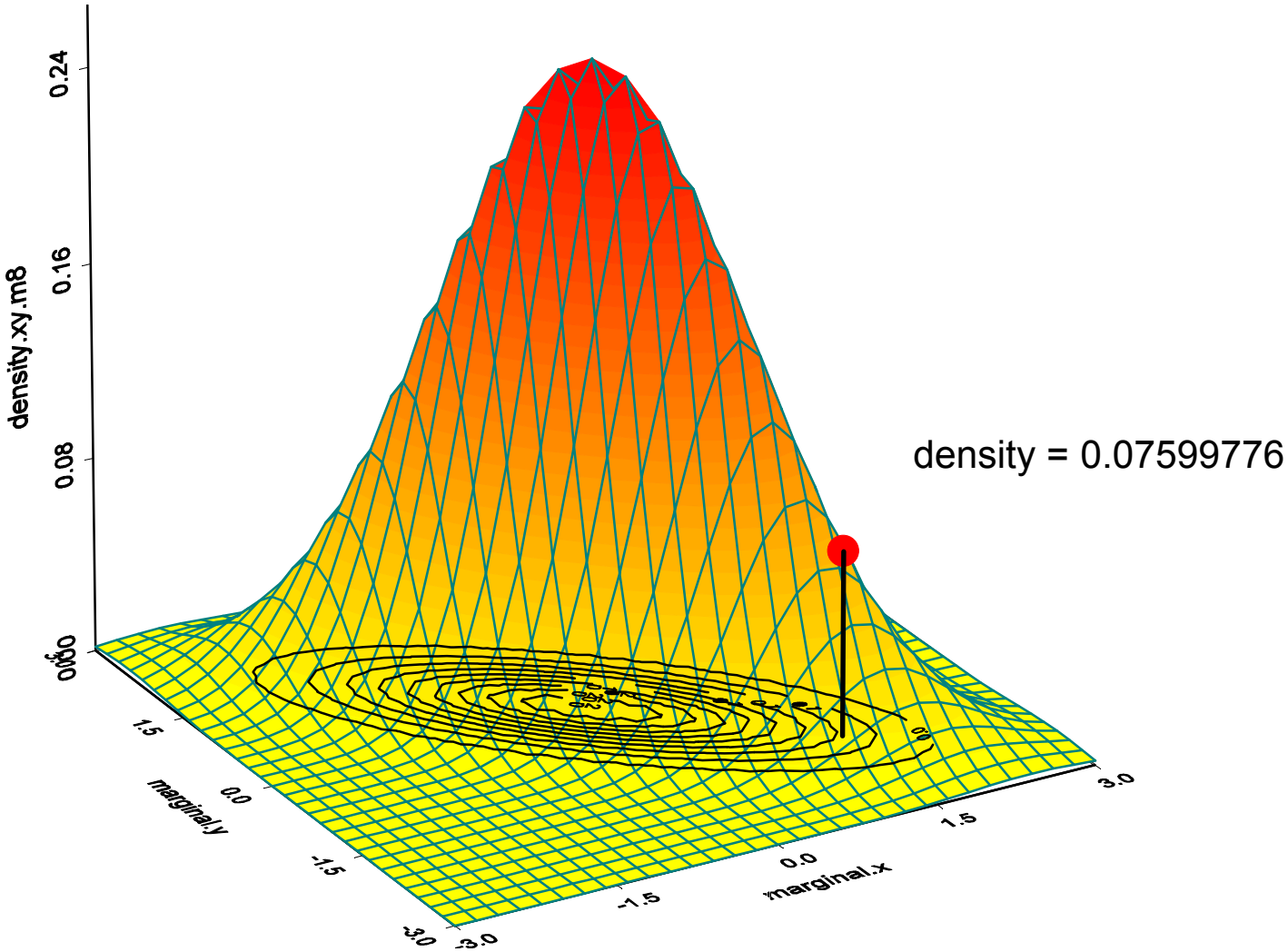
Other ways to think about probability:

- Odds = $\dfrac{p}{1-p}$
  - ... the ratio of the probability *for* an event to the probability *against*.
- Odds Ratio = $\text{odds}_1 / \text{odds}_2$
  - ... where subscripts refer to different "treatments."
  - eg: odds ratio comparing two engine maintenance scenarios.

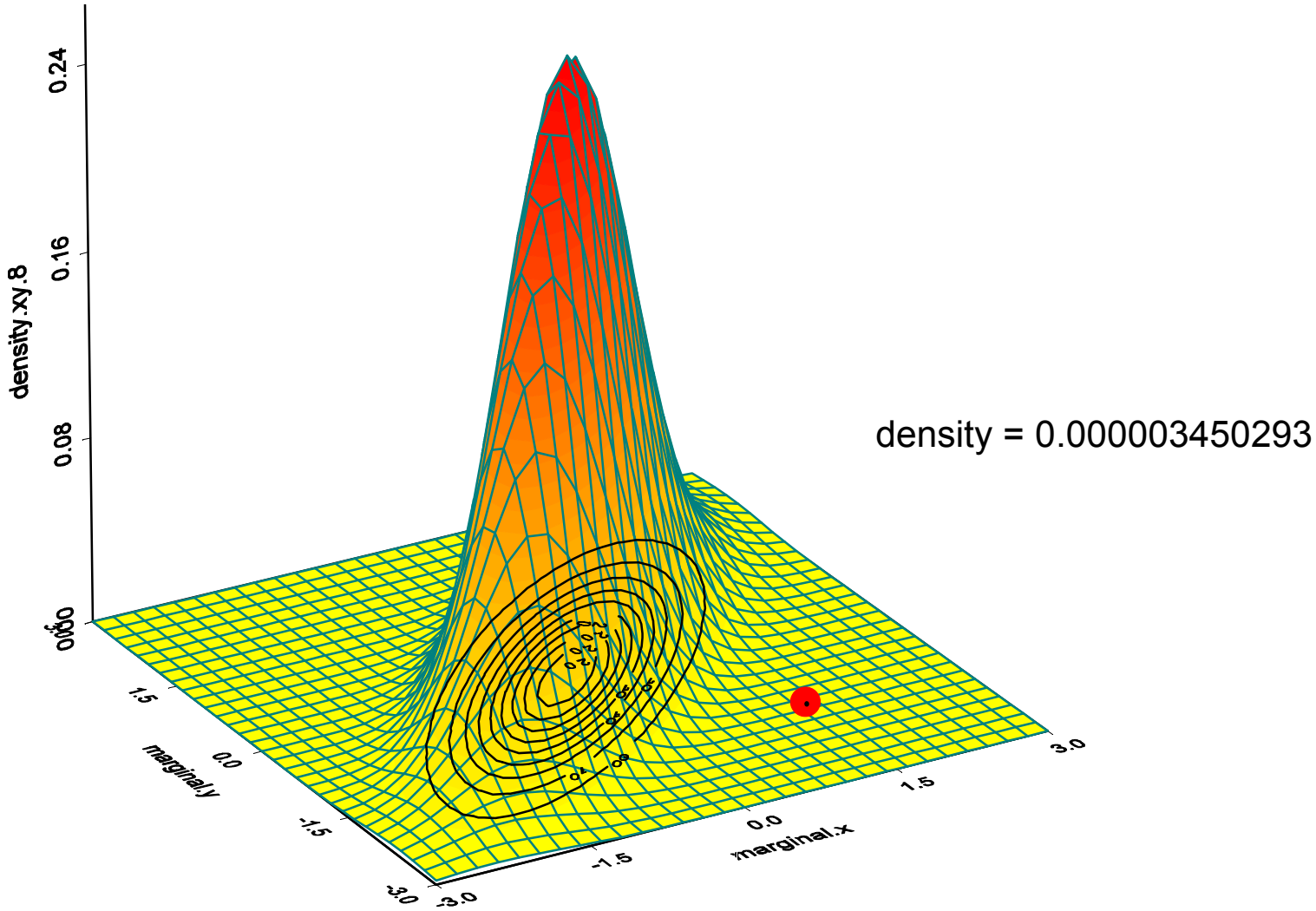
Joint, Marginal and Conditional Distributions



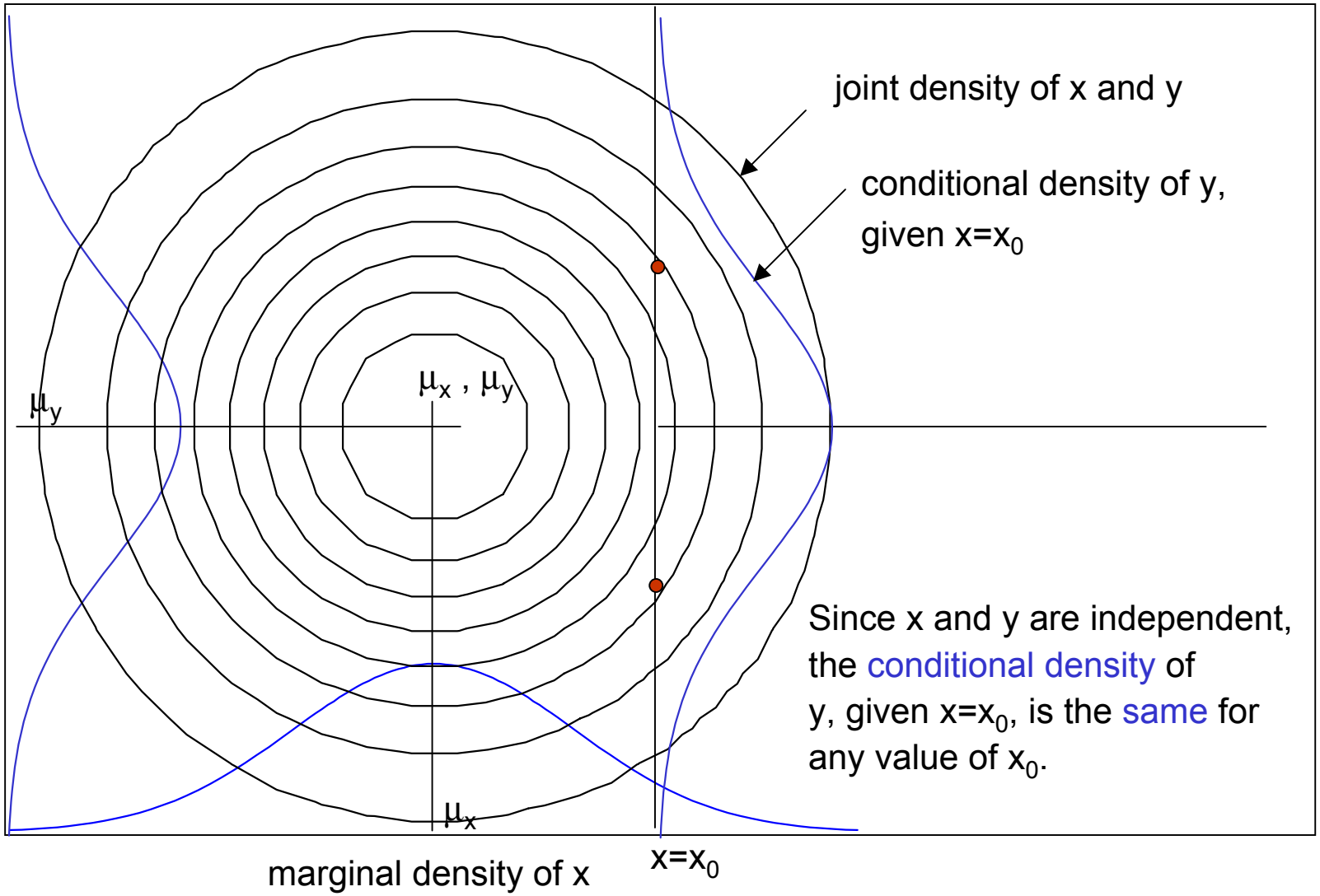
Joint, Marginal and Conditional Distributions



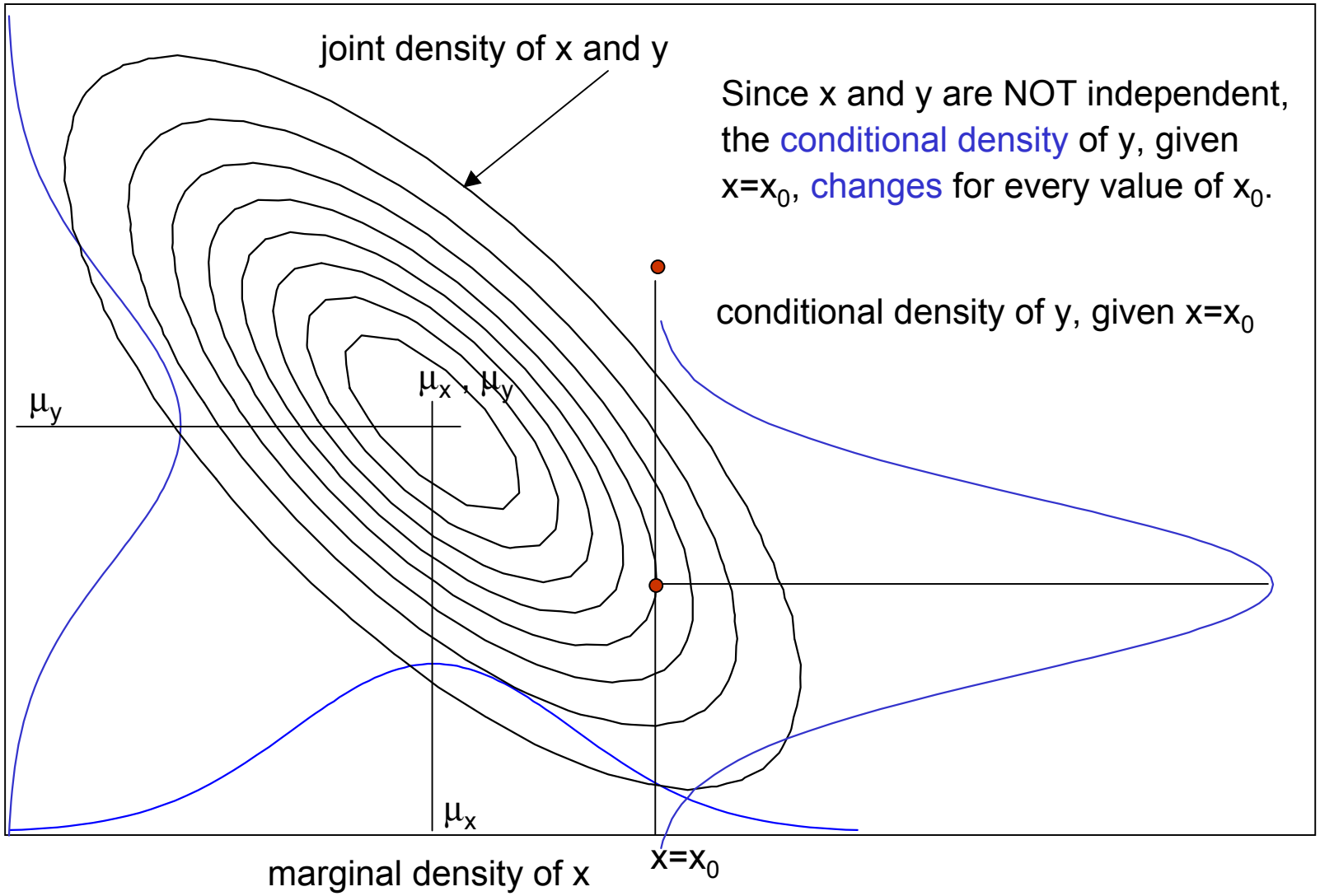
Joint, Marginal and Conditional Distributions



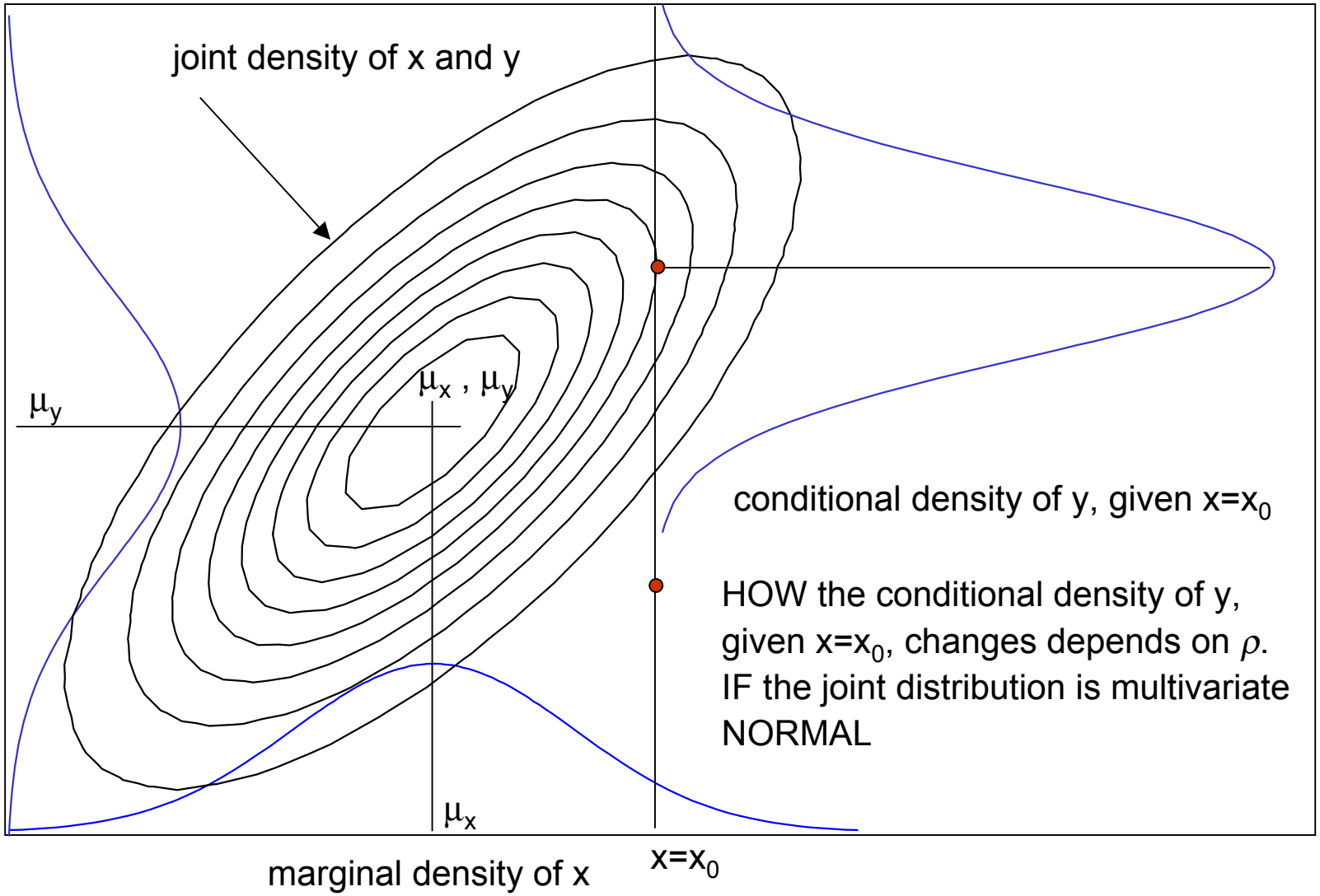
Joint, Marginal and Conditional Distributions



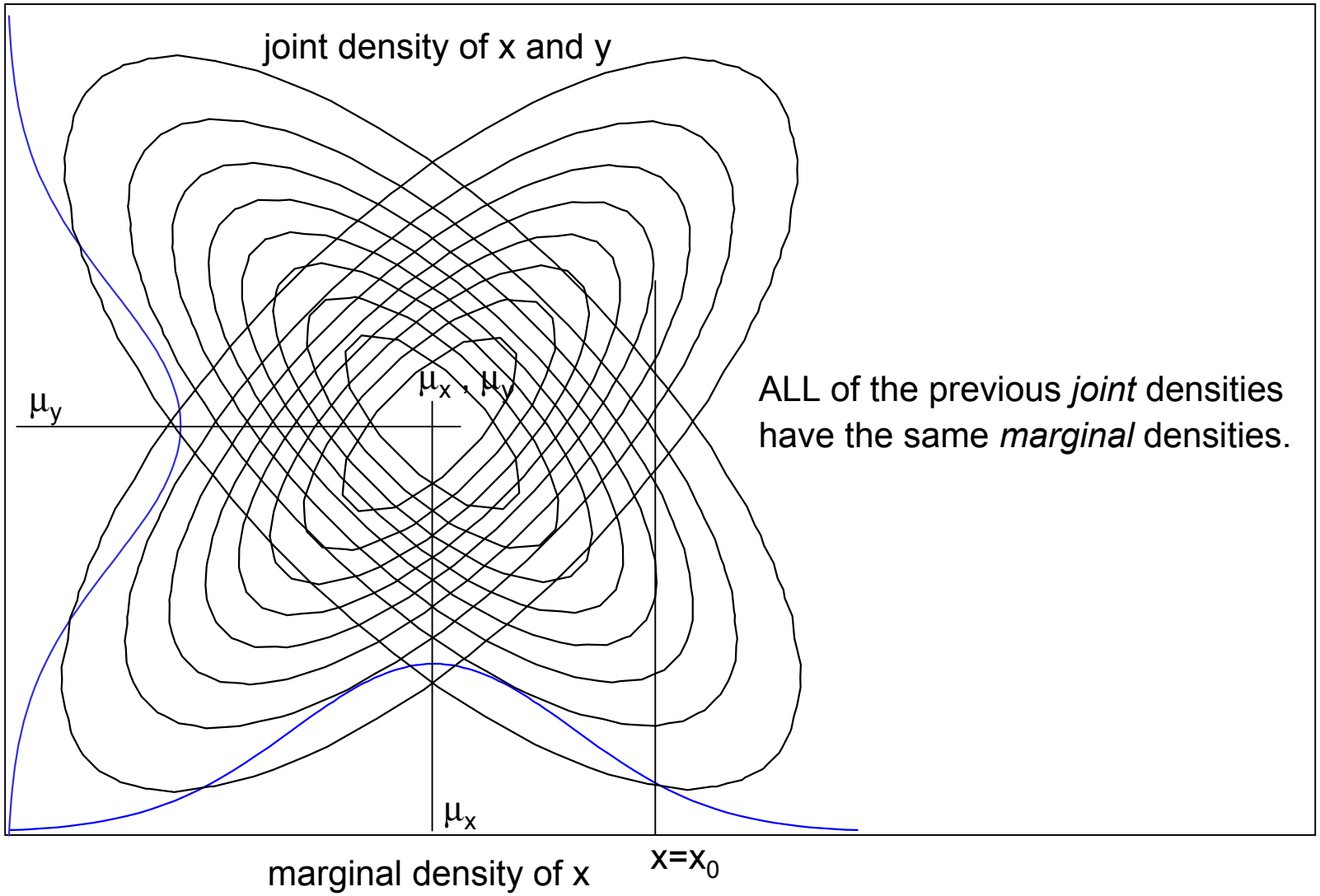
Joint, Marginal and Conditional Distributions



Joint, Marginal and Conditional Distributions

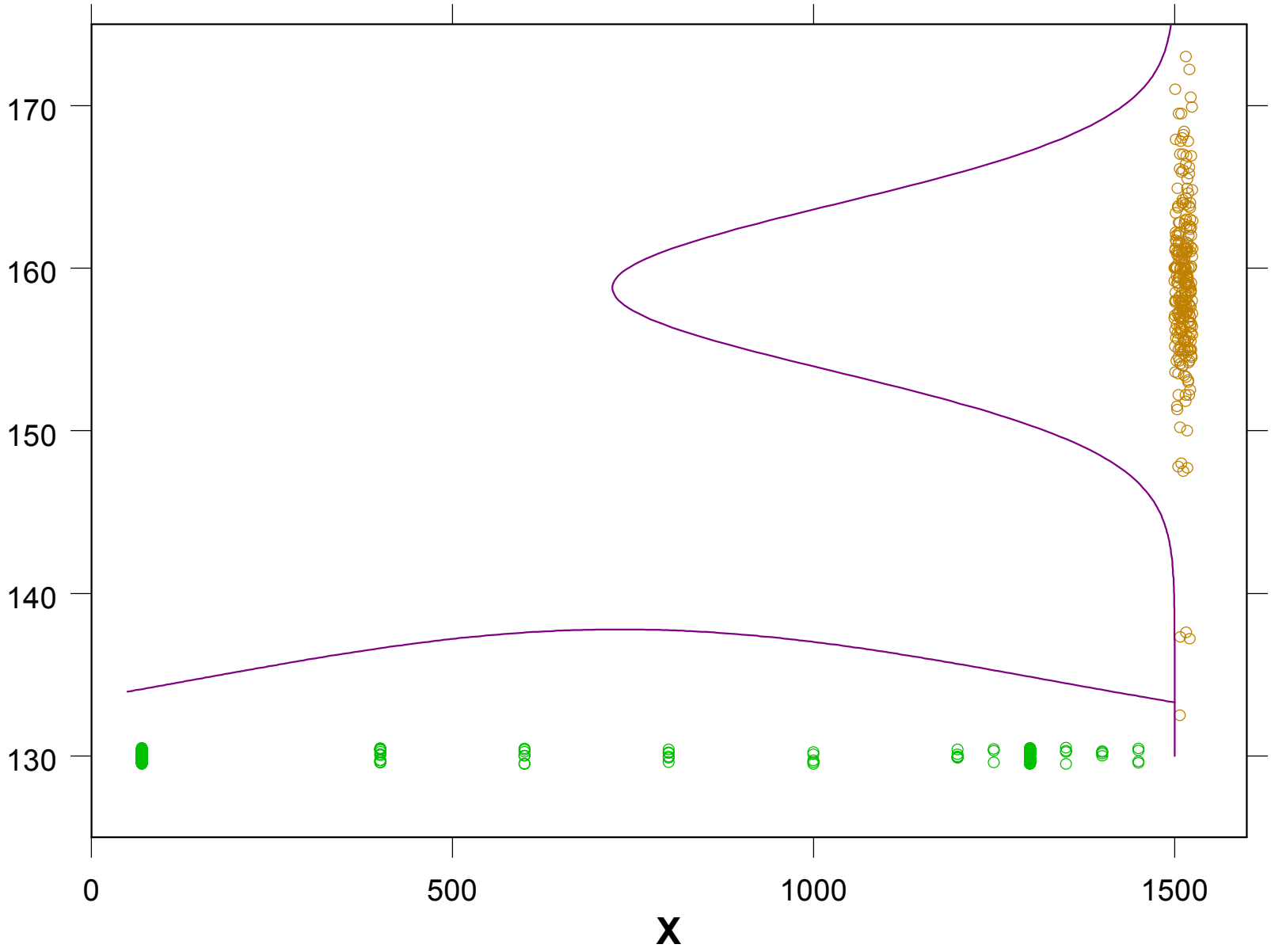


Joint, Marginal and Conditional Distributions

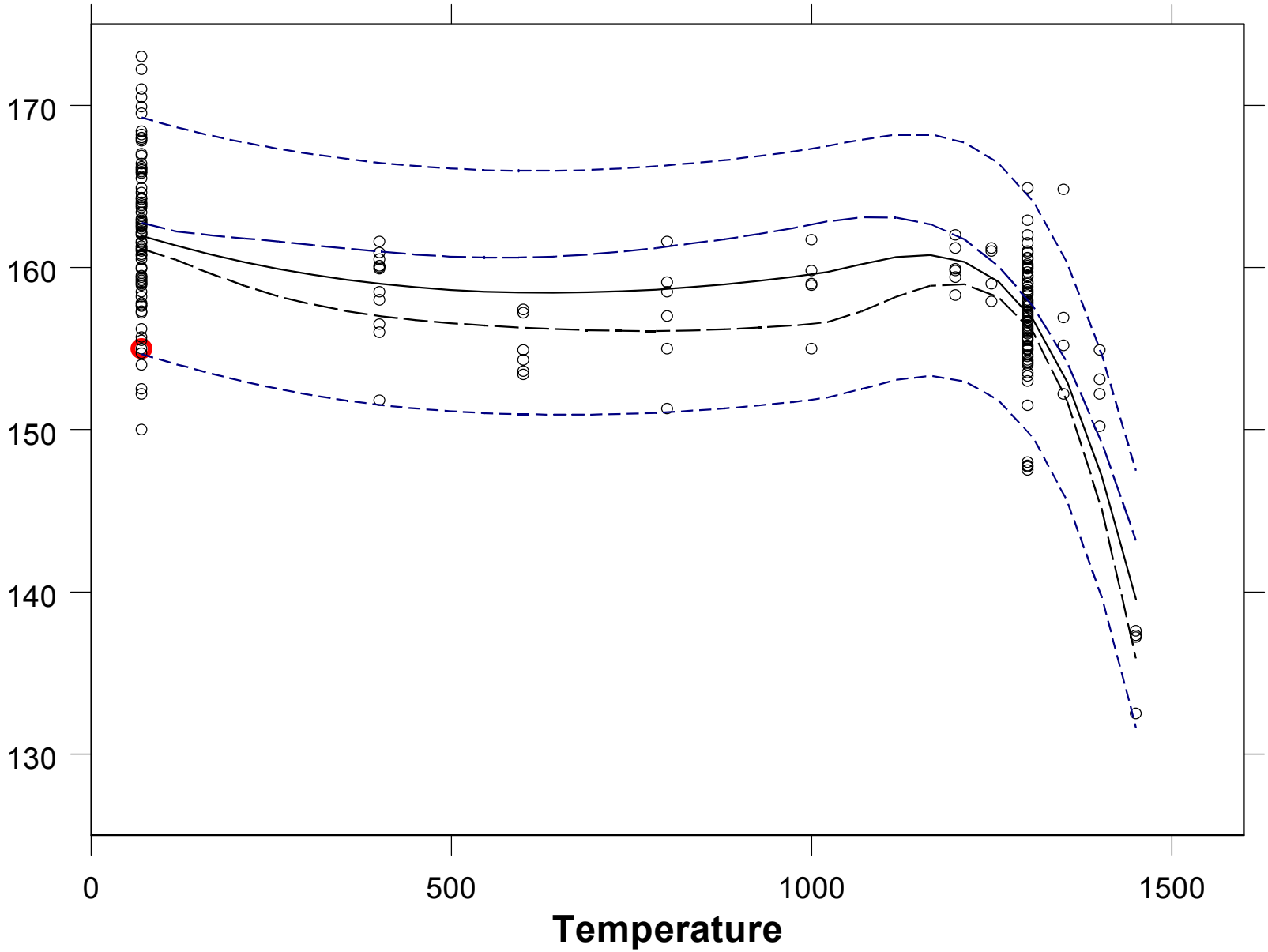


ALL of the previous *joint* densities have the same *marginal* densities.

Marginal Distributions are Misleading.



Conditional Distribution of Yield | Temperature



Important Math Stat Results:

... for Joint, Marginal and Conditional Distributions

- For a given *joint* density, you can specify the *marginal* densities. BUT, given the marginal densities only, you *cannot* uniquely specify their joint density.

- Assuming ρ is zero doesn't make it zero.

Bayes's Theorem:

... is based on the joint probability of two events

Think of *event A* as data, and *event B* as the model parameters. Then **AB** is the probability of both the data and the model.

$$P(A|B) \times P(B) = P(\mathbf{AB}) = P(B|A) \times P(A)$$

Simple algebra shows that: $P(B|A) = P(A|B) \times P(B)/P(A)$.

(This example is only for single-valued probabilities; probability *densities* are more complicated, but follow from this definition.)

Bayes's Theorem for Probability Densities

x is the data, and θ is the model parameters:

$$P(\theta \mid x) = \frac{P(x \mid \theta) P(\theta)}{P(x)}$$

where

$$P(x) = \int P(x \mid \theta) P(\theta)\, d\theta$$

$\boldsymbol{P(\theta)}$ is the *prior* distribution of θ, and is what is known about θ *before* the data are collected. $\boldsymbol{P(\theta \mid x)}$ is the *posterior* distribution of θ, and is what is known later, given the knowledge of the data.

Bayes's Theorem for Multiple Variables ...

... can Statistically Combine both Analytical and Experimental Knowledge.

experimental knowledge

combined knowledge

analytical knowledge

$$P(\theta \mid x) = \frac{P(x \mid \theta) P(\theta)}{P(x)}$$

where

all <u>feasible</u> outcomes

$$P(x) = \int \ldots \int P(x \mid \theta) P(\theta) \, d\theta$$

x is the data, and θ is the model parameters:

What if your ε-gage disagrees with your FEA?

You have an analytically predicted stress of 50 ksi and a strain gage measurement that's different, which should you believe?

How would you resolve the difference?

The common practice of adding the difference to the analytical result as a "correction" is dangerous. Do you know why?

What if your ε -gage disagrees with your FEA?

Disclaimer: Simplified hypothetical problem for exposition only.

- Given: ε predicted = 50 ksi; ε measured = 55 ksi
- Required: What is the best estimate of the true stress?

Solution:

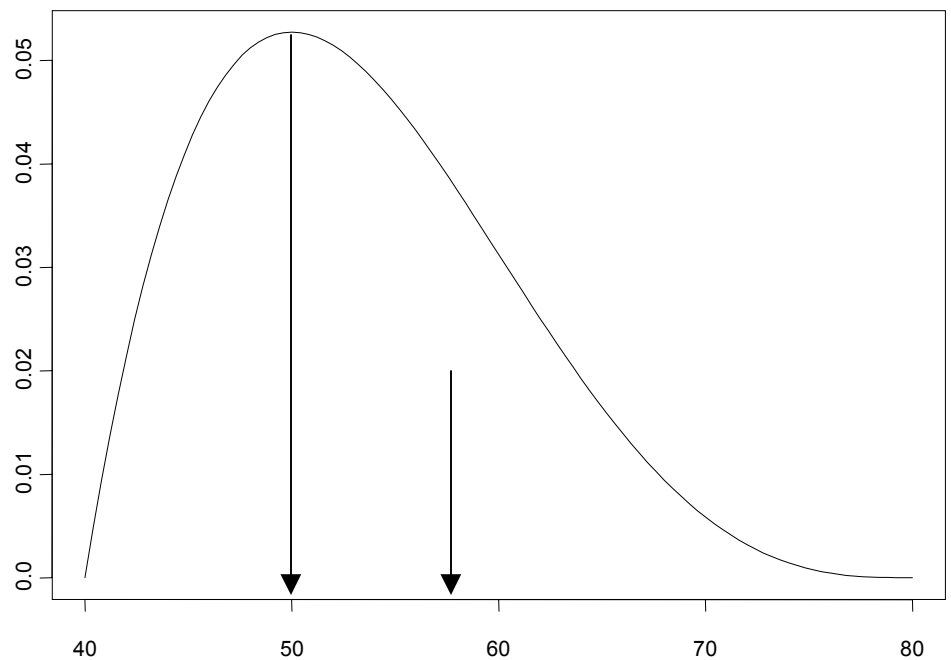
- Use Bayesian Updating.

Let x be the ε -gage measurement, and let θ be the *prior distribution* of ε, centered at the FEA value.

$$P(\theta \mid x) = \frac{P(x \mid \theta) P(\theta)}{P(x)}$$

where

$$P(x) = \int P(x \mid \theta) P(\theta)\, d\theta$$



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Solution:

- Use Bayesian Updating.

Let x be the ε -gage measurement, and let θ be the *prior distribution* of ε, centered at the FEA value.

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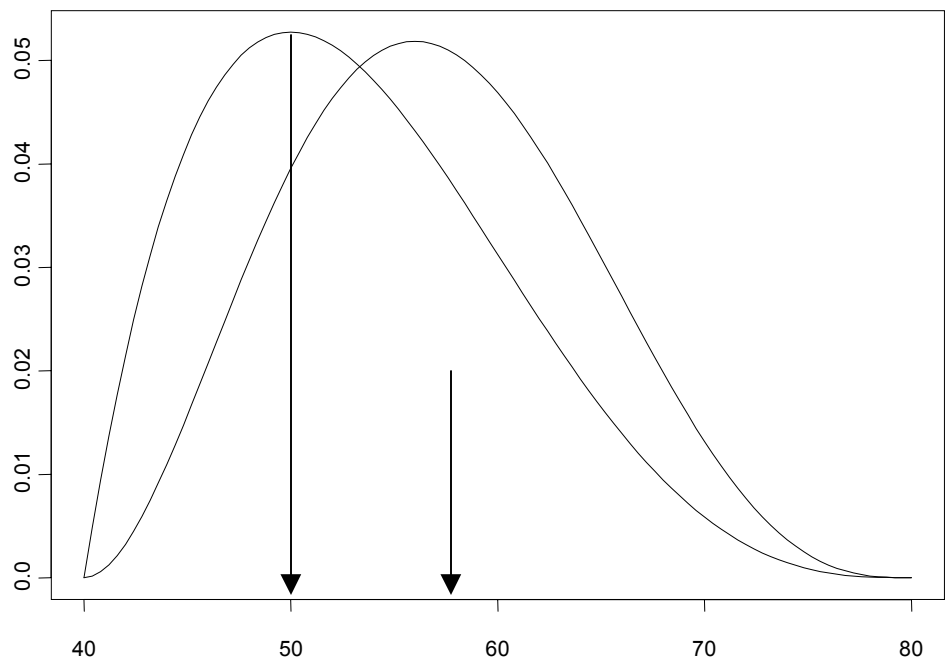
$$P(x) = \int P(x \mid \theta) P(\theta)\, d\theta$$



Summary and Review:

- Distributional interrelationships
- DOX
- Probability
- Statistics
- Joint, Marginal and Conditional Distributions
- Likelihood
- Fisher Information Matrix
- Central Limit Theorem
- Extreme Value Distributions
- Bayesian Philosophy

The Disparity Between Mechanistic and Empirical Modeling of Variability in Materials Damage Processes

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Analyses of the variability in material properties and damage processes are increasingly being used for reliability and durability assessments in the life-cycle design and management of engineered aircraft systems, *e.g.*, gas turbine engines. It is widely recognized that the traditional statistical and empirical methods are inadequate. These are appropriate for interpolations of existing data, but their usefulness for extrapolations outside that data is limited and questionable. Effective predictors, *i.e.*, those that provide precise estimates beyond the range of conditions employed in the development of supporting data and assessments of risk, must be based upon mechanistic models that capture the functional dependence of all the key internal and external variables. To reflect typical engineering applications, this type of modeling requires multidisciplinary and integrated research that considers the underlying processes that control damage evolution in materials and quantifies the stochastic aspects of these processes. This paper provides an exposition and critical comparison between a mechanistically based probability modeling methodology and a statistically based approach. The crucial differences between the two approaches are highlighted and demonstrated through modeling of the creep crack growth response of a high-strength steel. The impact of these differences on structural reliability and durability analyses for life-cycle design and management is discussed.

Research supported by the Air Force Office of Scientific Research under Grant F49620-98-1-0198 and the Division of Materials Research of NSF under Grant No. DMR-9632994.

The Disparity Between Mechanistic and Empirical Modeling of Variability in Materials Damage Processes

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Abstract: Analyses of the variability in material properties and damage processes are increasingly being used for reliability and durability assessments in the life-cycle design and management of engineered aircraft systems, *e.g.*, gas turbine engines. It is widely recognized that the traditional statistical and empirical methods are inadequate. These are appropriate for interpolations of existing data, but their usefulness for extrapolations outside that data is limited and questionable. Effective predictors, *i.e.*, those that provide precise estimates beyond the range of conditions employed in the development of supporting data and assessments of risk, must be based upon mechanistic models that capture the functional dependence of all the key internal and external variables. To reflect typical engineering applications, this type of modeling requires multidisciplinary and integrated research that considers the underlying processes that control damage evolution in materials and quantifies the stochastic aspects of these processes. This paper provides an exposition and critical comparison between a mechanistically based probability modeling methodology and a statistically based approach. The crucial differences between the two approaches are highlighted and demonstrated through modeling of the creep crack growth response of a high-strength steel. The impact of these differences on structural reliability and durability analyses for life-cycle design and management is discussed.

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References:

D.G. Harlow and R.P. Wei, Materials Aging and Structural Reliability, *International Journal of Materials and Product Technology* **16** (2001) 304-316.

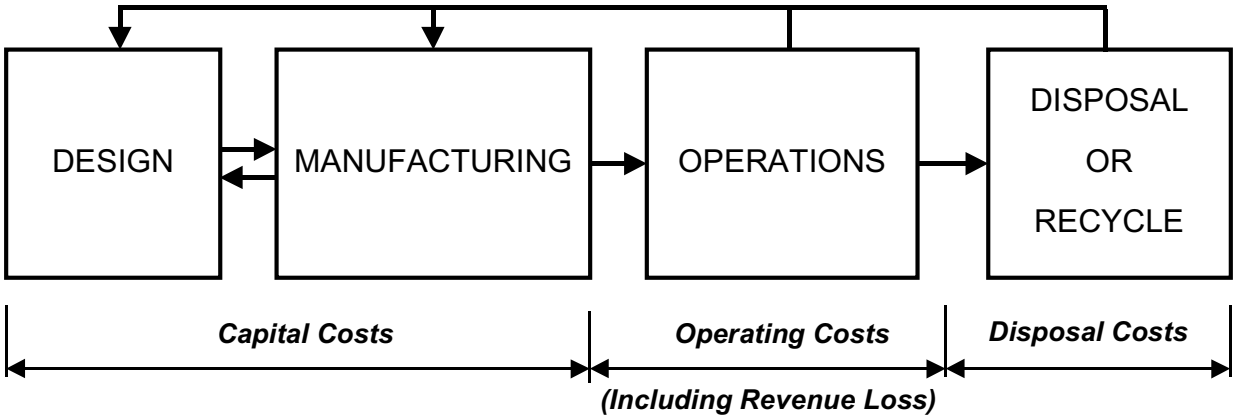
D.G. Harlow and R.P. Wei, Life Prediction – The Need for a Mechanistically Based Probability Approach, *Key Engineering Material: Probabilistic Methods in Fatigue and Fracture*, **200** (2001) 119-138.

Objectives

- Need for predictive (versus postdictive) model for structural reliability analysis in life-cycle design and management
- Use mechanistically based probability modeling for materials aging and structural reliability
- Contrast the differences between mechanistically based probability modeling and empirically based statistical modeling
- Challenge this community to lead in the application and further development of mechanistically based probability modeling

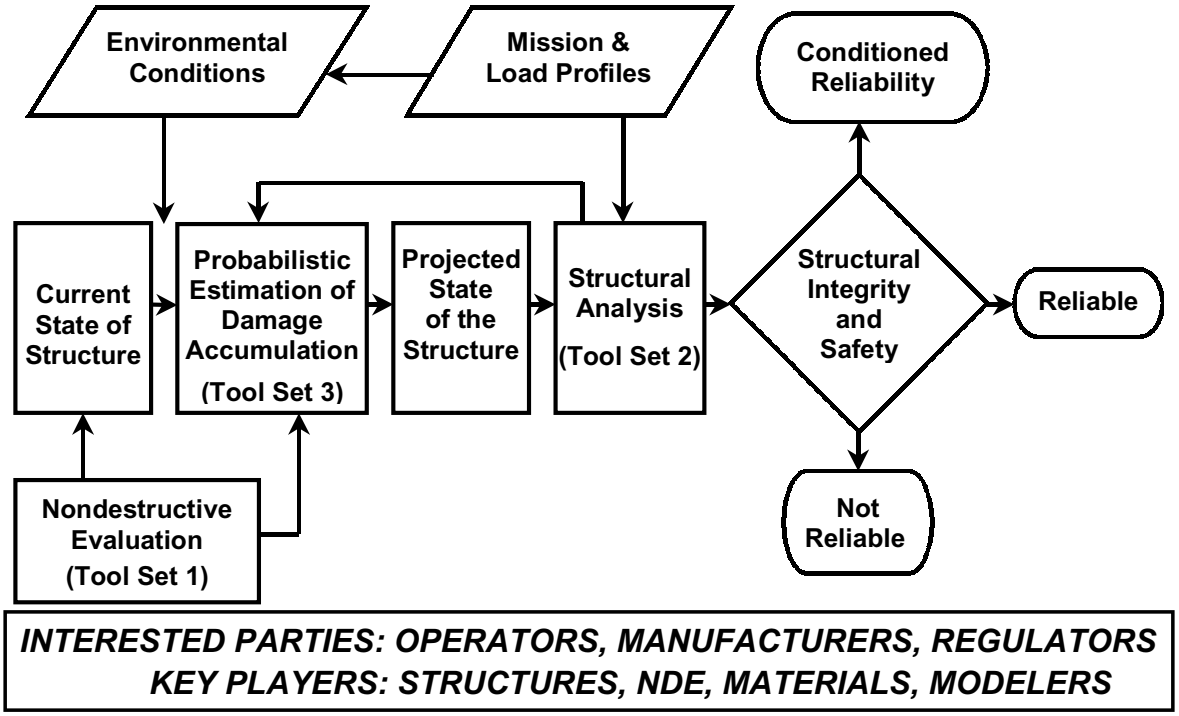
Life-Cycle Design & Management

FRAMEWORK



- Optimization of life-cycle cost (cost of ownership)
- Integrity, safety, durability, reliability, etc.
- Enterprise planning
- Societal issues (e.g., environmental impact)

Life-Cycle Design & Management



Mechanistic versus Empirical Modeling

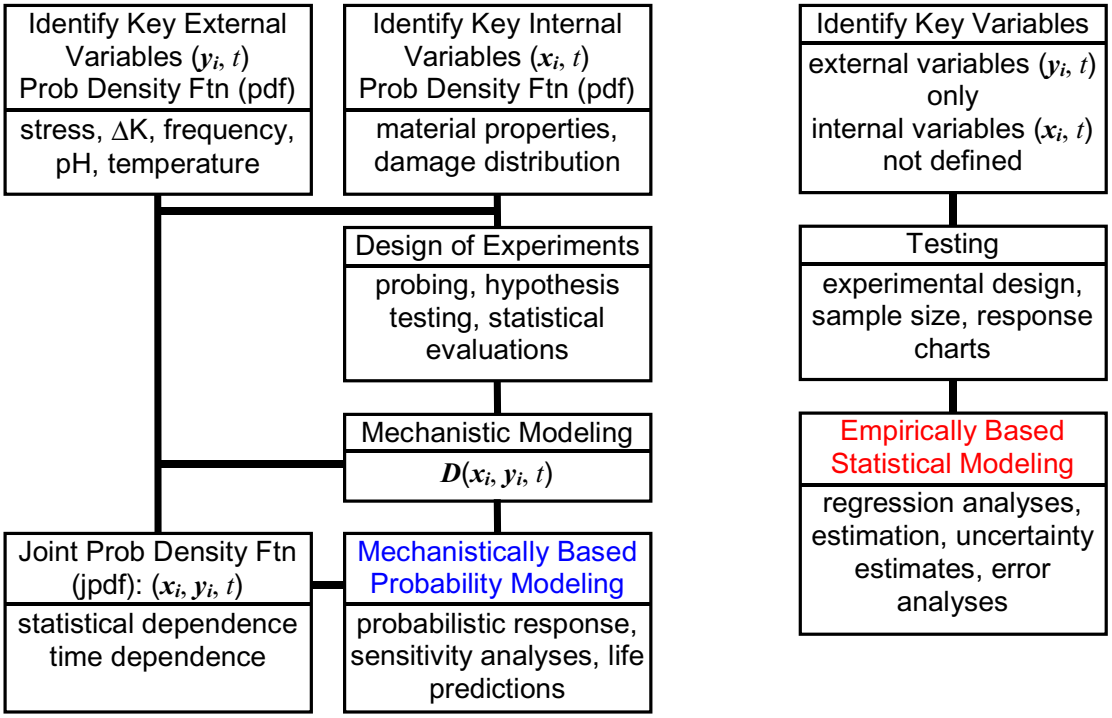
Mechanistically Based Probability Modeling

- Functions of key ***external*** and ***internal*** variables
- Extrapolation beyond the range of typical data
- Predictions outside of experience base
- Design under (prescribable) risk

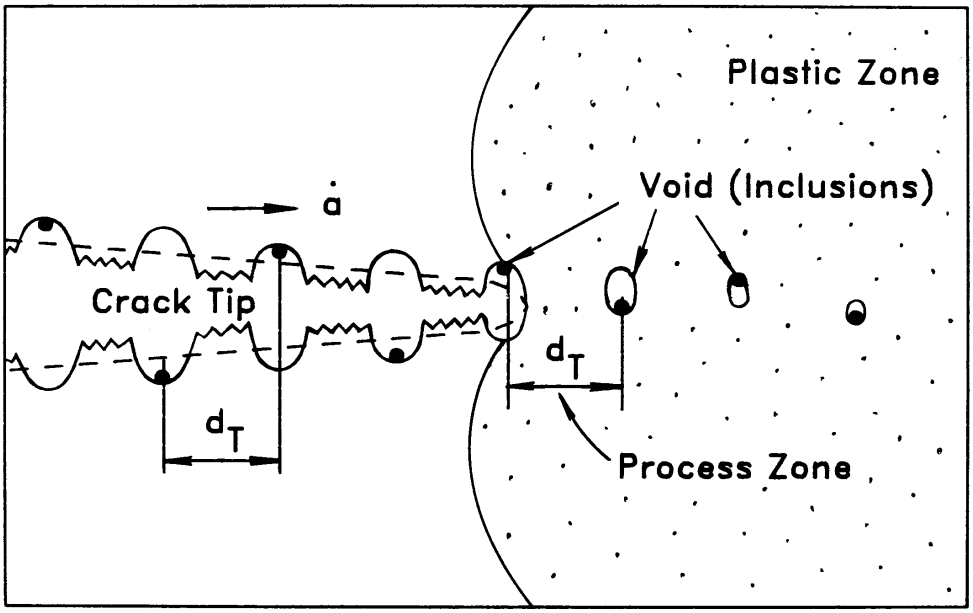
Empirically Base Statistical Modeling

- Data regression; reflects ***only external*** variables
- Interpolation within the range of available data
- Dangerous to “predict” outside of experience base
- Design under uncertainty (risk not quantifiable)
- Tends to be overly conservative and costly

Comparison of Approaches



Mechanistic versus Empirical Modeling



Tensile ligament instability model for creep crack growth

Mechanistic versus Empirical Modeling

Mechanistically Based Probability Creep Crack Growth: Tensile Ligament Instability Model

$$\dot{a}_s = \frac{(N+1)d_T \dot{A}^*}{[1-(K/K_c)^{2N/(N+1)}]}[(\sigma-\sigma^*)/G]^M$$

$\dot{a}_s$ – steady state creep crack growth rate
$N = 1/n$; n – strain hardening exponent
d_T – process zone size (*random variable*)
K – applied stress intensity; K_c – fracture toughness
$\dot{A}^*$ – creep rate coefficient (*random variable*)
σ – ligament stress; – hardness (*random variable*)
G – shear modulus; M – creep rate exponent

Mechanistic versus Empirical Modeling

$$d_T = \left(\frac{K_c}{\sigma_{ys}\sqrt{\pi}}\right)^2 (0.75N\varepsilon_{ys})^{(N+1)/N}$$

$$\sigma_{ys} = E\varepsilon_{ys}$$

σ_{ys} - yield stress; ε_{ys} - yield stress; E - elastic modulus

$$\sigma = 1.2\sigma_{ys}\left(\frac{K}{\sigma_{ys}\sqrt{\pi}}\right)^{2/(N+1)} d_T^{-1/(N+1)}$$

Three-Parameter Weibull cdf

$$F(t) = 1 - \exp\left\{ -\left[\frac{(t-\gamma)}{\beta} \right]^{\alpha} \right\}, \quad t \geq \gamma$$

α = shape parameter
γ = location parameter
β = scale parameter

rv	α	β	γ	μ	cv
d_T (μm)	15	8.28	56	64	8.2%
σ^* (MPa)	20	67	1560	1625	6.2%
$\dot{A}^*$ (1/s)	12	3.34e10	1.0e9	3.30e10	10.1%
a_o (mm)	1	0.2	1.3	1.5	100%

Deterministic Variables

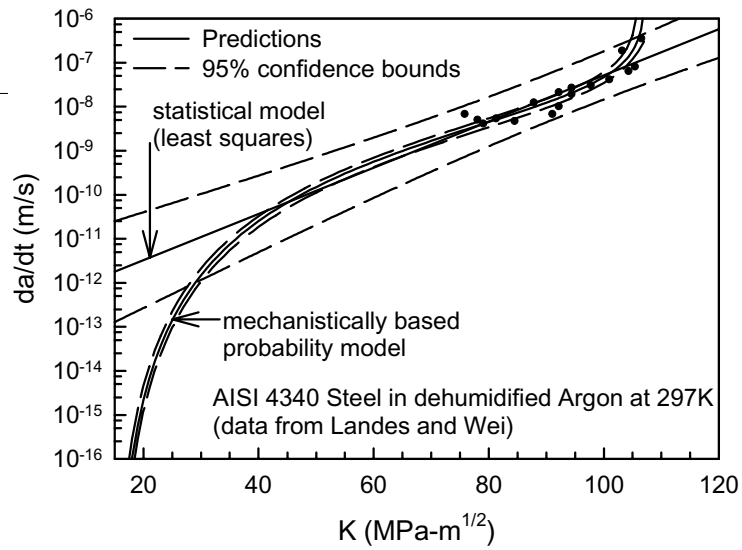
variable	
G	80 GPa
E	207 GPa
σ_{ys}	1447.5 MPa
N	9.55
M	7.63
σ_e	650 MPa
T	297 K

Mechanistic versus Empirical Modeling

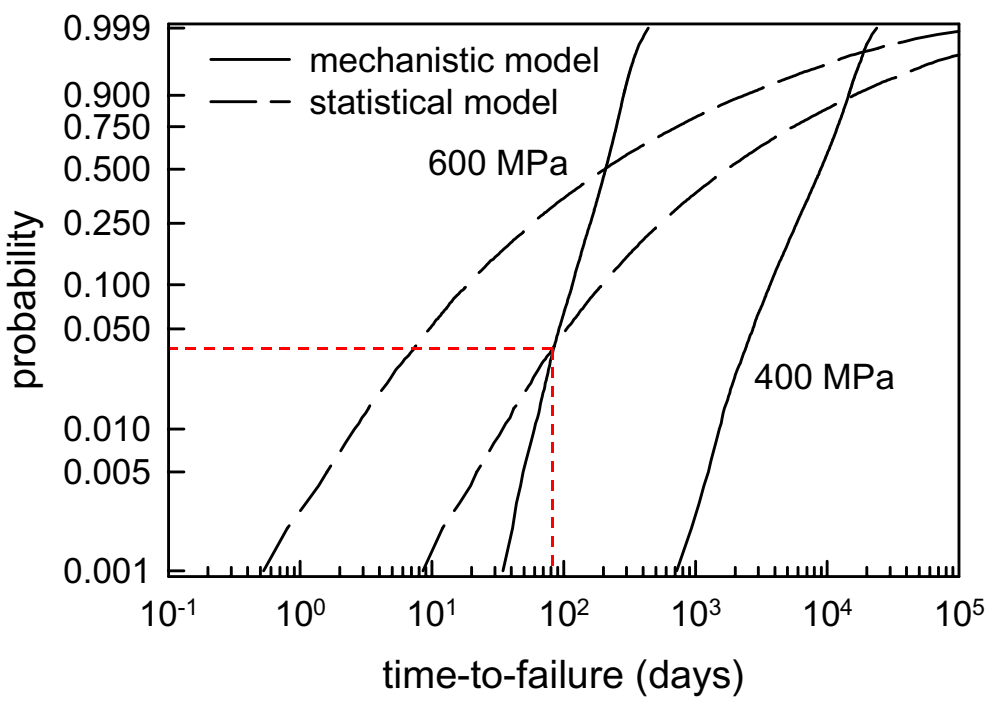
$$\dot{a}_p = \frac{(N+1)d_T \dot{A}^* \left[\frac{(\sigma - \sigma^*)}{G}\right]^M}{\left[1 - \left(\frac{K}{K_c}\right)^{\frac{2N}{(N+1)}}\right]}$$

$d_T, \dot{A}^*, \sigma^*, a_o$ - rvs

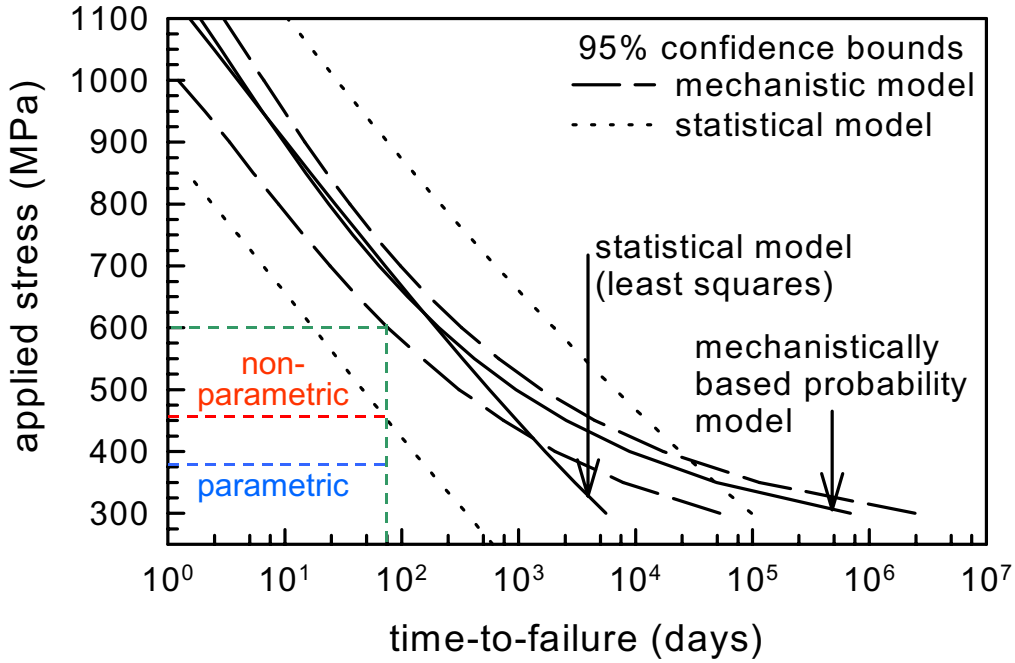
$\dot{a}_s = Ce^{bK}$; C, b - rvs



Mechanistic versus Empirical Modeling

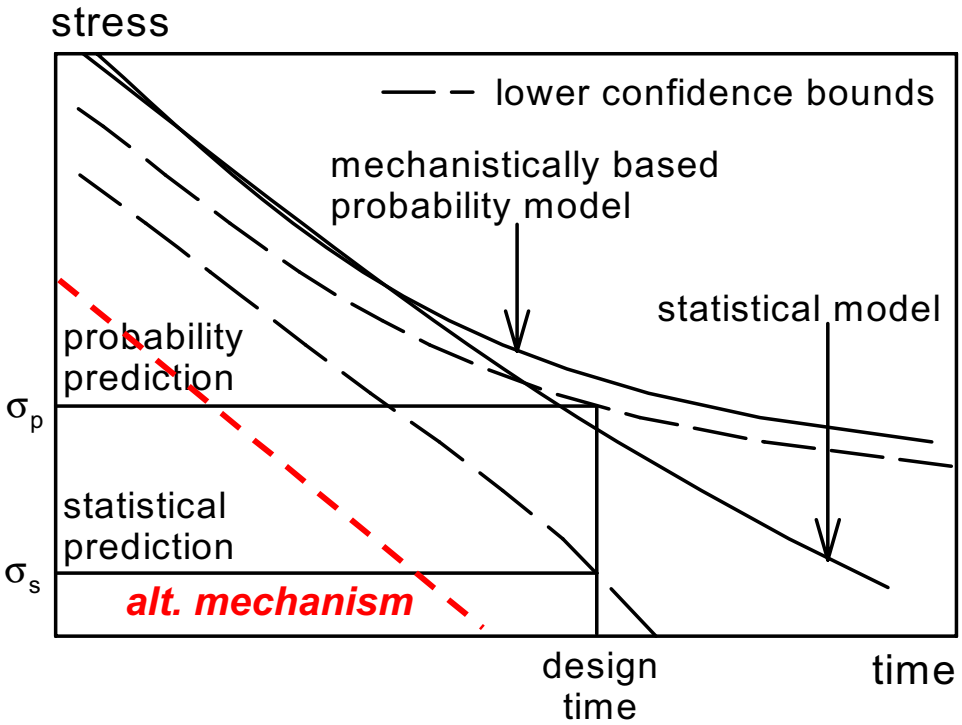


Mechanistic versus Empirical Modeling



Lower bounds estimated by statistical methods are not unique.

Mechanistic versus Empirical Modeling



Summary

- Distinct advantage demonstrated for mechanistically based probability modeling (versus empirically based statistical modeling) for use in materials aging and structural reliability in life-cycle design and management
- Mechanistic modeling is science based: solid and fracture mechanics, chemical and materials sciences
- Mechanistically based probability modeling provides:
  - rational approach for extrapolation beyond typical data
  - essential (rather than artificially enhanced) variability
  - estimates that are conservative, efficient, and economical
- Challenge the community to adopt and lead in the application and further development of mechanistically based probability modeling

The Use of Probabilistic Methods to Evaluate the Systems Impact of Component Design Improvements on Large Turbofan Engines

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Probabilistic Structural Analysis (PSA) is now commonly used for predicting the distribution of time/cycles to failure of turbine blades and other engine components. These distributions are typically based on fatigue/fracture and creep failure modes of these components. Additionally, reliability analysis is used for taking test data related to particular failure modes and calculating failure rate distributions of electronic and electromechanical components. How can these individual failure time distributions of structural, electronic and electromechanical component failure modes be effectively combined into a top level model for overall system evaluation of component upgrades, changes in maintenance intervals, or line replaceable unit (LRU) redesign?

This paper shows an example of how various probabilistic failure predictions for turbine engine components can be evaluated and combined to show their effect on overall engine performance. A generic model of a turbofan engine was modeled using various Probabilistic Risk Assessment (PRA) tools (Quantitative Risk Assessment Software (QRAS) etc.). Hypothetical PSA results for a number of structural components along with mitigation factors that would restrict the failure mode from propagating to a Loss of Mission (LOM) failure were used in the models. The output of this program includes an overall failure distribution for LOM of the system. The rank and contribution to the overall Mission Success (MS) is also given for each failure mode and each subsystem.

This application methodology demonstrates the effectiveness of PRA for assessing the performance of large turbine engines. Additionally, the effects of system changes and upgrades, the application of different maintenance intervals, inclusion of new sensor detection of faults and other upgrades were evaluated in determining overall turbine engine reliability.

Probabilistic Methods

Michael Packard

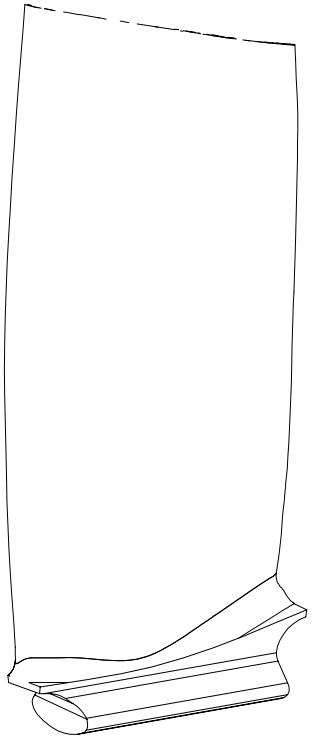
The Use of Probabilistic Methods to Evaluate the Systems Impact of Component Design Improvements on Large Turbofan Engines

Objectives

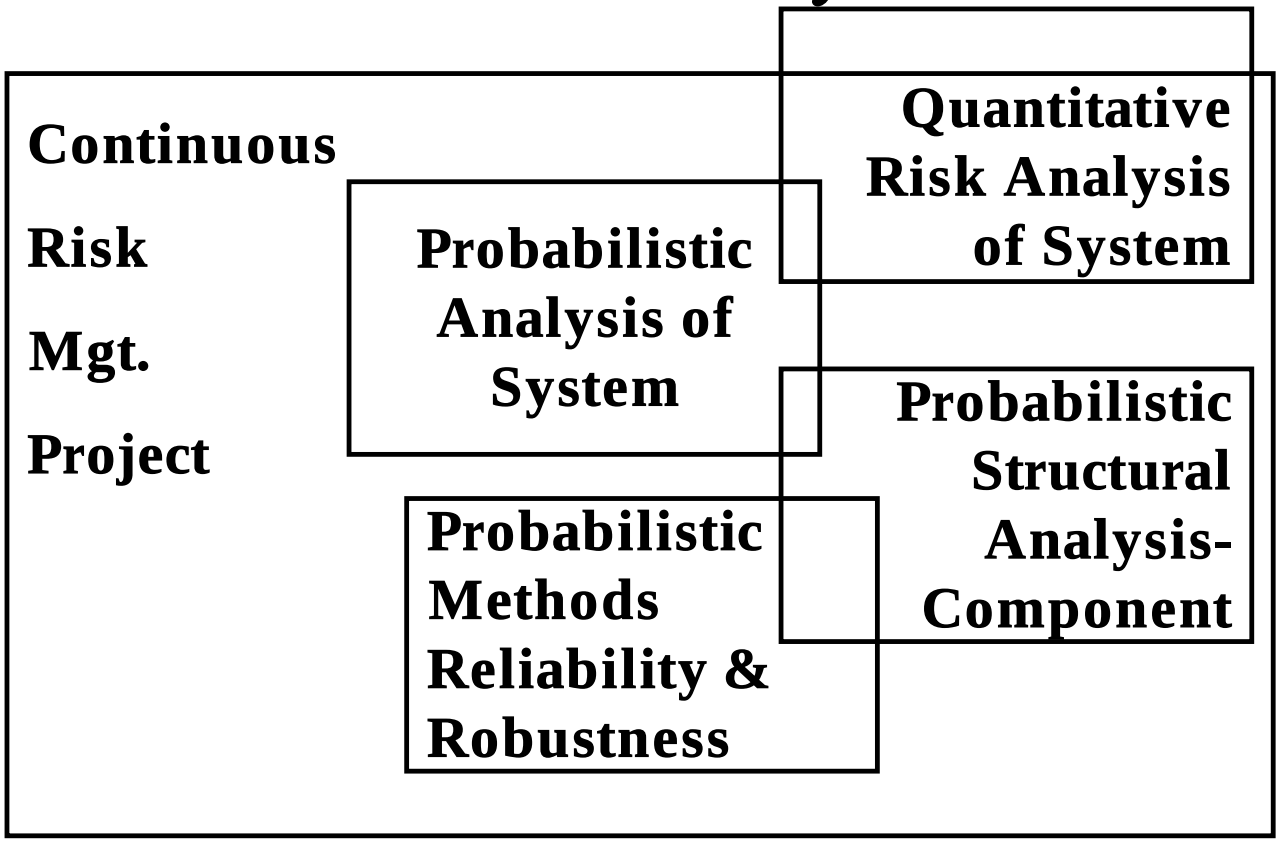
- Risk assessment of a mature system (generic).
- Quantitative probabilistic risk assessment.
- Quantitative probabilistic model development.
- Development of component data.
- Evaluating system upgrades for reducing risk.
- Conclusion

Customer Requirements - Risks in an Uncertain World

- Risks in the component design?
- Risks in the component modeling?
- Risks in the component SW model?
- Risks in the component environment?
- Risks in the component manufacture?
- Risks in the component deployment?
- Risks in the component installation?



Levels Risk of Analysis



New Designs -- Complex Risks

- High Thrust Rocket Engines/ Aerospike
- Tiles/ Heat Shields
- Computerized Systems
- Lightweight Liquid O_2 and H_2 Tanks
- Complex System Interactions
- Integration, Payload
- Logistic Cost/On Orbit Logistics Costs

Meeting the Needs - Risk Acceptance

Meeting the Needs - Understanding Risks

- Product Assurance Plan
- Testing -- Number of Units
- Required Tests -- Same Lot
- Variations in Compositions
- Variations in Fabrication
- Components and Systems

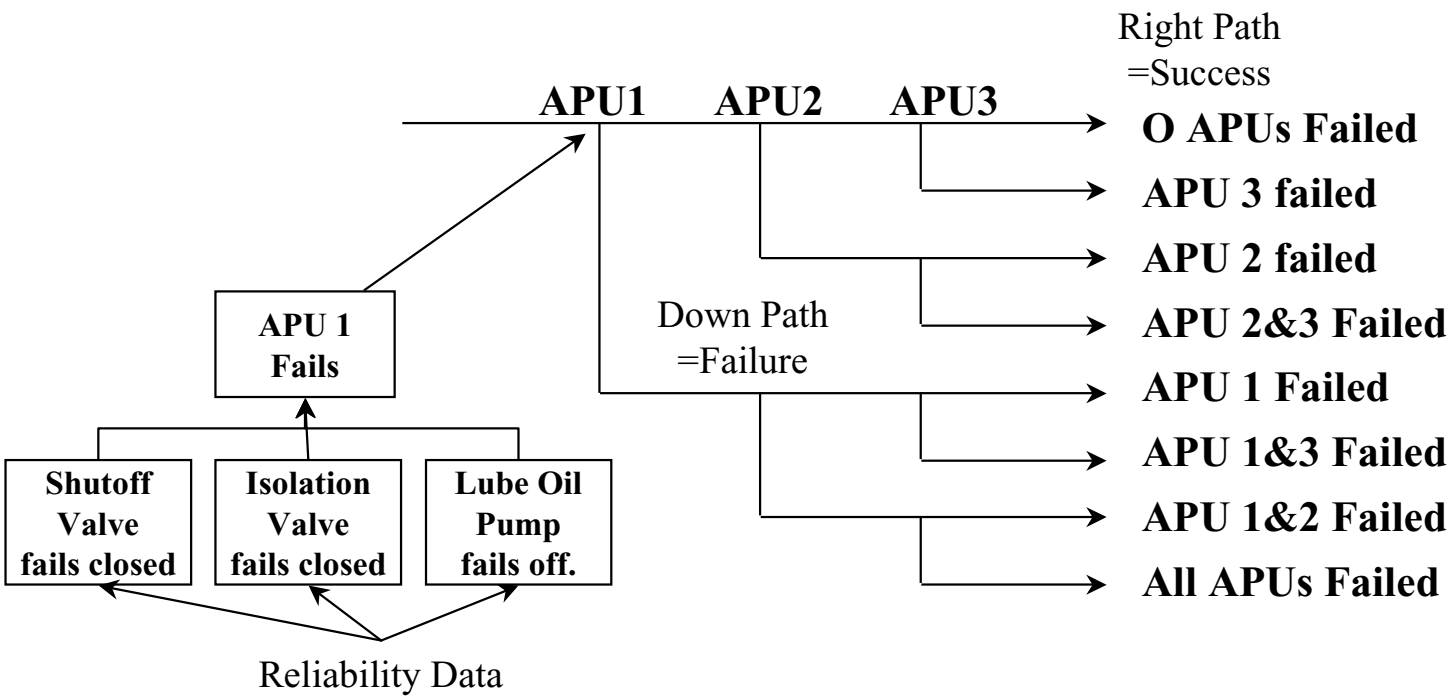
Types of Evaluation

- Reliability Assessment -- Usually performed on a system or component level. Objective is to determine probability of failure during a mission. Wearout also considered.
- Probabilistic Risk Assessment -- Goes beyond reliability and asks the question “What does the failure mean?” In addition to system/component reliability can account for other risk factors such as human error, external factors, etc.

Basic Tools Used in Evaluations

- Fault Trees -- Top down evaluation of an undesirable event. Usually used in system analysis to display/quantify reliability of the system/function.
- Event Trees -- Also a top down evaluation, but used to string together events leading to an “end state” in a logical time ordered progression. Events considered in the event tree may be based on fault trees.
- Reliability Assessments -- In order to quantify model component failure modes, need failure rates.

Example: Support System Event Tree



Background -- QRAS Description+

- Probabilistic models of subsystem failure modes based on latest available data (over time these data will be updated and improved to keep the tool current)
- Event-sequence diagrams will logically describe manner in which subsystem failure modes can lead to catastrophic failure or other end states, including the success or failure of mitigation events.

Background--QRAS Results

- QRAS results:
  - Intermediate and or top-level model failure probabilities and their uncertainty bounds.
  - A prioritization of the “risk drivers” i.e., subsystem failure modes which are contributing the most risk to the model.
- “What if?” (or sensitivity analysis):
  - Modify the model (modifications could include replacement of subsystems with what is known or expected from proposed upgraded subsystems, additions/deletions of failure modes, changes to failure probabilities and/or to their uncertainty bounds, etc.) and re-run it to obtain changes in risk from baseline.

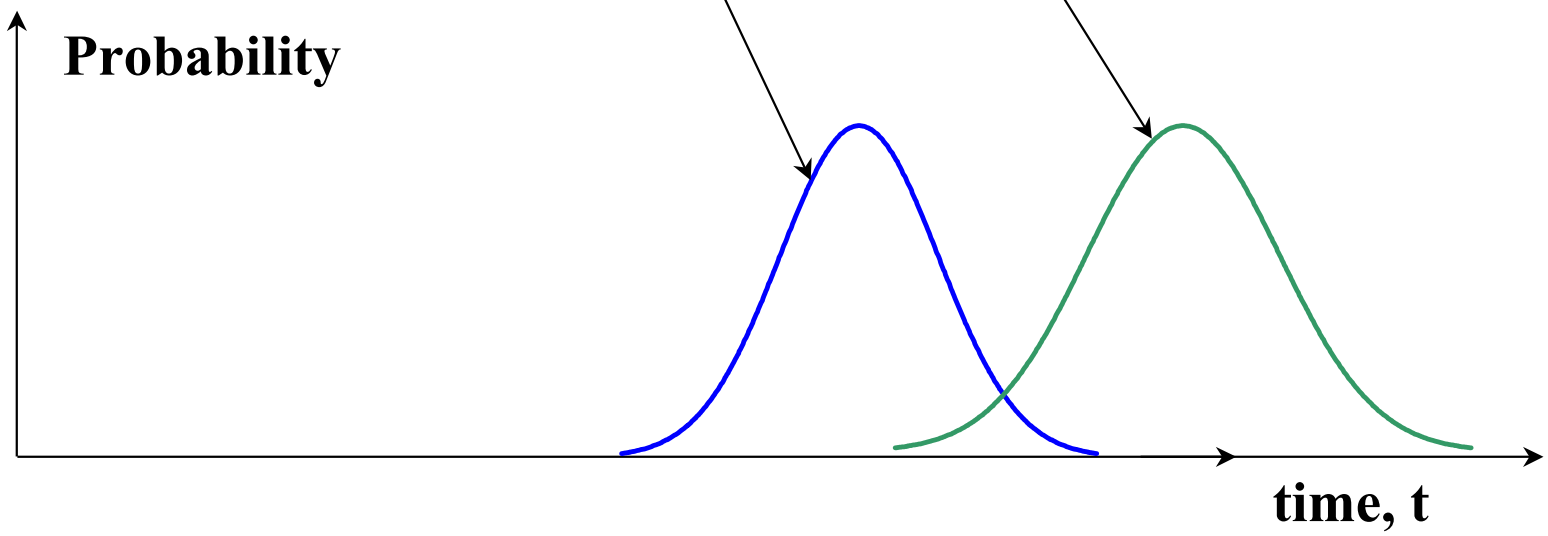
Data Used in Evaluations

- Reliability Data
  - PRACA Best source, shuttle specific, least amount of data.
  - Surrogate Data -- lots of data, not system specific.
  - Expert Opinion
  - Flight Rules -- required in some cases to determine response to a failure.
- System Operations and Design -- required to understand and correctly model the system

Basic PSA--Fatigue Failure+

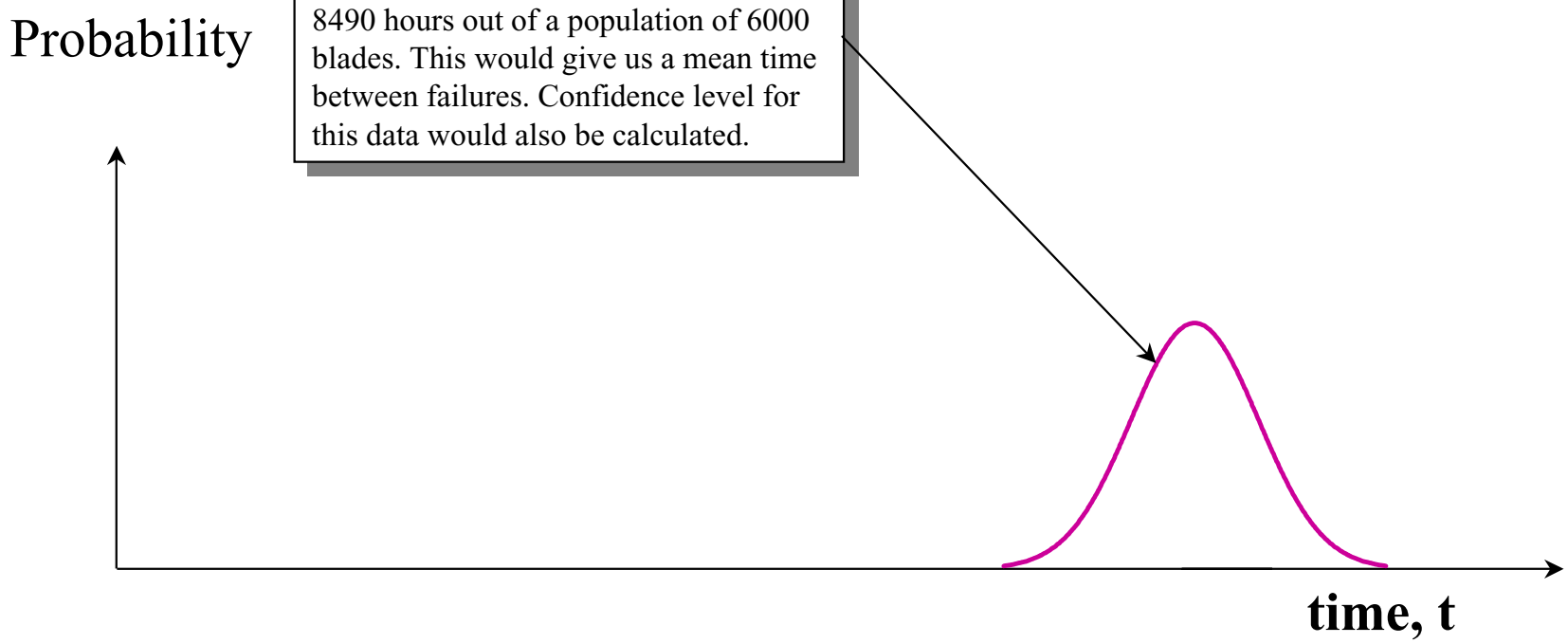
Based on a given duty cycle, and variations in material properties, dimensions and temperature effects the estimation of fatigue crack initiation is as follows:

Expanding on this analysis, the crack growth to a critical length or a length that can be discovered by inspection is as follows:



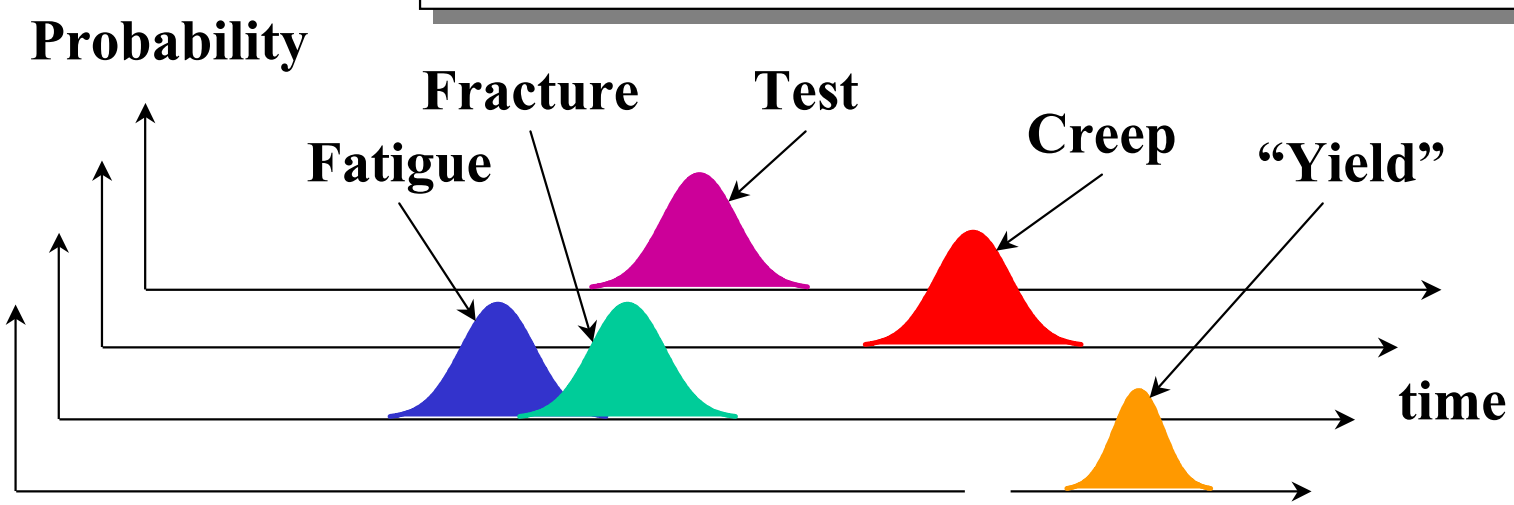
Basic PSA -- Testing

Based on test data, or field data, we might have 3 failures at 5230, 7640 and 8490 hours out of a population of 6000 blades. This would give us a mean time between failures. Confidence level for this data would also be calculated.



Combining Analysis

The different failure mechanisms and failure modes may or **may not be independent or mutually exclusive**. Typically yield of a component in the time domain would be far to the right on a time line.



QRAS Methodology

- Develop Key System Elements
- Develop Key Subsystem Components
- Develop Mission Timeline
- Develop Mission Operational Time Intervals
- Develop Failure Modes
- Develop Mitigating Events
- Develop Event Sequence Diagram

Develop Key System Elements

- Inlet Nozzle
- Low Pressure Compressor
- High Pressure Compressor
- Combustion System
- High Pressure Turbine Module
- Low Pressure Turbine Module
- Exhaust Module
- Afterburner Module
- Fuel Module
- Auxiliary Components
- Conditioning Monitoring

Develop Key Subsystem Components

- High Pressure Compressor
  - Compressor Rotor Assembly
  - Stage 1 Fan Disk
  - Sage 1 Blade Set
  - Front Shaft
  - No. 2 Outer Bearing
  - No. 3 Ball Bearing
  - Stage 2 Fan Disk
  - Stage 2 Blade Set
  - Stage 3 Fan Disk
  - Stage 3 Blade Set

QRAS -- Develop Mission Timeline/OTI

- ***Idle***
- ***Take Off***
- ***Cruise***
- ***Descent***
- ***Land***
- The events are then assigned to individual failure modes once they are developed. Alternatively overall operating time may be developed.

QRAS -- Develop Failure Modes

- High Pressure Turbine
  - Stage 2 Fan Disk
    - Turbine Blade (Stage 2) Structural Failure
    - Turbine Blade (Stage 2) Fatigue
    - Turbine Blade (Stage 2) Fracture with n Crack Length
    - Turbine Blade (Stage 2) Creep Failure
    - Turbine Blade (Stage 2) Ablation
    - Turbine Blade (Stage 2) Tip Contact

QRAS -- Develop Mitigating Events

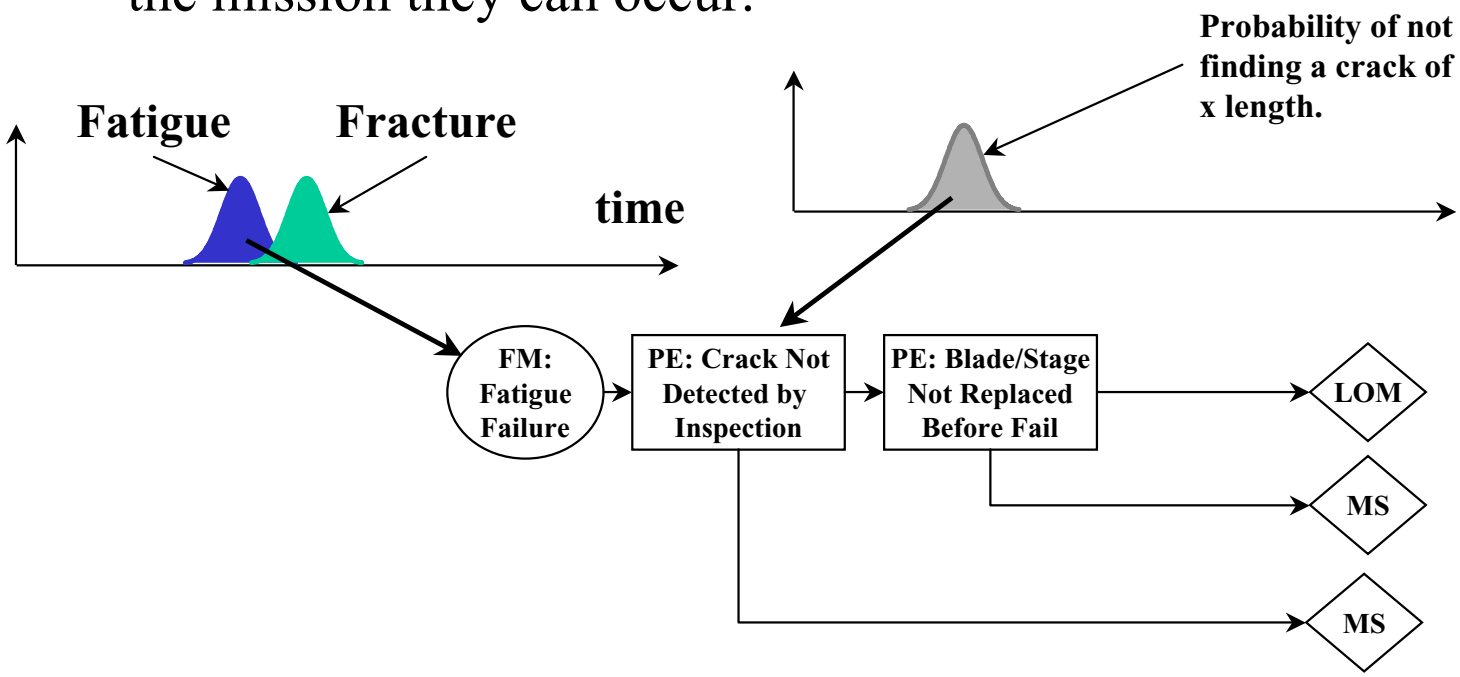
- Mitigating events are actions or other methods for mitigating or preventing the Failure Mode from propagating to a Loss of Mission or Catastrophic Failure.
- High Pressure Turbine
  - Stage 2 Fan Disk
    - **O** Turbine Blade (Stage 2) Fracture with n Crack Length
      - ☐ **Inspection Finds Fatigue Crack**
      - ☐ **Blade/Stage Changeout**

Event Sequence Diagram (ESD)

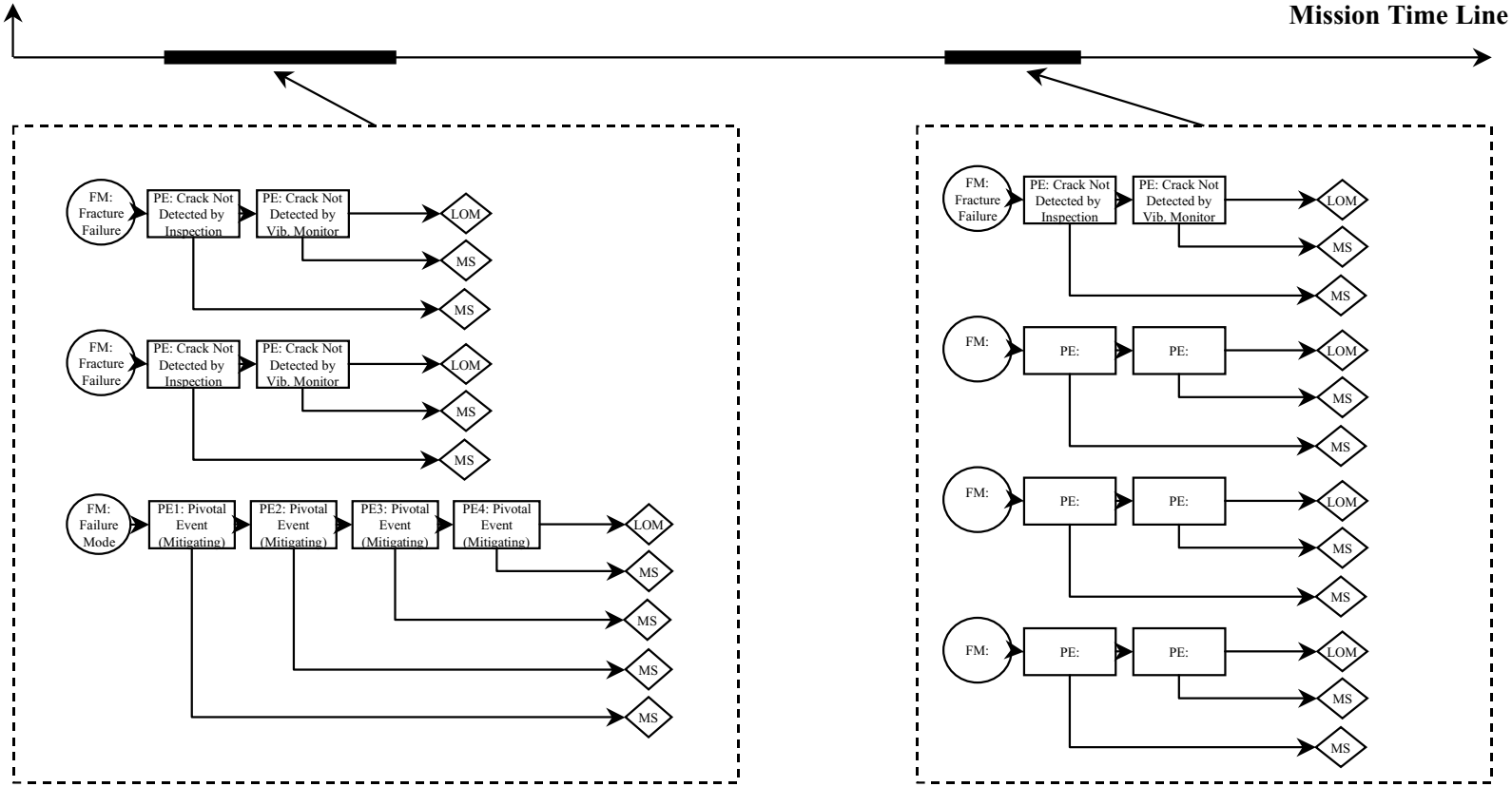
- The ESD is the basic element used to evaluate failure modes.
- The ESD evaluates the probability of a failure mode as well as mitigating events which prevent the failure from propagating to a LOM (Loss of Mission).
- Each ESD (failure mode) can be time phased as a unique part of the mission.
- The ESD has the same mathematical result as an event tree.

QRAS -- Assign Probabilities

- Probabilities are assigned to the failure modes and to the mitigating events. Failure modes are quantified as to when in the mission they can occur.



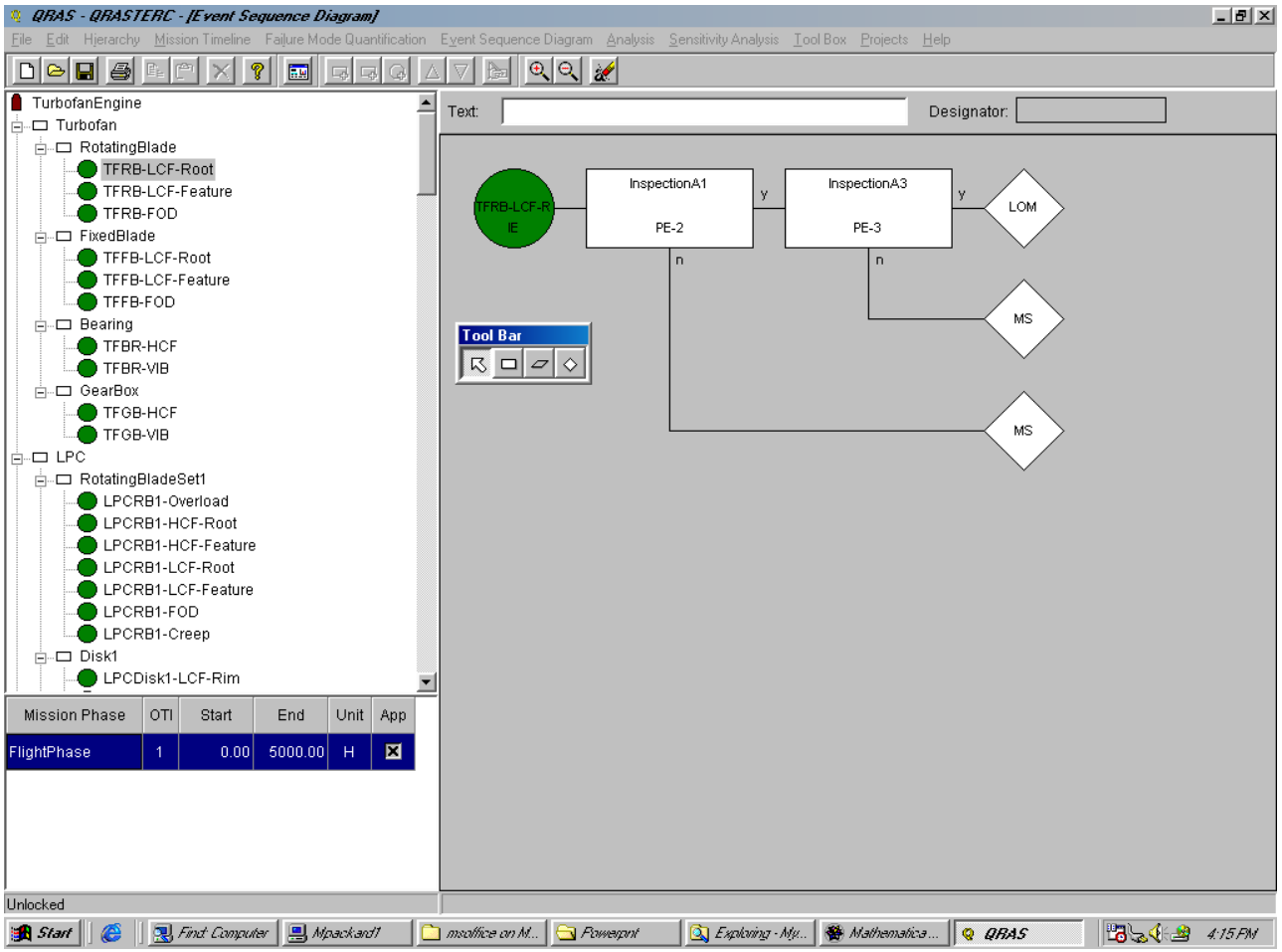
Combining Event Sequence Diagrams



Glenn Research Center

Aeronautic Risk Management

The Use of Probabilistic Methods to Evaluate the Systems Impact of Component Design Improvements on Large Turbofan Engines



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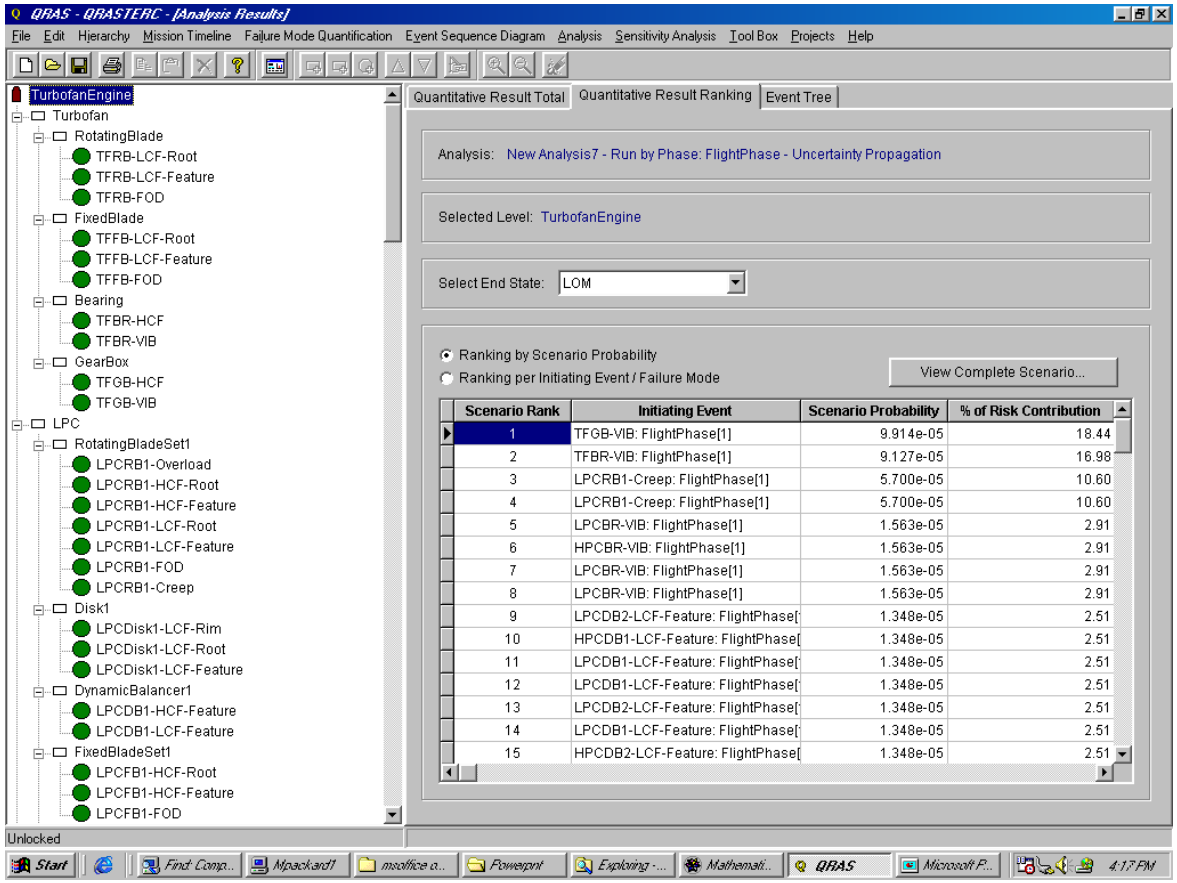
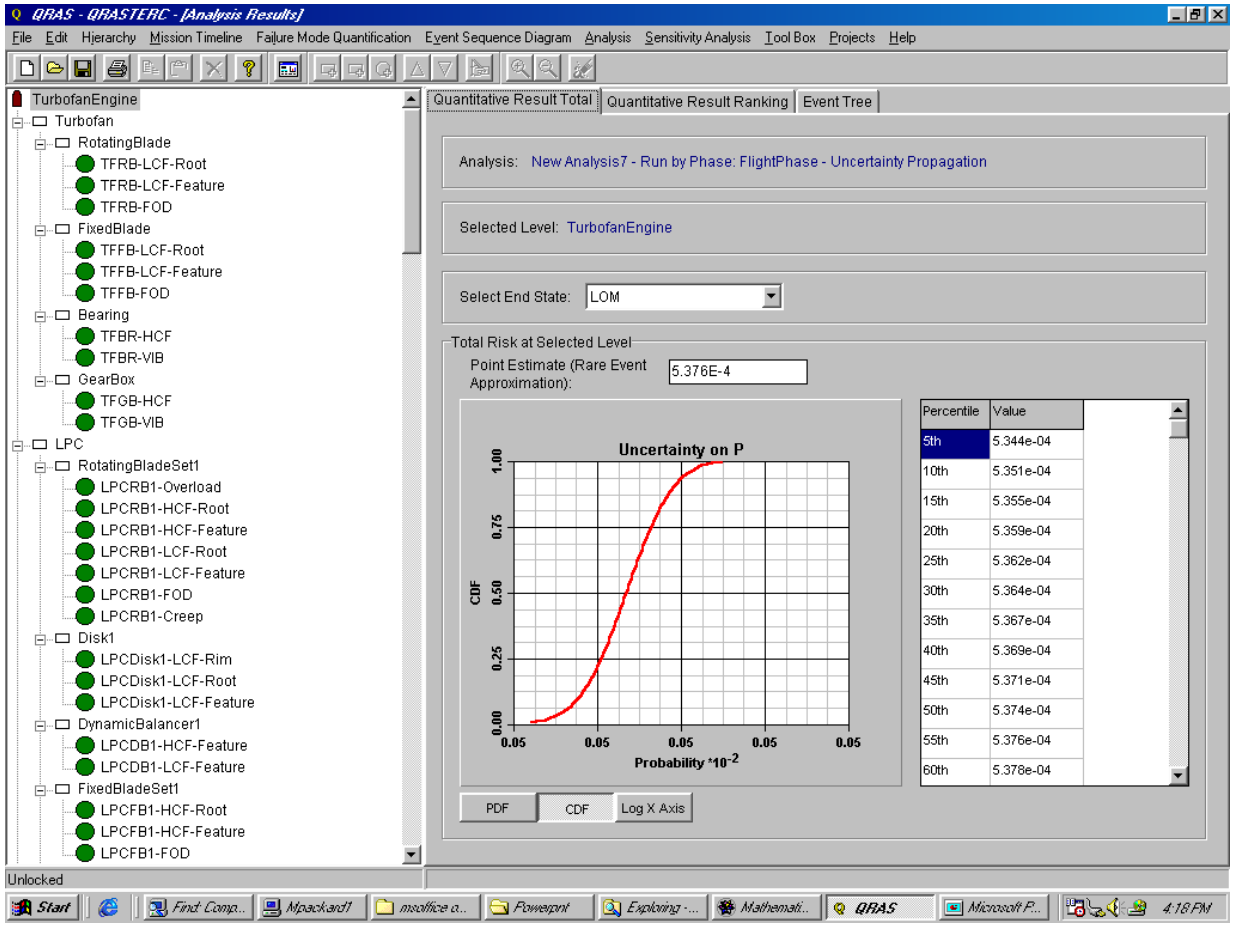


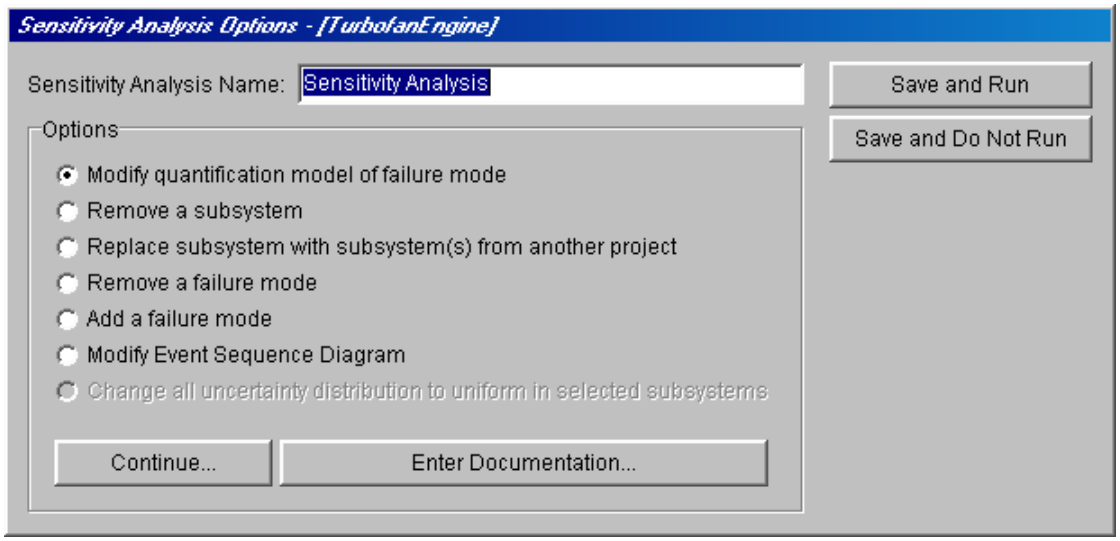
Scenario Rank	Initiating Event	Scenario Probability	% of Risk Contribution
1	TFGB-VIB: FlightPhase[1]	9.914e-05	18.44
2	TFBR-VIB: FlightPhase[1]	9.127e-05	16.98
3	LPCRB1-Creep: FlightPhase[1]	5.700e-05	10.60
4	LPCRB1-Creep: FlightPhase[1]	5.700e-05	10.60
5	LPCBR-VIB: FlightPhase[1]	1.563e-05	2.91
6	HPCBR-VIB: FlightPhase[1]	1.563e-05	2.91
7	LPCBR-VIB: FlightPhase[1]	1.563e-05	2.91
8	LPCBR-VIB: FlightPhase[1]	1.563e-05	2.91
9	LPCDB2-LCF-Feature: FlightPhase[	1.348e-05	2.51
10	HPCDB1-LCF-Feature: FlightPhase[	1.348e-05	2.51
11	LPCDB1-LCF-Feature: FlightPhase[	1.348e-05	2.51
12	LPCDB1-LCF-Feature: FlightPhase[	1.348e-05	2.51
13	LPCDB2-LCF-Feature: FlightPhase[	1.348e-05	2.51
14	LPCDB1-LCF-Feature: FlightPhase[	1.348e-05	2.51
15	HPCDB2-LCF-Feature: FlightPhase[	1.348e-05	2.51

Aeronautic Risk Management

The Use of Probabilistic Methods to Evaluate the Systems Impact of Component Design Improvements on Large Turbofan Engines



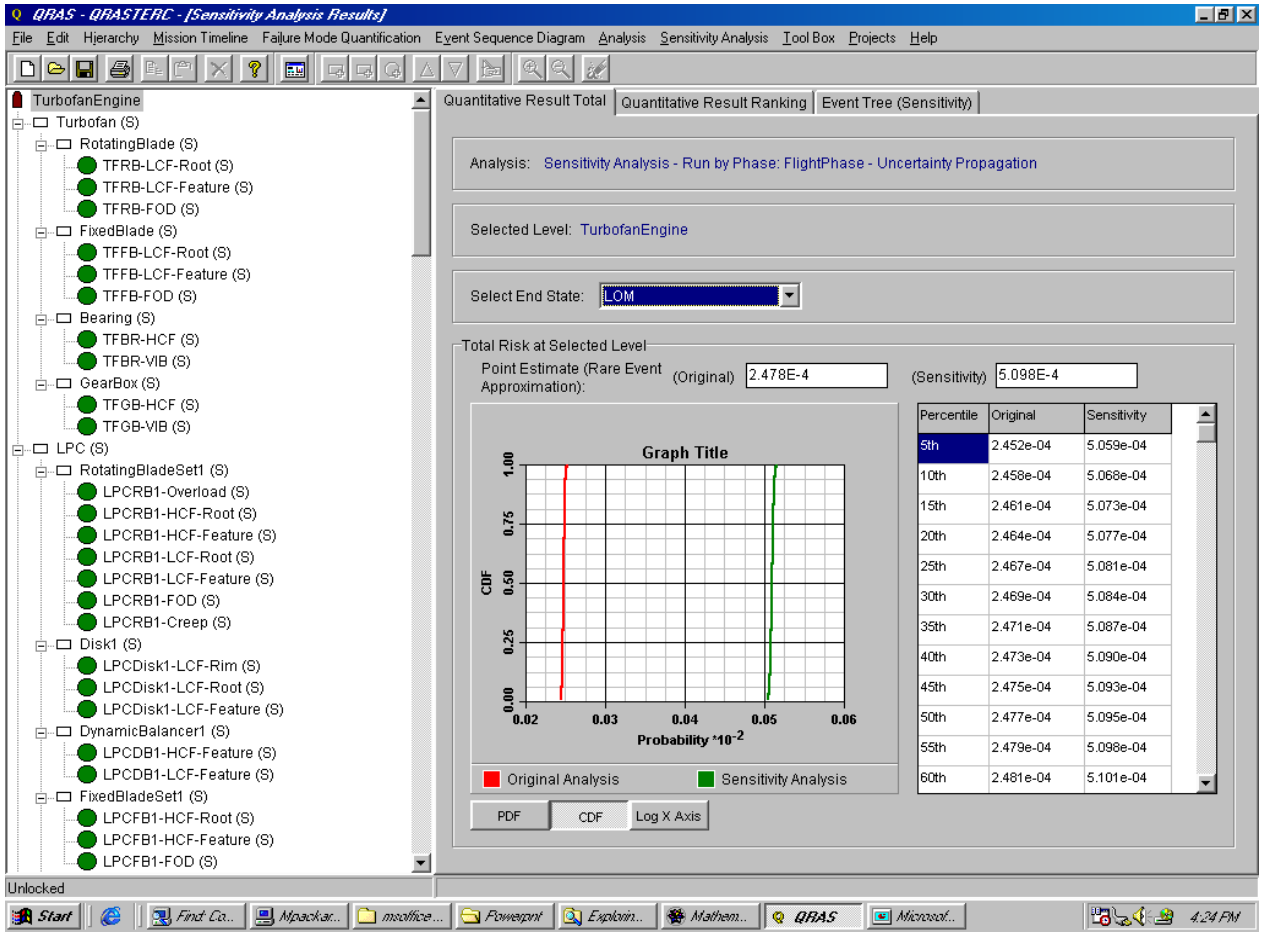
Analysis Options



Glenn Research Center

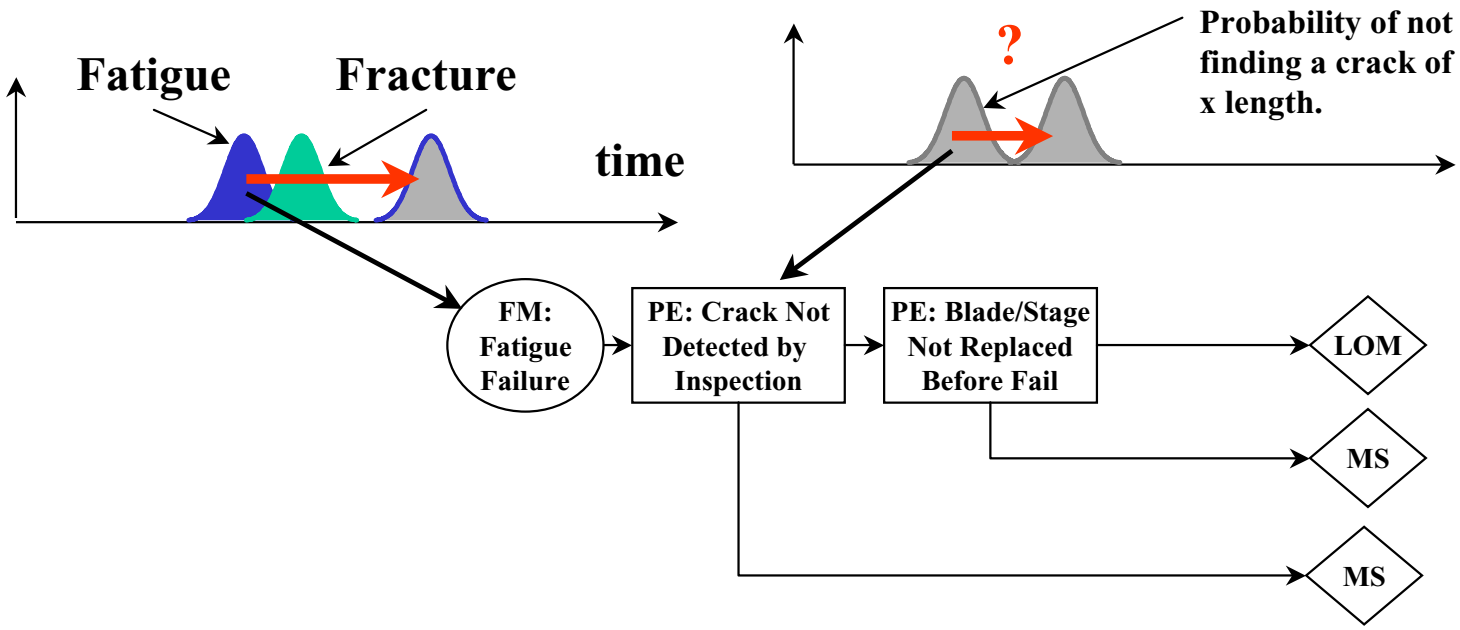
Aeronautic Risk Management

The Use of Probabilistic Methods to Evaluate the Systems Impact of Component Design Improvements on Large Turbofan Engines



Limitations

- If fatigue life improved, will inspection interval, change out, effect on other parts in stage change?



Limitations+

- Statistically independent variables, (change in blade geometry affects another stage?)
- System level failure…affecting multiple components?
- Improved design >>>> Increased power?
- Does not drive reduction in variability
- Individual failure modes probabilities interrelated
- Inspection dependency

Advantages

- Presentation of systems model/ upgrades to non-technical professionals.
- Quantitative measure of upgrade (assuming relationships between components understood)
- Takes into account, inspection, maintainability, detection, etc.
- Justify maintenance, change out schedule.

Next Steps

- Develop Standardized Methodology to Characterize Manufacturing Processes
- Develop methodology to evaluate/ optimize probability of detection; replacement options.
- Develop methodology for updating/ calling multiple NESTEM calculations.
- Develop methodology for dependencies.

Conclusions

- QRAS beneficial for modeling mature design.
- QRAS beneficial for evaluation of upgrades (assuming independence).
- QRAS assists in basic understanding of inspection, POD, maintenance on system reliability.

Generalized Response Surface Modeling for Stochastic Mechanics Problems

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One key aspect when developing a real-time in-flight risk-based health management system for jet engines is the development of accurate and robust fault classifiers. Regardless of the complex uncertainty propagation in the data fusion process, the selection of fault classifiers is the critical aspect of a health management system.

The paper illustrates the application of a hybrid *Stochastic-Fuzzy-Inference Model-Based System (StoFIS)* to fault diagnostics and prognostics for both the engine performance. The random fluctuations of jet engine performance parameters during flight missions are modeled using multivariate stochastic models. The fault diagnostic and prognostic risks are computed using a stochastic model-based deviation (using a gas-path analysis model) approach.

At any time the engine operation for the future is approached as a conditional reliability problem where the conditional data are represented by the past operational history monitored on-line by the engine health management (EHM) system. To capture the complex functional relationships between different engine performance parameters in the in-flight transient regimes, a stochastic-fuzzy inference system is employed. This increases significantly the robustness of the EHM system during highly transient in-flight conditions. Both the monitored and fault data uncertainties are considered in a multidimensional parameter space, with two probabilistic-based safety margins employed for fault detection, diagnostics and prognostics: (i) Anomaly Detection Margin (ADM) and (ii) Fault Detection Margin (FDM). Illustrative example are shown.

Generalized Response Surface Modeling for Stochastic Mechanics Problems

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Keywords: reliability, stochastic fields, turbine, series expansion, response surface, random

ABSTRACT: The paper describes stochastic models for idealizing complex random variations for gas turbine engine applications. Typically, these random variations are stochastic functions of space and/or time or different physical input random parameters. A key requirement for a good stochastic modeling is to be intimately related to the physics of the problem. The paper suggests different stochastic series models for approximation of stochastic surfaces that represent either input random surfaces or stochastic nonlinear response surfaces.

1 INTRODUCTION

Mechanical components and systems typically operate in a continuously varying pressure and temperature environment that may involve quite complex engineering modeling problems. In particular, for turbine engine applications, multiple stochastic fluid-structural dynamics interacting phenomena are always present. Steady and unsteady flow-induced pressures and temperatures within a turbine are varying in time and space inducing a continuously transient-spatially varying stress states in the components. Random aspects are an integral part of physical phenomena. Loading history or sequence plays an important role in component life prediction especially when the stress amplitude is highly variable in time, such as the case of turbine assemblies which operates at very different rotating speeds and temperatures (Ghiocel & Rieger, 1998, Ghiocel, 2000a).

Spatial geometry deviations due to manufacturing process can also influence significantly the turbine vibration responses and behavior. For a rotating bladed-disk assembly, the manufacturing deviations in geometry and material properties produce a loss of the cyclic symmetry of the system (cyclic symmetry assumes identical mass, stiffness and damping properties for all blades and associated disk sectors). The unfortunate aspect is that a slight departure from the bladed-disk system cyclic symmetry pattern may produce significant differences in blade vibration amplitudes and stresses.

2 LOADING, MATERIAL PROPERTIES AND MANUFACTURING DEVIATIONS

Stochastic surface models with known statistics are usually associated to the random inputs in the probabilistic analysis. For gas turbine engine applications these can be (i) space-time varying, fluctuating aero-pressure and temperature distributions on component surfaces, including inlet airflow distortions and multistage spatial interactions, (ii) space-time varying material properties, including existence of material micro-defects and (iii) spatially-varying of material properties and geometry deviations from baseline (nominal) due to manufacturing and assembly process.

Typically the *known statistics* are the marginal probability distribution functions, i.e. the probability distribution at each point over the physical domain, and the second-order statistical moments, i.e. the mean function and the covariance function over the domain. Stochastic field can be homogeneous or non-homogeneous, or/and isotropic or anisotropic depending if their statistics are invariant or variant to the axis translation, respectively, invariant variant to the

axis rotation in the physical parameter space. Depending on the physics of the problem, the above assumptions of stochastic modeling can affect negligibly or severely the accuracy of results.

Component loading distributions, material properties and manufacturing geometry deviations can be idealized using 3V-3D (3 component variables-3 dimensions) stochastic field models. From the mathematical modeling point of view, these stochastic fields are quite complex, being multivariate-multidimensional non-homogeneous, non-isotropic, non-Gaussian fields. To handle these complex structure fields, it is often advantageous to represent them in terms of a linear combination of orthogonal random functions, similar to a generalized Wiener-Fourier type series:

a) For Gaussian stochastic functionals $$u(\mathbf{x},\theta) = \sum_i u_i(\mathbf{x}) z_i(\theta) \quad (1)$$

b) For non-Gaussian stochastic functionals $$u(\mathbf{x},\theta) = \sum_{i=0}^{\infty} u_i(\mathbf{x}) f_i(\theta) = \sum_{i=0}^{\infty} u_i(\mathbf{x}) f_i(\mathbf{z}(\theta)) \quad (2)$$

where **z** is a set of independent standard Gaussian random variables, and **f** is a set of orthogonal random functions (can be further expressed in terms of the set **z**). A simple selection of **f** can be a set of uncorrelated non-Gaussian random variables.

For general case, several techniques can be used for the factorization of stochastic fields. For example, the use of the Pearson differential equation for defining different types of stochastic series representations including Hermite, Legendre, Laguerre and Cebyshev orthogonal polynomials. One major application of theory of factorable stochastic fields is the spectral representation of stochastic fields (Loeve, 1977, Ghanem & Spanos, 1991, Grigoriu, 1996, Ghanem & Ghiocel, 1998, Ghiocel, 2000b). The Karhunen-Loeve (KL) representation is an optimal spectral representation with respect to the second-order statistics of the stochastic field. For typical continuum mechanics problems the KL expansion is fast convergent, i.e. it needs only few expansion terms.

Figures 1 through 4 illustrate the importance of using stochastic field models for idealizing the blade geometry variations in turbine rotating assemblies. Figure 1 shows the bladed-disk model used in the research investigation. Two stochastic modeling assumptions were considered: (i) *stiffness-based mistuned response* that corresponds to a random percentile variation of each blade-disk sector stiffness (random variable-based mistuning model – currently applied in engineering practice) and (ii) *geometry-based mistuned response* that corresponds to realistic variation of blade geometries (stochastic field-based mistuning model – proposed herein). Figure 2 shows the Interference Diagram (plot of natural frequency as a function of nodal diameter, assuming cyclic symmetry) of the bladed-disk model for a given rotating speed of 6,000 rpm. It should be noted that in the frequency range 5,000-7000 Hz there are clustered family of modes that potentially can interact significantly if the cyclic symmetry pattern is perturbed. Based on tuned response analysis (cyclic symmetric bladed-disk model) the largest blade tip vibratory responses are obtained for two natural modes with frequencies around 6,650 Hz and 6,900 Hz, respectively. Between these two modes there is another mode at a frequency of around 6,800Hz that has a reduced response. Figure 3 indicates that *for stiffness-based mistuning* there is no visible dynamic coupling between the two modes and the intermediary mode. However, if the blade geometry deviations are more realistically described by a stochastic field, then the dynamic coupling between the two modes and the intermediary mode can be significant. Figure 5 shows that for *geometry-based mistuning* the blade vibratory response in the intermediary mode increases severely, about 8 times. For few blades, a significant part of vibration energy of the two modes is transferred and localized into the intermediary mode.

Validity of Ergodicity Assumption

The ergodicity assumption is a typical assumption for stochastic field modeling in engineering

applications. Basically, ergodicity assumption implies that any random sample is representative for the overall statistics of a stochastic quantity. Under ergodic assumption the statistical-averaging is assumed equivalent to spatial-averaging over physical parameter space. Obviously, the ergodicity assumption is not true when several random sample subsets with different statistics are mixed together in an overall statistical database. Figures 5 and 6 show a sample surface vs. the ensemble mean surface of a spatial statistical database that indicates a strong non-ergodic character (the random surface data are spatial variation of material property data in a continuum non-homogeneous medium). It should be noted that in contrast to the large differences in amplitude variation of the two plotted surfaces, their correlation structure is much more similar as shown in Figures 7 and 8. To compute the single-sample correlation, two stochastic models were employed:

(i) Non-homogeneous Model. Spatial-averaging is done along a selected direction, while statistical-averaging is done along the perpendicular direction (stochastic field is assumed homogeneous in one-direction and non-homogeneous in the other direction). The stochastic field is assumed to be quadrant symmetric with an independent correlation structure in the two orthogonal directions.

(ii) Homogeneous Model. Spatial-averaging is done along both orthogonal directions (stochastic field is assumed homogeneous-isotropic over the entire domain).

It should be noted that both assumed models can be crude for a given set of sample data. In Figure 7, the single-sample correlation function was computed using the non-homogeneous stochastic field model with an independent correlation structure along the grid axes, X and Y. For the investigated situation, the non-homogeneous field model was an appropriate representation of the spatial variability since this variability can be accurately expressed by a product of two random one-dimensional spatial variabilities, in X direction and in Y direction, respectively. For other situations when a significant amplitude fluctuation is present in an oblique direction, the independent correlation structure assumption can be inappropriate, especially when multiple oblique preferential correlation directions exit (multiple anisotropy). Such situations can often occur in industry applications due to the systematic and controlled nature of manufacturing process that can create multiple preferential anisotropy directions in the material properties or component geometry deviations.

3 NONLINEAR RESPONSE SURFACE

The stochastic response statistics are not known apriori. Usually, only a limited number of sample data are available or can be generated by the analyst. The approximation problem is to find a stochastic field model that optimally fits with a minimum mean-square error the statistical data. Statistical data can be experimental data or solution point data obtained through computational analysis. The most popular approach is to the response surface method (RSM) applied in conjunction with design of experiment (DOE) rules (Schueller, Pradlwarter & Bucher, 1991). The response surface (RS) is a sum of a macro-scale variation (deterministic quadratic surface) and a micro-scale variation (random vector):

$$\mathbf{u}(s,\theta) = \overline{\mathbf{u}}(s) + \boldsymbol{\varepsilon}(\theta) \tag{3}$$

The macro-scale variation is obtained by regression assuming a quadratic polynomial approximation:

$$\overline{\mathbf{u}}(s) = \beta_0 + \sum_{i=1}^{p}\beta_i u_i + \sum_{i=1}^{p}\beta_{ii} u_i^2 + \sum_{i<j}\beta_{ij} u_i u_j \tag{4}$$

It should be noted that equation 3 is based on the assumption that the macro-scale variation and micro-scale variation are fully decoupled and added as independent terms. This assumption is not generally valid and may introduce errors that depend on the degree of coupling between the macro-scale and micro-scale variations. The RSM method is applicable to problems that don't involve highly nonlinear relationships. Another important limitation of the RSM is that the magnitude of the shifts around the mean point used in the DOE rules are subjectively selected

by the analyst. Therefore, the accuracy of the RS approximation is highly dependent on the analyst's experience and his luck.

Because of the significant limitations of the classical RSM for approximating stochastic nonlinear responses, alternative approaches using stochastic field models are proposed herein: (i) stochastic field expansion techniques, (ii) stochastic field interpolation techniques and (iii) stochastic clustering techniques.

Stochastic Field Expansion Techniques

A general form for a stochastic expansion model is given in equation 9. The stochastic expansion model can be formally expressed as a nonlinear functional of a set of Gaussian variables, or in other words expanded in a set of random orthogonal random functions. Herein, for example, a stochastic expansion model of the stochastic solution in any point over the field domain is suggested via a polynomial type series. The polynomial expansion model often called "polynomial chaos" is defined by the series (Ghanem and Spanos, 1991, Ghiocel & Ghanem, 1998):

$$u(\mathbf{x}, t, \theta) = \sum_{j=0}^{p} u_j(\mathbf{x}, t)\psi_j(\theta) \tag{5}$$

The polynomial expansion functions are orthogonal in the sense that their correlation, $E[\psi_j \psi_k]$, is zero. A given truncated series can be refined along the random dimension either by adding more random variables to the set $\{z_i\}$ or by increasing the maximum order of polynomials included in the stochastic expansion. For practical implementation is desirable to use a reduced number of data/solution points to compute the stochastic coefficient of the chaos expansion. Then, the built expansion model is employed to simulate a large number of samples using Monte Carlo. The approach is conceptually similar to the RSM; use a limited number of points to build the stochastic response model and then further use this model to simulate a large number of samples. Specific sampling techniques have been developed to address the practicality aspects of the chaos expansion implementation.

For an efficient numerical implementation, in order to increase the chaos series convergence, especially when stochastic response is highly nonlinear, a transformed-space representation can be used. The transformation is applied in such a way, so that the non-Gaussian field would be represented by a quasi-Gaussian image field. Specifically, such a transformation may be appropriate for modeling stochastically the local stresses near material crack tip, contact stresses, etc. whose variations can be highly non-Gaussian.

Stochastic Field Interpolation Techniques

Stochastic field interpolation models are optimal RS representations with respect to given data sets. The theory behind the stochastic field interpolation models is precisely the Wiener-Kolmogorov theory for a time series with a finite history. If the optimality criterion is the mean-square error with respect to the given data set, then the optimum stochastic interpolator is the conditional mean estimator. If the optimality criterion is the absolute error with respect to data, then the optimum interpolator is the median estimator. Very importantly, for Gaussian fields, the optimum stochastic interpolator is a linear combination of the data points. Using the optimum stochastic interpolation models the correlation between values of a nonlinear response surface at short distances is explicitly taken into consideration. This remark also applies to values at data points, so that the "weight" of each point in a cluster is automatically reduced. Importantly, no homogeneity/stationary condition is needed.

If the trend (mean) surface is assumed to be known then the stochastic response surface can be fully defined by the difference process between the process and its mean, $\varepsilon(\mathbf{x}) = u(\mathbf{x}, \theta) - u(\mathbf{x})$. A "simple" linear optimal predictor (simple krigging estimator) can be defined by a linear combination of data points (Cressie, 1991):

$$\hat{\varepsilon}(\mathbf{u}) = \sum_i \lambda_i \varepsilon(u_i) = \boldsymbol{\lambda}^T \boldsymbol{\varepsilon} \tag{6}$$

that minimizes the mean-square error functional

$$E[\varepsilon(\mathbf{u}) - \hat{\varepsilon}(\mathbf{u})]^2 = \mathrm{Var}(\varepsilon(\mathbf{u})) - 2\sum_i \lambda_i \boldsymbol{\Sigma}(u_i, \mathbf{u}) + \sum_i \sum_j \lambda_i \lambda_j \boldsymbol{\Sigma}(u_i, u_j) \tag{7}$$

$$= \mathrm{Var}[\mathbf{u}] - 2\boldsymbol{\lambda}^T \boldsymbol{\varsigma}(\mathbf{u}) + \boldsymbol{\lambda}^T \boldsymbol{\Sigma} \boldsymbol{\lambda} \tag{8}$$

where $\varsigma_{ij} = \boldsymbol{\Sigma}(u_i, u_j)$, $\boldsymbol{\varsigma}(\mathbf{u}) = \boldsymbol{\Sigma}(\mathbf{u}, u_i)$, $\boldsymbol{\lambda}$ is a function of $\mathbf{u}$. Since equation 11 is a quadratic form in $\boldsymbol{\lambda}$, it can be minimized by finding its stationary point. It should be noted that because the covariance matrix $\boldsymbol{\Sigma}$ is strictly positive definite there is no restriction in practice.

Stochastic interpolation techniques are appropriate for describing isotropic or geometrically-anisotropic stochastic fields. For the general case of non-homogeneous, non-isotropic, non-Gaussian stochastic fields, the stochastic interpolation techniques are much more limited than the stochastic expansion models that can handle very complex correlation structure fields. Stochastic interpolation can be applied to non-Gaussian fields by performing a space transformation from the original space to a transformed space, where a Gaussian image field is defined. Then, stochastic interpolation interpolated Gaussian image is back transformed to the original space (trans-Gaussian krigging, Cressie, 1991).

Stochastic interpolation can be also applied for cases where the mean function of the stochastic field is unknown. The optimum stochastic interpolator is called in these cases "universal" predictor ("universal" krigging). An alternate stochastic interpolation technique is to use smoothing C-splines assuming that the correlation structure of the field is independent for different parameter spaces (Chen, Gu and Wahba, 1989). For each dimension the autocorrelation function is assumed to be an one-dimensional cubic polynomial that produce one-dimensinal cubic spline sample. The assumption of independent correlation structure for each dimension can be drastic for practical engine applications.

Stochastic Clustering Techniques

Clustering techniques can be used to describe complex structured non-stationary non-Gaussian fields that can include multiple solutions or highly non-monotonic random variations. Cluster techniques have been succesfully applied for pattern classification problems (Patrick, 1972). The basic assumption is that the probability distribution of a given sample is a composed distribution obtained by integrating over sample domain, the conditional probability distributions of the clusters existing within the sample (local-average representation). The sample probability distribution is defined by:

$$H(\mathbf{u}) = \int F(\mathbf{u}|\alpha) dG(\alpha) \tag{9}$$

where $G(\alpha)$ is the mixing distribution. In discrete form, the mixing distribution can be expressed by

$$G(\alpha) = \sum_{i=1}^{N} P(\alpha_i)\delta(\alpha - \alpha_i) \tag{10}$$

in which $\delta(\alpha - \alpha_i)$ is the Kronecker delta operator. Typically the parameter α_i are assumed or known and the mixing parameters $P(\alpha_i)$ are the unknowns. The sample probability distribution can be rewritten in discrete form by

$$H(\mathbf{u}) = \sum_{i=1}^{N} F(\mathbf{u}|\alpha_i) P(\alpha_i) \tag{11}$$

The parameters α_i can represent the second-order moments of the random clusters.

Application of clustering techniques can be expedient for large dimensionality problems. The accuracy is maximum for well separated clusters, and depreciates for highly overlapping clusters. Unfortunately, for typical nonlinear stochastic responses the clusters overlap

significantly. The smoothness of the approximating functions is highly dependent on the statistics of the clusters. The optimal clustering structure can be determined using a maximum entropy functional or minimum mean-square error criteria under a Gaussian separability assumption.

Figure 9 shows the application of clustering to approximate a 3D highly nonlinear stochastic surface. Only 35 solution points were used. The sample data set was decomposed in 3 and 5 clusters, respectively. Figure 13 illustrates the computed mean surface obtained for 3 and 5 clusters, respectively. The mean response surface was obtained by tracing the center of gravity of the mixed distribution over the physical parameter space. It should be noted that the smoothness of mean response surface is highly dependent on the number of clusters selected by the analyst. The analyst's judgment plays a key role in the accuracy of the stochastic response approximation. If a reduced number of clusters are used, the smoothing effect on mean estimation can be significant, then a multivariate stochastic field model has to be used to idealize the random deviations from the estimated mean surface.

4 CONCLUDING REMARKS

Stochastic surface modeling for engineering applications represents still an engineering art rather than a standardized, well-established procedure. The experience and background of the analyst, and finally his judgement play a key role in the stochastic modeling process. The analyst has to understand both the physics of the problem and the limitations of the stochastic modeling tools.

The unconditional use of simplistic stochastic models can be inadequate for capturing uncertainties associated to key physical aspects of the investigated problem. In this paper, this is exemplified for mistuning phenomenon that often occurs in turbine applications.

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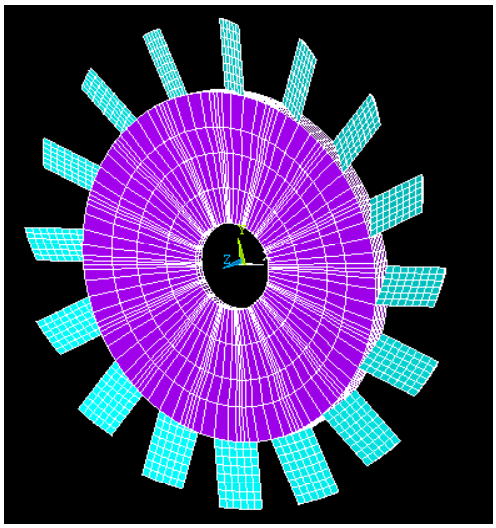


Fig. 1. Research Bladed-disk FE Model

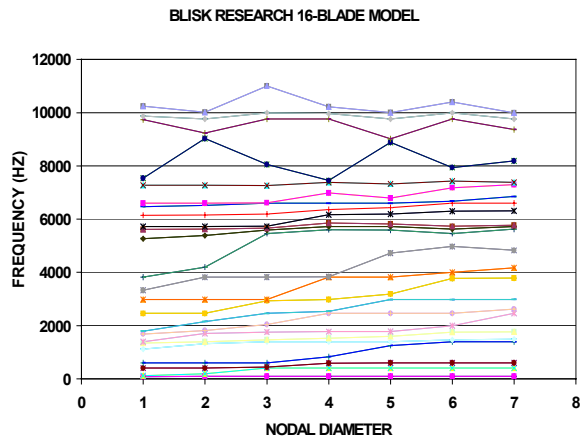


Fig. 2. Interference Diagram of Bladed-disk

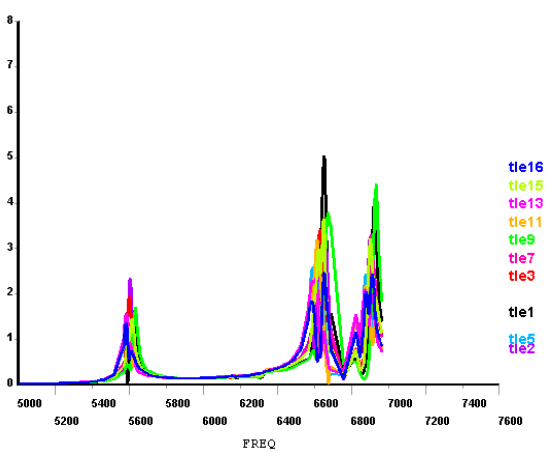


Fig. 3. Stiffness-based Mistuned Response

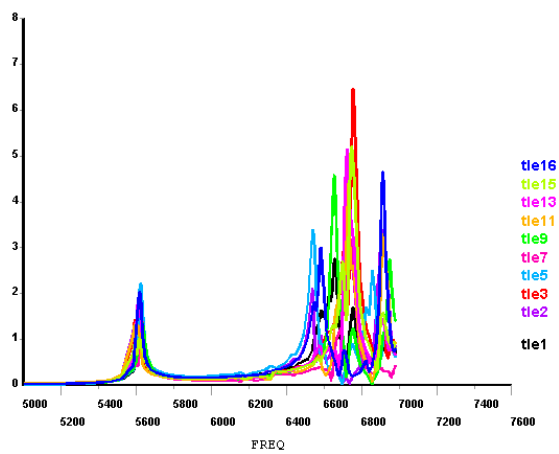


Fig. 4. Geometry-based Mistuned Response

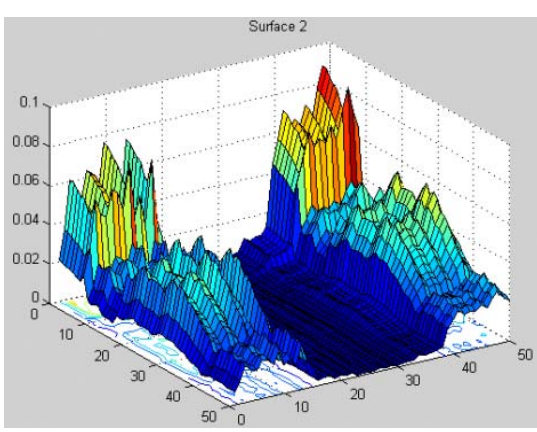


Fig. 5. Random sample of property variation

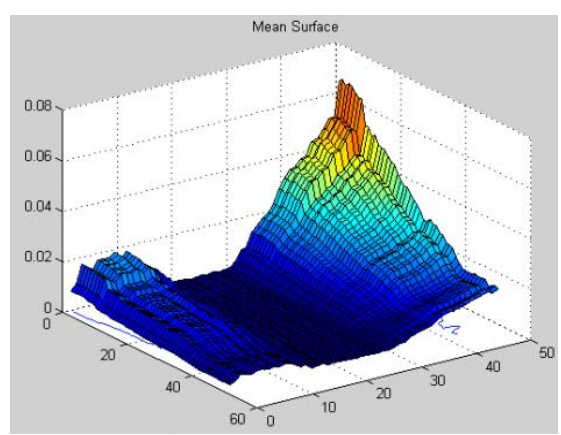


Fig. 6. Ensemble mean of property variation

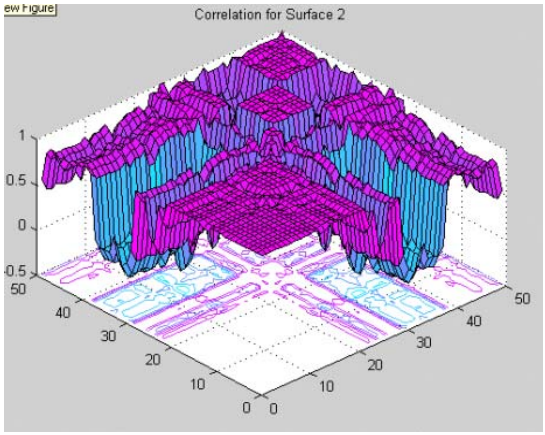


Fig. 7. Sample correlation function

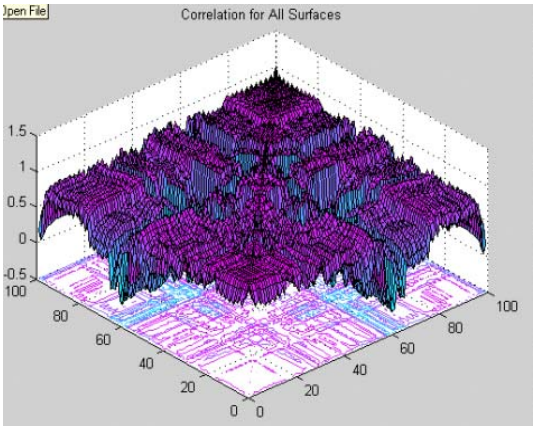
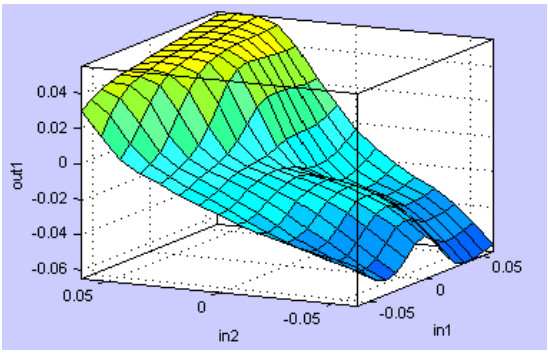
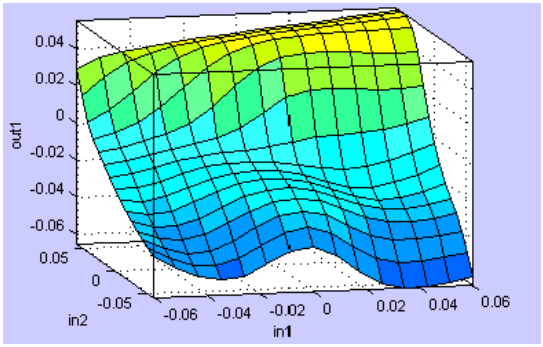


Fig. 8. Ensemble correlation function

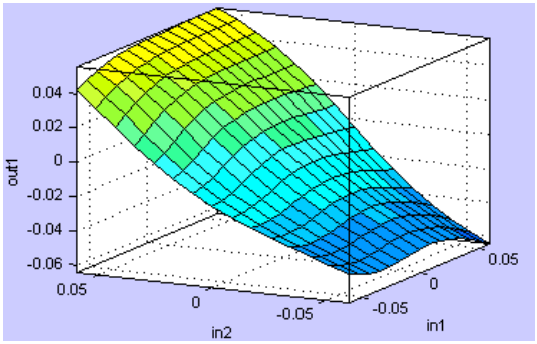


Variable x1

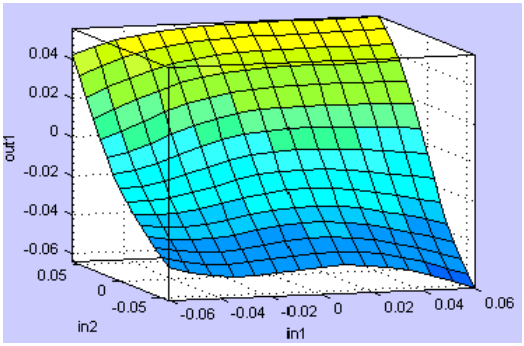


Variable x2

a) 5 clusters



Variable x1



Variable x2

b) 3 clusters

Figure 9. Estimated Mean Response computed using Stochastic Clustering Techniques

Probabilistic Design Methodology and its Application to the Design of an Umbilical Retract Mechanism

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A lot has been learned from past experience with structural and machine element failures. The understanding of failure modes and the application of an appropriate design analysis method can lead to improved structural and machine element safety as well as serviceability. To apply Probabilistic Design Methodology (PDM), all uncertainties are modeled as random variables with selected distribution types, means, and standard deviations. It is quite difficult to achieve a robust design without considering the randomness of the design parameters which is the case in the use of the Deterministic Design Approach.

The US Navy has a fleet of submarine launched ballistic missiles. An umbilical plug joins the missile to the submarine in order to provide electrical and cooling water connections. As the missile leaves the submarine, an umbilical retract mechanism retracts the umbilical plug clear of the advancing missile after disengagement during launch and retrains the plug in the retracted position. The design of the current retract mechanism in use was based on the deterministic approach which puts emphasis on factor of safety. A new umbilical retract mechanism that is simpler in design, lighter in weight, more reliable, easier to adjust, and more cost effective has become desirable since this will increase the performance and efficiency of the system.

This paper reports on a recent project performed at Tennessee State University for the US Navy that involved the application of PDM to the design of an umbilical retract mechanism. This paper demonstrates how the use of PDM lead to the minimization of weight and cost, and the maximization of reliability and performance.

PROBABILISTIC DESIGN METHODOLOGY AND ITS APPLICATION TO THE DESIGN OF AN UMBILICAL RETRACT MECHANISM

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AND

OLUSESAN AMEYE

(GRADUATE STUDENT)

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MECHANICAL ENGINEERING DEPARTMENT

TENNESSEE STATE UNIVERSITY

5TH Annual FAA/Air Force/NASA/Navy Workshop on the Application of Probabilistic Methods to Gas Turbine Engines June 11-13, 2001

FUNDINGS ON PROBABILISTIC DESIGN METHOD

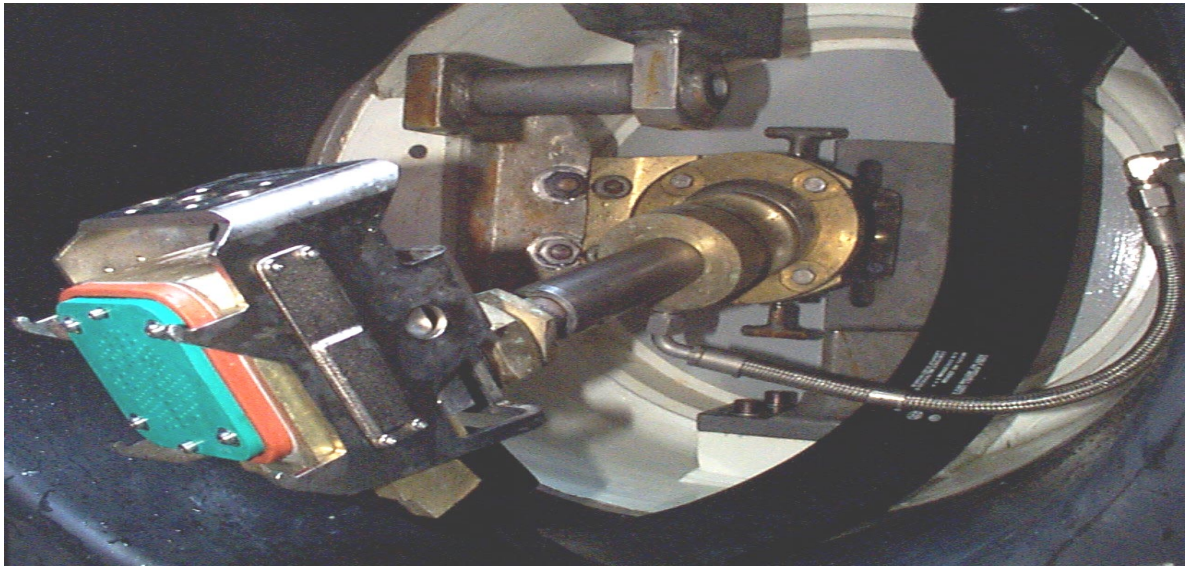
- **NASA LEWIS RESEARCH CENTER 1993-1996**
  (Training of students on Probabilistic Design Methodology and Application of NESSUS)

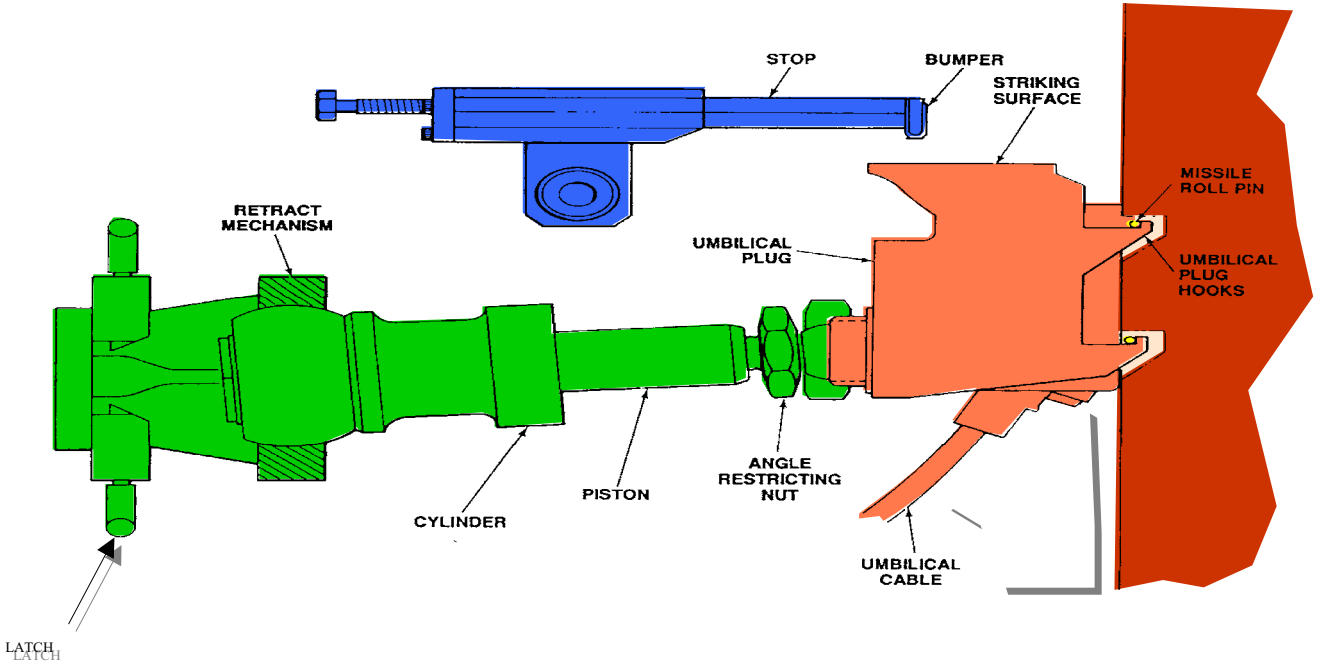
- **APPLIED RESEARCH LABORATORY, PENNSTATE 1998-1999**
  (Application of Probabilistic Design to Simulation Based Design with emphasis on the design of Torpedo)

- **SUPPORT FROM THE UNIVERSITY (Continuous)**

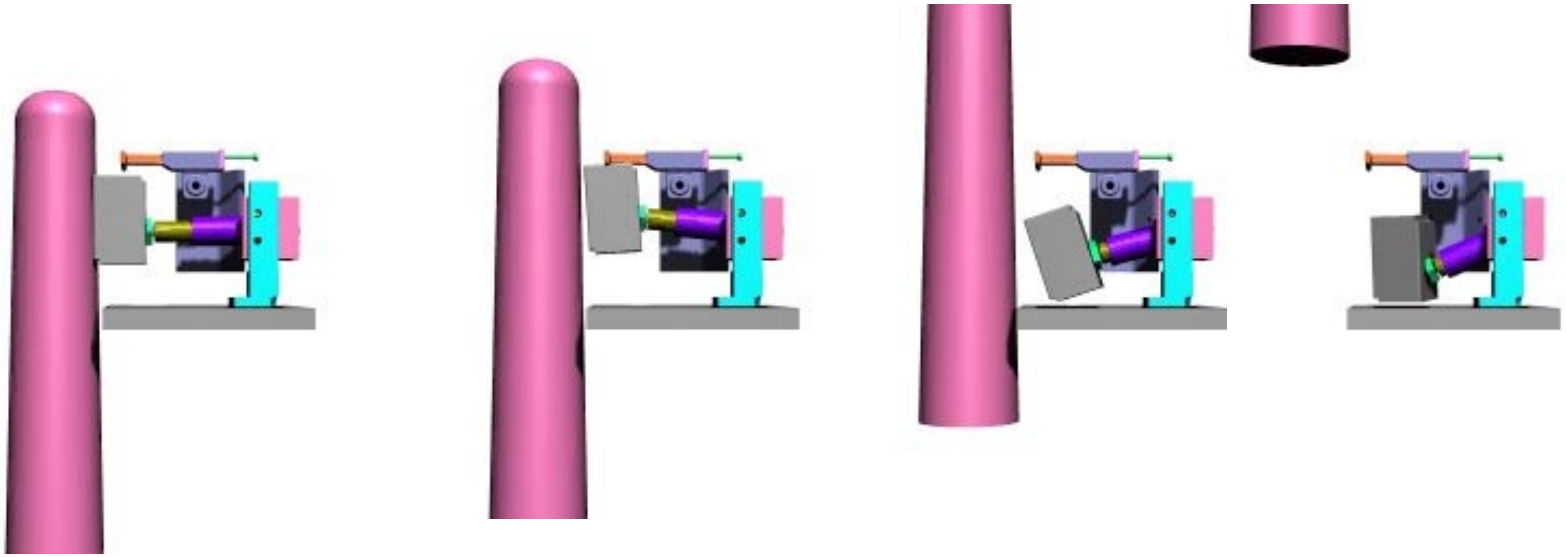
UNBILICAL RETRACT MECHANISM PROJECT (Funded by the US Navy, Strategic Systems Program)
• CONCEPTUALIZE, ANALYZE, AND DESIGN A D5 UMBILICAL RETRACT MECHANISM
• DEVELOP AND FABRICATE A PROTOTYPE UMBILICAL RETRACT MECHANISM BASED ON NEW DESIGN

RESEARCH TEAM
•DR. LANDON ONYEBUEKE (SUPERVISOR)
•NNAMANI IKECHUKWU
•AMEYE OLUSESAN
•THOMAS KPABAR
•ROMAIN MCGHEE
•SONYA CLARK
•CHINEDU
•DAVIS NICOLE CASANDRA
•VESTANIA HOLLINGTON




STOP
BUMPER
STRIKING SURFACE
MISSILE ROLL PIN
UMBILICAL PLUG HOOKS
UMBILICAL PLUG
RETRACT MECHANISM
ANGLE RESTRICTING NUT
PISTON
CYLINDER
UMBILICAL CABLE
LATCH

THE DESIGN OBJECTIVE

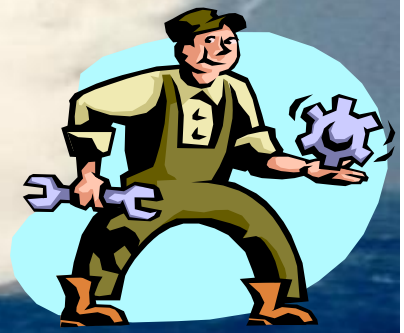


STAGE 1 STAGE 2 STAGE 3 STAGE 4

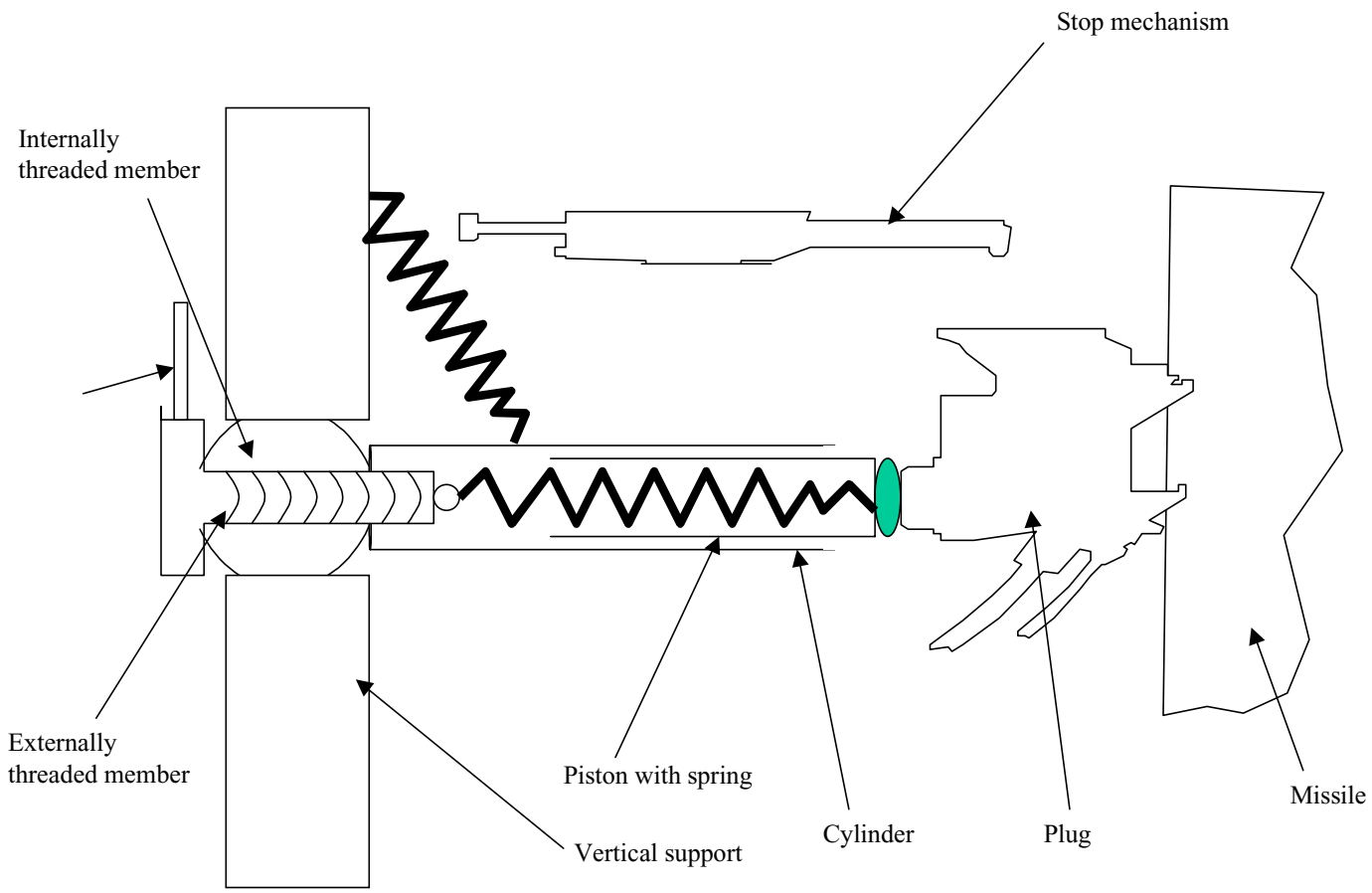
DESIGN CONSIDERATIONS
• SPACE LIMITATIONS
• WEIGHT LIMITATIONS
• MATERIAL LIMITATIONS
• RELIABILITY
• INTERFACING WITH OTHER GROUPS
• DESIGN FOR ASSEMBLY

AIM AND OBJECTIVES

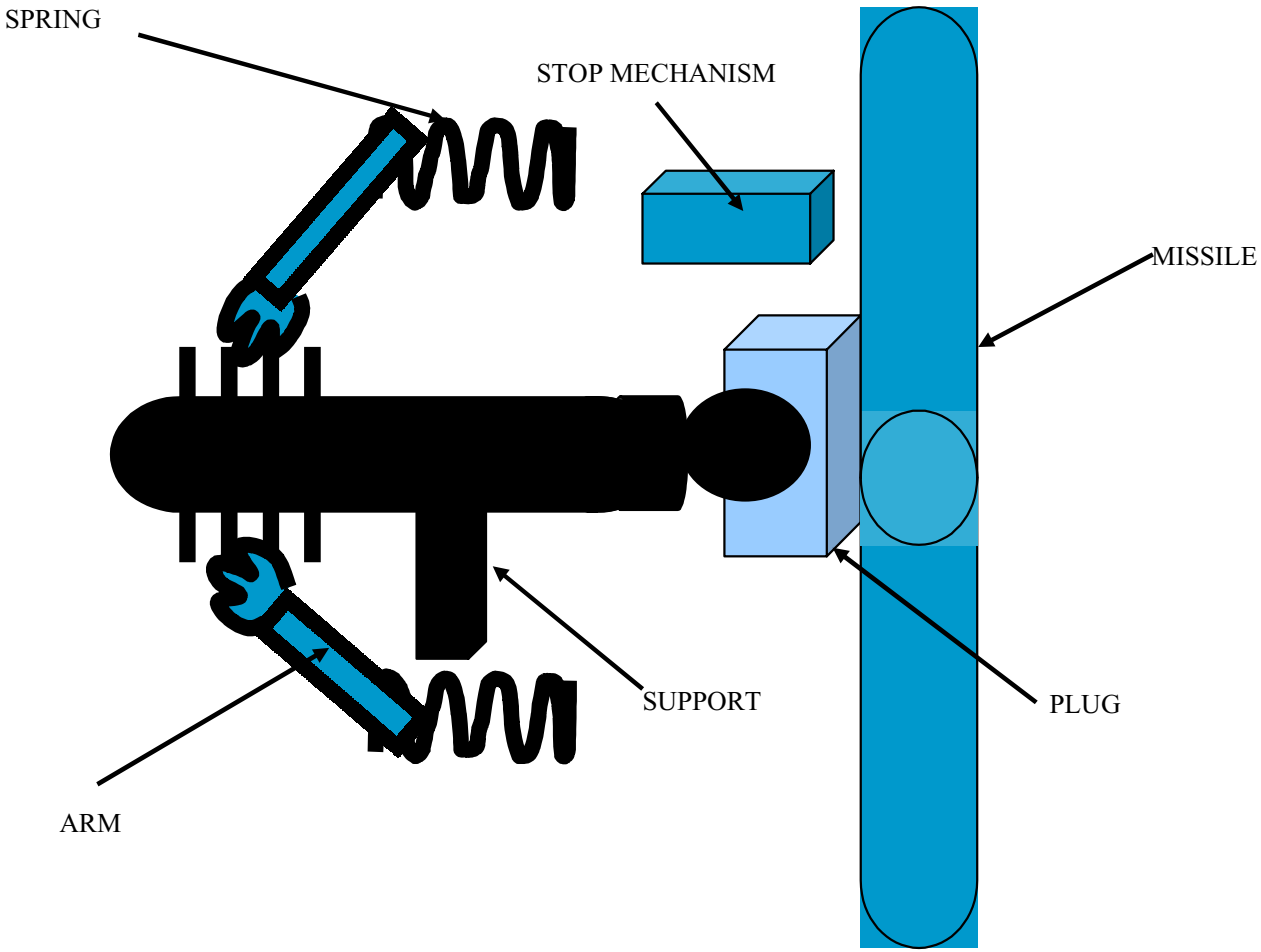
CONCEPTUALIZE, ANALYZE, DESIGN, AND PROTOTYPE A D5 UMBILICAL RETRACT MECHANISM



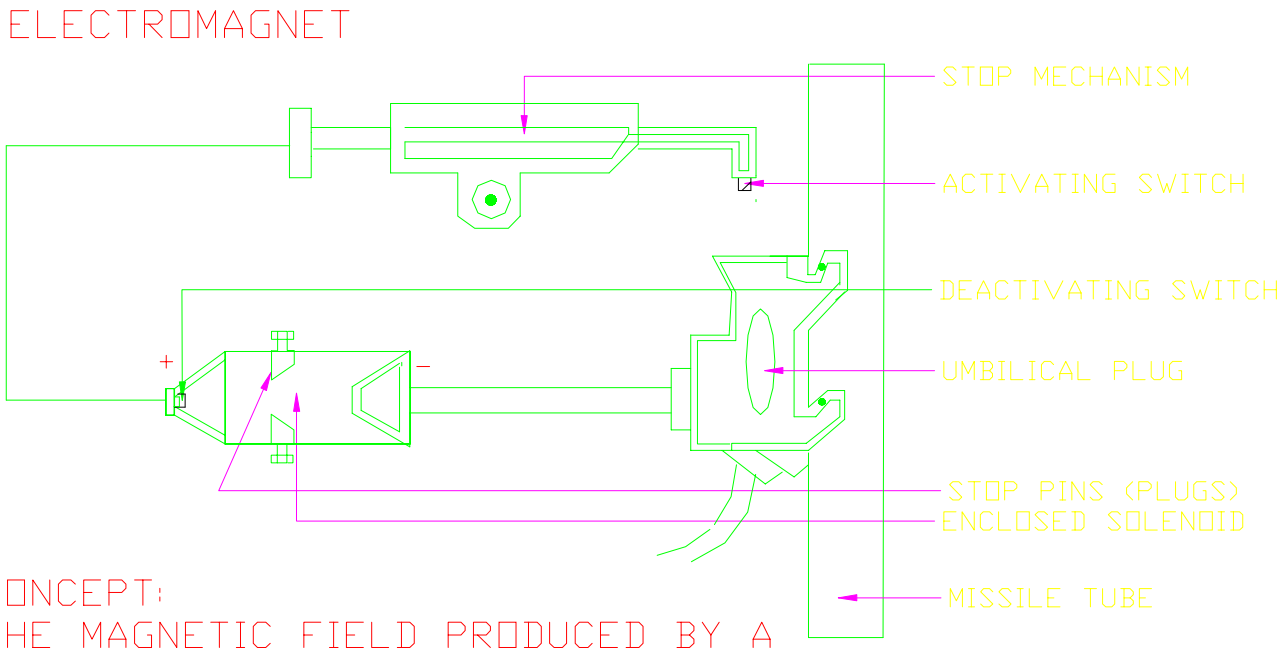
DESIGN CONCEPT 1



DESIGN CONCEPT 2



DESIGN CONCEPT 3

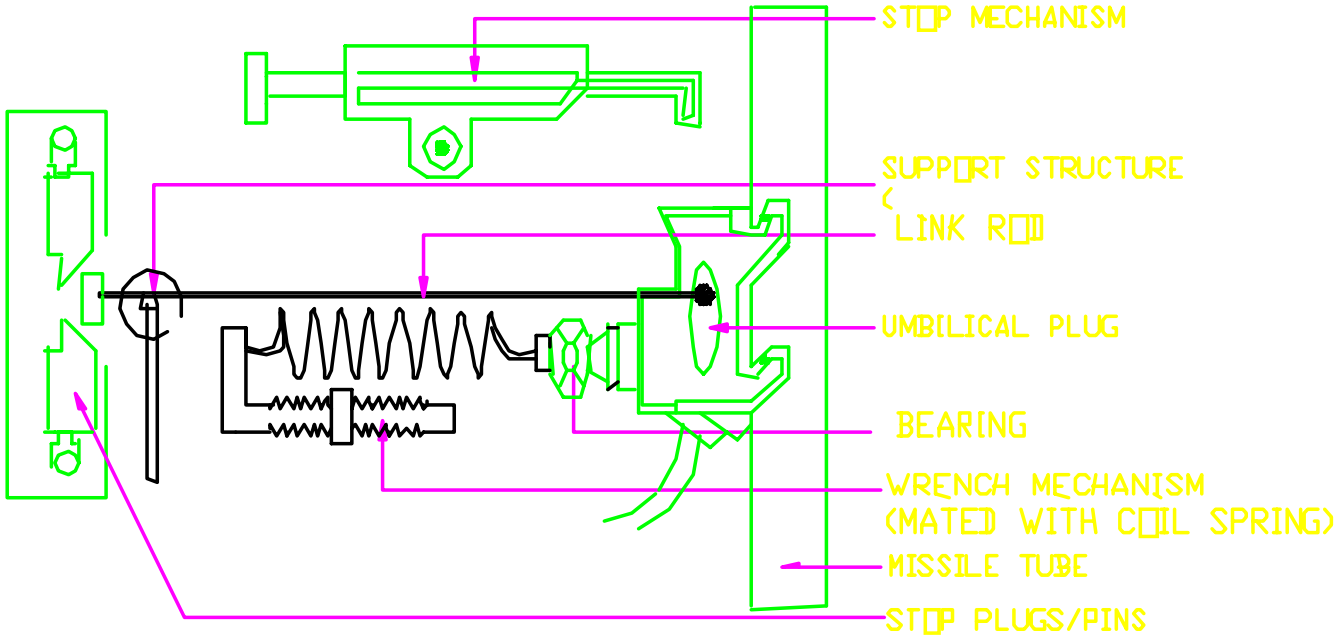


CONCEPT:
THE MAGNETIC FIELD PRODUCED BY A CURRRENT CARRYING CONDUCTOR IS UTILIZED FOR THE RETRACTION OF THE UMBILICAL PLUG

10-24-99

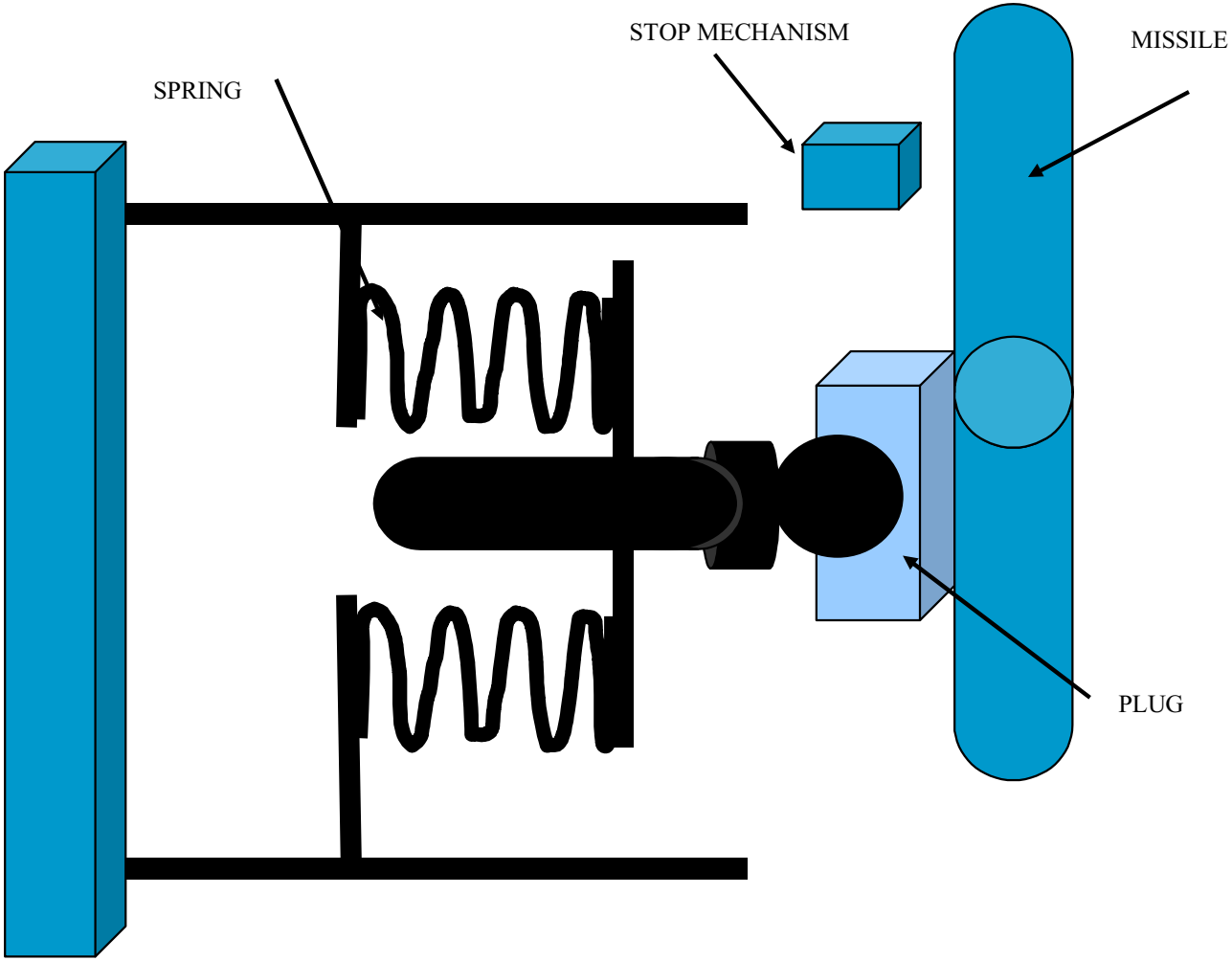
DESIGN CONCEPT 4

WRENCH/COIL SPRING MECHANISM

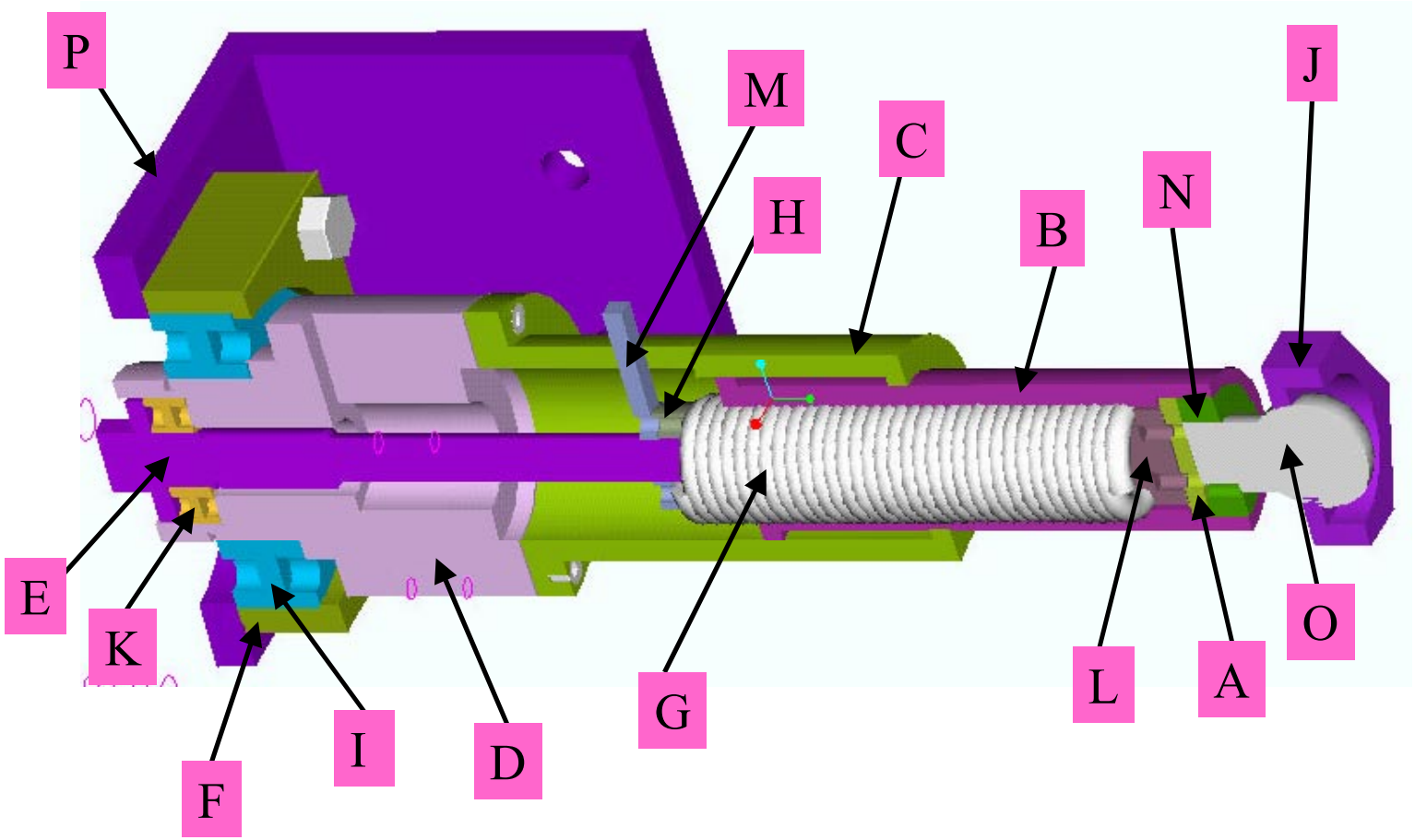


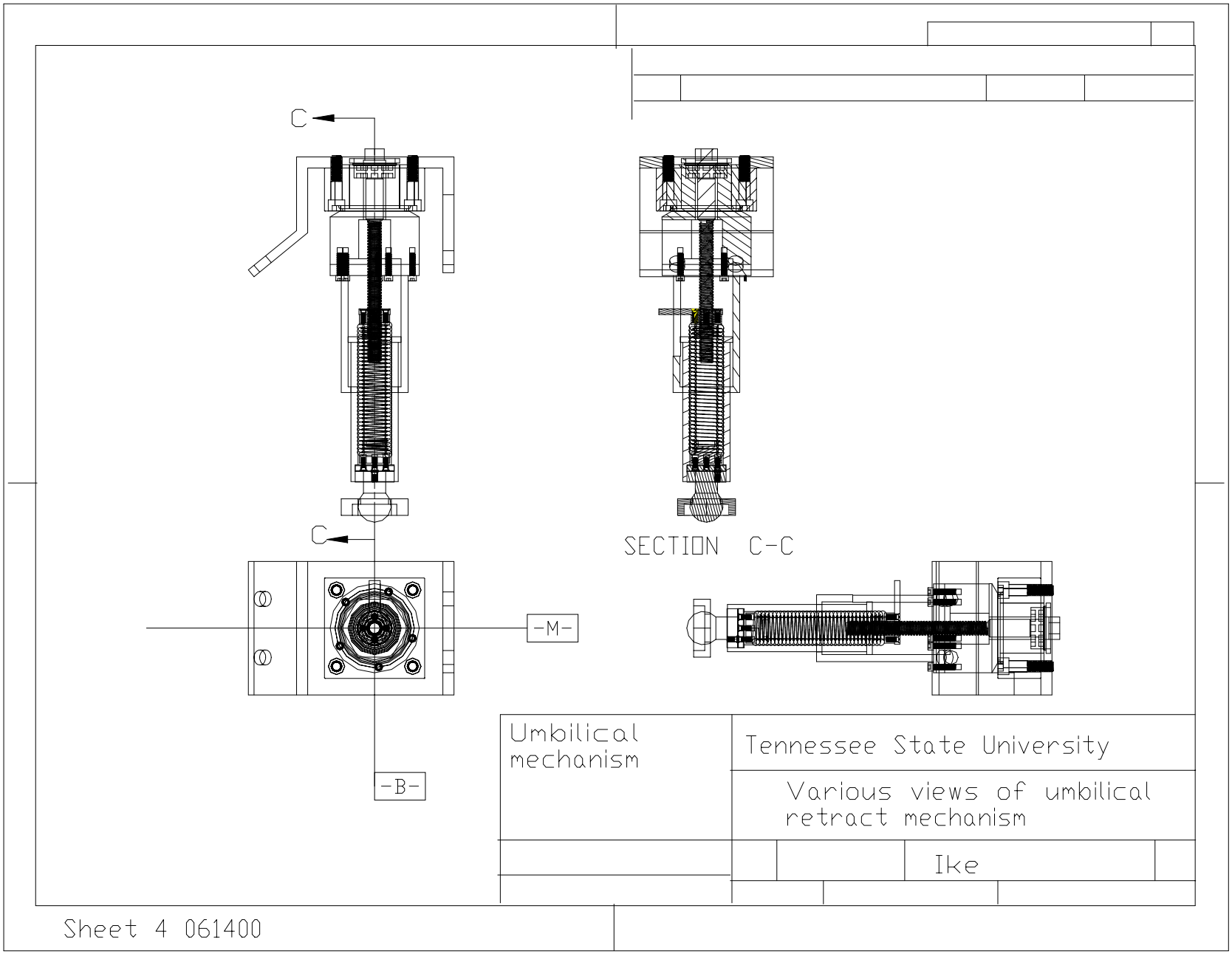
CONCEPT:
\ ≥ POTENTIAL ENERGY STORED IN THE SPRING IS UTILIZED FOR THE RETRACTION OF THE UMBILICAL PLUG.

DESIGN CONCEPT 5

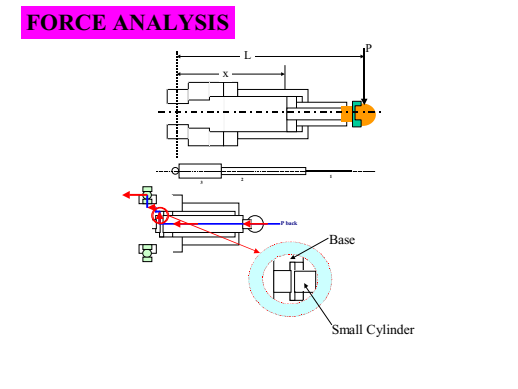


FINAL DESIGN CONCEPT



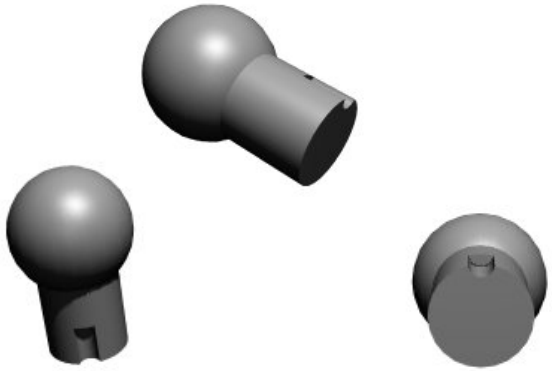

C
C
SECTION C-C
-M-
-B-
Umbilical mechanism
Tennessee State University
Various views of umbilical retract mechanism
Ike
Sheet 4 061400

DESIGN ANALYSIS

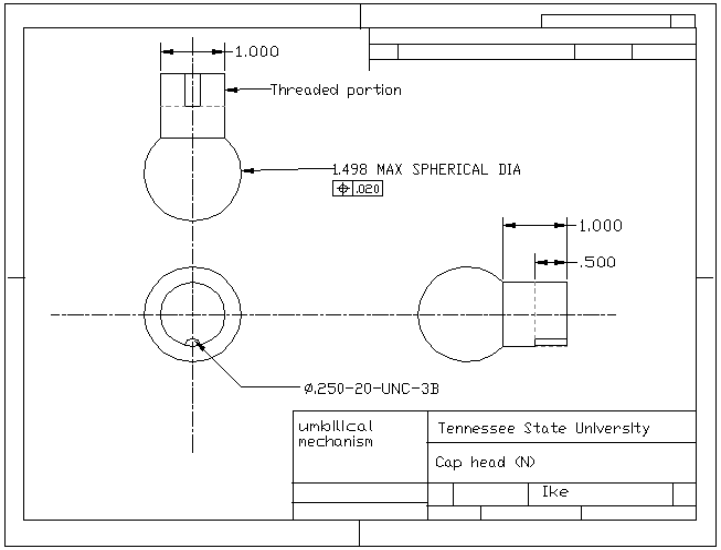


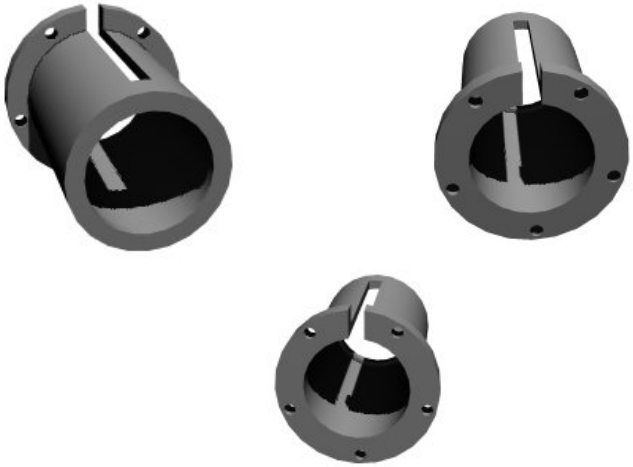
- **DETERMINISTIC DESIGN METHOD**
- ***Difficult to meet design and functional requirements***

- **PROBABILISTIC DESIGN METHOD**
- ***Limit State Function***
- ***Probabilistic Fault Tree Analysis***
- ***Sensitivity Analysis***
- ***Easier to perform component and system design***
- ***Easier to meet design and functional requirements***

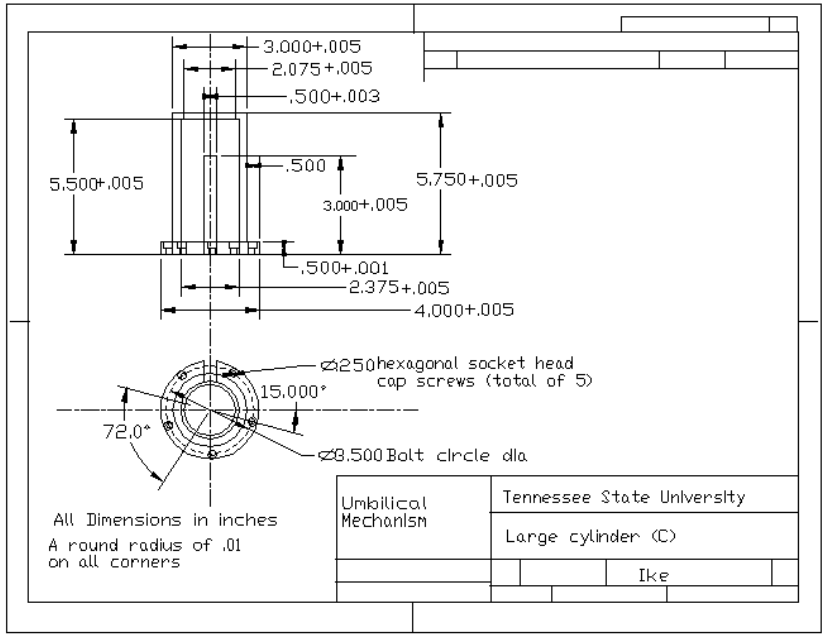


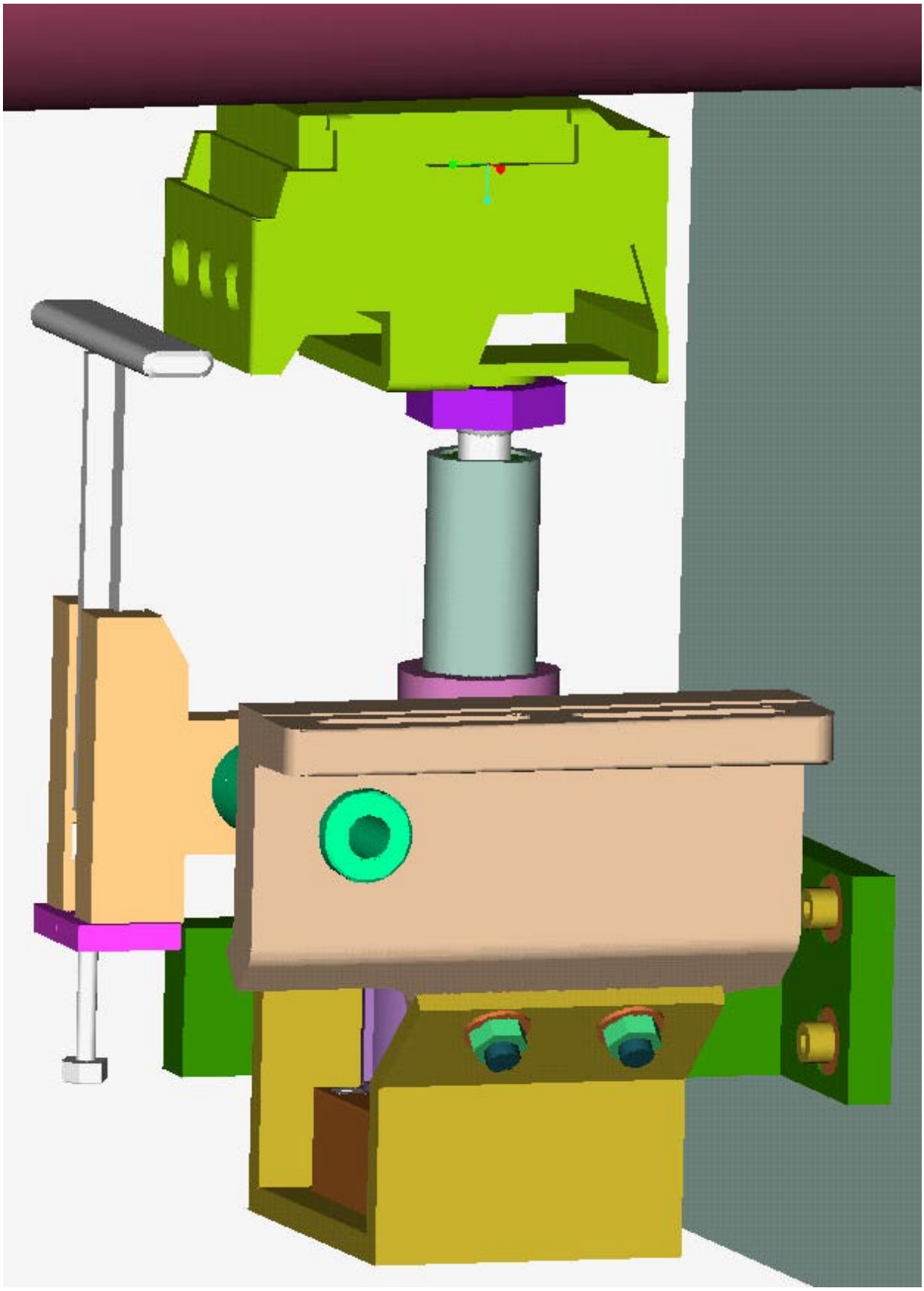
CAP HEAD (N)

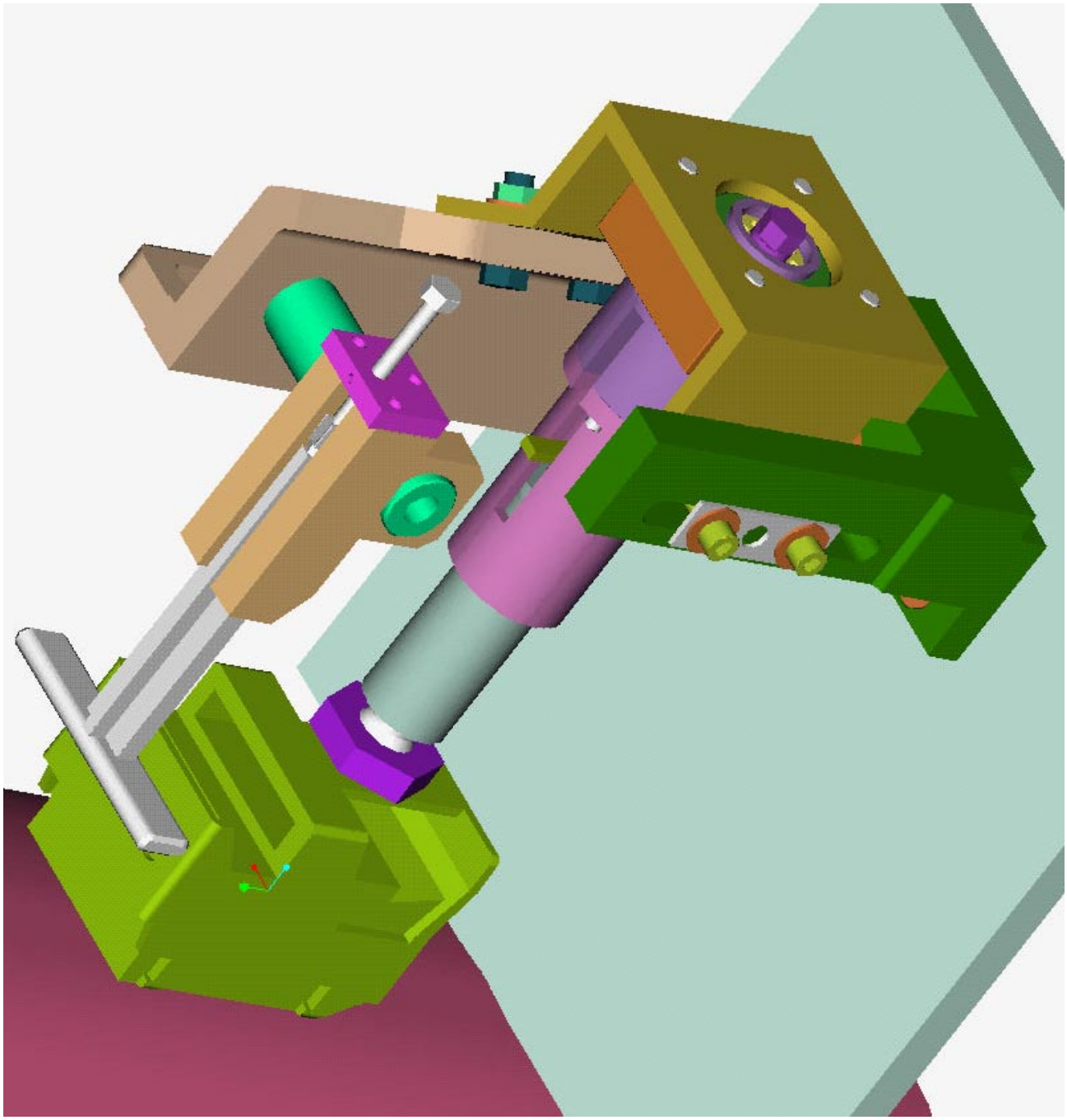


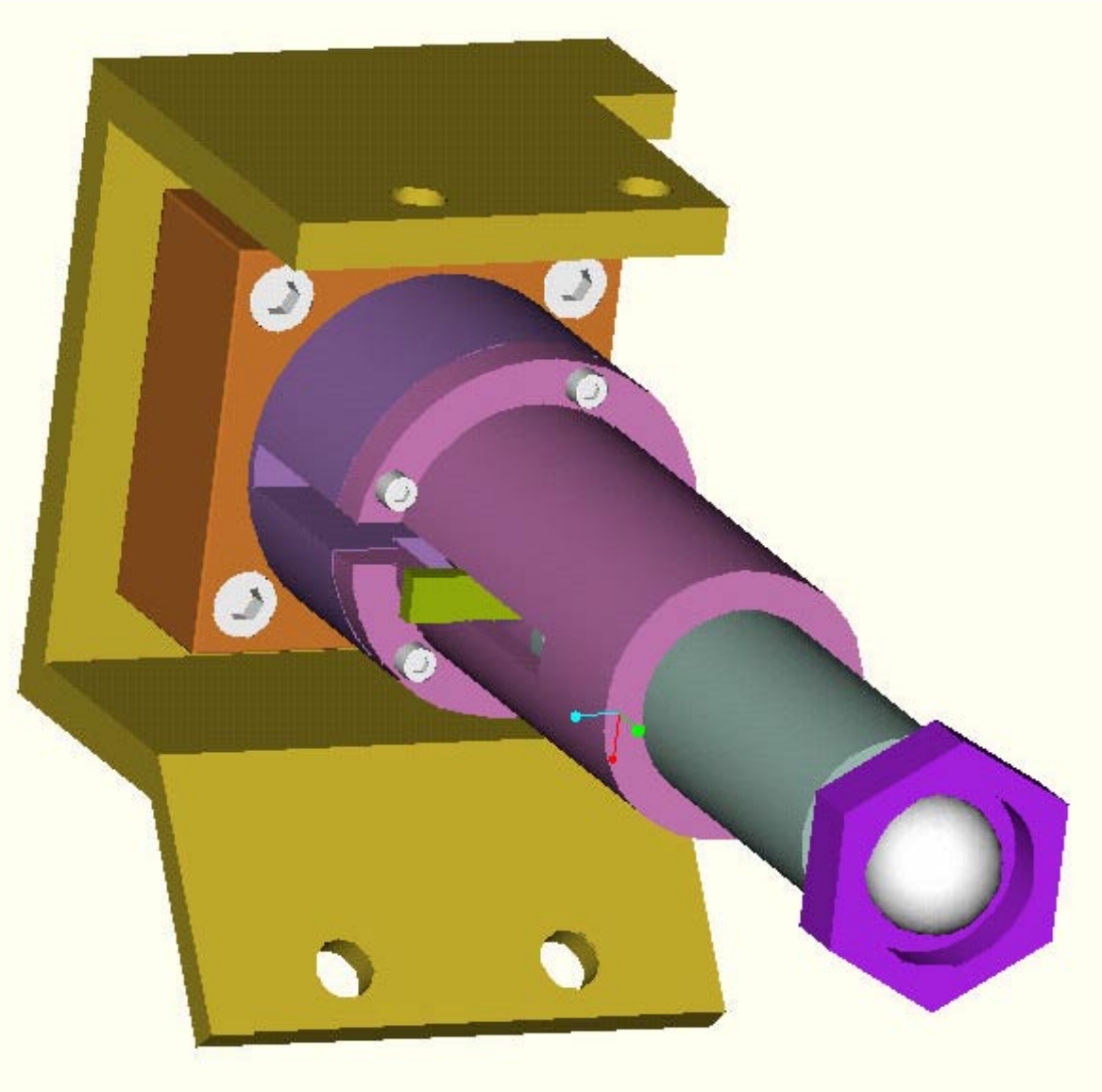


LARGE CYLINDER (C)

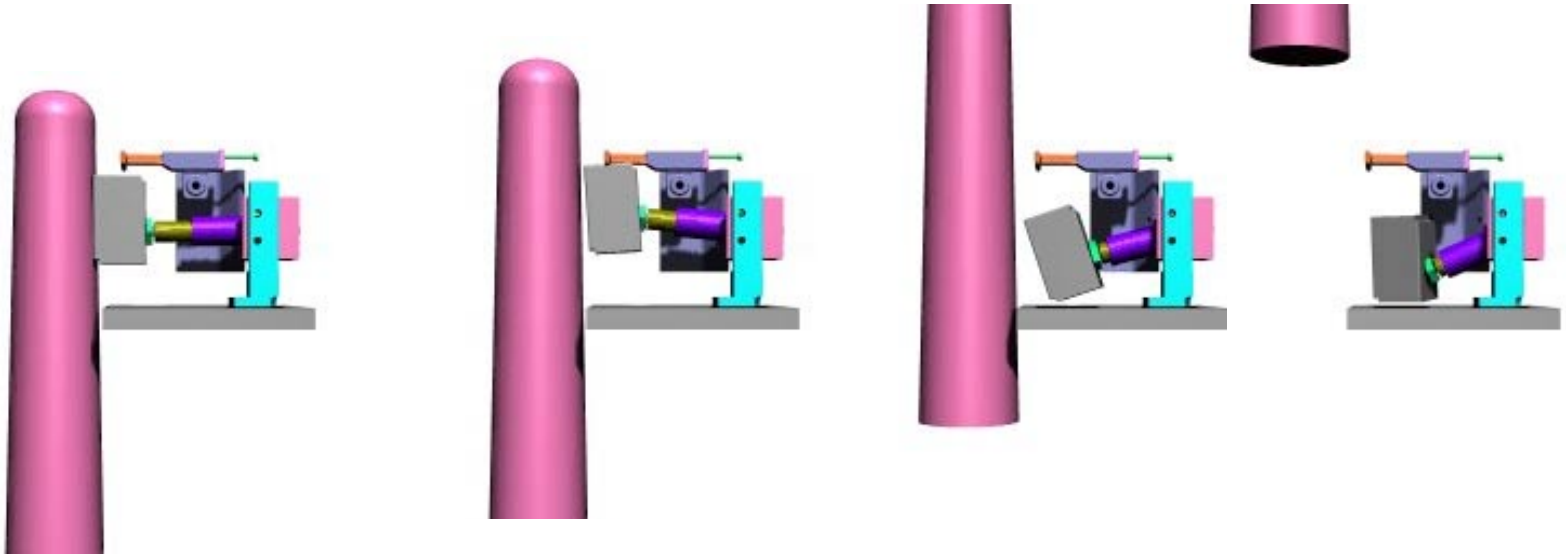




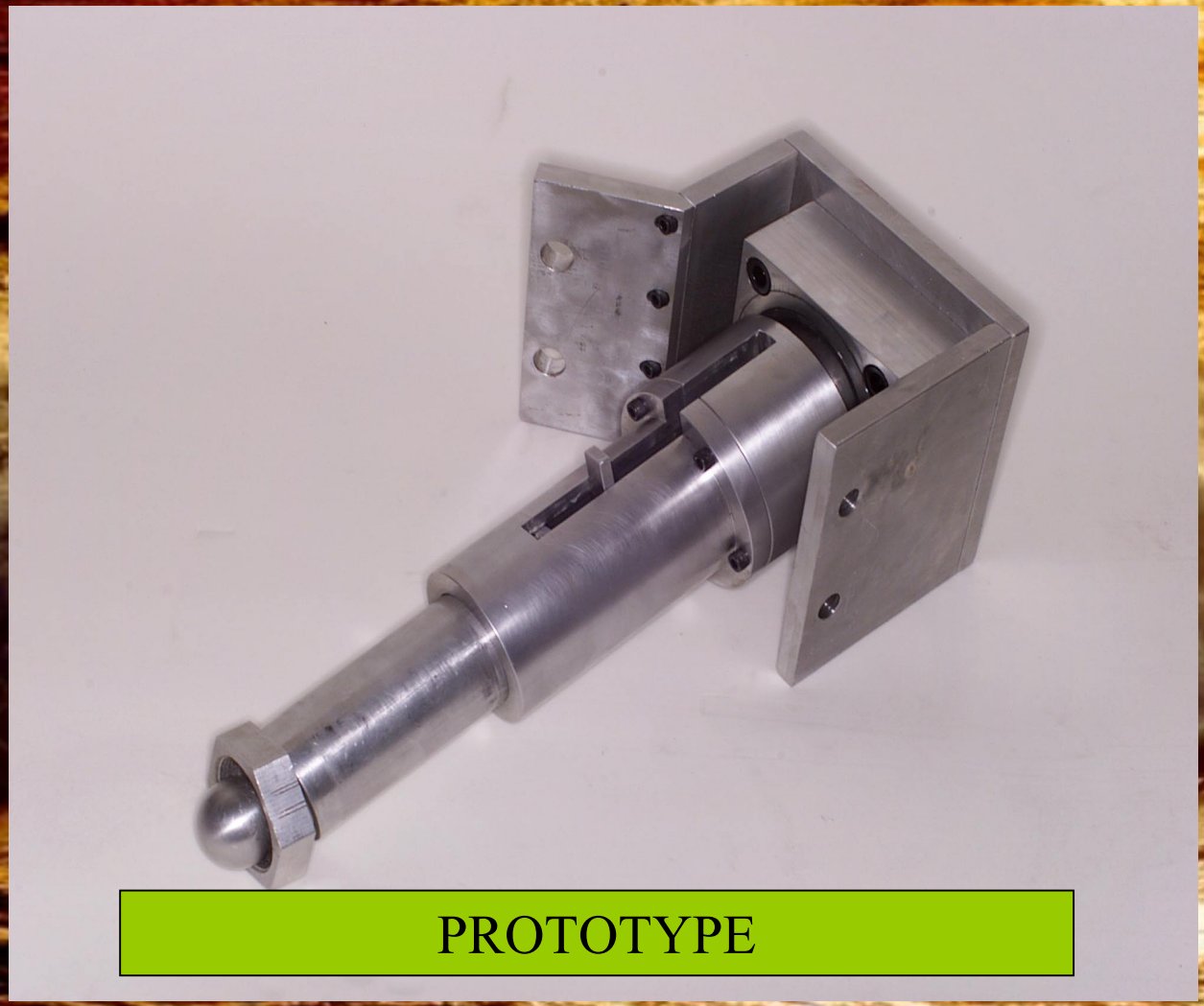


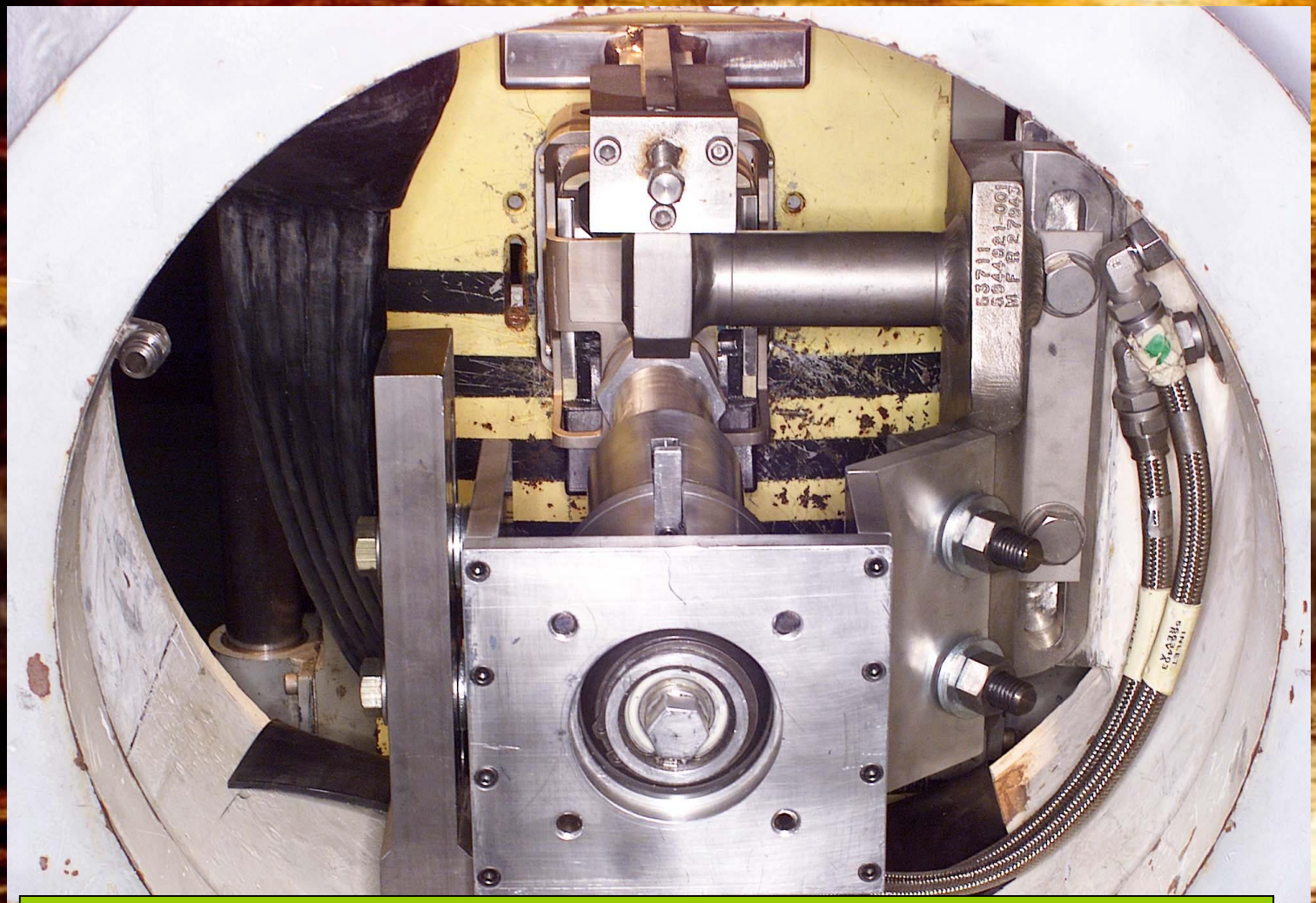


THE DESIGN OBJECTIVE

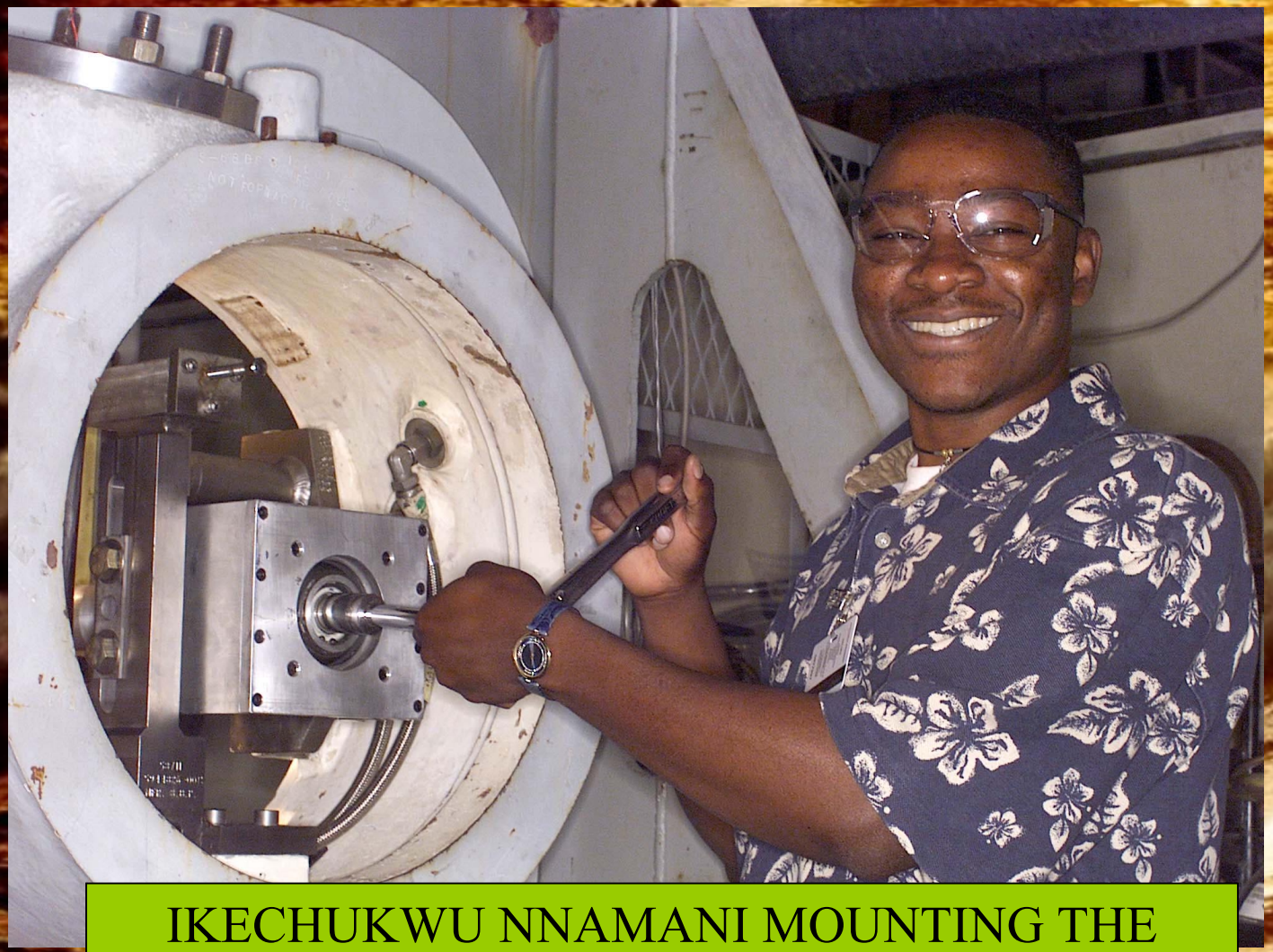


STAGE 1 STAGE 2 STAGE 3 STAGE 4


PROTOTYPE



THE UMBILICAL MECHANISM MOUNTED IN THE TEST FIXTURE



IKECHUKWU NNAMANI MOUNTING THE PROTOTYPE

SUCCESSFUL TESTING

CONCLUSION

- Project was completed on time and within the original budget
- The new design is half the weight of currently used retract mechanism
- The cost of manufacturing the new design is a fraction of the cost of the currently used retract mechanism
- Prototype passed a total of twelve test successfully
- The application of probabilistic design methodology contributed to an optimum and robust design
- The project was declared very successful by the US Navy

ACKNOWLEDGEMENT

- Most of the material in this presentation are based upon work supported by NASA Lewis Research Center, Applied Research Laboratory at Penn State, and the US Navy (Strategic Systems Programs). They are gratefully acknowledged

Probabilistic Reliability Validation of an Impeller Using DARWIN™

Sandeep Muju, Rick Nelson, and Jeff Lentz
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DARWIN (Design Assessment of Reliability With INspection) is a computer program for prediction of probability of fracture in aircraft engine rotor disks. Its risk prediction process includes finite element analysis based stress distribution, fracture mechanics based crack growth calculations, material defect distributions and nondestructive inspection simulation. Southwest Research Institute is developing this program as part of the Turbine Rotor Material Design (TRMD) contract under FAA sponsorship.

As part of the TRMD program, Honeywell is conducting failure risk prediction validation of DARWIN for hard alpha analysis using actual component experience. Specifically, the case considered herein involves a fielded impeller that has accumulated significant service cycles but has not experienced any hard alpha issues in the field. However, during routine production overspeed an impeller of this type did experience a spin-pit event due to a hard alpha inclusion.

This case challenges the two extremes of risk prediction process. First, the overspeed spin-pit case will be analyzed for DARWIN validation from the standpoint of high failures per cycle (single cycle failure). Second, the same impeller will be analyzed using field conditions for DARWIN validation from the “null hypothesis” (extremely low failures per cycle) probability standpoint. Figure 1 shows the stress results for the spin-pit overspeed condition.

This work presents the results of the DARWIN predicted failure risk probability and shows calibration results with both field and spin-pit experience.

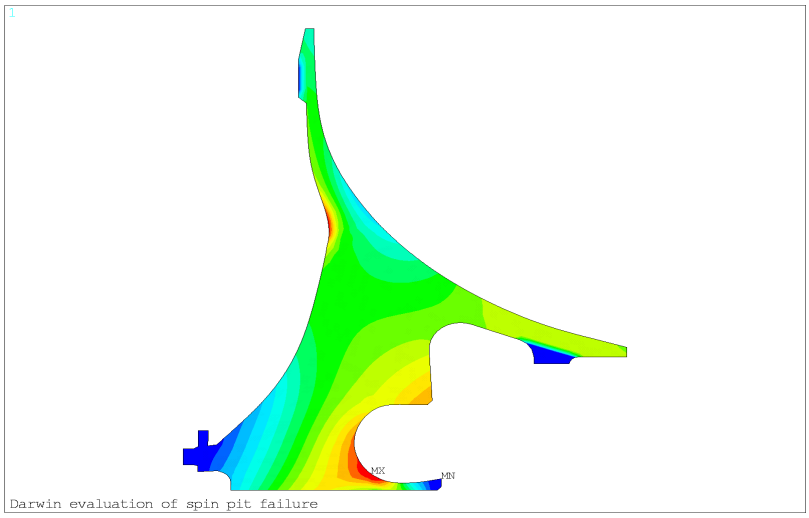


Figure 1: Spin-pit Overspeed Condition, Principal Stress Contour

NASA/CP—2002-211682

Probabilistic Reliability Validation of an Impeller Using DARWIN

Sandeep Muju, Rick Nelson and Jeff Lentz
Honeywell Aerospace Engines & Systems
Phoenix, Arizona

5th Annual FAA / Air Force / NASA / Navy
Workshop on the Application of Probabilistic Methods to Gas Turbine Engines
Cleveland, Ohio

June 11-13, 2001

Agenda

- DARWIN Overview & History
- Impeller - Field Experience
- Impeller - Spin Pit Experience
- Design Considerations
- Conclusions & Recommendations

DARWIN Is a Practical Risk Analysis Tool

- Developed by Southwest Research Institute and engine OEM's
- FAA funded
- Steering Committee includes major OEM's
- Performs probabilistic risk analysis for critical components
  - -Monte Carlo based
  - -Several types of crack growth models
  - -Includes effects of inspection schedules & POD curves
- Full featured GUI automates many critical pre/post-processing tasks

Impeller Problem Challenges Extremes of Risk Prediction

(A) Low-risk "null-hypothesis" prediction for zero failure field experience

Key Characteristics:

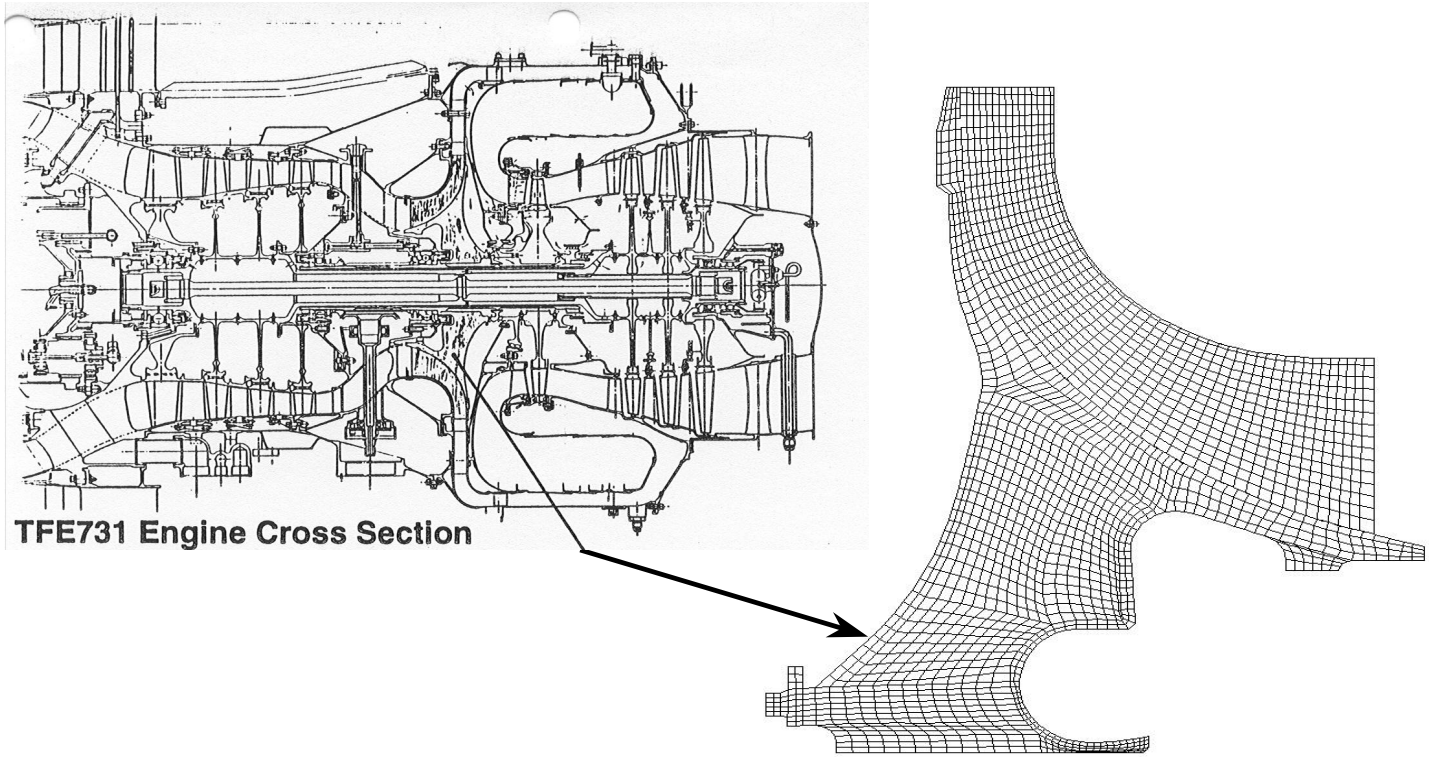
- No field failures experienced
- Large number of field cycles accumulated (>10^6 field cycles)

(B) High-risk "infant mortality" prediction for spin-pit overspeed failure

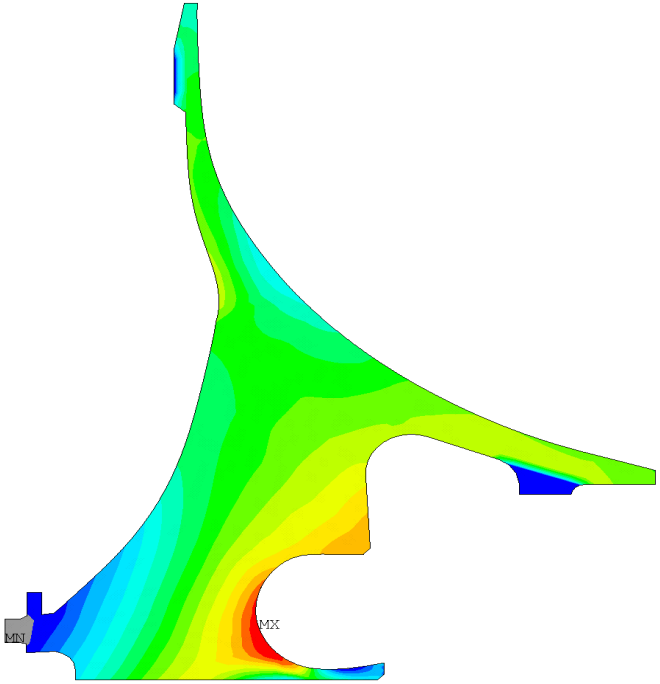
Key Characteristics:

- Hard alpha (HA) near the peak stress (LCF limiting) location
- Large size HA
- FPI inspection missed the HA defect
- Peak stress roughly 40% higher than field experience

Impeller FE Model Provides Basis for Risk Analysis



Field Impeller Case: Peak Stresses Occur During Takeoff Transient

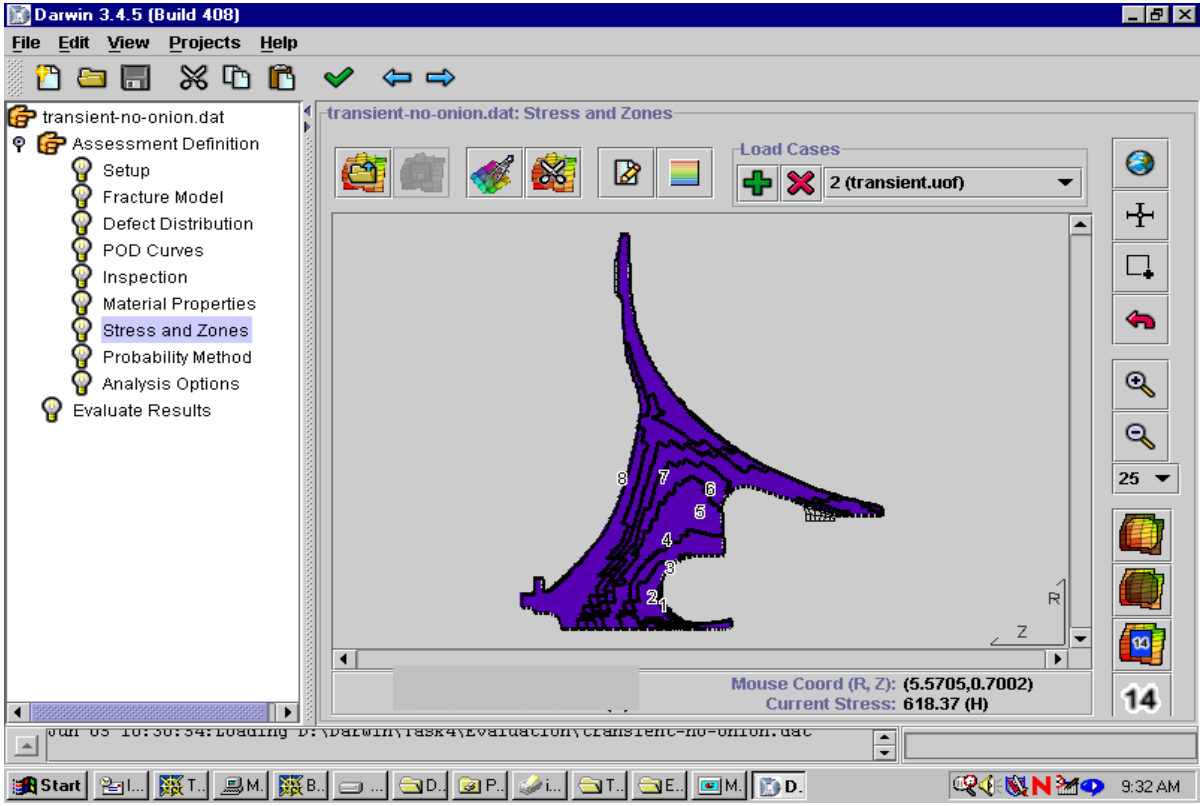


Transient Case Risk Analysis Shows Strong Contribution of High Stress Zone to Risk Prediction

- Risk analysis based on 1 zone representing the high stress location and volume scaled to the full impeller.
  - risk results ~ 10^{-10} failures/cycle

- Risk analysis based on 8 zones (covering the full impeller volume).
  - risk results ~ 10^{-10} failures/cycle

GUI Worked Well for Transient case Risk Analysis



Results for Field Impeller Agree With Experience

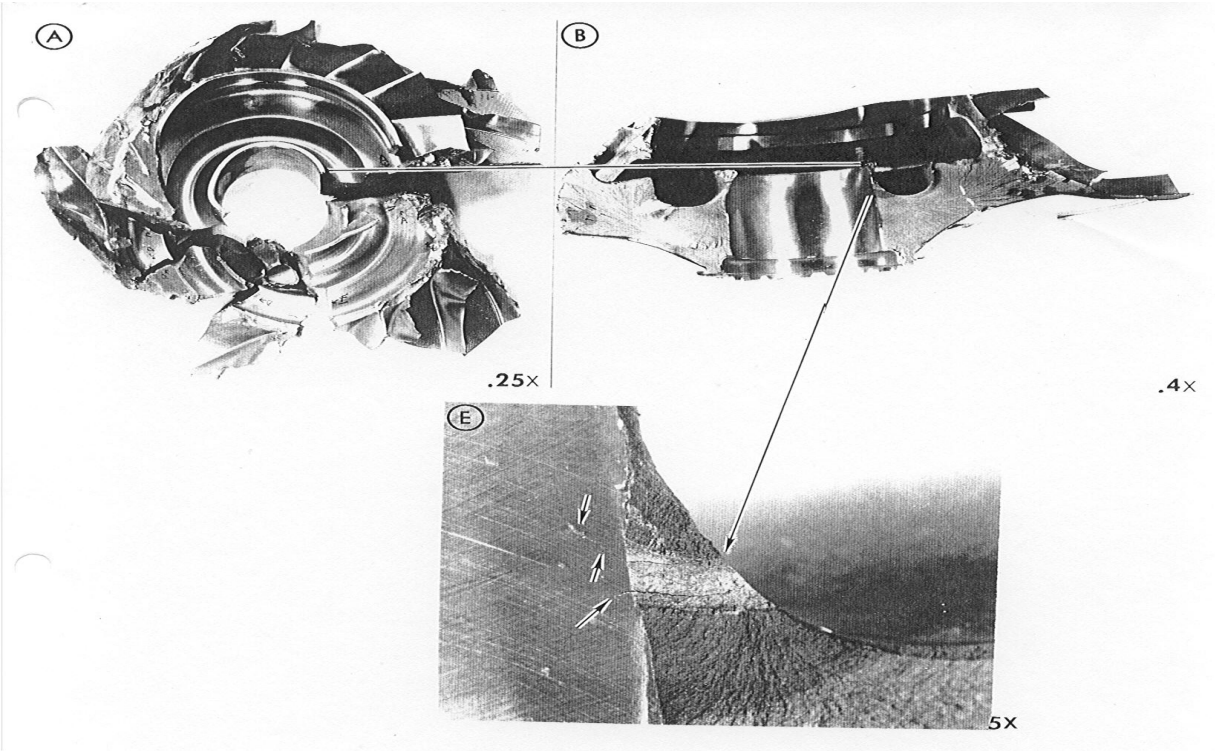
Key Findings:

- Risk analysis results sensitivity to defect distribution is high

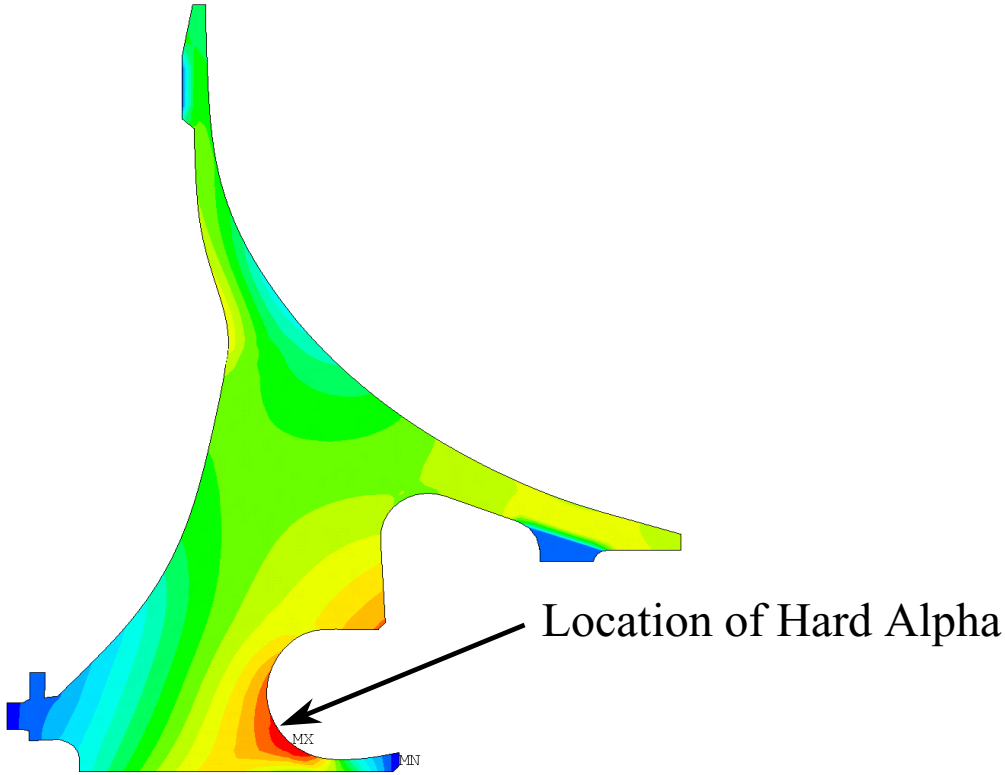
- Risk contribution from the highest stressed zone dominates
    - Zone refinement from 1 to 8 only changed results by ~20%

- Risk results may vary slightly between multiple risk analysts due to variability associated with zone (stressed volume) and fracture mechanics (plate) definitions.
    - “Best Practices”/”Design Criteria” for risk-analysis processes may need to be developed to reduce this variability.

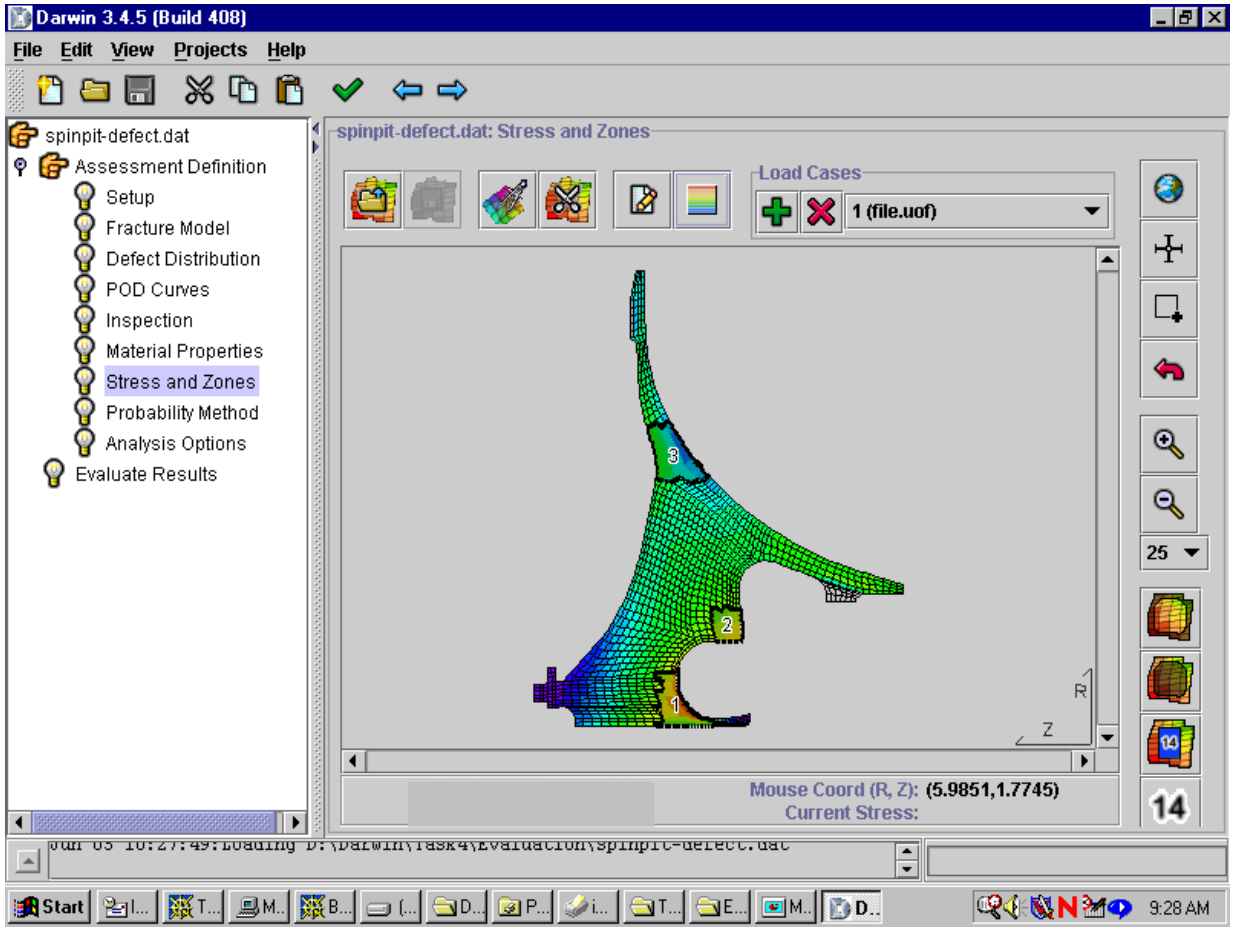
Spin-pit Impeller Case: Disk Fractured in One Cycle During Routine Production Overspeed



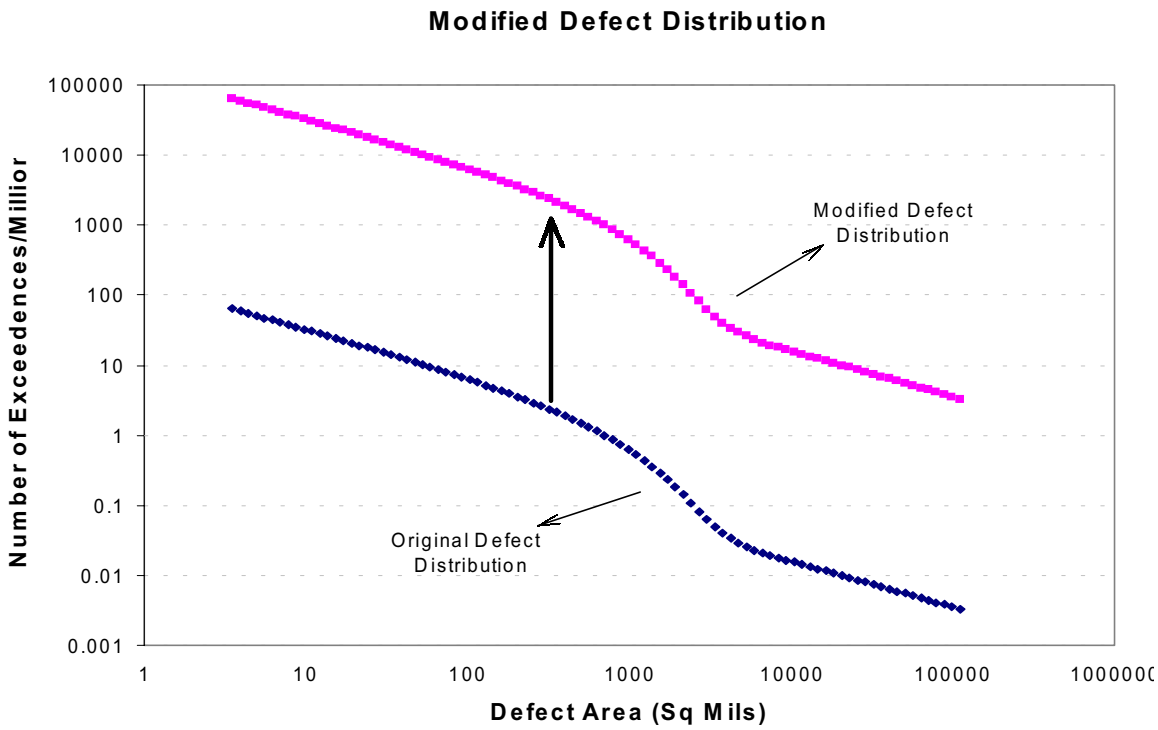
Spin-pit Stress Analysis Results Show Max Stress Near Hard Alpha Location



Spin-pit Analysis Has Three Highly Stressed Risk Zones



Standard Vs Modified Defect Distributions Used to Analyze Spin-pit Case



Spin-pit Case Was Analyzed Using Both Standard and Scaled Defect Distributions

Fracture Calculations done by Flight-Life Darwin Module
(Peak stresses ~40% greater than field transient stresses)

- Results with AIA defect distribution (overspeed condition)
    - Crack Growth Life ~ 10^3 Spin-pit cycles
    - Risk result ~ 10^-9 failures/spin-pit cycle

- Results with scaled AIA defect distribution (overspeed condition)
    - Crack Growth Life ~ 0 Spin-pit cycles
    - Risk result ~10^-5 failures/spin-pit cycle

Spin-pit Overspeed Analysis Highlights Importance of Appropriate Defect Distribution

- Defect distribution is a strong factor in risk predictions.
- Use of standard defect distributions (AC 33.14) is unable to capture the infant-mortality risk scenario.
    - Dominant reason: For the one particular spin-pit impeller the standard defect distribution predicts low probability of occurrence of the defect of the size found.
- Artificially scaling the defect distribution to predict the defect found in the impeller volume produces reasonable life/risk results.
- Volumetric stress more important than local stress variations in determining overall risk (HA or surface related).
- Focusing zone(s) only on high stress volume and using the appropriate volume produced acceptable results.

Design Practice Must Address Risk Considerations

•Previous Design Practice:

– Disk is rough sized based on Burst, LCF, etc. capability

– Further refinements of the design utilize detailed analyses and performance requirements

•Risk (HA or Surface) Based Design Practice:

–Since overall failure risk is mainly driven by stresses integrated over the volume, the risk level is established during early design.

–Further design refinements will likely have only have minor effects on overall risk predictions.

•Risk and Life (LCF, CCGR, Burst) analysis complement each other in producing reliable and efficient designs.

•NDE inspection is still critical to identify defects for process control.

Conclusions and Recommendations

- Risk result comparison of in-house codes (RISKANAL & NASCRAC) vs. DARWIN was very favorable (FAA AC Test Case, August 2000).
- DARWIN based risk predictions for the spin-pit and fielded cases compare well with experience.

On a general level (Surface as well as HA Risk):

- Defect distributions play a critical role in risk predictions.
- Since risk predictions are by definition for a large number of parts/components, extreme risk predictions for a particular part may not be feasible.
- NDE inspection is still critical to identify defects for process control.
- Risk analysis must complement Life (LCF, CCGR) analysis. One provides a fleet averaged estimate of failure probability and the other a deterministic "safe life" prediction for a particular part/component. Both are valuable to a designer.

5th Annual FAA/Air Force/NASA/Navy Workshop

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13. ABSTRACT ***(Maximum 200 words)***

We were pleased that you were able to attend the 5th Annual FAA/Air Force/NASA/Navy Workshop on the Probabilistic Methods for Gas Turbine Engines hosted by NASA Glenn Research Center and held at the Holiday Inn Cleveland West. The history of this series of workshops stems from the recognition that both military and commercial aircraft engines are inevitably subjected to similar design and manufacturing principles. As such, it was eminently logical to combine knowledge bases on how some of these overlapping principles and methodologies are being applied. We have started the process by creating synergy and cooperation between the FAA, Air Force, Navy, and NASA in these workshops. The recent 3-day workshop was specifically designed to benefit the development of probabilistic methods for gas turbine engines by addressing recent technical accomplishments and forging new ideas. We would like to thank you for your participation in the workshop, because you were the key in accomplishing our goals of minimizing duplication, maximizing the dissemination of information, and improving program planning to all concerned. This CD Proceeding includes the final agenda, abstracts, presentations, and panel notes, plus the valuable contact information from our presenters and attendees. We hope that this CD Proceeding will be a tool to enhance understanding of the developers and users of probabilistic methods. The fifth workshop doubled its attendance and had the success of collaboration with the many diverse groups represented including government, industry, academia, and our international partners. So, “Start your engines!” and utilize these proceedings towards creating safer and more reliable gas turbine engines for our commercial and military partners.

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