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A Primer in Advanced Fatigue Life Prediction Methods

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1999 NASA Seals/Secondary Air System Workshop

Cleveland, Ohio
October 28-29

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A Primer in Advanced Fatigue Life Prediction Methods

Gary R. Halford, NASA Glenn Research Center

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 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.

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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.)*
- *Multi-Factor Approach*
- *Damage Mechanics Models*
- *Fatigue Crack Growth Models*
- 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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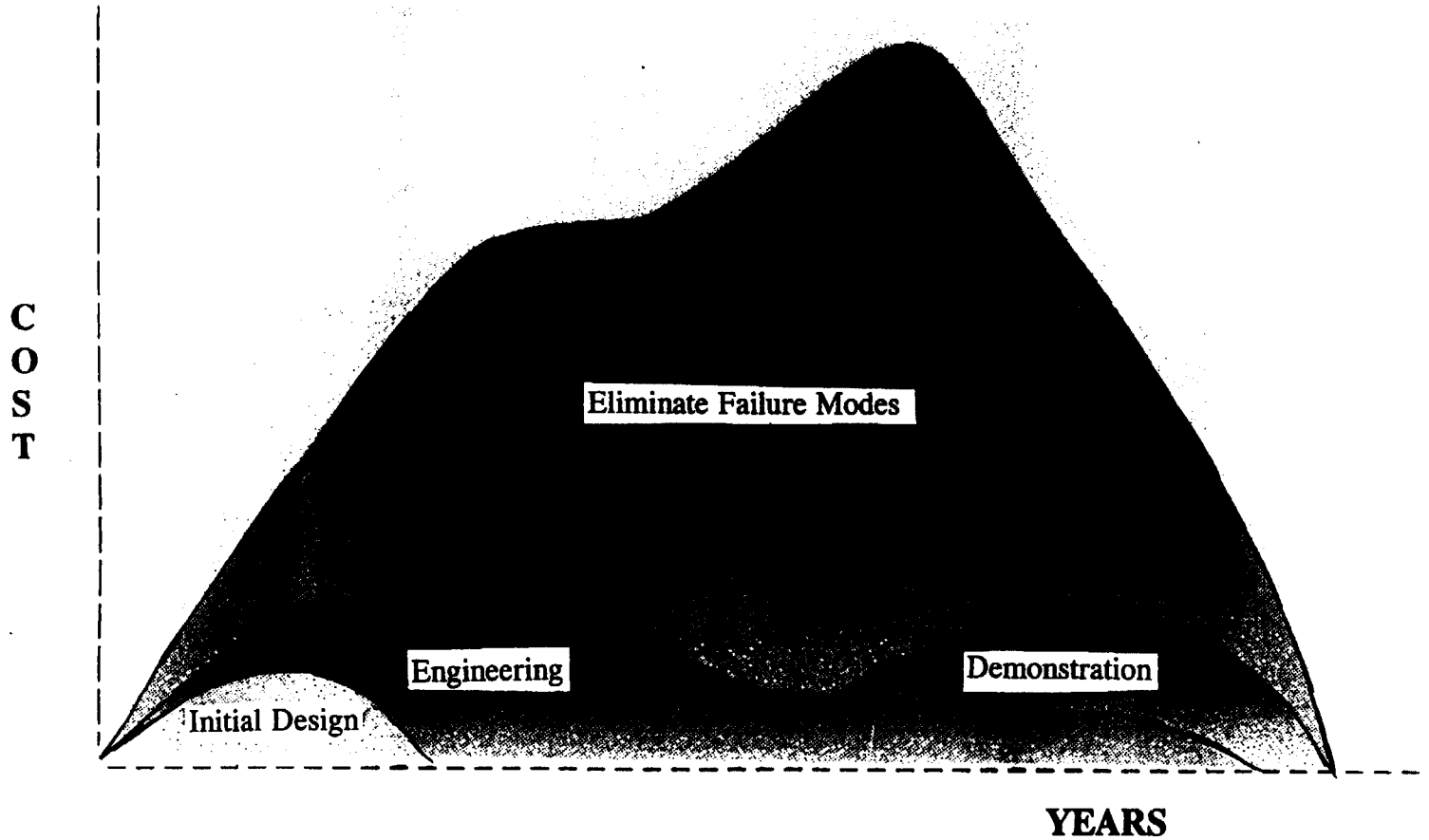
DEVELOPMENT COSTS DRIVEN BY FAILURES

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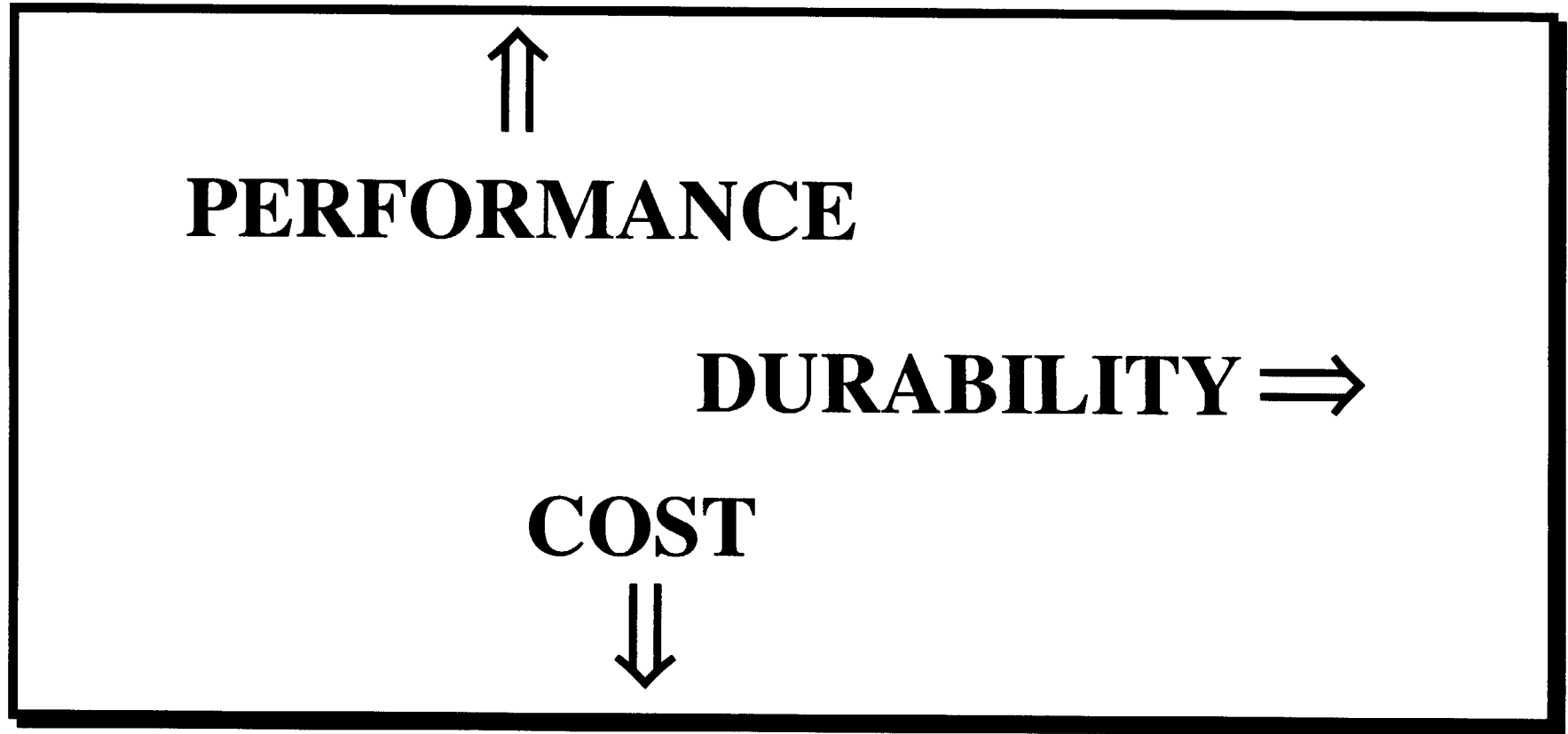T

Eliminate Failure Modes

Engineering

Demonstration

Initial Design

YEARS

COST FACTORS

Elimination Failure Modes	73%
Engineering	15%
Demonstration	10%
Initial Design	2%

Fig. Courtesy: Rockwell International

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Primary Trade-off Troika Drivers

⇑

PERFORMANCE

DURABILITY ⇒

COST

⇓

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Overriding Requirements
- Legislated or Public Outcry

⇑   ⇑

⇐SAFETY   & ENVIRONMENTAL ⇒

⇓   ⇓

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Elements of Durability Analyses

0 - Mission and Environmental Loading Analysis

0 - Global Structural Response Analysis

0 - Internal 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

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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

0 - Continuously update analytic models

0 - Take full advantage of probabilistic analyses

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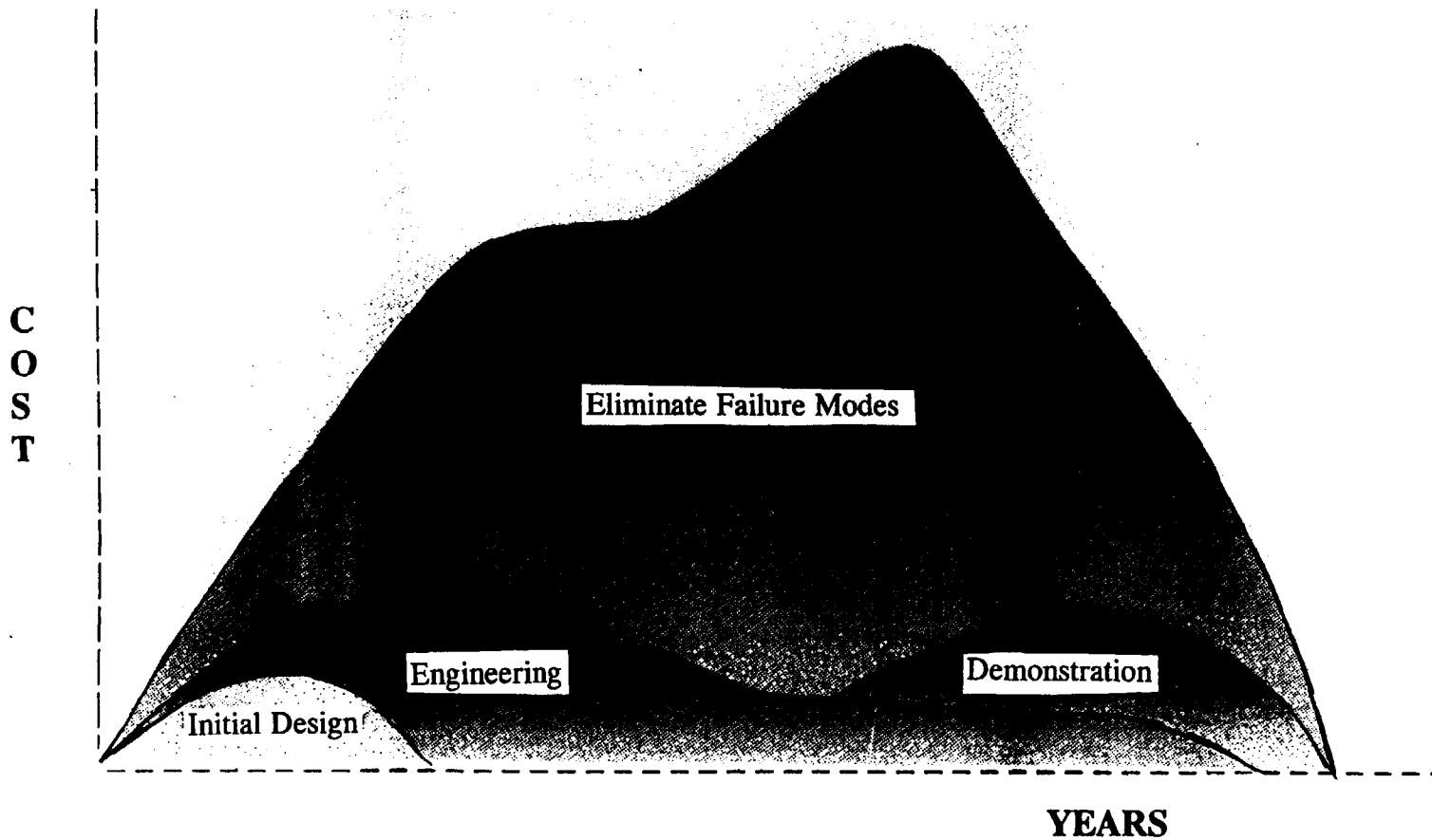
Glenn Program	Description
-PMUS	***Estimates Fatigue Resistance of Materials*** - Tensile Ductility & Tensile Strength - Cryogenic, Ambient, High Temperatures (10% Rule)
-LIFE	***Predicts Cyclic Life of Components Below Creep Regime*** - Multiaxiality via Triaxiality Factor - Mean Stress Correction
-PNOTCH	***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 - 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 at Identified Critical Sections of High Temperature Components*** - 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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**Ensuring Structural Durability/Reliability of
Advanced Structural Systems and Materials
Will Require:**

0 - Less Reliance on Past Systems/Materials Experience

0 - More Reliance on Analyses

0 - More Reliance on Understanding the Physics (Cause & Effect)

0 - Maximizing Information from each and every Test by Analysis

0 - Take Full Advantage of Probabilistic Analyses

0 - Greater Extrapolations

0 - Greater Expense

0 - Acceptance of Greater Risk until Systems Mature

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DEVELOPMENT COSTS DRIVEN BY FAILURES

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YEARS

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