Prognosis

TMS 2003 Annual Conference

San Diego, California

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Acknowledgements

TMS for sponsoring the symposium

Session organizing committee

Numerous contributors who have helped shape our thinking on the subject

Sessions contributors

DEDICATED TO THE LATE ARTHUR DINESS -- A GREAT FRIEND AND INSPIRATION

Goals of the Presentation

Define “Prognosis”

Establish the context for “Prognosis”

Encourage collaboration across disciplines (materials, sensor technology, data processing and fusion, feature extraction, etc.).

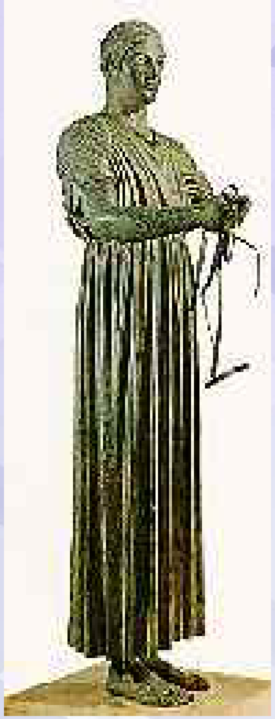
Provide an example of an approach

Definition

PROGNOSIS: -- Knowledge of future performance based on reliable prediction capability of individual platforms.

Context: -- Materials and Structures

Prognosis - Power is Knowing the Future



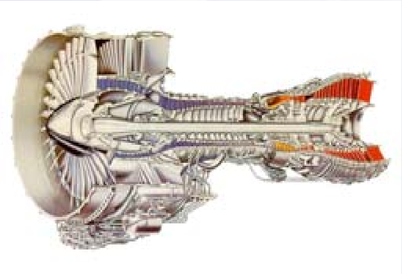
Delphi Oracle

Prognosis-based Asset Management Approach

- **Management, deployment and use of assets based on PROGNOSIS -- knowledge of future performance based on reliable prediction capability of individual platforms.**
  - **Managing according to knowledge of the individual and actual remaining performance**
  - **Managing uncertainty by reliable (physics-based?) predictive capability**
  - **Enabling material "state awareness"**

Prognosis Translates Knowledge and Information Richness to Physical Capability

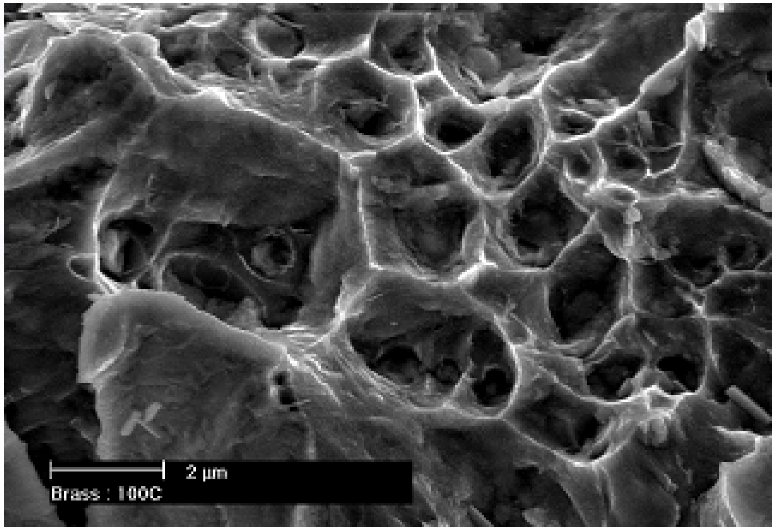
Present Paradigm

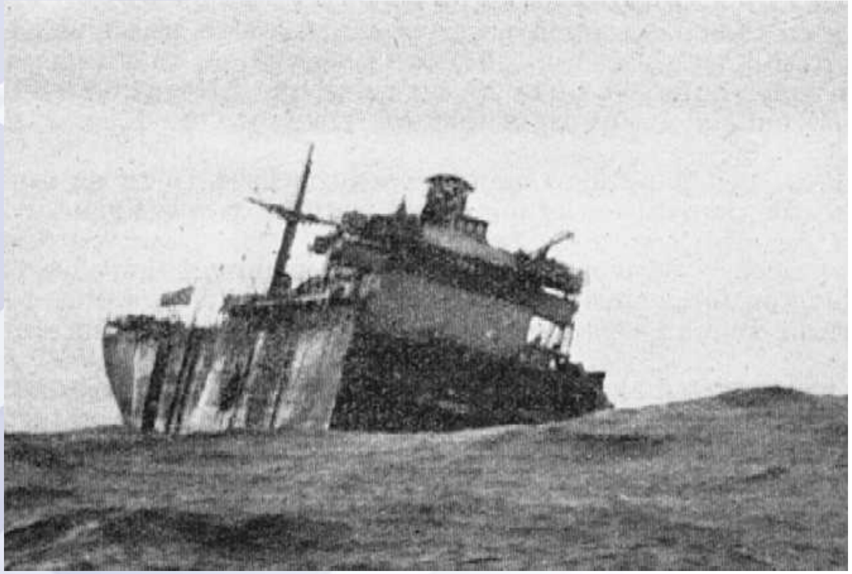


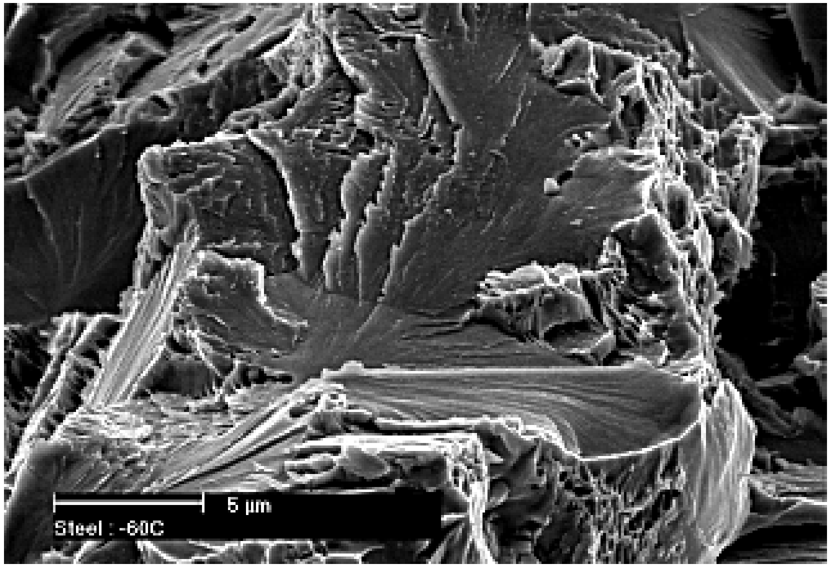
Presently, "Fear of Failure" controls our design, management, deployment and use of all critical elements of complex mechanical systems (aircraft, helicopters, space vehicles, submarines, ships, UAVs, etc.).

- **Forces undue conservatism (large safety factors) reducing performance.**
- **Severely impacts system availability and readiness.**
- **Forces non-optimal use of available assets.**
- **Results in high cost.**

Fear is Justified: Materials Failure Matters!







Fear is Justified: Materials Failure Matters!

Fear is Justified: Materials Failure Matters!

PROBABLE CAUSE: "The National Transportation Safety Board determines that the probable cause of this accident was the inadequate consideration given to human factors **limitations in the inspection** and quality control procedures used by United Airlines' engine overhaul facility which resulted in the **failure to detect a fatigue crack originating from a previously undetected metallurgical defect located in a critical area of the stage 1 fan disk** ……... The subsequent catastrophic disintegration of the disk result in the liberation of debris in a pattern of distribution and with energy levels that exceeded the level of protection provided by design features of the hydraulic systems that operate the DC-10's flight controls." (NTSB/AAR-90/06)

Date: 19 JUL 1989

Type: McDonnell Douglas DC-10-10

Operator: United Air Flight 232

Registration: N1819U

Year built: 1973

Total airframe hrs: 43401 hours

Cycles: 16997 cycles

Total: 111 fatalities / 296 on board

Location: Sioux City-Gateway, IA

The Present

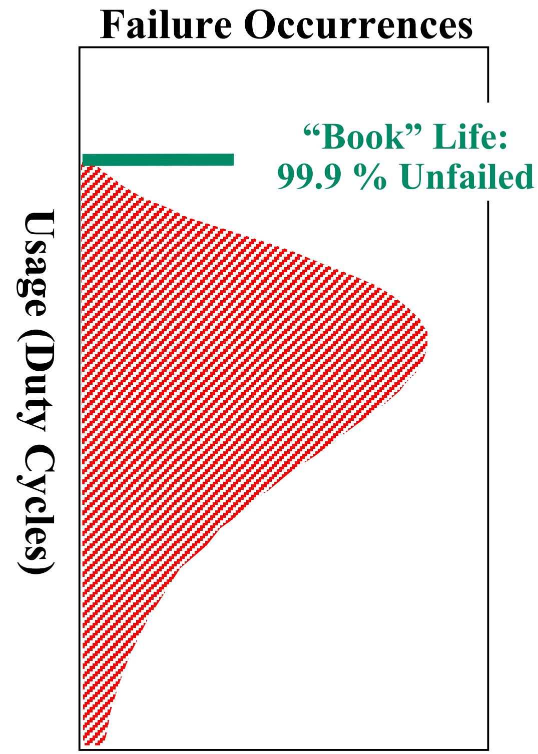
Management, deployment and use of high value systems is dominated by our fear of failure

Inspect

Empirical Criteria

Decision

Yes



NO

~~Database: Mission History, Maintenance, Life Extension and Design.~~

Impact of Uncertainty

The Prognosis Vision

Interrogation

State Awareness

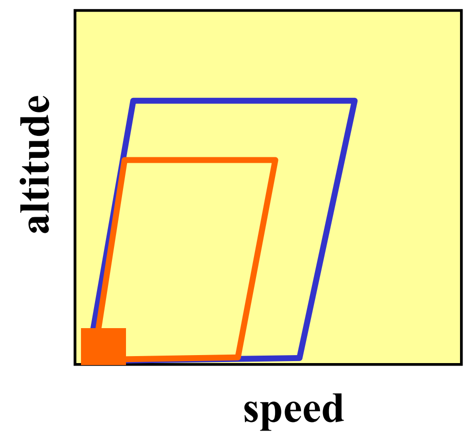
Failure physics, damage evolution, predictive models

Prognosis

Database: Mission History, Maintenance, Life Extension and Design.

Yes

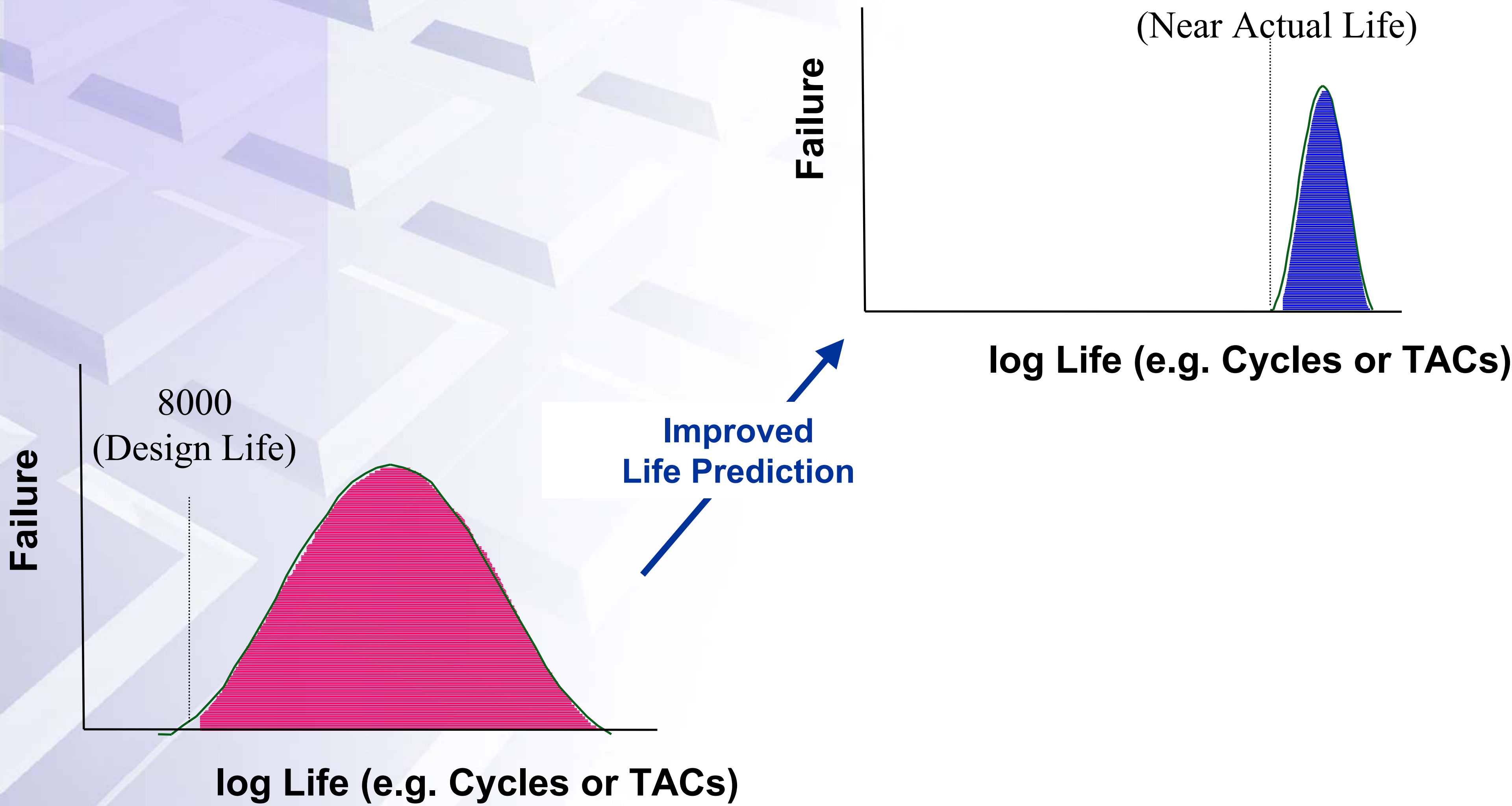
Capability Profile, e.g



NO

Prognosis Translates Knowledge and Information Richness to Physical Capability

Life Management Through Prognosis



Technical Approach

What are the enabling elements of a Prognosis paradigm?

How would one practice Prognosis?

What would one actually do?

How do you go from “dislocations” to throttle settings?

Interrogation and State Awareness

Interrogation

State Awareness

Conceptual:

- Not inspection
- Allows the material and structure to communicate its state

Practical:

- Local (embedded/in-situ) or global information
- Multi-spectral, -spatial, temporal
- May require external perturbation or pre-defined maneuver(s)
- Benchmarked (initially and subsequently?)
- MAY demand inspection (last resort)

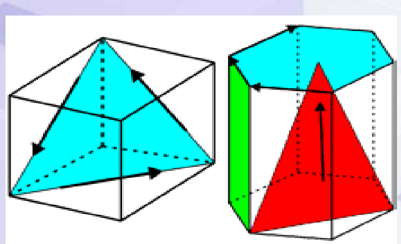
Computational:

- Feature extraction
- Dimensionality reduction
- Reliable error estimation

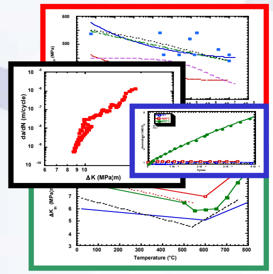
Physics of Failure

Model Development

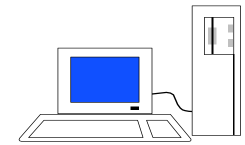
Crystal Plasticity Models



Auxiliary Models
- Subscale Processes
- Subscale Properties
- Defect Distributions
- Microstructural Data
- Residual Stresses



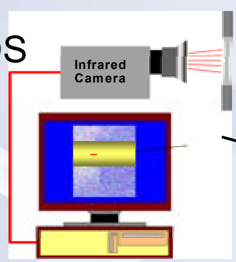
Scalable Computational Models and Algorithms
- Explicit FEA
- Adaptive Meshing
- Multi-scale Models



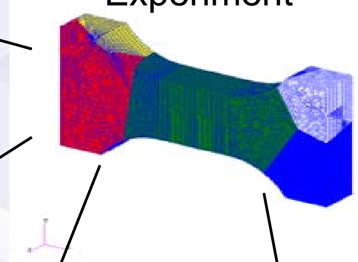
Physically Based Life Prediction Model

Model Validation

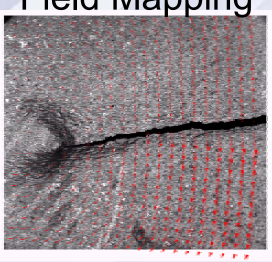
IDDS



Interactive Analysis and Experiment



Displacement Field Mapping



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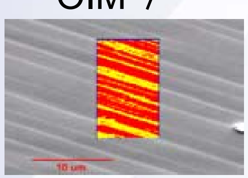
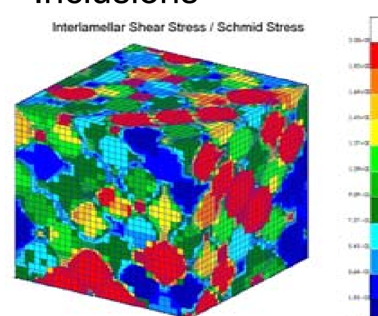


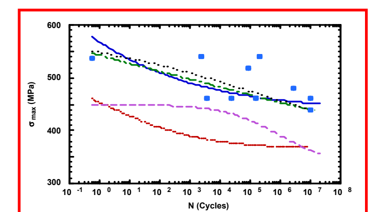
Conventional Testing

Life Prediction

Analytical Predictions
- Polycrystal Plasticity
- Machining Defects
- Inclusions



Probabilistic Material Characterization

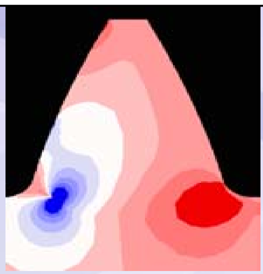


Crack Initiation and Growth Prediction

The Link

System Parameters (throttle setting)

CFD, FEM



Temperature, stress, time, environment, etc. (incl. distribution)

Component, e.g., disk

Physics of Failure

Temperature, stress, time, environment, etc. (incl. distribution) inputs to state equations

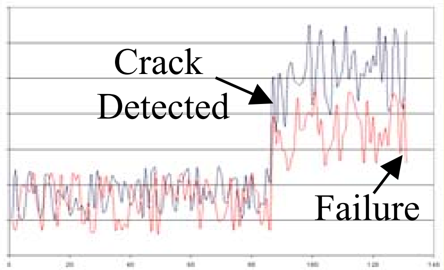
Creep ?↔ HCF ?↔ LCF

Fret. ?↔ Embr. ?↔ Envr.

Interrogation Tools for State Awareness

Global

- Thermal
- Acoustic
- Vibration



Local

- Laser Ultrasonics
- Thermoacoustic
- Thermoelectric

Evolving Material Microstructure

Failure is Neither Random or Unpredictable

Failure mode DOMAINS well defined (fatigue, creep, corrosion, etc.)

Failure is progressive:

NUCLEATION/INITIATION

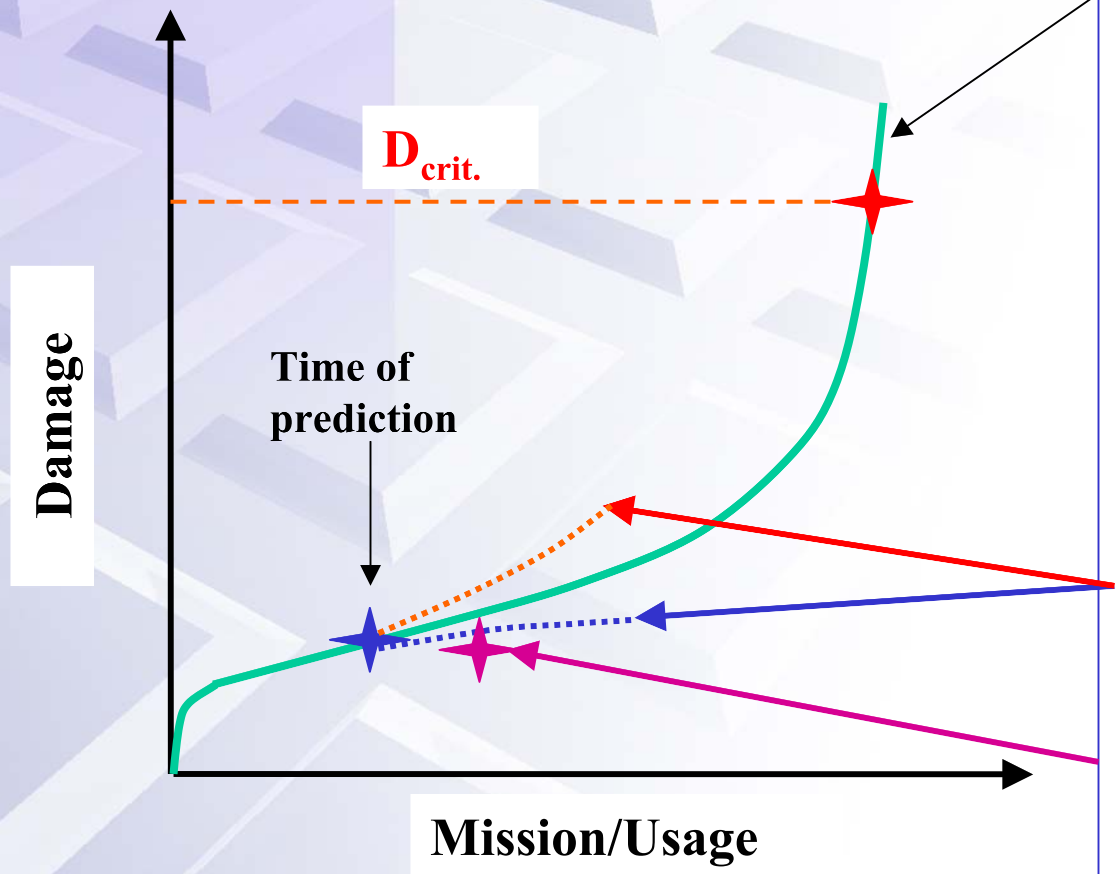
PROPAGATION/ESCALATION

COALESCENCE

Reliable failure PREDICTION will be accomplished by combination of;

1. Models of physics of failure
   - Evolution of damage
   - Coupled effects
2. Interrogation tools for state awareness
   - Local AND global
   - Signature manifestations

Conceptual Model/State Awareness Fusion



Knowledge of failure domains establishes functional behavior of damage evolution.

Tracking changes not absolute values.

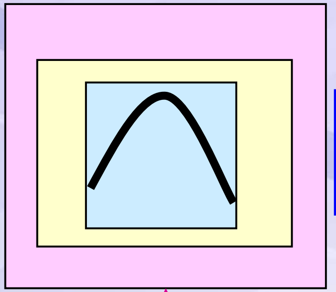
Fidelity/reliability increases with prognosis system usage and maturity.

Short term predictions more reliable than long term "lifing" predictions.

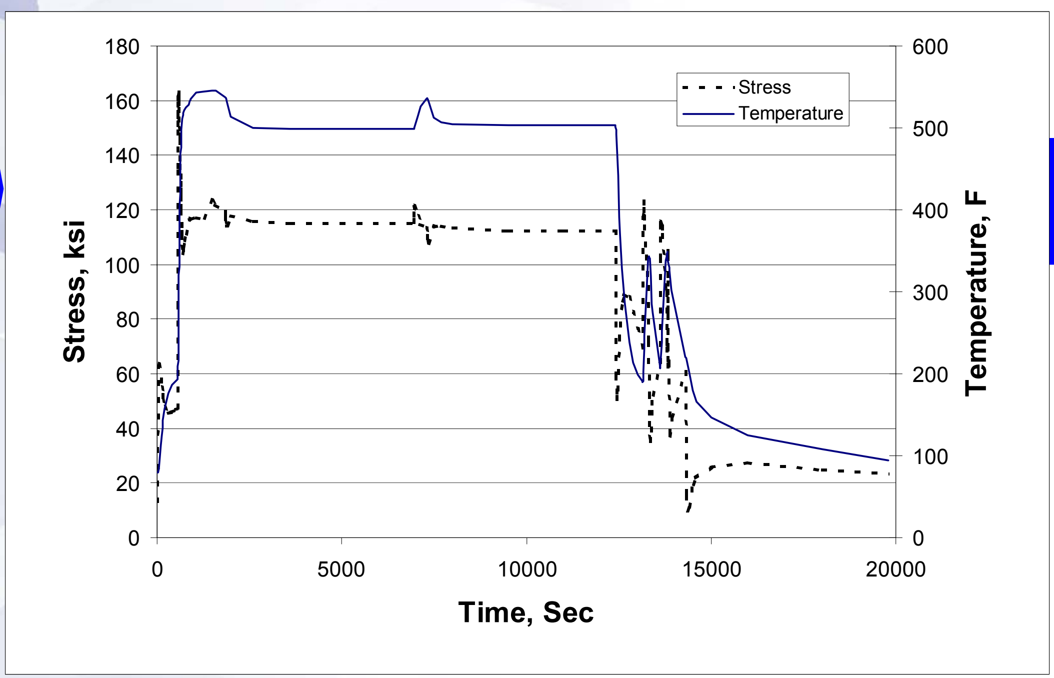
Uncertainty in model predictions modulated by state awareness tools.

How Does it Work?

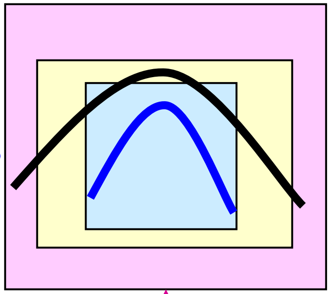
State at time, t



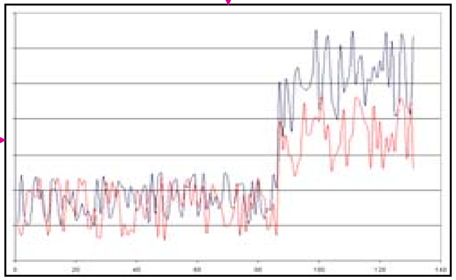
Model Mission



State at time, t+Δt



Signature of "new state" provides confidence that model prediction is within expected regime.



Vision: Materials Damage Prognosis

Key science and technology disciplines

- Coupled physics-based models of materials damage and behavior
  - Interaction of multiple damage/failure mechanisms
  - Multi-scale, mechanism-based
  - Microstructurally-based stochastic behavior
  - Integrated information from state-awareness tools
- Interrogation of damage-state
  - Intelligently exploit existing sensors
  - Feature extraction from global sensors
  - Materials-damage-state interrogation techniques and recorders
  - Sensor signature analysis
- Data management and fusion
  - Capability matched to mission
  - Component usage data
  - Component history and pedigree

Concluding Remarks

- Urge vigorous discussion
  - Constructive dialogue not (just) criticism
- Thinking “out of the box”
- Encourage inter- and multidisciplinary research
- Attack the hard problems
  - How do use sensor data to update model predictions?
  - How to efficiently link localized (micro) damage to macro behavior?
  - How can complexity be reduced?
- Accept that models, sensors and IT techniques will continue to evolve and improve thus attempt to establish methodologies/protocols for communicating, fusing and exploiting the different disciplines <u>now</u>.

Questions?

Interrogation and State Awareness

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Computational:

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- Reliable error estimation

Existing Database (History and Past Missions)

Database:
Mission History, Maintenance, Life Extension and Design.

DO REALLY use past mission history

- Identify salient features of every mission

DO take into account knowledge of the system behavior

- Track trends

DO take into account maintenance history

Exploit expert knowledge

Leverage previous efforts

Exploit IT revolution.

Damage Evolution

Failure physics, damage evolution, predictive models

Use knowledge of applicable physics.

Invoke and exploit coupled and interacting mechanisms.

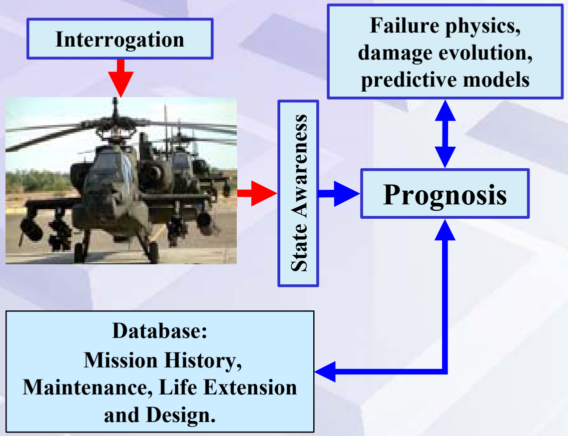
Use multiple models (if available).

Physics-based and data-driven models will evolve—allow for updates.

Reduced and full models.

Sensor data can modulate model predictions.

Prognosis Reasoning System



Integrates of all elements, system knowledge and logic

Predicts of capability

Provides multiple decision makers the required information (operator, local commander, theatre director, maintenance, etc.

Provides confidence levels on predictions

Employs sophisticated and evolving reasoners

Conveys pertinent information for easy assimilation

Relies on local and rapid e.g. onboard (reduced) response and more complete e.g., remote control center (full) system models

Benchmarked at convenient times and locations

Based on open and modular architecture

Prognosis Content

- Science and Technology
  - Predictive, coupled, multi-scale damage evolution/physics of failure models
  - (Non-intrusive) state awareness techniques and tools.
  - Math techniques for feature extraction and characterization of the state of the system.
  - Performance projection capability based on current state.
  - Adaptive mission strategies and (on-board) reasoning/intelligence system
  - Tools to give multiple users reliable and accurate capability status in "real time"
- Technology
  - Existing/develop test beds to validate tools and models
  - Leverage data fusion technologies to implement Prognosis architecture and reasoning system
  - Exploit effective data mining techniques (from IT?)
- Demonstrations
  - Demonstrate impact through analysis and physical demonstrations
  - Deliver decision tools for pervasive (sub)system manned or unmanned systems.