

The Prognostic Requirement for Advanced Sensors and Non-Traditional Detection Technologies

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Prognostic Horizon Level Targets

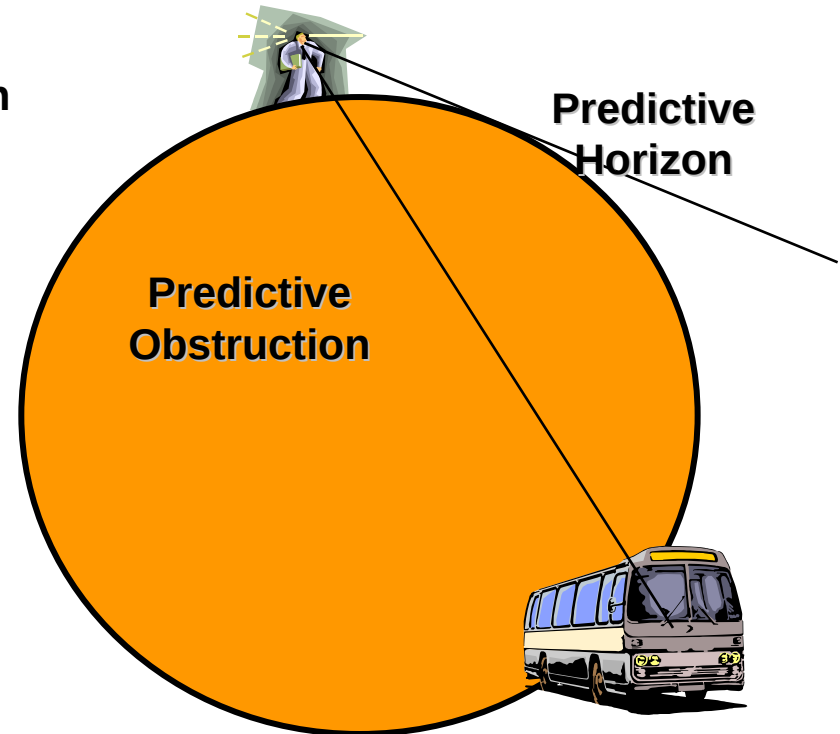
How Far Do You Want to See Into the Future?

Prognostics: What's Your Perspective?

- Needs and Benefits
- Capabilities: Available and Desired
- Technology “Holes” to be Filled
- Philosophy, Strategy, Implementation
- Integration and Implementation
- Questions:
 - Is It Possible?
 - How are you going to use It?
 - What's Good Enough?

Choose One

- Detect Bus Just Before it Hits You, or
- Detect Bus Far Enough in Advance to Take The **“Right”** Evasive Action



Current Logistics Structure

High Availability

Ability to Predict Future Health Status

Max Life Usage

MAX SGR

Ability to Anticipate Problems and Req'd Maint Actions

Better
FD/FI
Efficiency

Quick
Turn Around
Time

Small Logistics Footprint

No RTOK

Performance
Based Maint

Low #
of Spares

No False Alarms

Accurate Parts and Life
Usage Tracking



Maintenance
Mgt



No Surprises

Opportunistic
Maintenance



Configuration
Tracking

Mission
Planning

Short and Responsive
Supply Pipeline

No/Limited
Secondary Damage

No/Min
Inspections

Limit Impact
of Quality Control
Problems

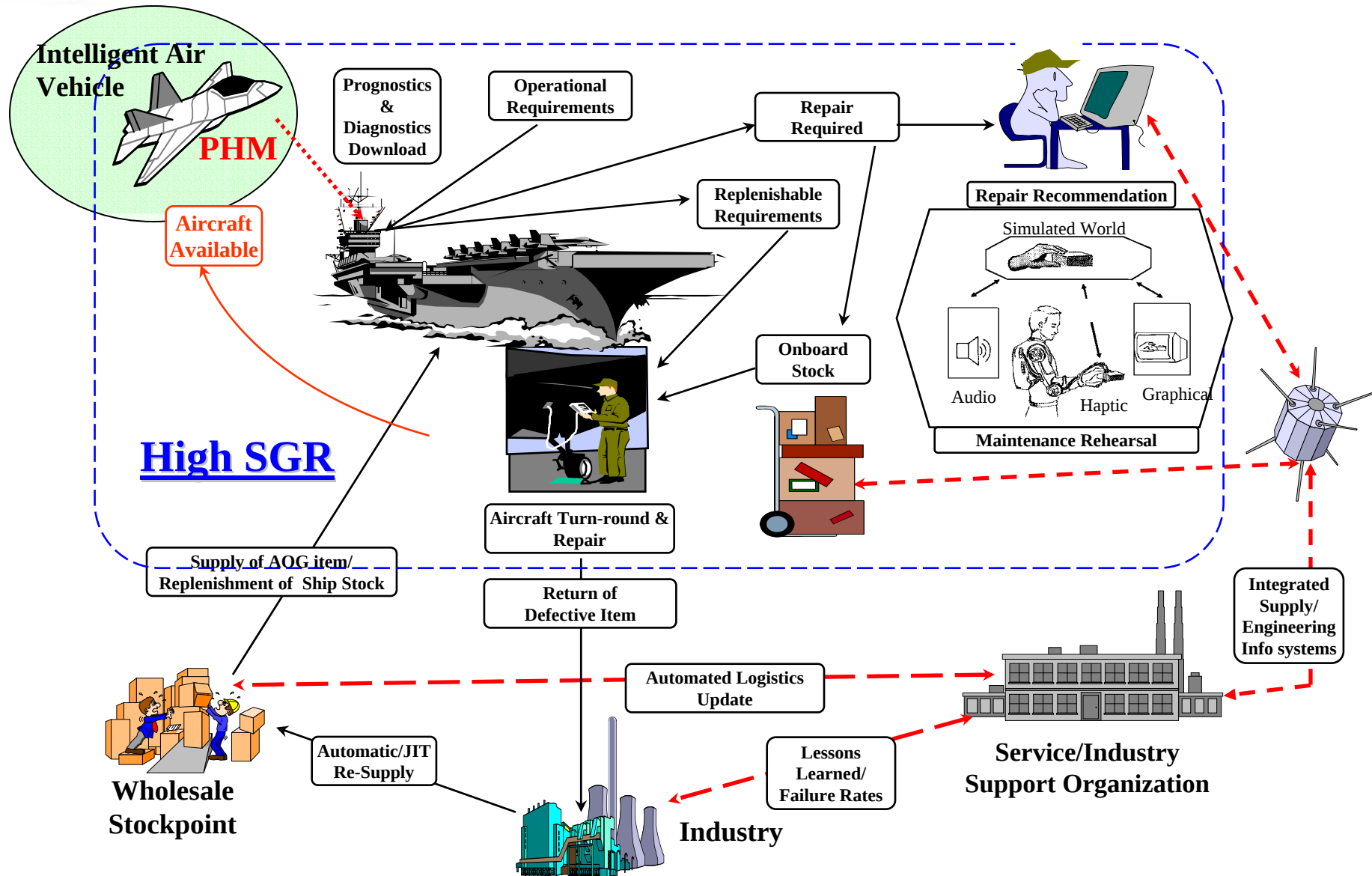
Too Large & Costly

System
Performance
Feedback

Immediate Access to all Available Information



Autonomic Logistics Structure





Goals of PHM

- **Enhance Mission Reliability and Aircraft Safety**
- **Reduce Maintenance Manpower, Spares, and Repair Costs**
- **Eliminate Scheduled Inspections**
- **Maximize Lead Time For Maintenance and Parts Procurement**
- **Automatically Isolate Faults to 1 LRC**
- **Eliminate CNDs and RTOKs**
- **Provide Real Time Notification of an Upcoming Maintenance Event at all Levels of the JSF Logistics Chain**
- **Catch Potentially Catastrophic Failures *Before* They Occur**
- **Detect Incipient Faults and Monitor Until Just Prior to Failure**
- **Opportunistic Maintenance Reduces A/C Down Time**

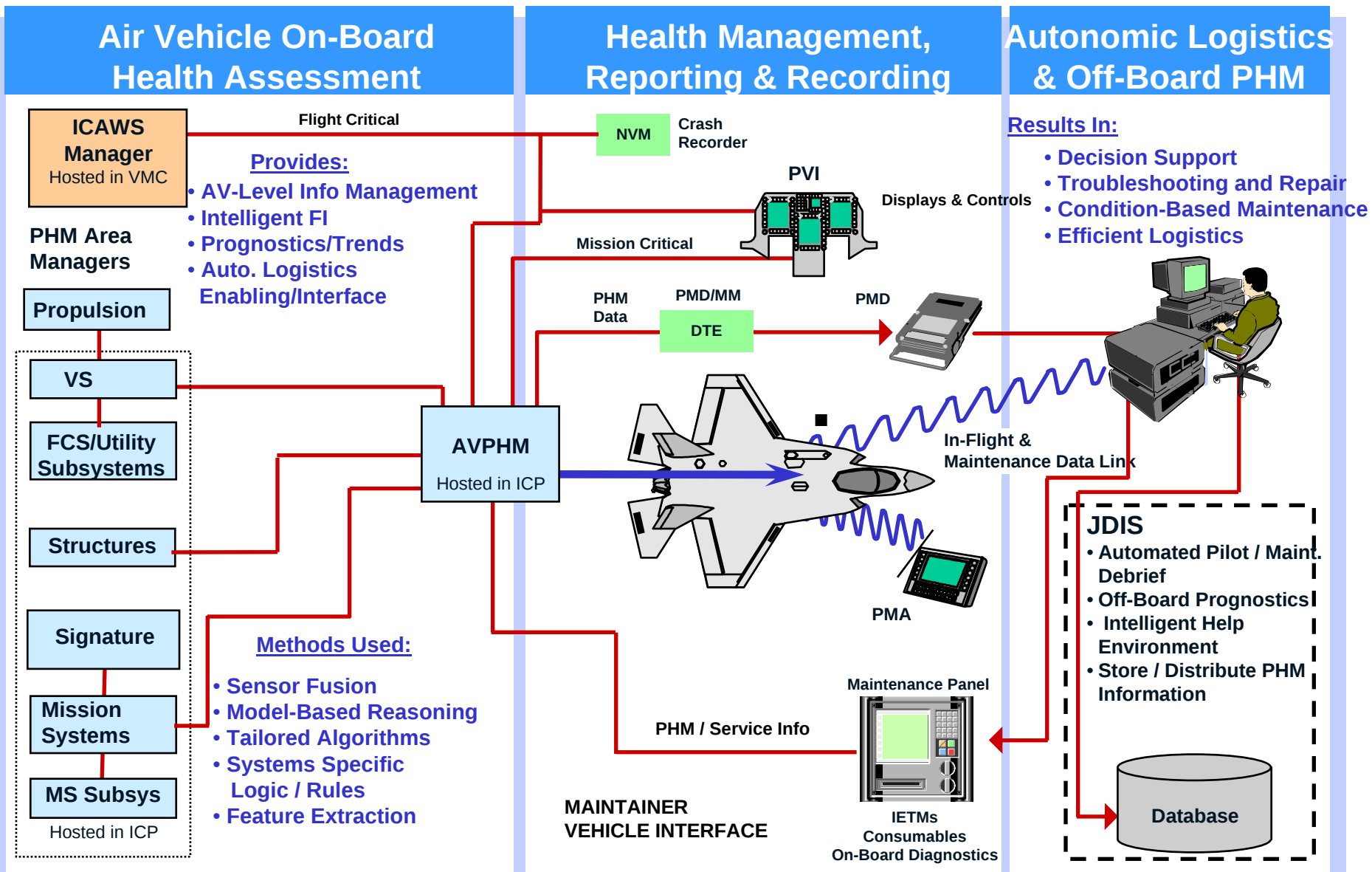


Some Facets of Diagnostics and PHM

- Fault Detection
- Fault Isolation
- Advanced Diagnostics
- **Predictive Prognostics**
- Useful Life Remaining Predictions
- Component Life Tracking
- Performance Degradation Trending
- Warranty Guarantee Tracking - Enabling New Business Practices
- Selective Fault Reporting
 - Only tells pilot what NEEDS to be known immediately
 - Informs Maintenance of the rest
- Aids in Decision Making & Resource Management
- **Fault Accommodation**
- Information Fusion and Reasoners
- Information Management
 - Right info to right people at right time



PHM Architecture and Enabling Technologies

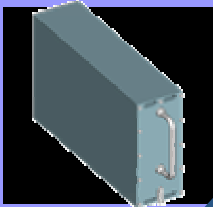




Air Vehicle PHM IPT Products

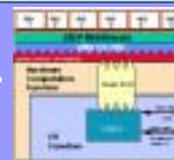
VS/MS PHM SEIT

- Optimal Diagnostic / BIT Capabilities for Subsystem IPT's



- Diagnostics / BIT Work with the IPT's / supplier teams to achieve the best and most cost effective coverage
- Pertinent data acquisition at sensor, component and sub-system levels.
- Requirements, top level design, use cases, verification.

VS/MS PHM Area Manager (product)



- Enhanced diagnostics, beyond the legacy testability / BIT capabilities, through system models, corroboration, correlation, and information fusion
- **Prognosis**, collect data, compute life usage

Interface to Off-board PHM (product)

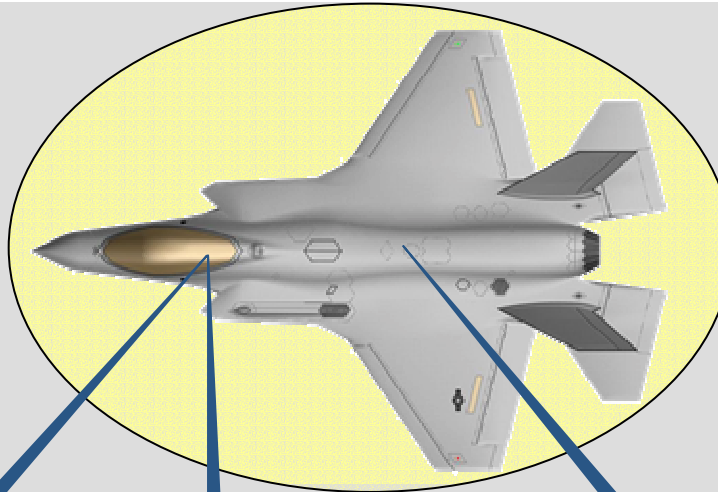


- **Prognosis algorithms**, estimation of remaining component life
- Failure resolution algorithms

Interface to Air Vehicle PHM (product)

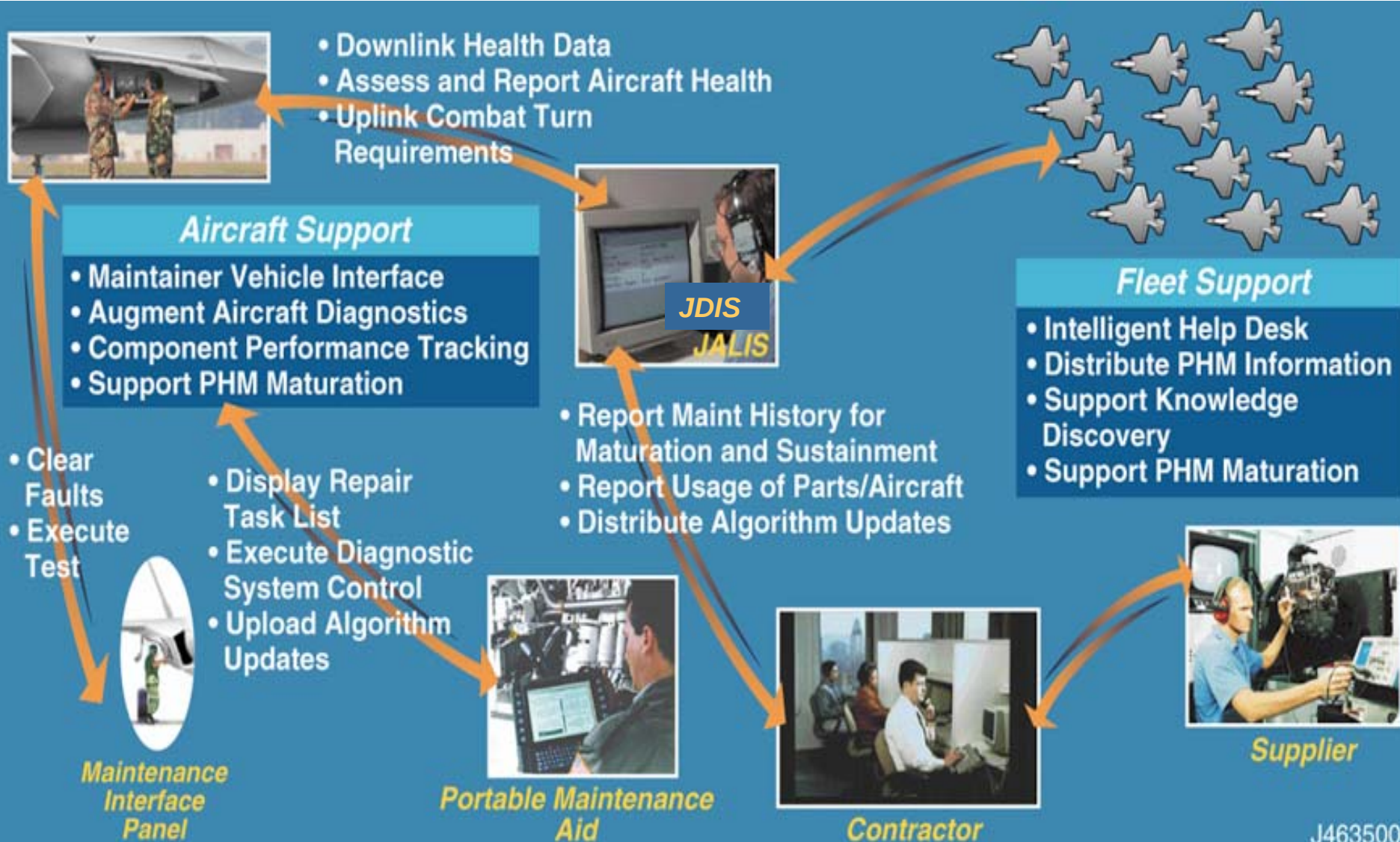


- Health management functional dependencies to be resolved at AV level
- Information broker for on- and off-board users
- High-level service requirements for data reduction, file management





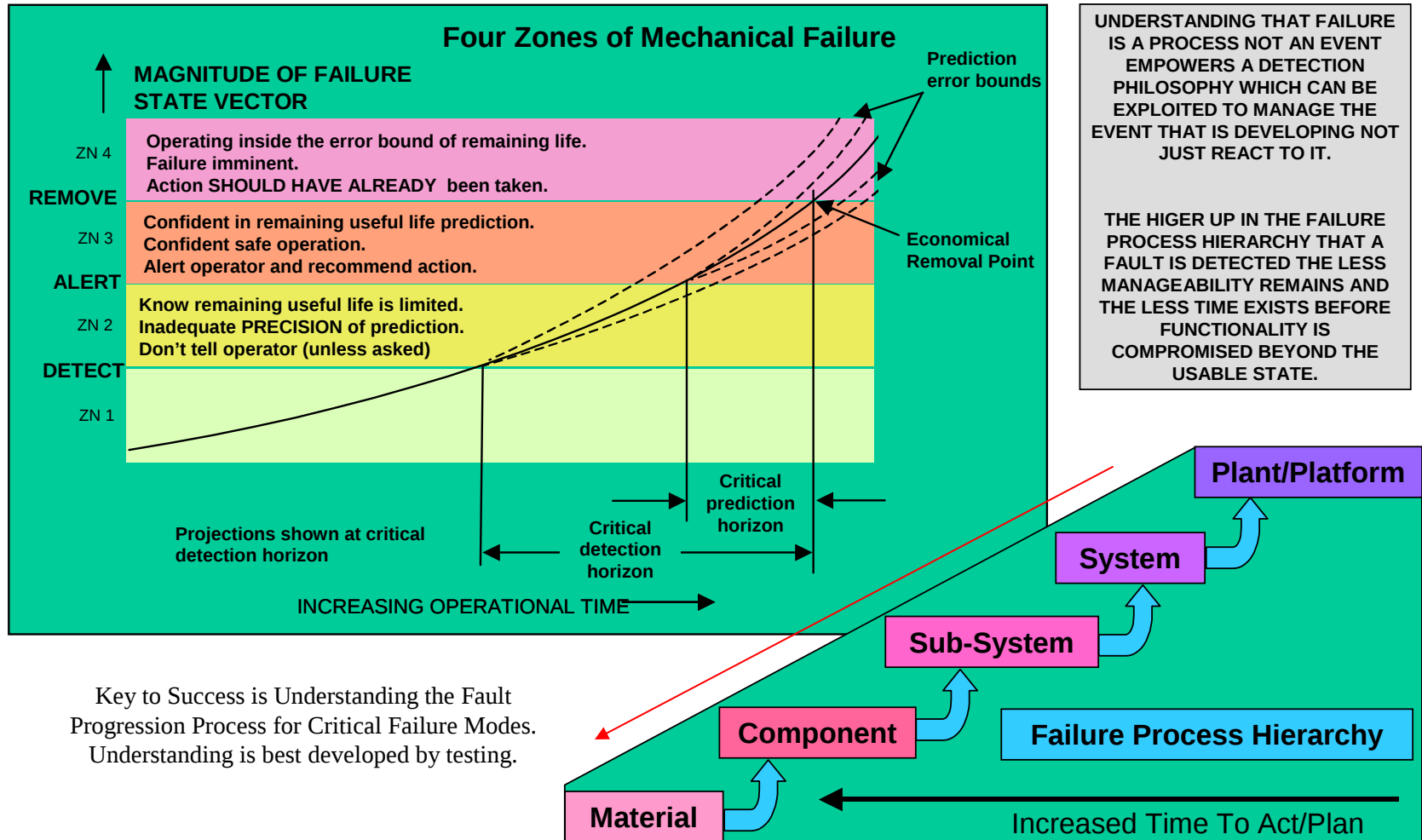
Off-Board PHM Overview



JSF Subsystem PHM Coverage slide

- PHM Requirements including Prognostic “Flowed Down” to All Subsystem Suppliers

Typical Mechanical Failure Progression Questions



Failure Progression Timeline

Prognostics

Need: To Manage
Interaction between
Diagnostics and
Prognostics

Diagnostics

Very early incipient
fault

System, Component, or Sub-
Component Failure

Secondary Damage,
Catastrophic Failure

Proper
Working
Order - New

Need: Understanding of fault to
failure progression rate
characteristics

Predicted useful life remaining

Determine effects on
rest of aircraft

State Awareness Detection

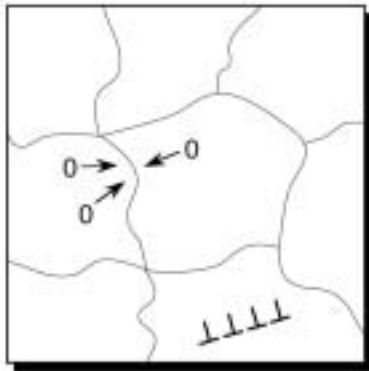
Desire: Advanced Sensors
and Detection Techniques
to “see” incipient fault

Develop: Useful life
remaining prediction
models – physics and
statistical based

Need: Better models to
determine failure effects
across subsystems

The Goal is To Detect “State Changes” as Far to the Left As Possible

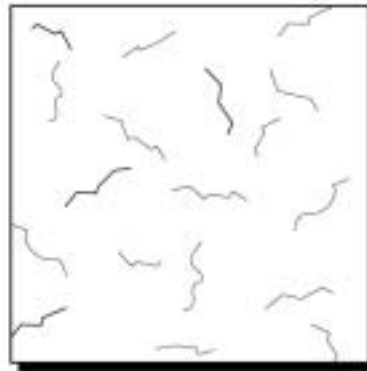
DAMAGE EVOLUTION



Stage I

Microstructural
Changes

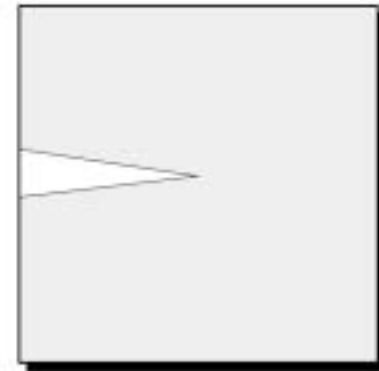
(Diffusion, dislocation
activity, grain
boundary movement)



Stage II

Microcrack
Development

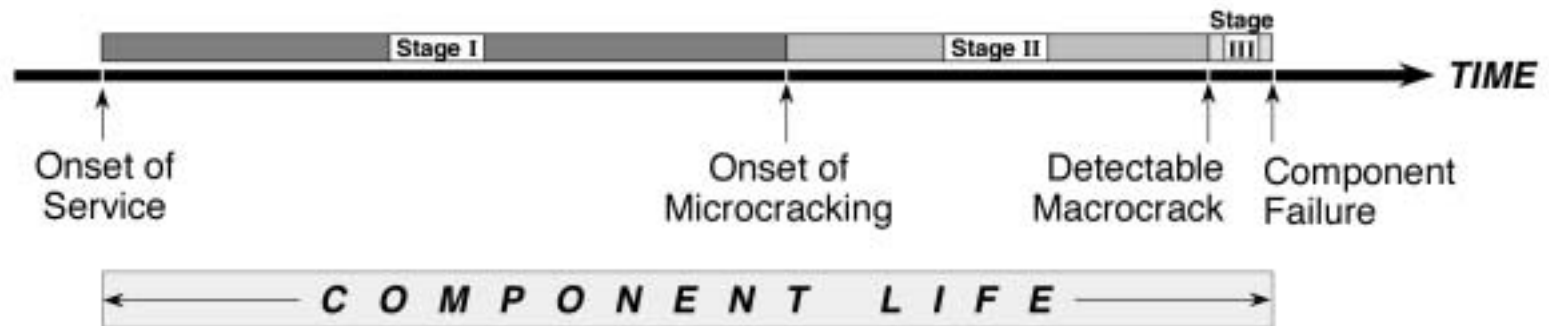
(Nucleation, growth
and coalescence of
microfailures)



Stage III

Macrocrack
Growth

(Slow growth
of detectable
cracks)



Seeded Fault Crack Growth Successfully Detected Using Traditional Vibration Sensor and Advanced Frequency Analysis Techniques

H-60 IGB Pinion Gear Surface Inspection



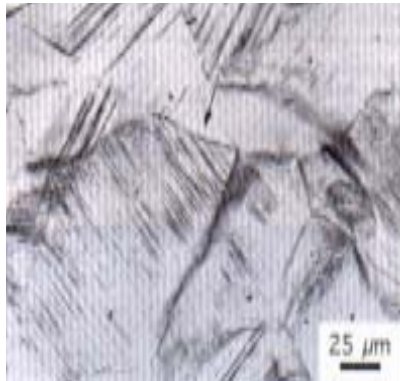
Image of heel notch inner end after Run 15, showing small chip liberated (arrow). No noticeable change until run 18.



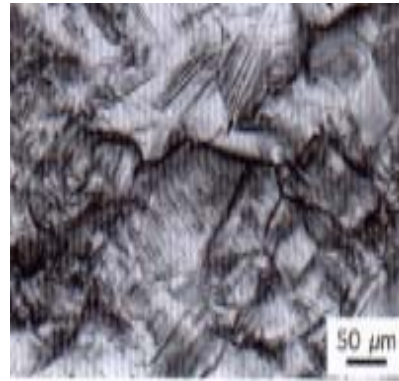
Image of heel notch outer end after Run 18, showing obviously visible crack (arrow).

EVOLUTION OF FATIGUE DAMAGE IN NICKEL

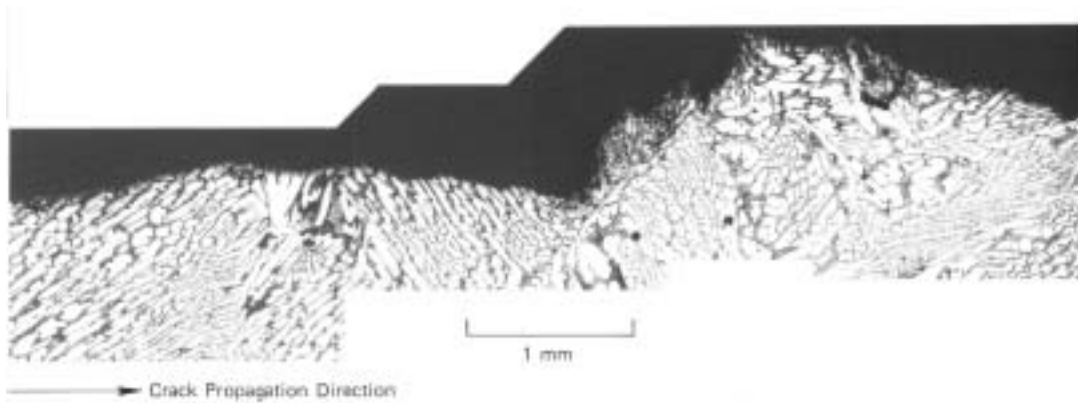
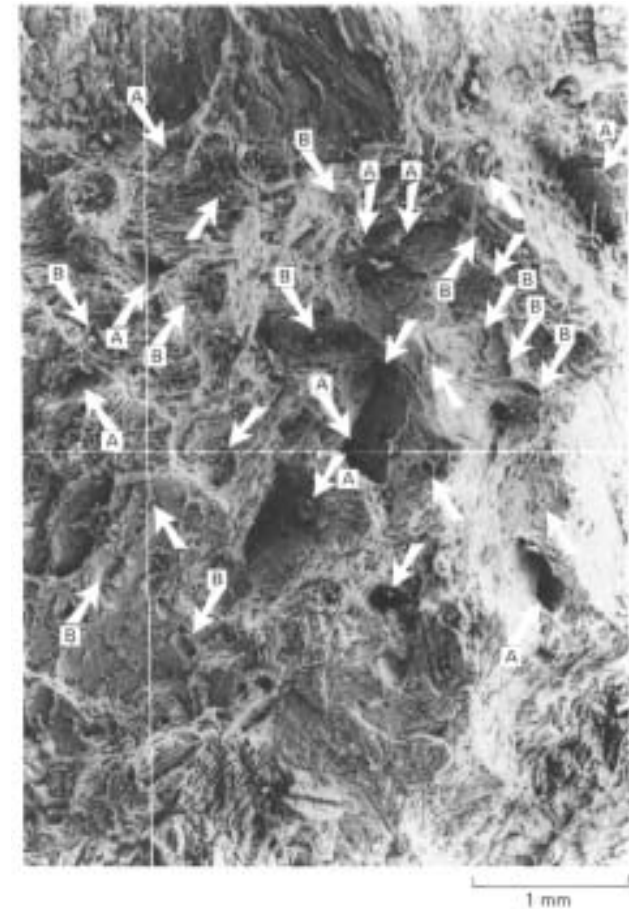
After 1200 cycles



After 4000 cycles



**Damage Nucleation Sites
in the Microstructure**

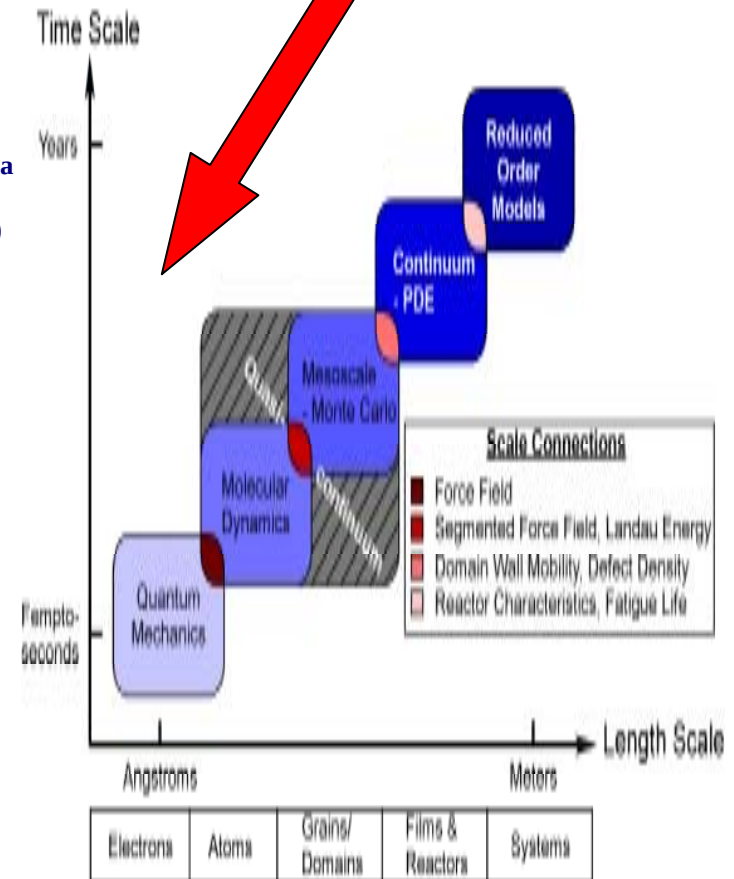
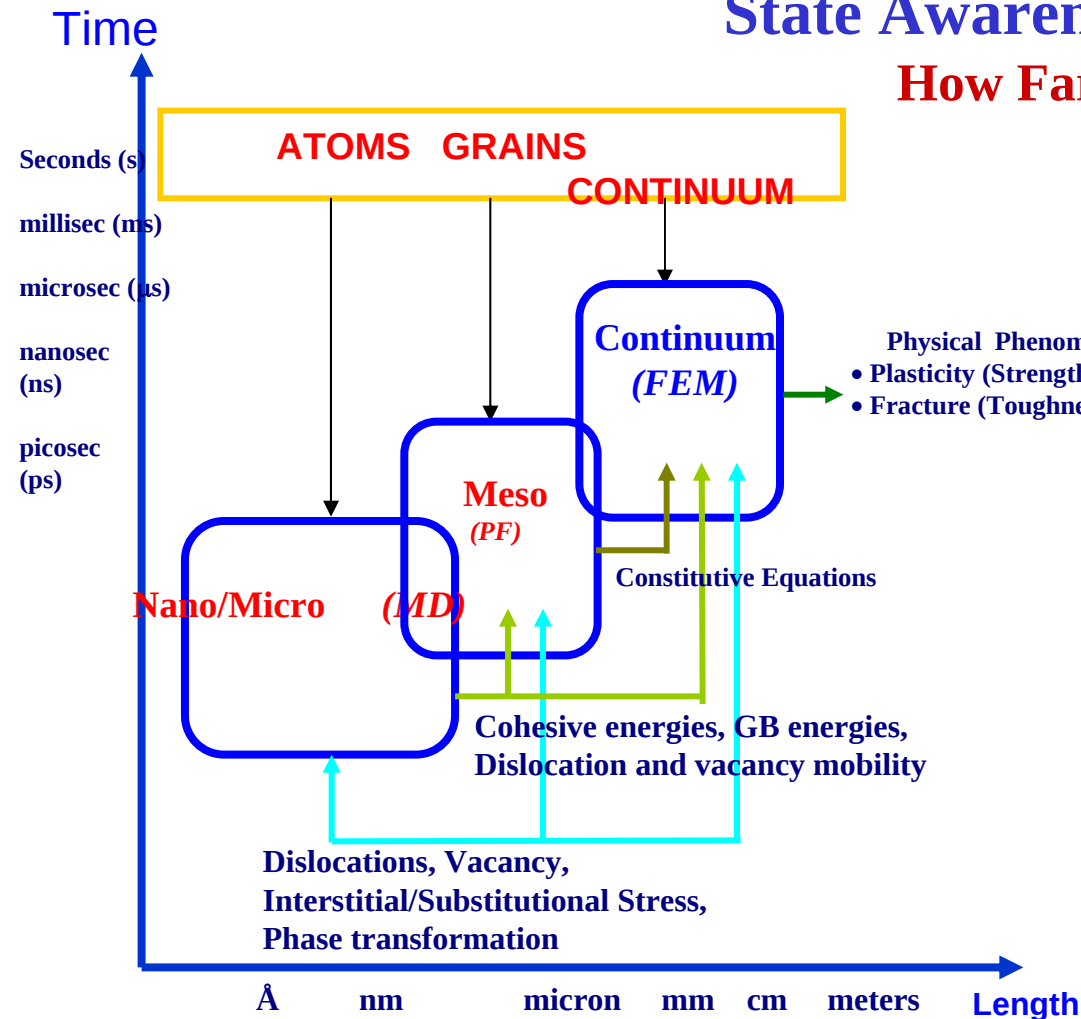


Microstructure damage beneath fracture surface

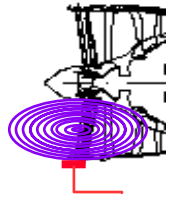
State Awareness Detection – How Far Can We Go ?

Bridging the Physical Scales

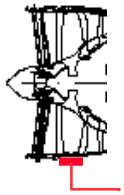
State Awareness Detection: How Far Can We Go?



Examples of Some Advanced Sensors and Non-Traditional Detection Techniques

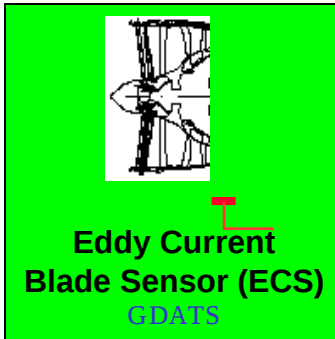


Acoustic FOD Detector (AFD)

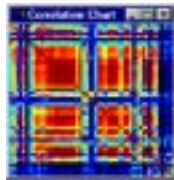


Blade Vibration Meter (BVM8X)

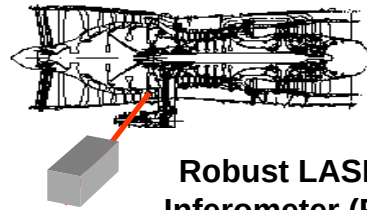
Hood Technology



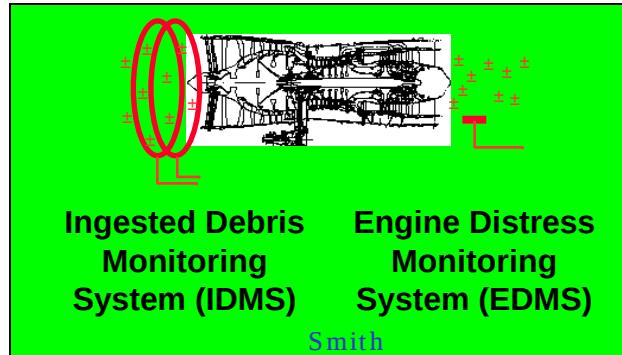
Eddy Current Blade Sensor (ECS)
GDATS



Beacon-Based Exception Analysis for Maintenance (BEAM)
JPL



Robust LASER Interferometer (RLI)
Epoch Engineering



Ingested Debris Monitoring System (IDMS)
Engine Distress Monitoring System (EDMS)
Smith

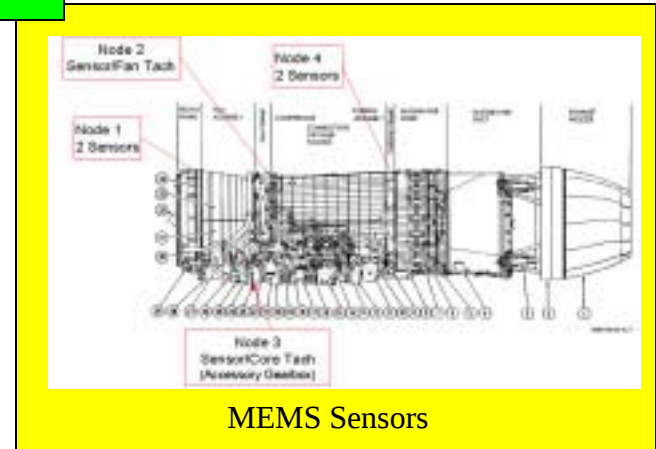
Chip Detector



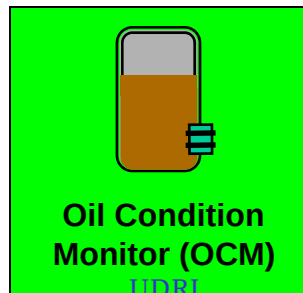
Advanced Vibration

Piezoceramic Patch Crack Detection (PZT)

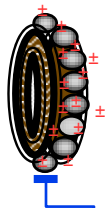
UTRC



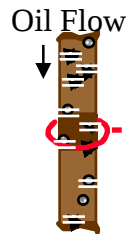
MEMS Sensors



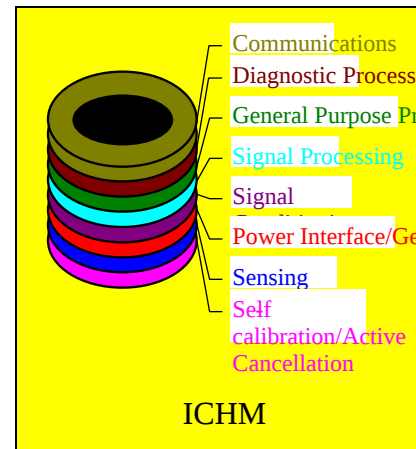
Oil Condition Monitor (OCM)
UDRI



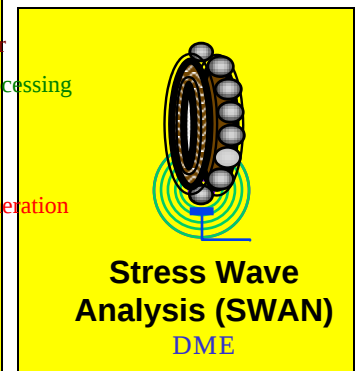
Electrostatic Bearing Monitor (EBM)
Smith



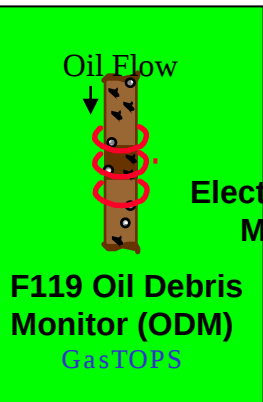
Electrostatic Oil Debris Monitor (EODM)
ExperTech / SHL



ICHM



Stress Wave Analysis (SWAN)
DME



F119 Oil Debris Monitor (ODM)
GasTOPS

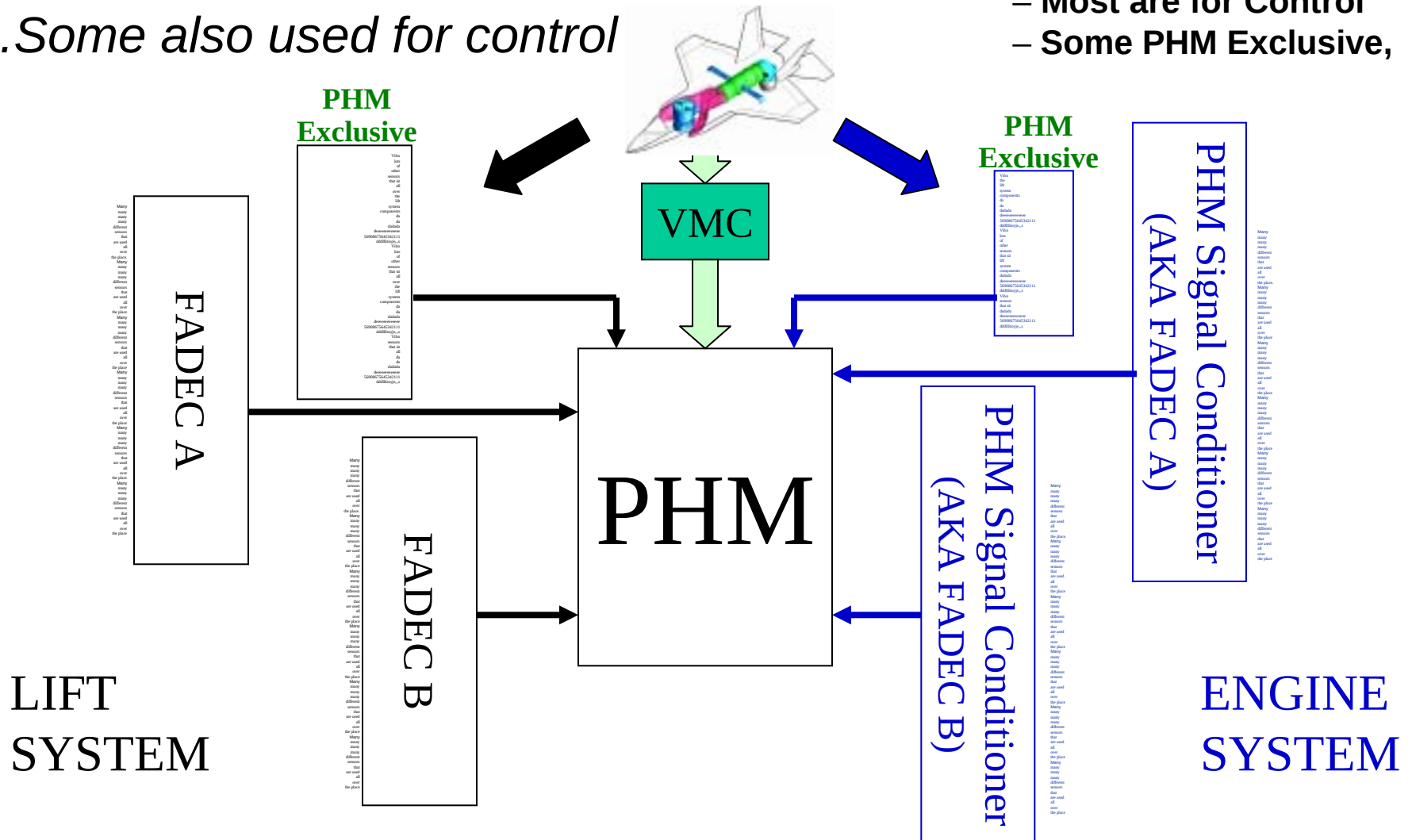
Example Propulsion PHM Elements....Sensors

Sensors are part of the solution

All Sensors are PHM Sensors

...Some also used for control

- **Many Signals**
 - Most are for Control
 - Some PHM Exclusive,

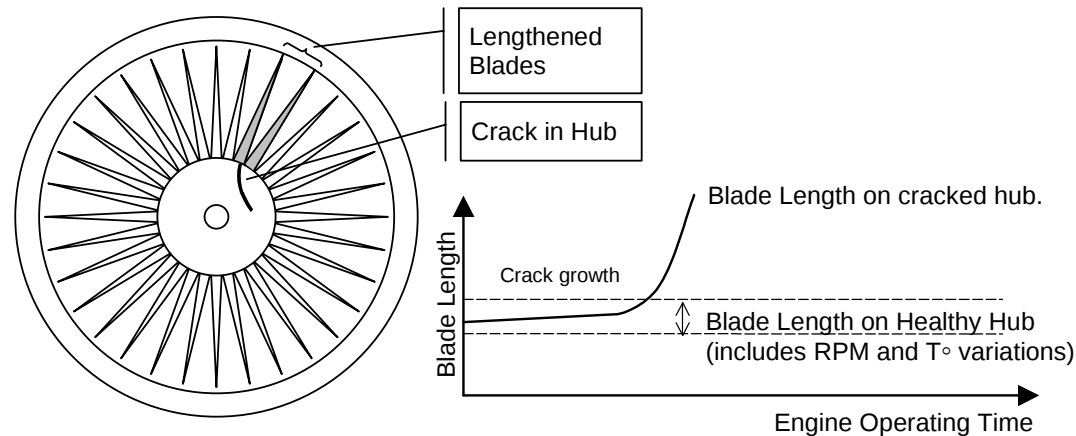


Non-Traditional Detection Technologies

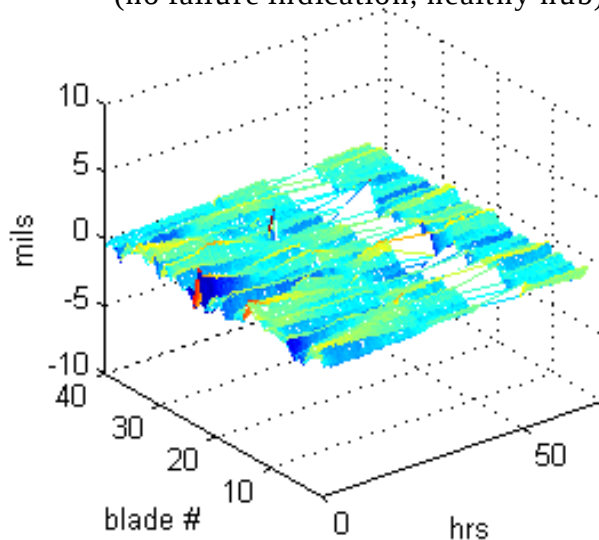
- **Eddy Current Blade Tip Sensors Used for Disk Crack**
- **Electro-Static Exhaust Debris Used for Blade Rub and Turbine “hot end” Degradation**
- **Electro-Static Wear Site Detector for Bearing Degradation**
- **Very High Frequency Vibration Analysis, +1000 KHz**
- **Apply Laboratory and Test Instrumentation, Bench Inspection and NDT Techniques in Innovated Ways**
- **New and Aggressive Use of MEMS Technologies**
- **Advanced, Sophisticated, and Innovated Data Analysis**
 - **Applied from Other Disciplines**

Non-Traditional Detection Technologies

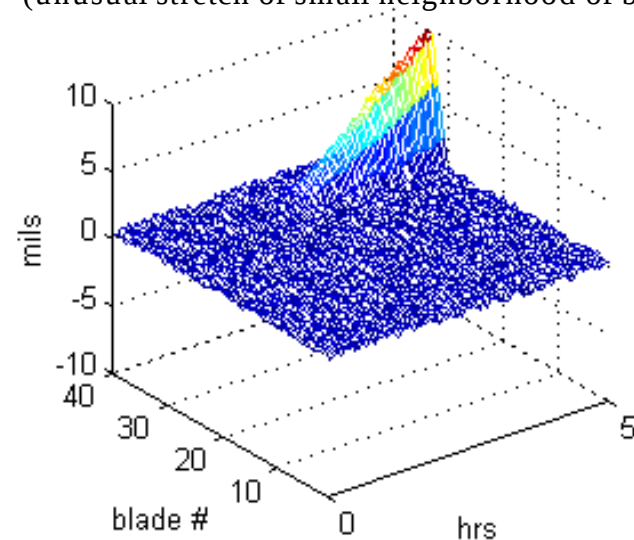
Disk Integrity – Crack Detection



Measured Unusual Blade Stretch
(no failure indication; healthy hub)



Simulated Anticipated Hub Burst Failure Signature
(unusual stretch of small neighborhood of blades)



Blade clearance compensated for temperature and imbalance has been measured to within $\pm .001''$.

Smart Sensing Technologies

- **Smart Sensors**

- **Very Small, Wireless, Much Processing Power**
- **MEMS based**

- **Smart Materials**

- **Skins, Coatings, Layered, etc**
- **Part of Design and Manufacturing Process**

- **Embedded Sensors**

- **Integral with Material and/or Design**

- **Embedded Detectable Materials**

- **Enable Easier and/or Earlier Detection**
- **Make Traditional Sensors More Capable**
- **Make Detection Techniques More Sensitive**

Notional Strategy and Template for Prognostics

- **Identify and Target Components and Sub-Elements Suitable for Prognostics**

- Those with understandable fault to failure progression characteristics
- Those that are Important to do: Safety/Mission Critical, High Value, etc.
- Eliminate those impossible or too hard to consider

- **Use and/or Develop Suitable Detection Techniques and Technologies**

- Sensor and Parameter Based
- Very Data Analysis Driven
- Used Advanced and Non-Traditional Approaches
- Take Advantage of Information (“Hear and Usage”) at the Material Level

- **Develop and/or Obtain Advanced Integrated Models**

- Understand the Physics of Failure, Component Design, and Materials Properties
- Fault to failure progression characteristics
- Useful life remaining
- Physics Based, Statistical Based, Detector Driven, Usage Based

- **Perform Experimental Seeded Fault Tests**

- As many as affordable
- Designed for Specifically the Development of Prognostic Capabilities

- **Verify and Validate Models**

- Blind Testing
- Modeling and Simulation

- **Modify Useful Life Remaining Prediction Model to Account for Real World Considerations**

- Power Driven Parameter Profiles
- Actual Mission Usage Profiles
- CONOPS

- **Integrate Capabilities with System Architectures and Logistics Concepts**

Detection, Isolation & Prognosis

Detection

Through sensors, Models etc

Isolation

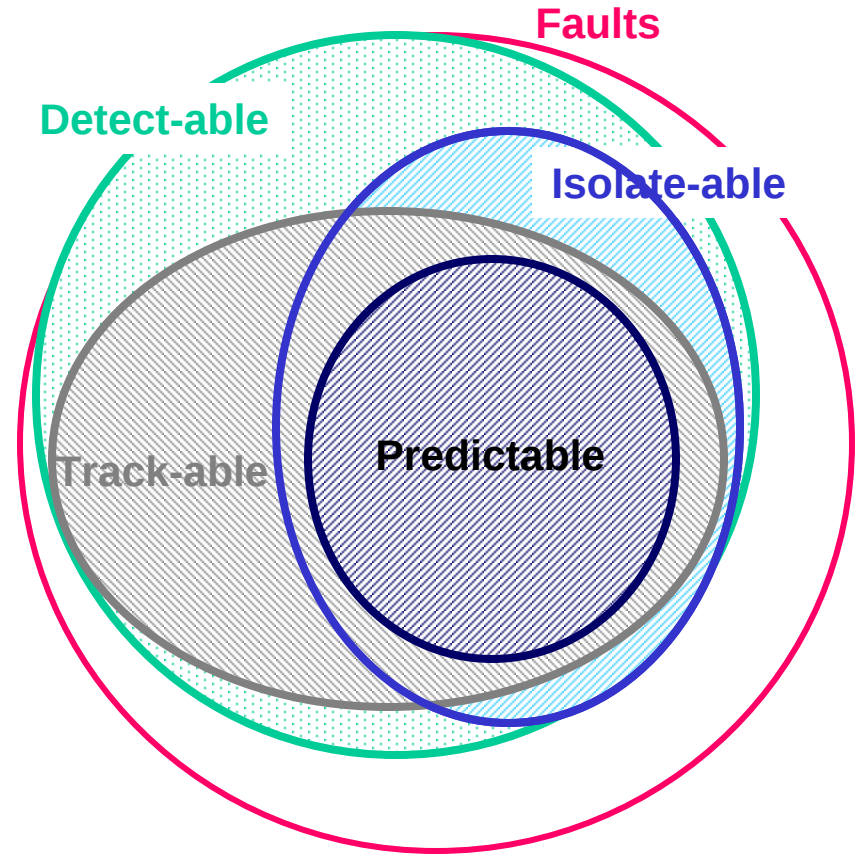
Information fusion from sensors,
Models etc.

Tracking/Trending

Processed PHM data

Prediction/Prognosis

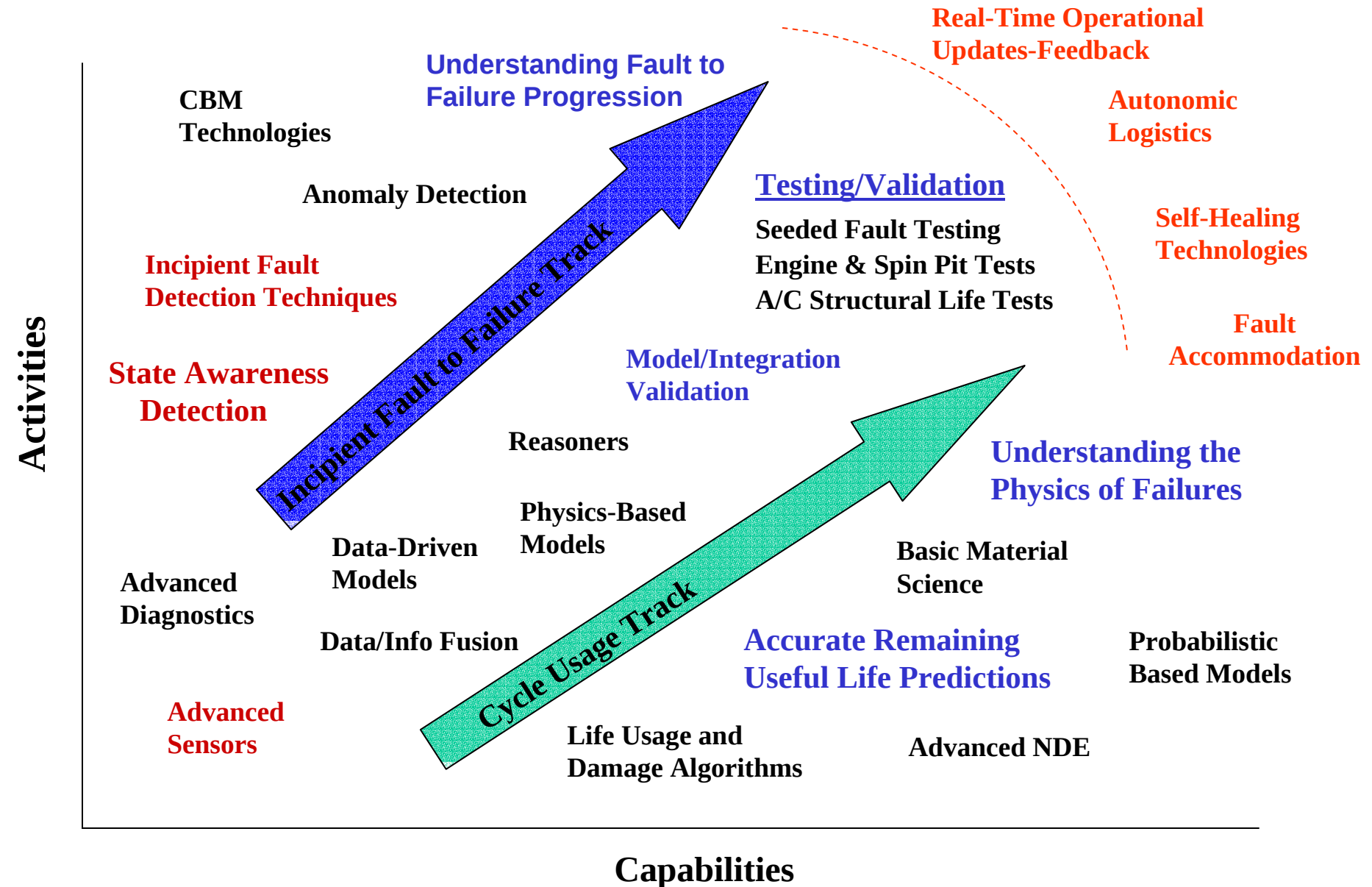
Based on tracking/trending, and lifing
models



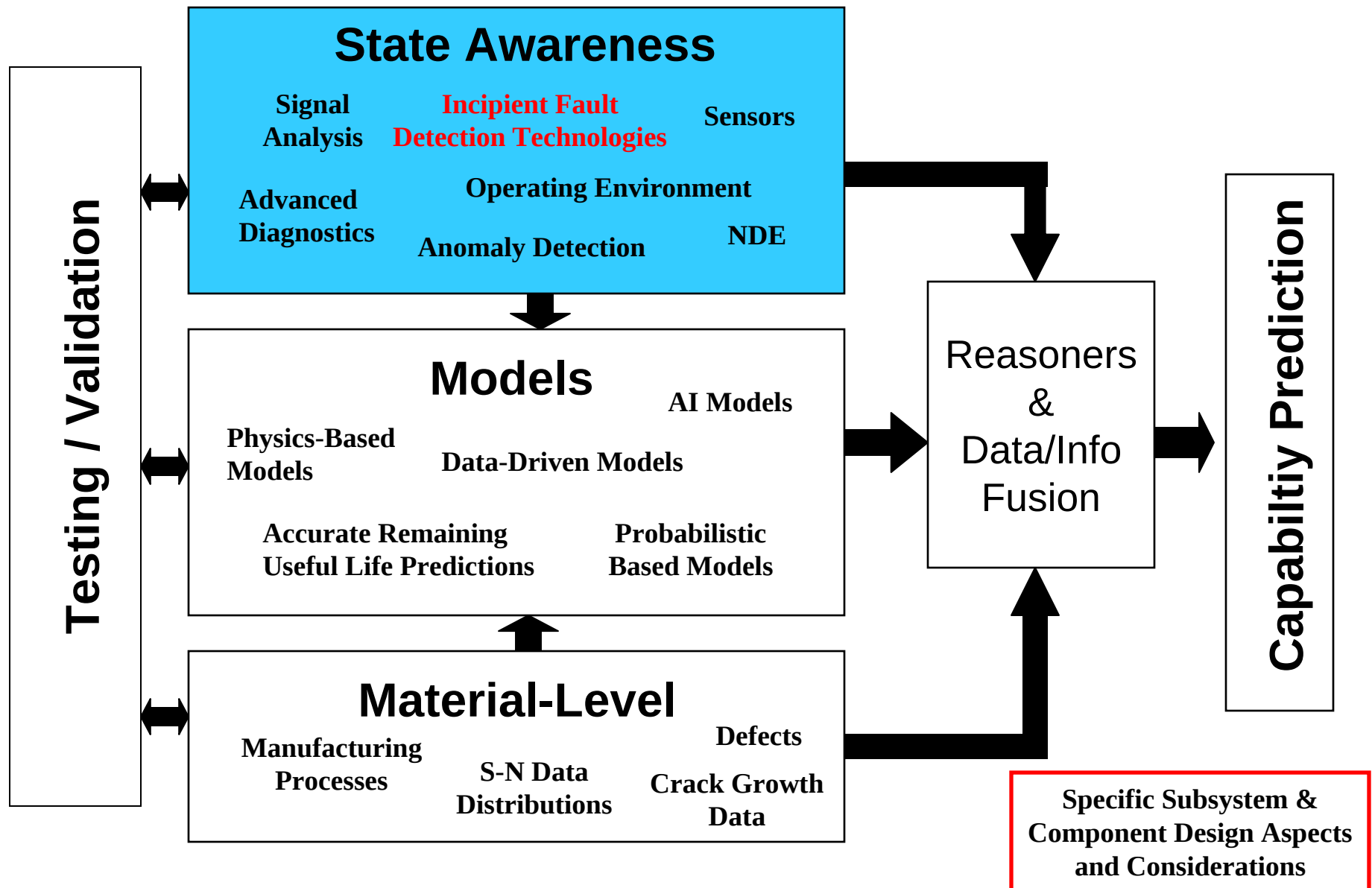
Prognostics: What We Are Missing ?

- **Better Understanding of Physics of Failure**
- **Condition Based Performance Predictions**
- **Better State Awareness Techniques**
 - **Advanced Sensors**
 - **Non-Traditional Detection**
 - **Smart Materials**
 - **Embedded Sensors and Detectable Materials**
- **Better Understanding of Incipient Crack Growth**
- **Better Understanding of Fault/Failure Progression Rates**
- **Better Understanding of Material Properties Under Different Loading Conditions and Mission Usage**
- **More Capable and Integrated Models: Physics, Statistical, Detector, Fleet Mission and Actual Usage based, etc.**
- **Better Data Fusion Methods**
- **Better Knowledge of Effects of Failures Across the Air Vehicle**
- **Study to Determine What Components to Perform Prognostics On**
- **Impacts of Changing Mission Mixes in Actual Fleet Usage**
- **A Comprehensive “Way Forward” Strategy, More Detailed Planning, and “Funded Support” Programs**

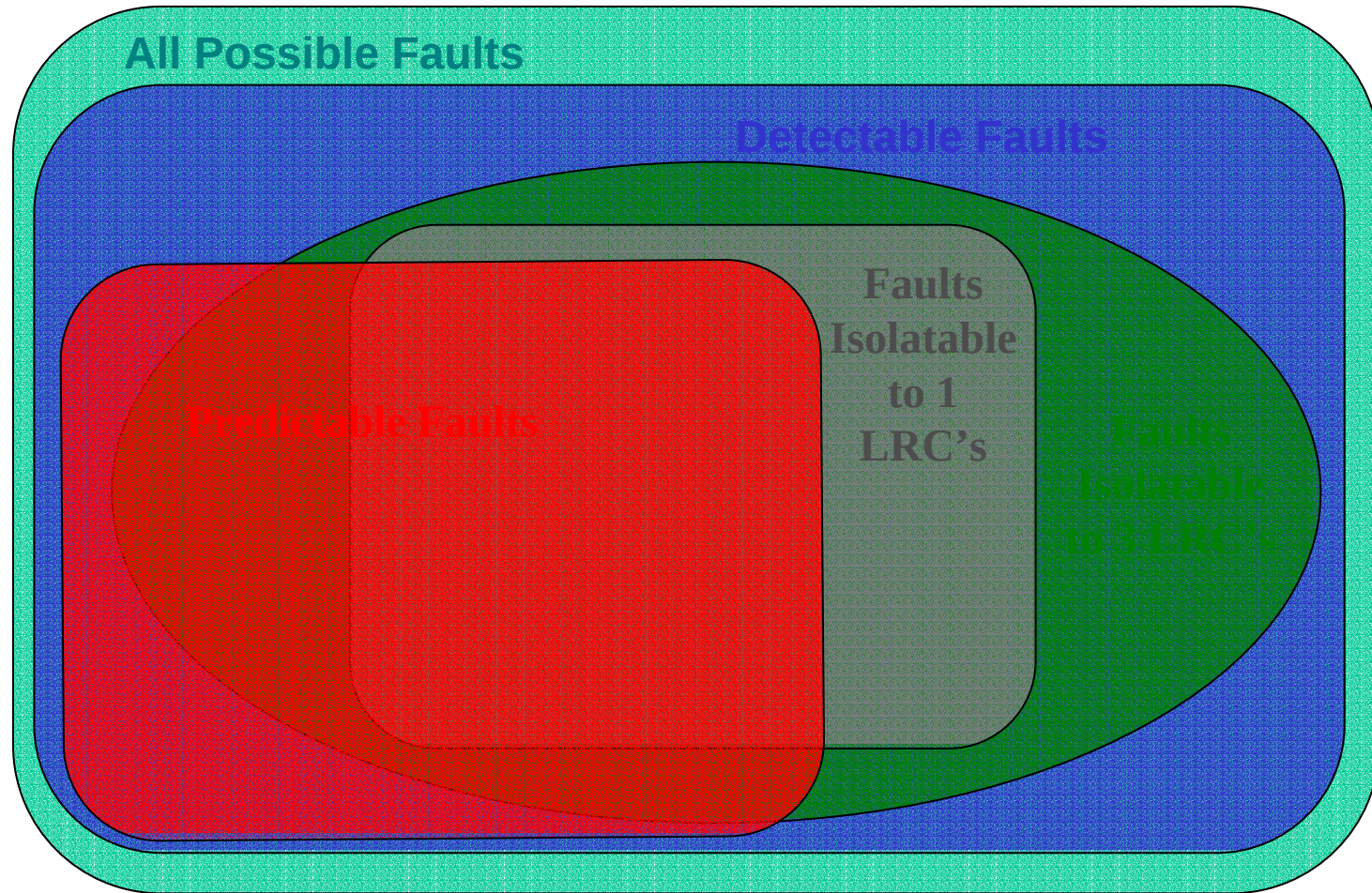
Roadmap to Predictive Prognostics



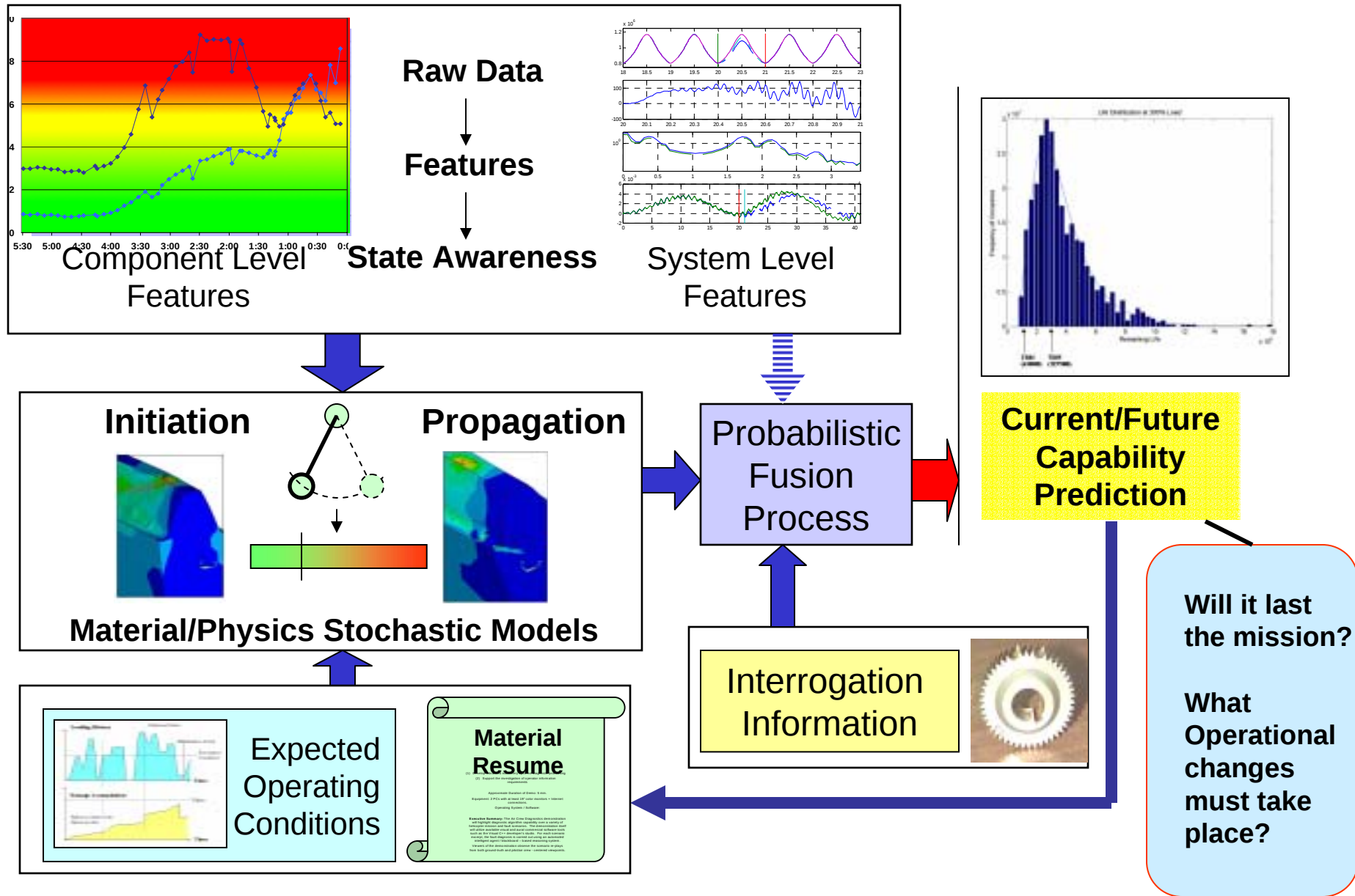
Predictive Prognostics - Integration Tasks



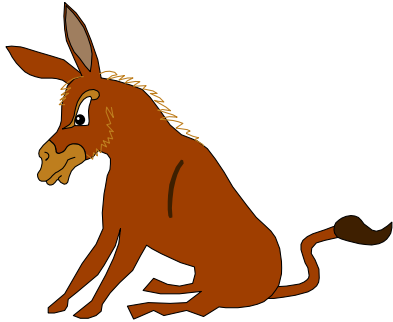
Detection/Isolation Analysis Update



H-60 IGB S-B Gear Fatigue Prognostics Module



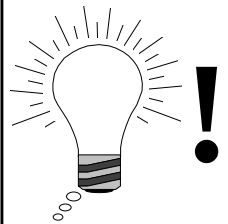
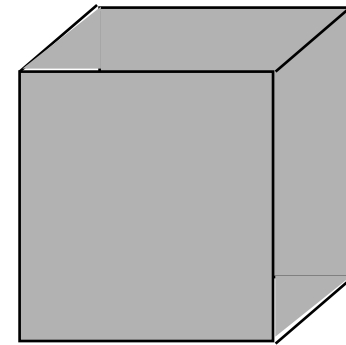
The Question is: Why Not Prognostics and Health Management?



People resist change.



Protect rice bowls



Limited vision.

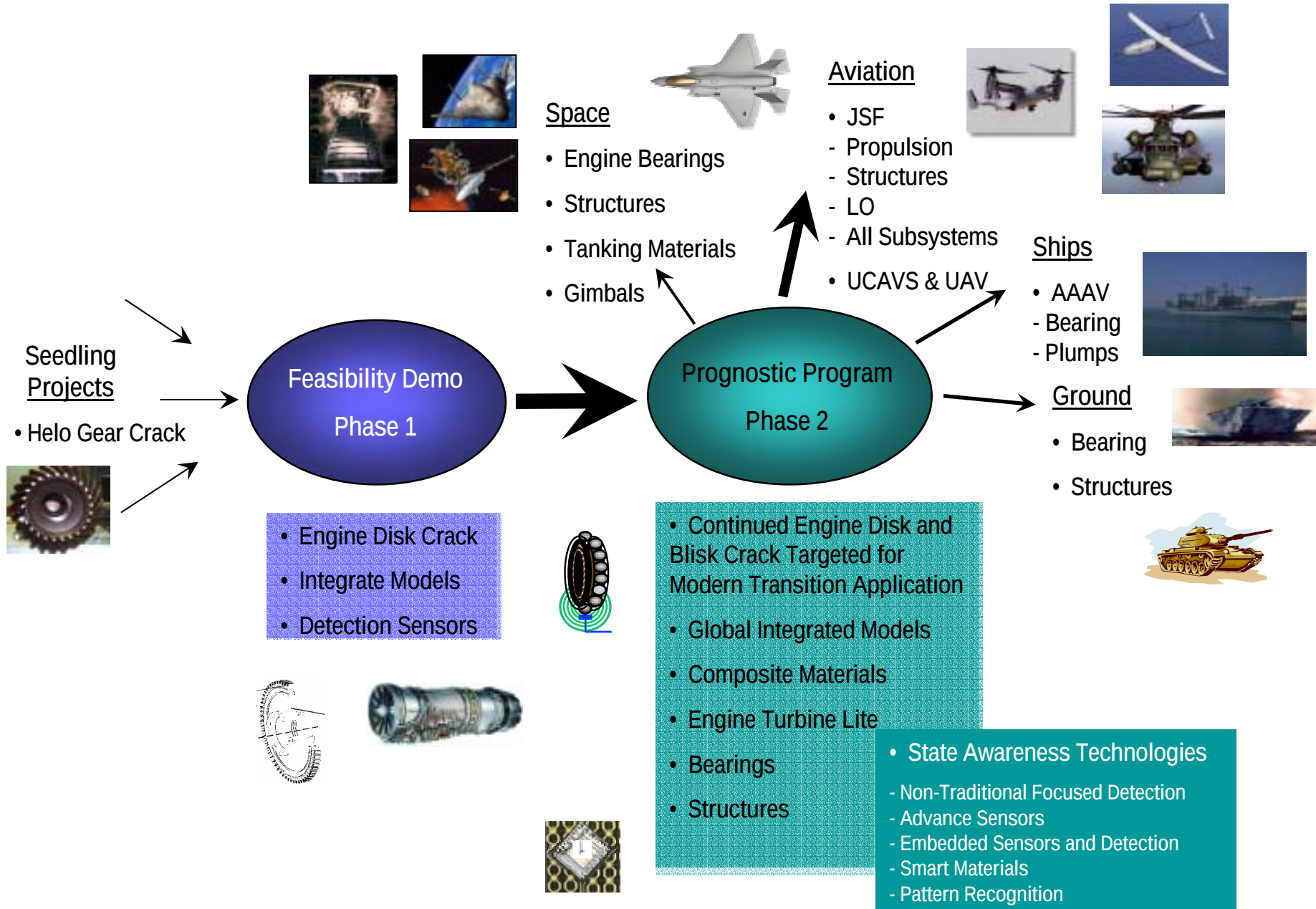
Problem is not **ONLY** in the capabilities, technologies and expected benefits; but in having the wrong people in the right positions, making the wrong decisions

Summary

- The Needs Are Apparent
- Technology is Now NOT the Limiting Factor
 - And It will Only Improve With Time
 - **There are Still a “Holes” to Fill in the Prognostics Base**
- There are Enough Success Stories and Documentation that Justify Prognostics is Worth Pursuing
- All Elements are Coming Together To Enable Our Visions of Prognostics and Real Health Management
- We Must Implement and Apply Smartly and Wisely to Obtain Maximum Benefit
- Prognostics Not Just a Dream, Can Be Reality with Properly Directed Efforts
- Fill ‘holes’ in the Technology Base and Expand “Tool Kit”

The Aggressive Application of On-Board, Real Time Prognostics is Within Reach, We Just Need the Proper Resources and Focus to Obtain It

DARPA PROGNOSTICS ROAD MAP



DARPA Seedling and Phase 1 Feasibility Demo

Anticipated Accomplishments

- Identify and Target Components and Sub-elements Suitable for Prognostics
 - Those with understandable fault to failure progression characteristics
 - Eliminate those impossible or too hard to consider
- Prove Feasibility and Tractability
- Flush out and Define Successful and non Successful Technologies, Techniques, Methodologies, Approaches (areas)
- Document Lessons Learned
- Perform Experimental Seeded Fault Tests
 - As many as affordable
 - Designed for Specifically the Development of Prognostic Capabilities
- Define Most Workable Way Forward
- Demo and Refine an Approach Process Template that May be Used for any or many Types of Subsystem components
- Identify Needs and “Holes” in the Technology Base