Introduction to Prognostics and Health Management (PHM)

Presented by Sonia Vohnout

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Sonia Vohnout holds an MS in Systems Engineering from the University of Arizona. She is a board member of the Society for Machinery Failure Prevention Technology (MFPT), an interdisciplinary technical organization strongly oriented toward practical applications. Ms. Vohnout has a diverse background and years of experience in the electronics and prognostics industry. She has published several papers on electronic prognostics and PHM applications.

About Ridgetop Group, Inc.

- Innovative Research and Technology Firm
  - Incorporated in 2000, and headquartered in Tucson, AZ
  - Design services, prognostics and condition-based maintenance (CBM) solutions
    - AS9100-C and ISO 9001:2008 Certified
    - DO-178 and DO-254 compliant quality system
  - Strong market position with commercial and government customers in USA, Canada, Europe, and Asia
  - Servicing Aerospace, Automotive, Industrial, Medical segments
  - U.S. Government: U.S. Department of Defense, Department of Energy, and NASA customers

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ANAB ACCREDITED

Outline

- What is prognostics?
- Condition-based maintenance (CBM)
- A prognostic framework
- Prognostic methods
- Examples
- Challenges and future direction
- Q&A

Evolution of Maintenance Practices

Going from REACTIVE to PROACTIVE/PREEMPTIVE

Repair/Replace when Broken

Maintenance as Suggested by Manufacturer

Enhanced Diagnostics of Components

Condition-based Maintenance (CBM)

Reactive

Proactive (Prognostics)

In medicine, the most cost-effective way to cure disease is to **PREVENT** it

Definitions

Mean Time Between Failures (statistical)

Vs.

Condition-Based Maintenance (real-time)

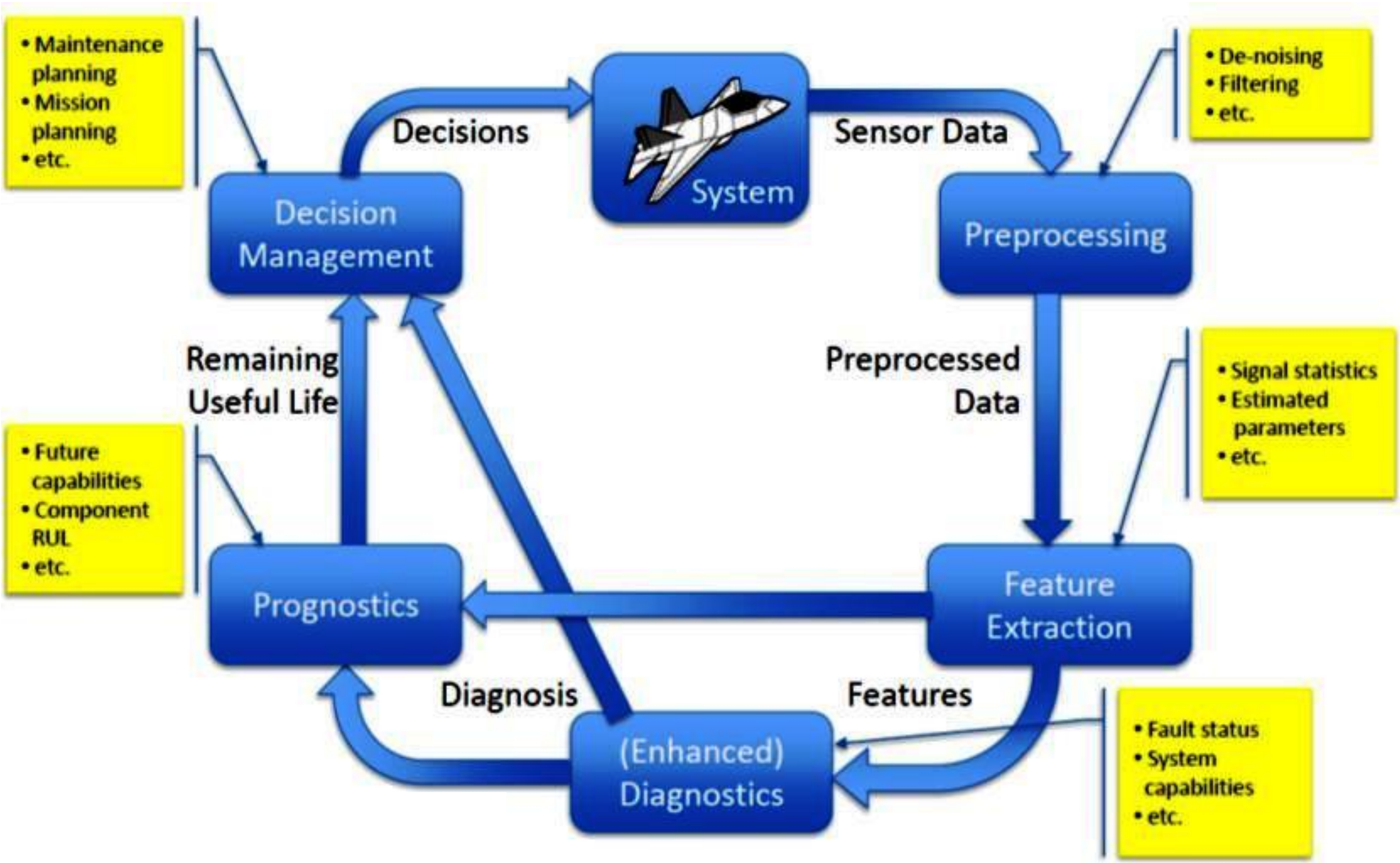
Prognostics = **Diagnostics (State of Health)** + **Remaining Useful Life (RUL)**

Remaining Useful Life (RUL): The amount of time a component can be expected to continue operating *within its given specifications* ***(not necessarily a failure).*** Dependent on future operating conditions (input commands, environment, and loads).

Prognostics

- Predictions are based on:
  - Analysis of failure modes
  - Detection of early signs of wear, aging, and fault conditions and current state of health
  - Correlation of aging symptoms with a description of how the damage is expected to increase (“damage propagation model”)
  - Effects of operating conditions and loads on the system

Health Management



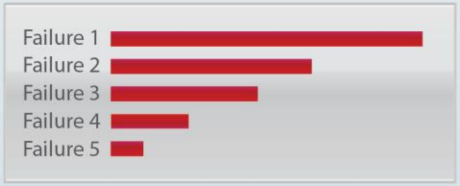
Source: Scott Clements, “Introduction to Prognostics”, PHM Society Conference, Montreal 2011

Simplified PHM Process

STEP 1

Characterize Device or System Failures

Key Failure

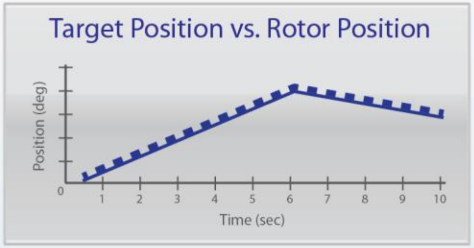


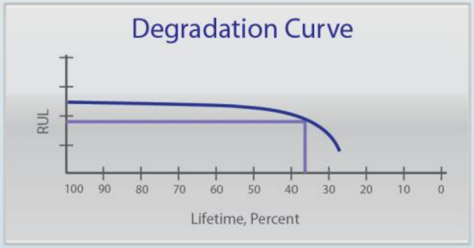
Pareto Ranking of Key Failures

STEP 2

Extract Precursor Signatures to Failure

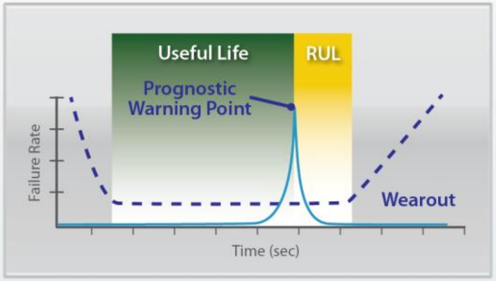
Example Precursor Signatures





STEP 3

Calculate Remaining Useful Life (RUL)

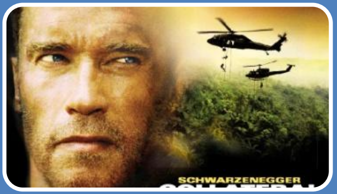


Device or System Lifetime

Goals of Prognostics

Increase Safety and Mission Reliability

- Improved mission planning
- Ability to reassess mission feasibility



Decrease Collateral Damage

- Avoid cascading effects onto healthy subsystems
- Maintain consumer confidence, product reputation

Decrease Logistics Costs

- More efficient maintenance planning
- Reduced spares

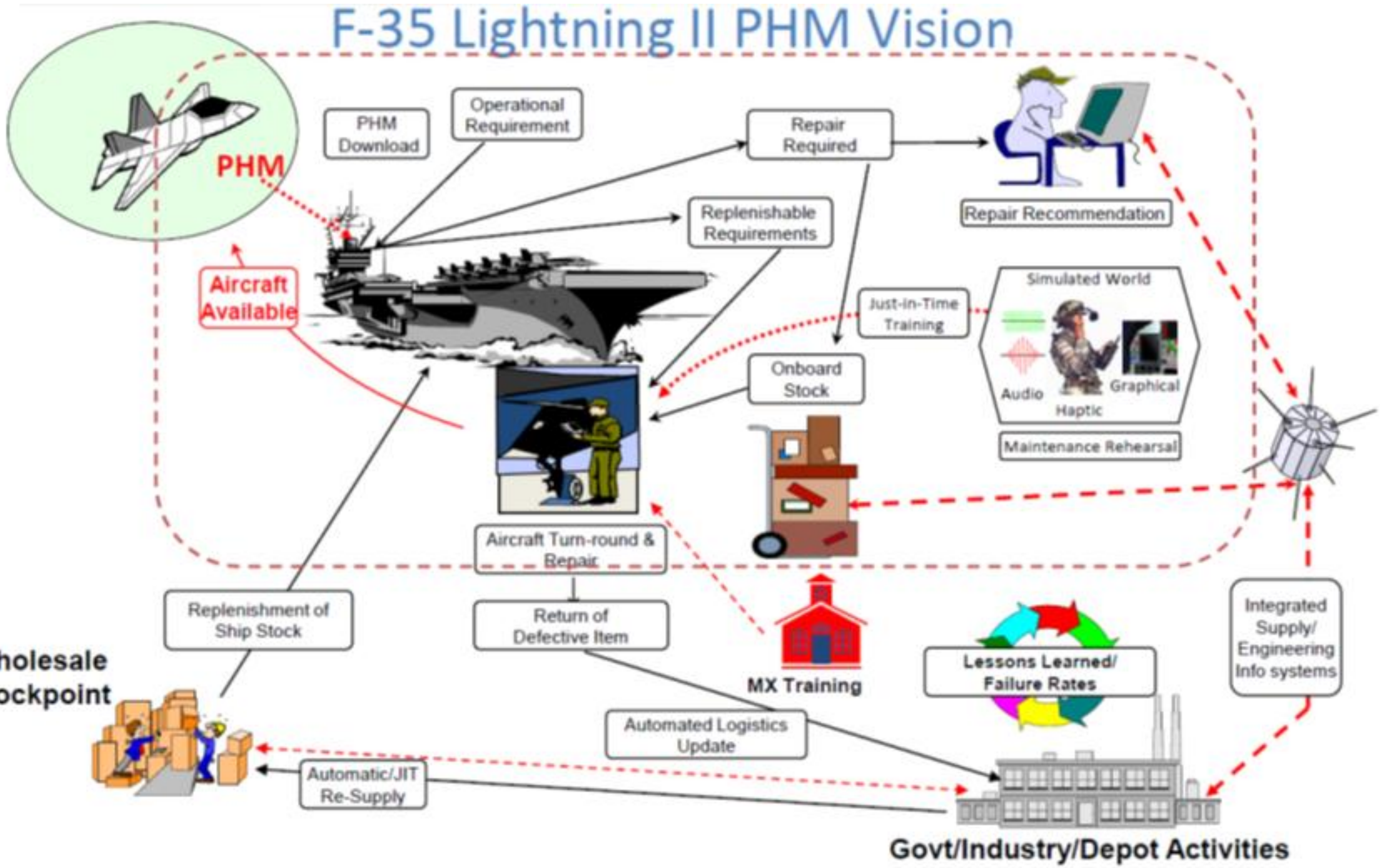
Decrease Unnecessary Maintenance

- Service only specific systems which need service
- Service only when it is needed

Stakeholder Perspectives

- **Maintainers**
  - Scheduling maintenance
  - Opportunistic maintenance
  - System Uptime
  - Minimum unnecessary maintenance
  - Training
- **Logisticians**
  - Spares positioning
  - Reduced spares count
  - Logistics footprint
- **Engineers**
  - Requirements satisfaction
  - Improved capabilities
  - Robustness
- **Safety**
  - Avoid catastrophic failures
  - Minimum impact to other systems
- **Mission Planners**
  - Mission capability
  - Mission assignment
- **Program Management**
  - Meeting customer expectations
  - Proposals Development
  - Cost

PHM System Example



Source: JSF Program office

Condition-based Maintenance (CBM)

- Set of maintenance processes and capabilities derived from real-time assessment of system condition
- Goal of CBM is to perform maintenance **ONLY** upon evidence of need
- Ultimate intent of CBM is to increase system operational availability throughout the system life cycle at a reduced cost
- **CBM and Electronic Prognostics**
  - Electronics are the keystone to successful deployment of complex systems
  - Large mean time between failures (MTBF) numbers alone are not sufficient
  - Technology exists to pinpoint systems that are degrading before they fail; supporting operational readiness objectives and cost-saving CBM initiatives

Degradation Rates Dependent on Environmental Conditions

Usage Environment

- Usage monitoring would provide a safety benefit if actual usage is more severe than predicted **(see the red region, T_1)**.
- Service life can be extended beyond normal replacement time if the actual usage severity is known **(see the green region, T_2)**.

MTBF statistical expected life

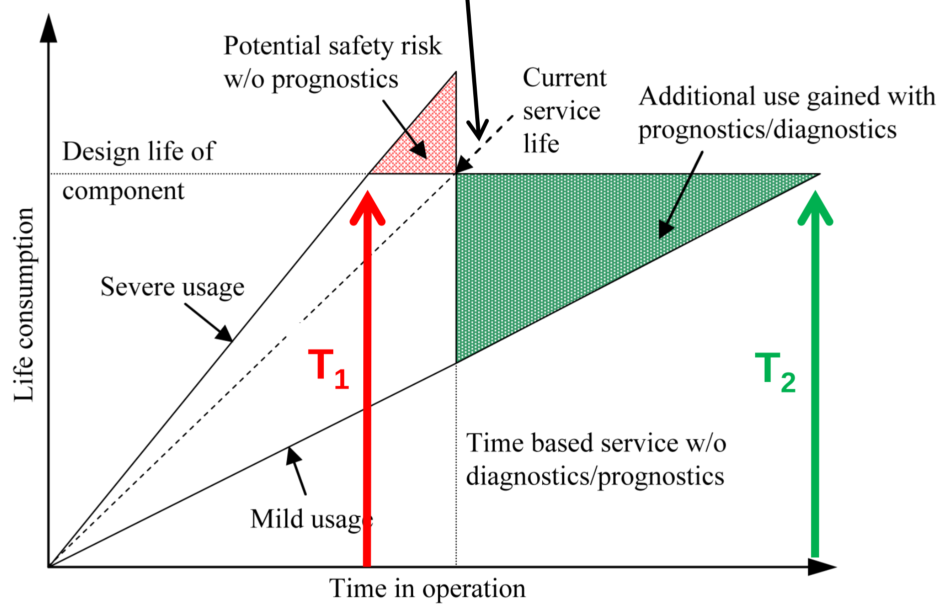


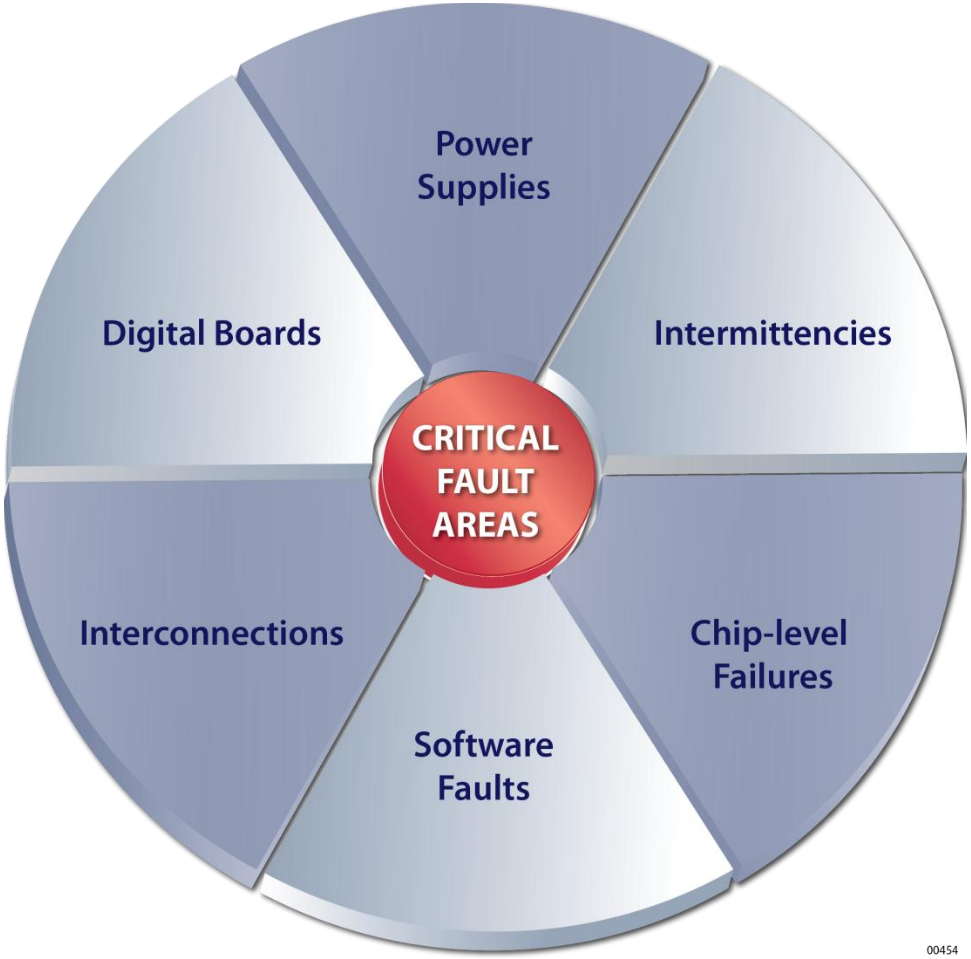
Figure 1: Economic and Safety Benefits of Diagnostics & Prognostics (Romero et al.1996).

Prognostics and Health Management (PHM) enables replacement only upon evidence of need

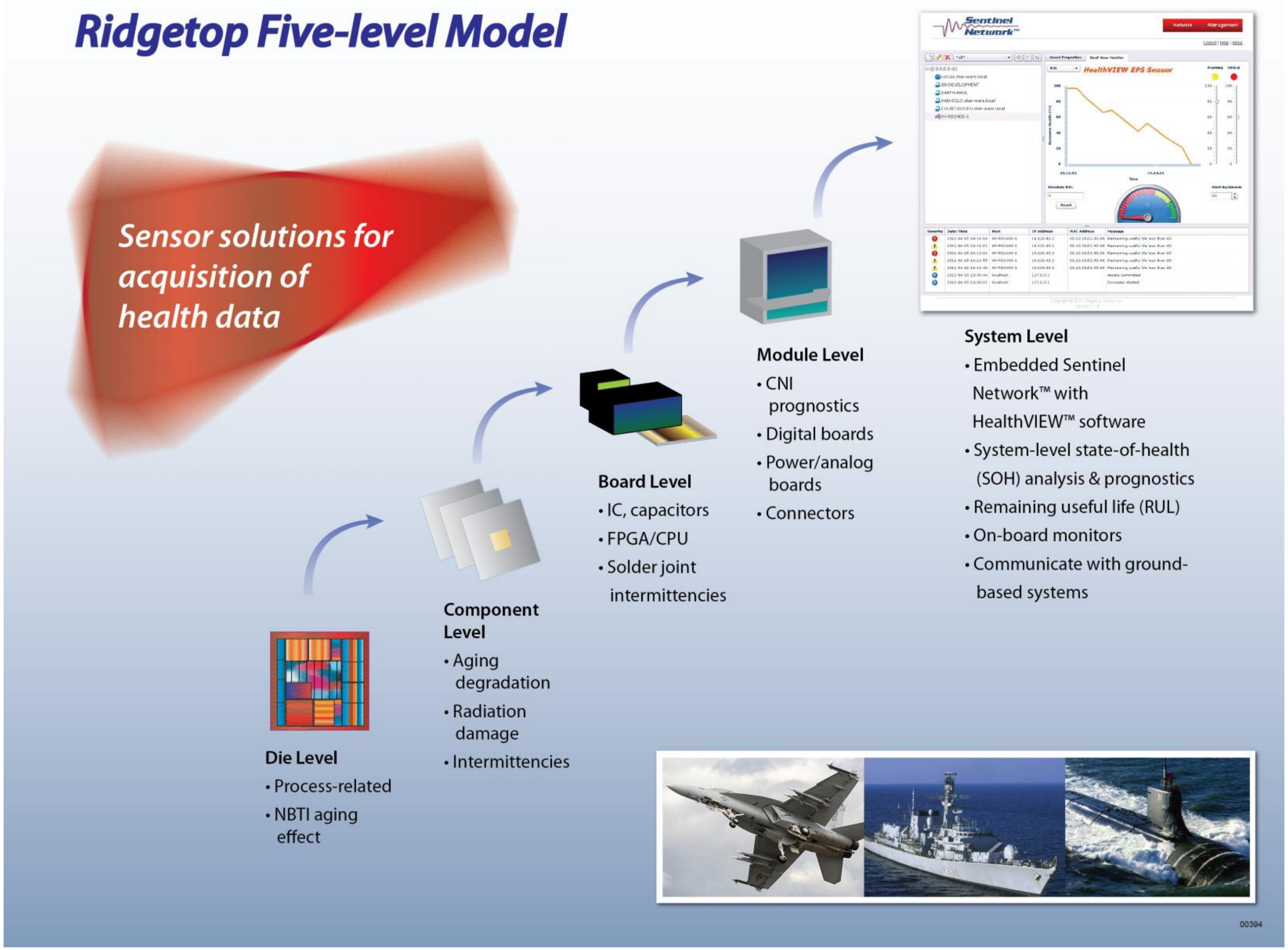
Faults in Complex Electronic Systems

Existing innovative technologies address all of these critical fault areas with real-time sensors for:

- **Aerospace**
- **Automotive**
- **Industrial**
- **Medical**



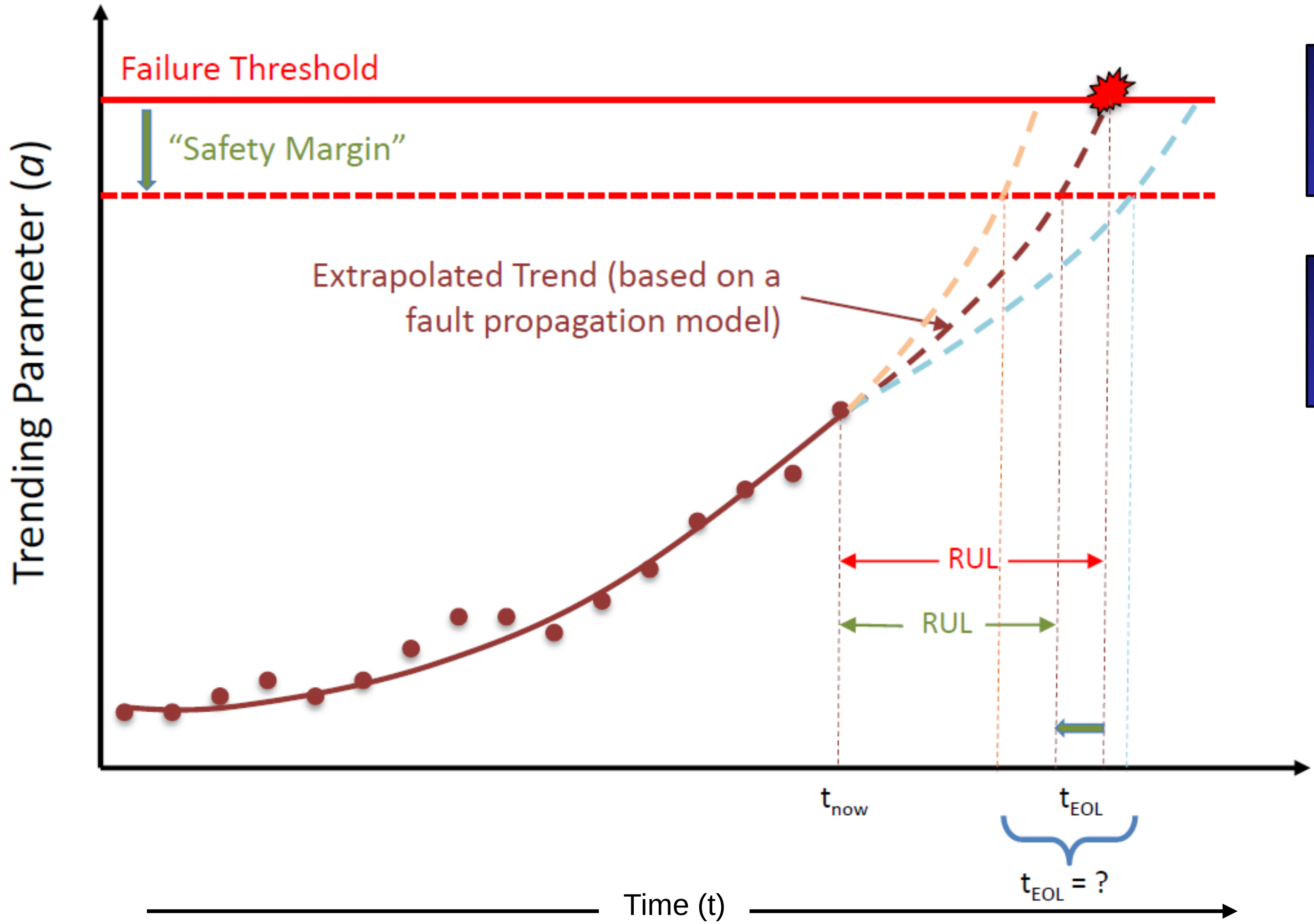
PHM Five-Level Model



Prognostic Algorithm Categories

- Reliability data-based
  - Statistical models
  - Consider historical time-to-failure data, used to model the failure distribution
- Stress-based
  - Fault adaptive model – learned from accumulated knowledge
  - Consider environmental stresses
- Condition-based
  - Estimate the life of a specific component under specific usage and degradation conditions

Prognostic Framework: Trends, RUL, Uncertainty



Decision Risk
How soon is too soon and how late is too late?

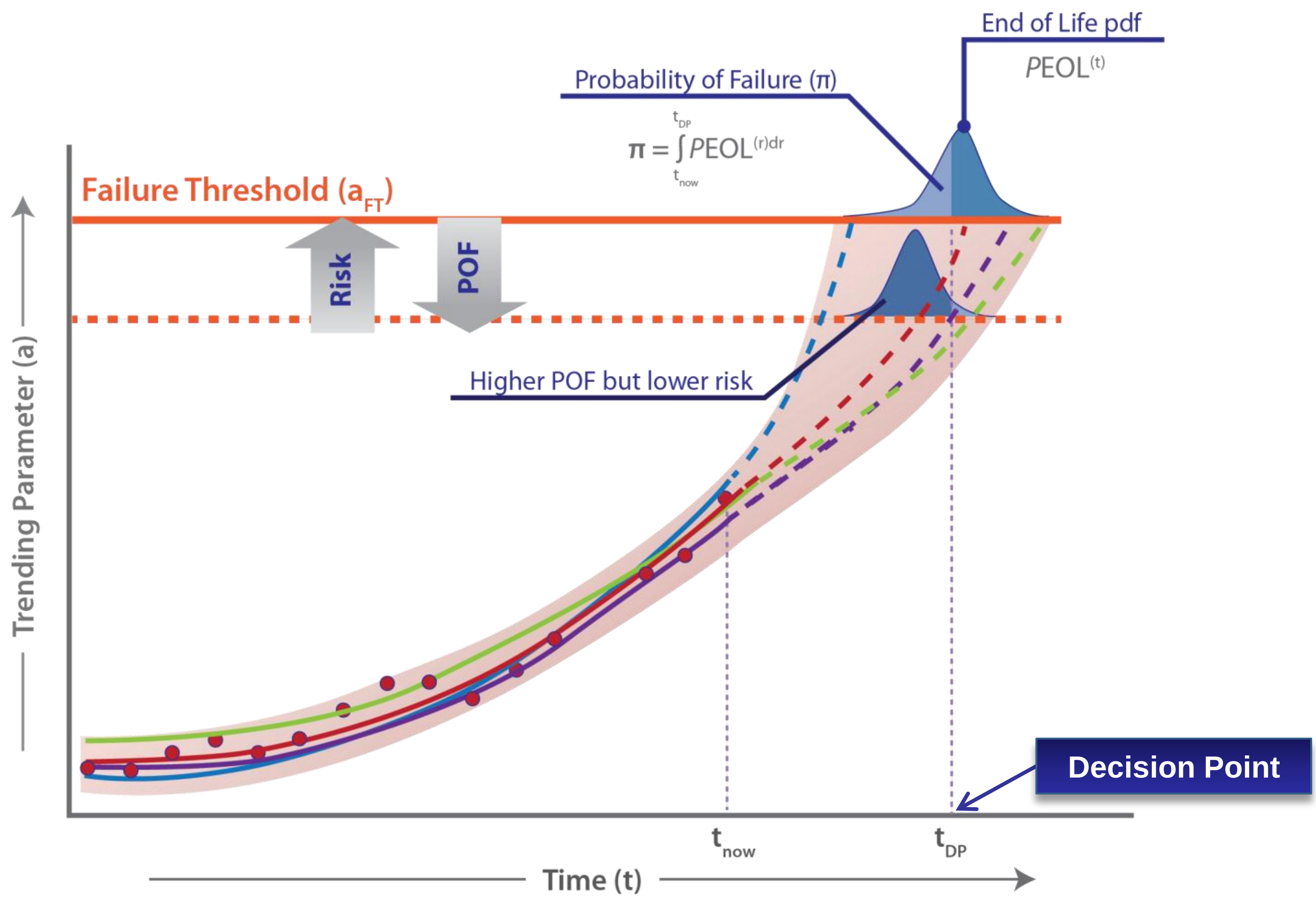
Model Uncertainty
Which model to trust?
No model is perfect

Source: Scott Clements, "Introduction to Prognostics", PHM Society Conference, Montreal 2011

Prognostics Framework: Types of Uncertainties

- Real and accurate data is difficult to acquire
- We have measurements, which we correlate to damage through complex algorithms or reasoners
- Noise may influence the model's outcome
- Decision risk
  - How soon is too soon and how late is too late?
- Uncertainties:
  - Model uncertainty
  - Input data uncertainty
  - Measurement uncertainty
  - Operating environment uncertainty
- Measurement noise leads to more uncertainty

Risk vs. Probability of Failure (POF)



Source: Scott Clements, “Introduction to Prognostics”, PHM Society Conference, Montreal 2011

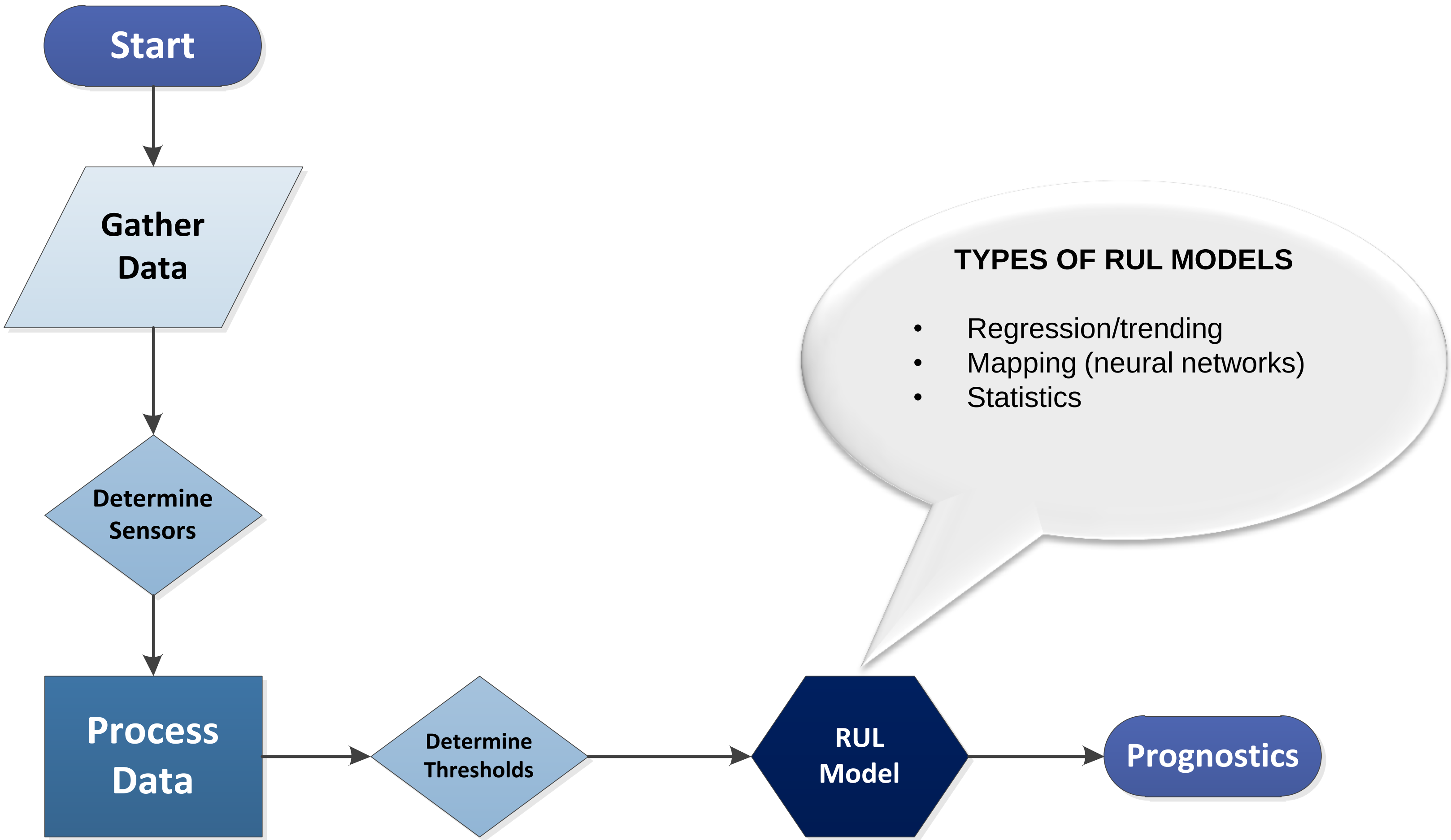
Methods For Gathering Knowledge

- Failure Modes and Effect Analysis (FMEA)
- Failure Modes, Effects, and Criticality Analysis(FMECA)
- Fault tree analysis
- Designers / reliability engineers
- Seeded failure testing / accelerated life testing
- Fielded systems

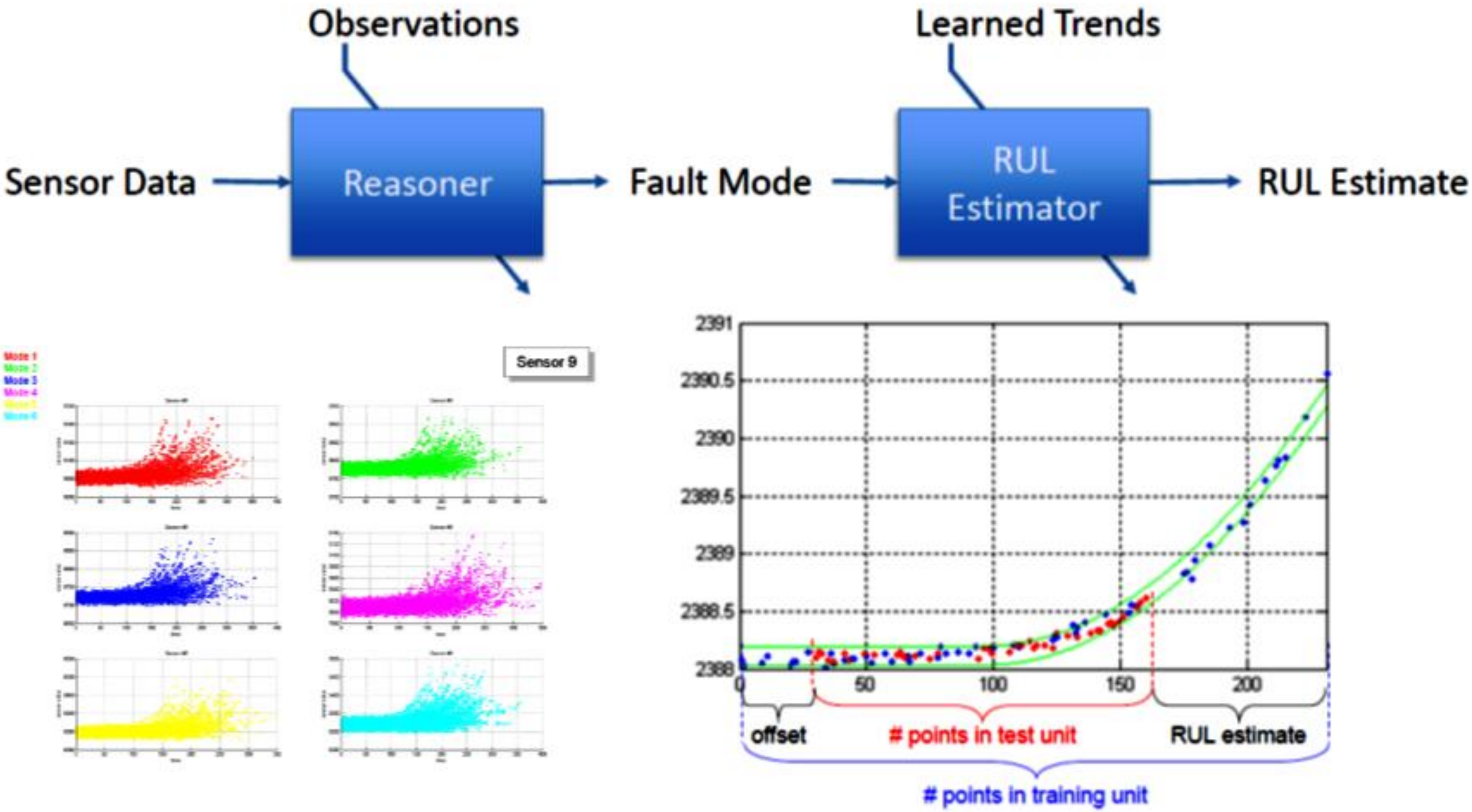
Data-Driven Methods

- Models are based on historical operational data that characterize the system health
- Data are collected from sensors
- Data are analyzed and extrapolated to determine damage thresholds
- These models determine the remaining useful life solely from the data collected
- This approach is useful when the understanding of first principles of the system operation is not well known or when the cost of developing an accurate model is expensive

Data-Driven Methods – Common Process



Data-Driven Example



Source: Scott Clements, "Introduction to Prognostics", PHM Society Conference, Montreal 2011

Data-Driven Methods: Pros & Cons

PROS

- Easy and fast to implement/deploy
- Usually cheaper compared to other approaches
- May identify relationships that were not previously considered

CONS

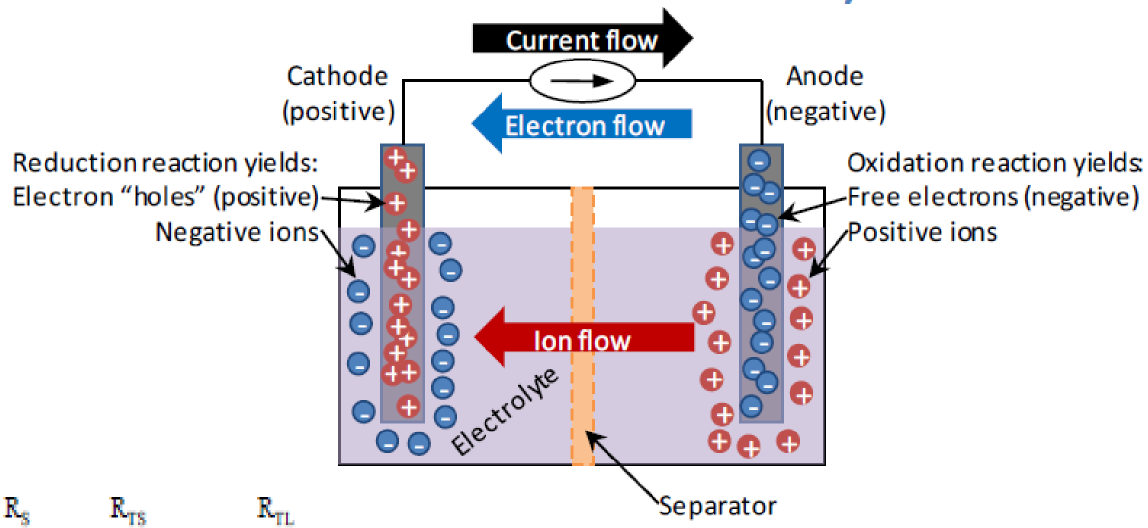
- Requires lots of data
- It might be difficult to obtain run-to-failure data (lengthy and costly)
- May require a lot of training
- Results may be counter intuitive
- Data collected might be noisy
- Can be computationally intensive, both for analysis and implementation

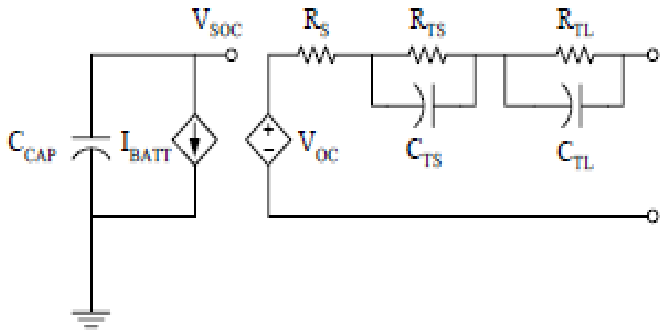
Physics-Based Methods

- What is a “Physics-Based” Model?
  - Model derived from “First Principles”
  - Empirical model chosen based on an understanding of the dynamics of a system
    - →Equations define relationships between time, load, damage, environment, and operational conditions
    - →Damage propagation (crack growth model, fatigue of bearings)
  - Mappings of stressors onto damage accumulation
- We are looking for a correlation to the failure mode(s) of interest

Physics-Based Method Example

Lithium Ion Battery

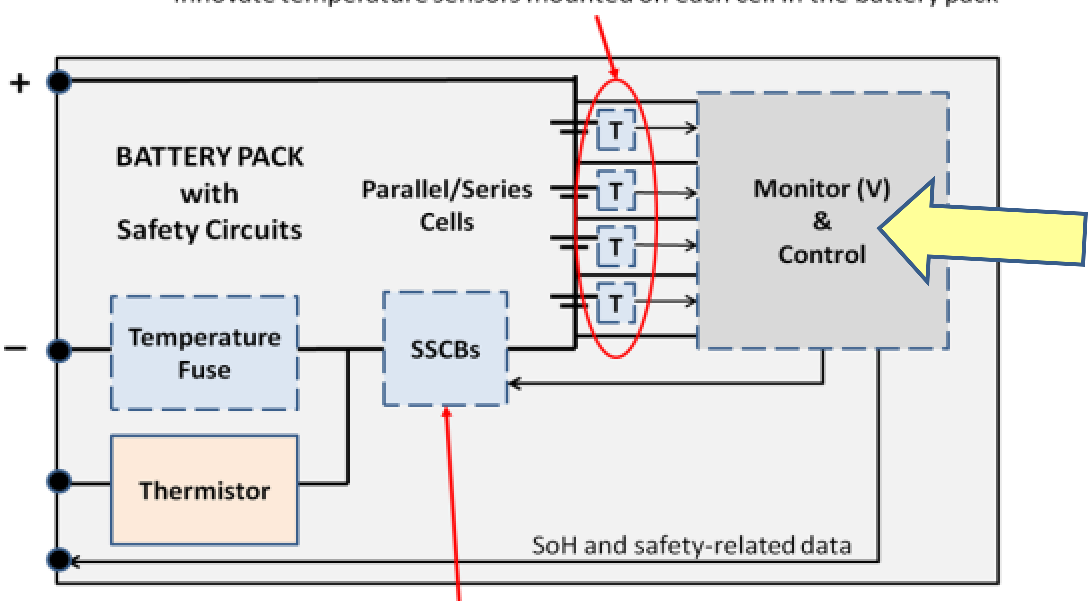




$$v_{SOC}(t) = v_{SOC}(0) - \frac{1}{C_{CAP}} \int_0^{\tau} i(\tau)\, d\tau$$

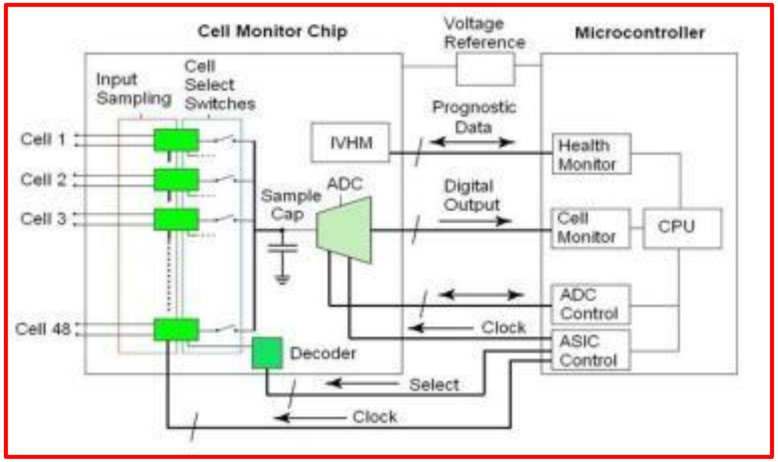
Ridgetop Battery Monitoring Systems

Intelligent Battery Control Module to Measure Rate of Voltage and Temperature Change



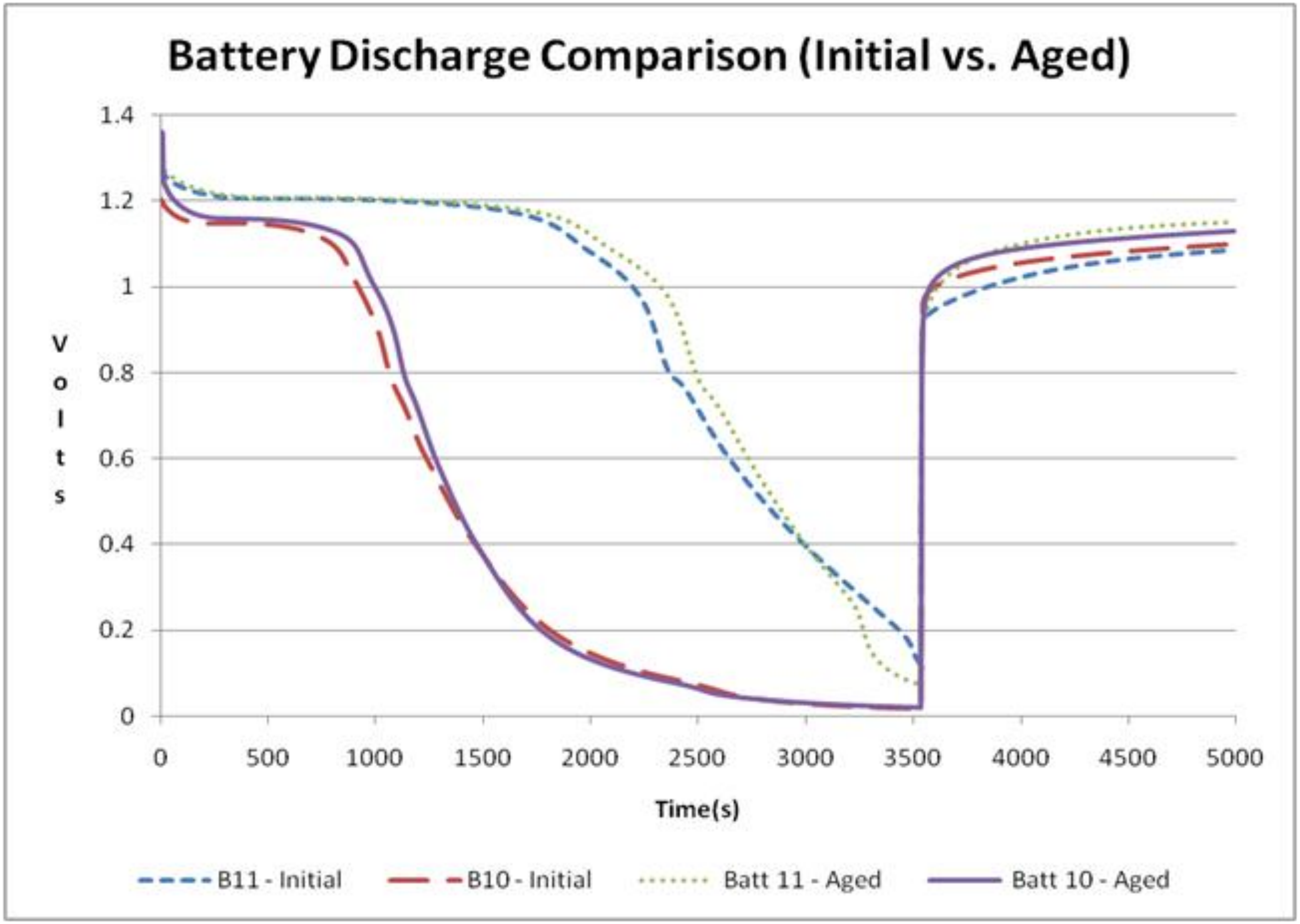
Solid State Circuit Breaker on/off state dependent on both voltage and temp

Monitor ASIC



Ridgetop has designed an ASIC to monitor cell voltages.
ASIC being modified for lithium-ion cells and batteries .

Battery Data

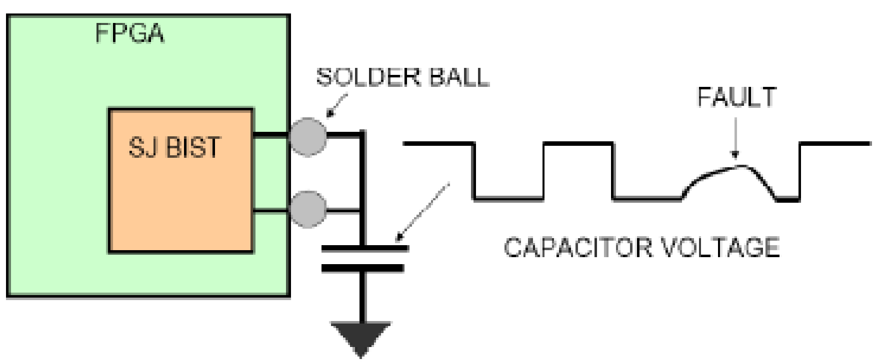


Source: Bush, J., Vohnout, S., Hofmeister, J., "PROGNOSTIC HEALTH MANAGEMENT (PHM) SOLUTIONS FOR BATTERY PACKS USED IN CRITICAL APPLICATIONS", MFPT 2011

Sentinel SJ BIST HealthView™ & SJ HALT™

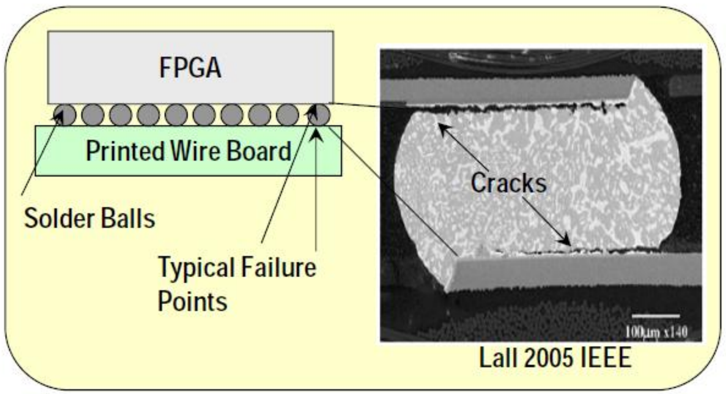
SJ BIST™ Operation

- Verilog firmware core (patent pending)
  - Each core tests two I/O pins
  - Pins are externally wired together
  - Small capacitor connected to the two pins



Mechanics of Failure

- Plastic work (thermo-mechanical stress)
- Solder balls crack and then fracture



- **Real-time in-situ monitoring of BGA interface health**
- **Canary sensor trigger or declining heath indicator**

Eliminates <u>Could Not Duplicate</u> and <u>No Trouble Found</u> intermittent problems associated with FPGAs

Physics-Based Models: Pros & Cons

PROS

- Usually results tend to be intuitive
- Models can be reused
- If incorporated early enough in the design process, can drive sensor requirements
- Computationally efficient to implement

CONS

- Model development requires a complete understanding of the system and physics
- High-fidelity models can be computationally intensive
- Models need to account for uncertainty management

Hybrid Models

- In practice, many implementations use both Data-Driven and Physics-Based Model methods:
  - Use data to learn model parameters
  - Use knowledge of physical process to determine the type of analysis to apply
  - Data-Driven System Model in combination with a Physics-Based Fault Model (or vice versa)
  - Identify potential correlations between physics model and correlate using a data-based approach
  - Data fusion

Hybrid Models: Pros & Cons

PROS

- Combines the strengths of each approach
- Robustness in design
- Results are both intuitive and match observations
- Can "mix and match" approaches to customize for the current situation

CONS

- There is still a need for data
- It can still be computationally intensive
- Need for in-depth system knowledge

PHM Challenges

Requirements Specifications

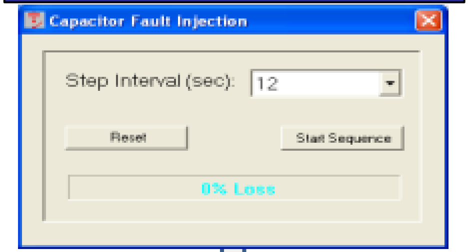
Validation and Verification

Integration

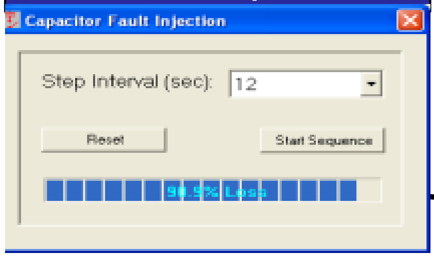
Uncertainty Management

Power Supply Prognostics

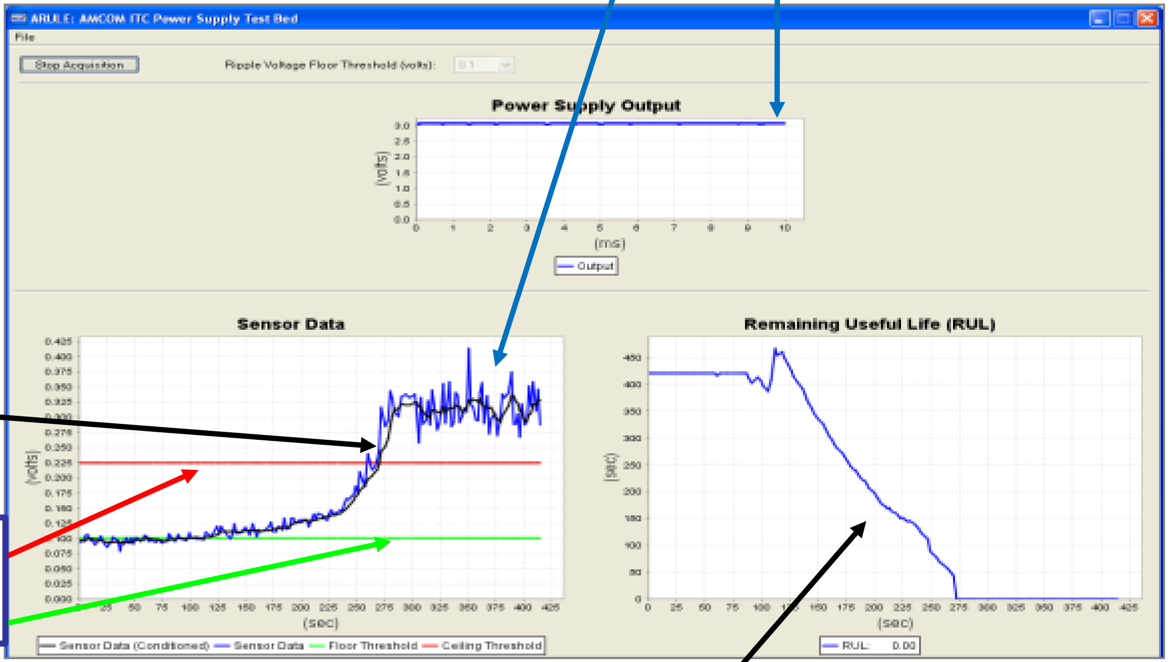
Graphical interface to specify fault-injection step interval



Fault injection stops after 90.9% loss of capacitance



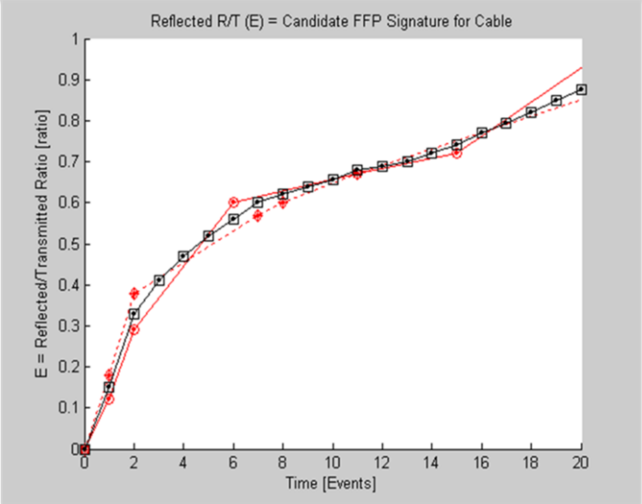
Power supply has failed (91% degraded)
- **Output is still being regulated**
- **But noise is too large**

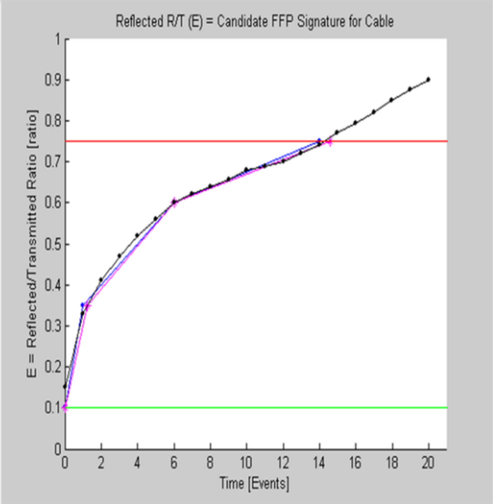


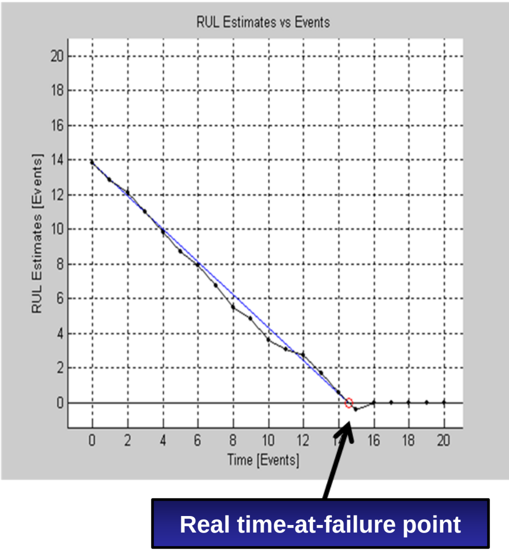
FMEA-determined thresholds
- **Exceeds predefined spec**
- **Defined as good as new**

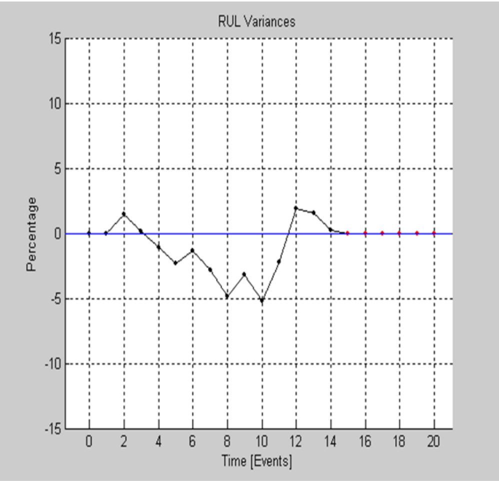
RUL declines as degradation damage progresses: becomes zero once degradation reaches FMEA predefined failure threshold

Cable Prognostics



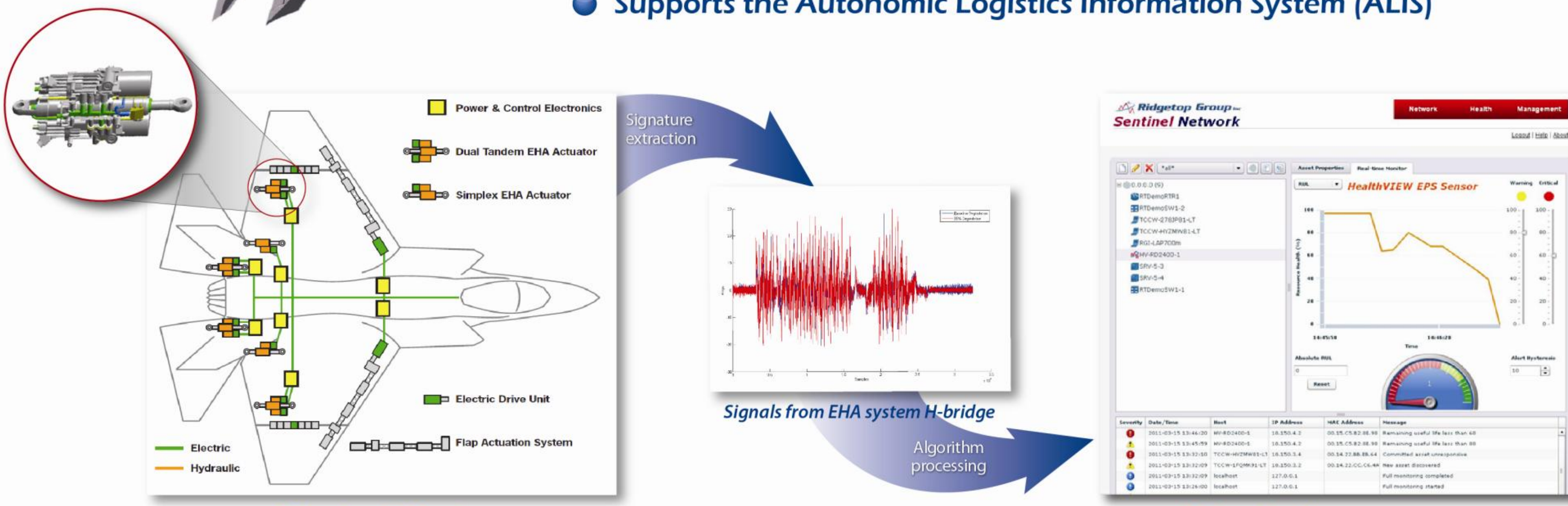






Condition-Based Maintenance (CBM) for F-35

- Electrohydrostatic actuator (EHA) prognostics
- Degradation signature extraction for state of health (SoH)
- Algorithmic processing of SoH for remaining useful life (RUL)
- Supports the Autonomic Logistics Information System (ALIS)



F-35 on-board EHA system

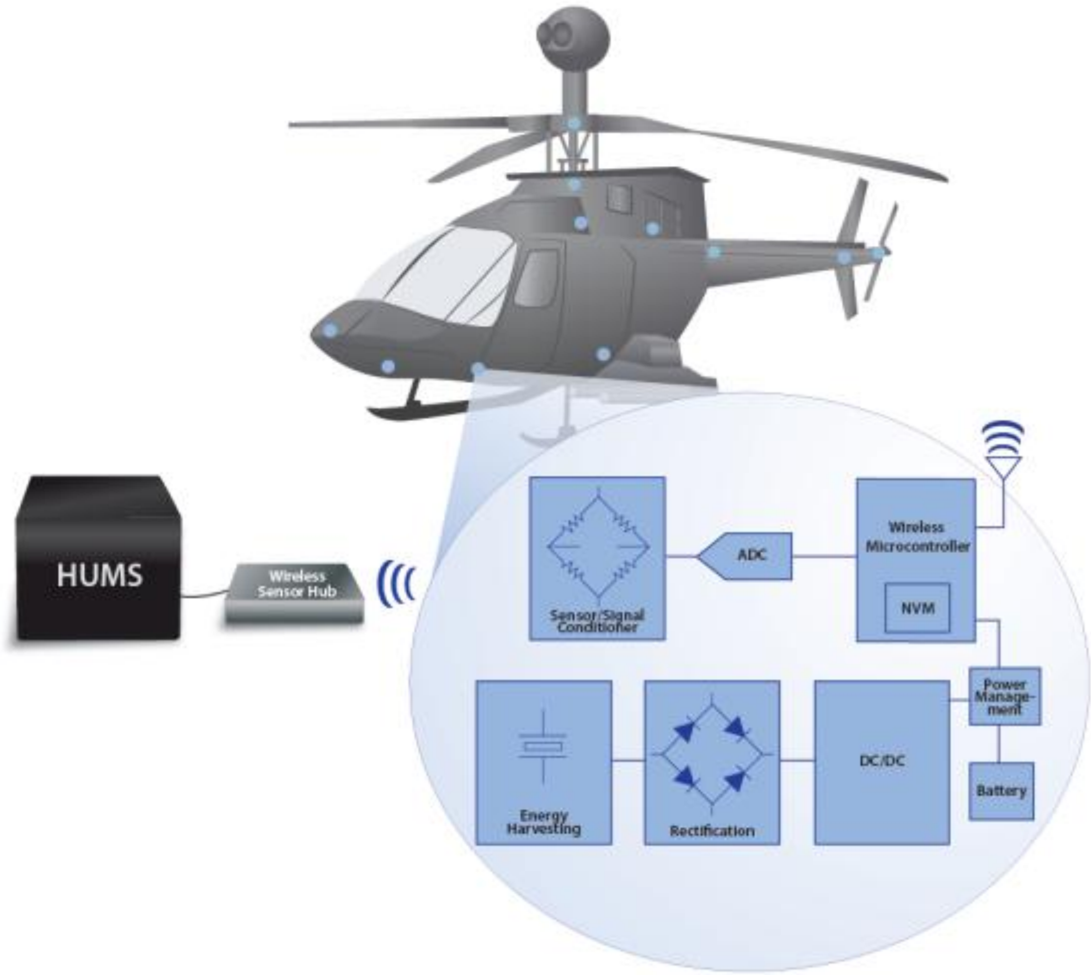
Signals from EHA system H-bridge

Off-board health management system

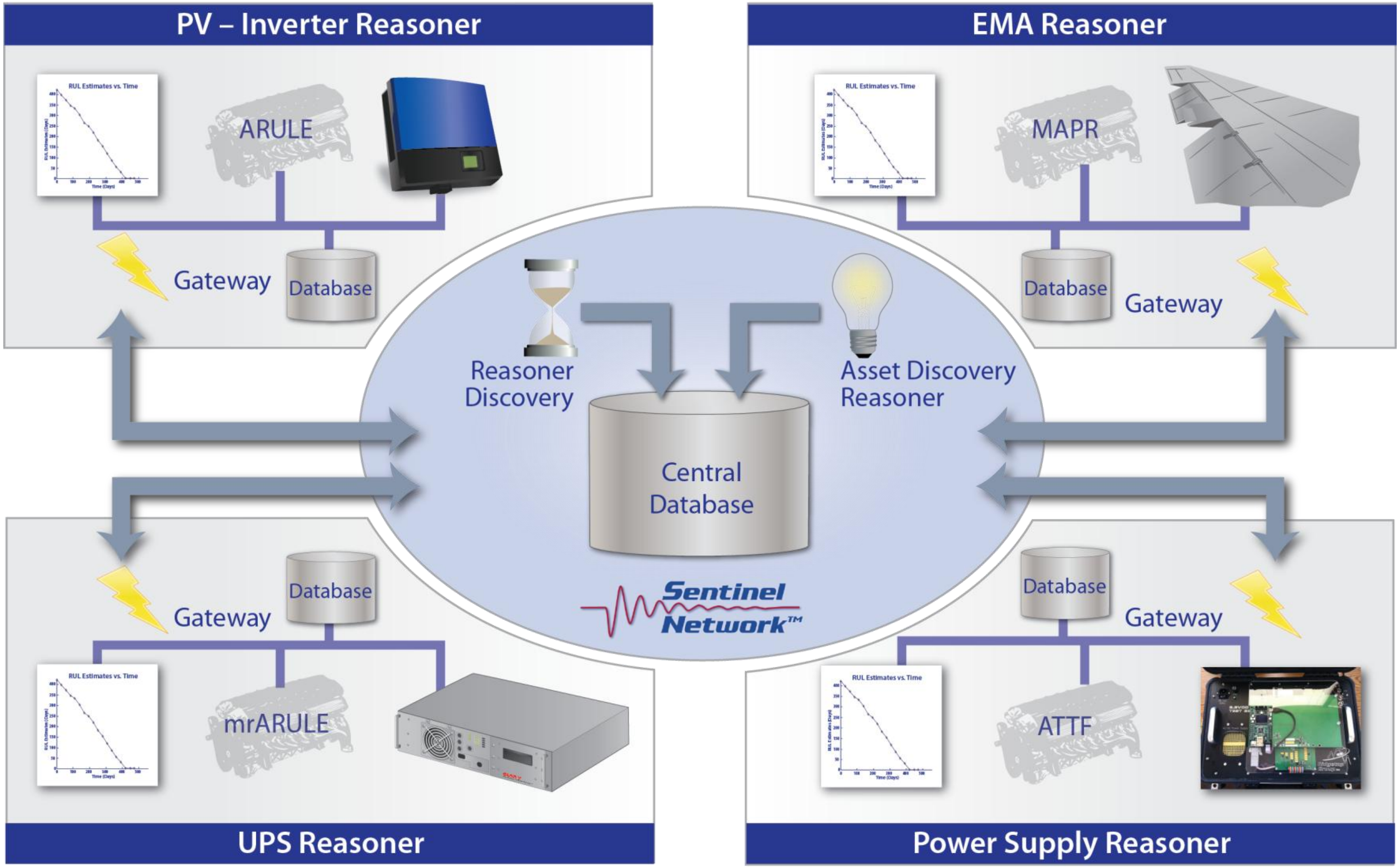
00415 REV1

MEMS Sensor Technology

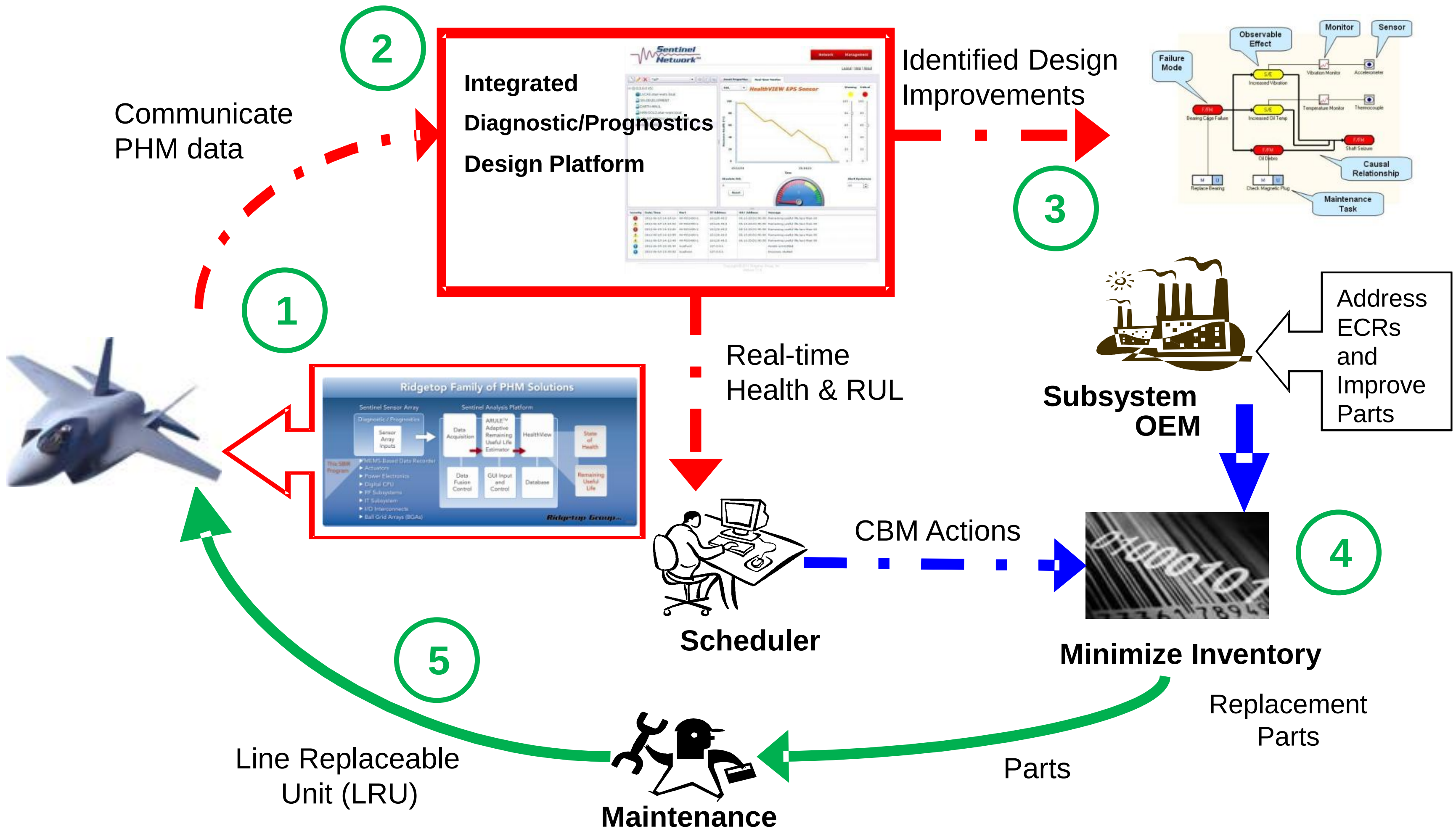
EP Mechanical Requirements	Description	Parameter
EP-1	Accelerometer peak impact	> 200 g
EP-2	Components and IC temperature rating	> 180 °F
EP-3	Sensor housing cap shall be RF transparent, i.e. teflon	
EP-4	Sensor housing	Press fit into 1.5" diameter shaft
EP Electrical Requirements	Description	Parameter
EP-5	Sensor data memory	2Mbytes
EP-6	Accelerometer sensitivity	< 20 mV/g at 100Hz
EP-7	Wireless full duplex data transfer	
EP-8	Wireless data rate	250 kbits/s
EP-9	Passive relay antenna used for passing data out of the transmission	
EP-10	Battery powered	3.6V high temp battery, 4.5 Ah, 200 C
EP-11	Battery life	4 months
EP-12	Data format shall be raw data, unprocessed	
EP-13	Sensor and signal conditioning bandwidth	20 kHz
EP-14	ADC number of bits	16 bits
EP-15	ADC conversion rate	> 250kHz
EP-16	Crystal oscillator frequency variance	< 40 ppm



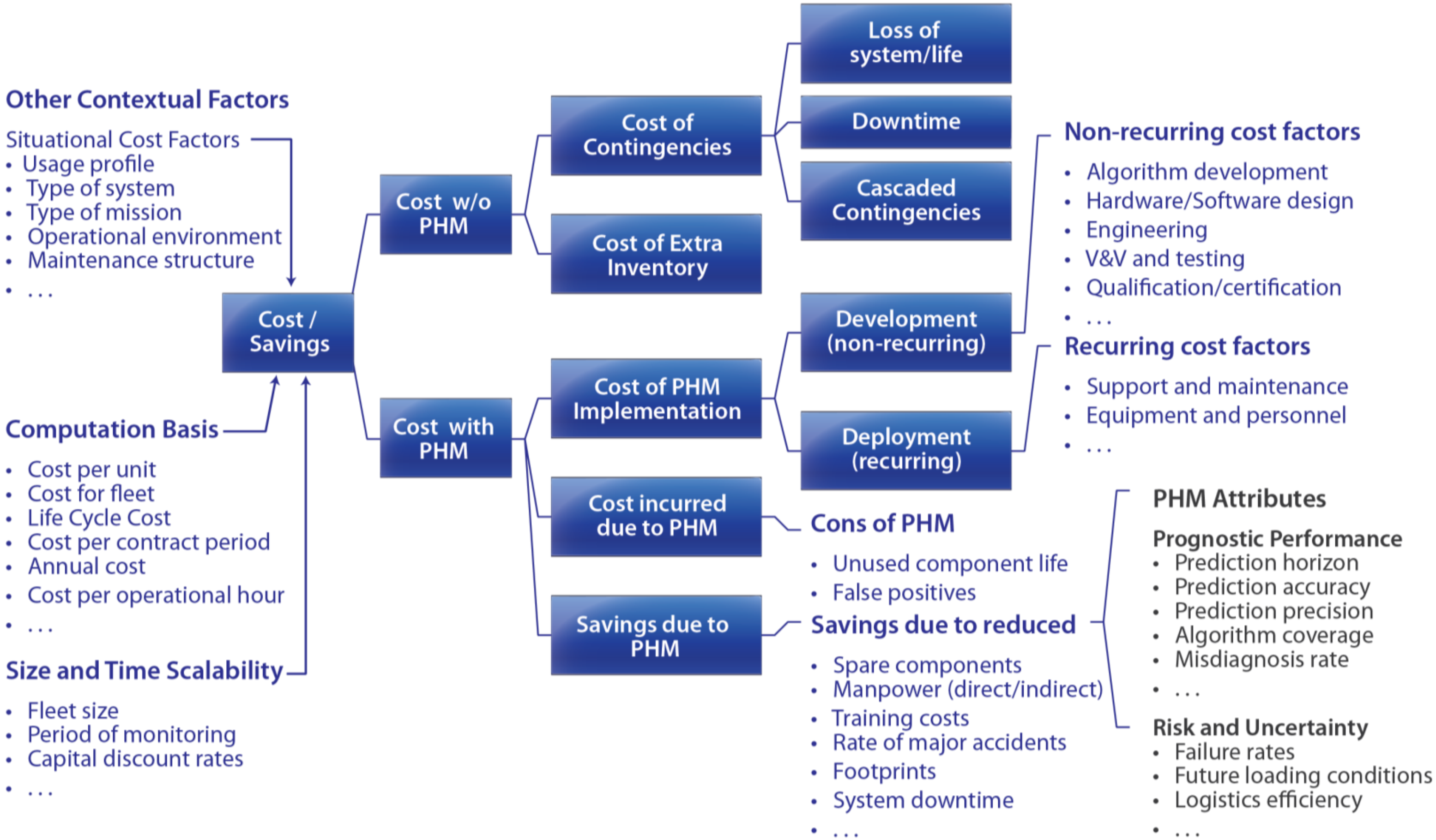
PHM Software Architecture Diagram



Prognostic Health Management



Cost Benefit Analysis: Summary



Source: Saxena, A., Celaya, J., Saha, B., Saha, H., Roychoudhury, I., Goebel, K., "Requirements Specification for Prognostics Performance – An Overview", AIAA Infotech @ Aerospace, Atlanta GA, April 2010.

Future: A PHM Sensor

- A PHM sensor is a system that:
  - Is a collection of one or more different sensors
  - Acquires data
  - Processes and analyzes the data
  - Stores information
  - Built-in capability to respond with:

State of Health + Remaining Useful Life (RUL) → Prognostics

Questions?

Upcoming Webinars

Ridgetop Group Inc
ENGINEERING INNOVATION

Topic	Date	Time
Overview of Prognostics and Health Management (PHM) in the IT Industry	Wed. Mar 21, 2012	1:00 - 2:00 PM PDT
ARULE (Adaptive Remaining Useful Life Estimator) – ATTF (Advanced Time-to-Failure) to Diagnose and Predict System Health	Wed. Apr 25, 2012	1:00 - 2:00 PM PDT
IC Characterization with ProChek, a Compact Benchtop System	Wed. May 30, 2012	1:00 - 2:00 PM PDT
Implementation of Prognostics in Solar Applications	Wed. Jun 27, 2012	1:00 - 2:00 PM PDT
Troubleshooting Analysis and Decision Support in Complex Applications	Wed. Jul 25, 2012	1:00 - 2:00 PM PDT

For more information about Ridgetop Group Webinars, email us at info@ridgetopgroup.com

Thank you!