Technology Advances to Improve Reliability – A Broad View

Diganta Das, Ph.D.
Center for Advanced Life Cycle Engineering (CALCE)
University of Maryland, College Park, MD 20742
diganta@umd.edu
301-405-7770

University of Maryland: 2011

- Started in 1856
- About 48,000 students
- Ranked 13^{th} in the world in engineering programs, by The Institute of Higher Education and Center for World-Class Universities
- Ranked 8^{th} in engineering in the USA: Wall Street Journal
- Ranked 3^{rd} among the engineering programs in Wall Street Journal employer survey
- Ranked 5^{th} best value in public education by Kiplinger's

CALCE Overview

- The Center for Advanced Life Cycle Engineering (CALCE) formally started in 1984, as a NSF Center of Excellence in systems reliability.
- One of the world's most advanced and comprehensive testing and failure analysis laboratories
- Funded by over 150 of the world's leading companies
- Supported by over 120 faculty, visiting scientists and research assistants
- Received NSF innovation award in 2009

CALCE Organization

Education

- MS and PhD programs
- International visitors
- Web seminars
- Short courses for industry

Electronic Products and Systems Consortium

- Risk assessment, management, and mitigation for electronics

Prognostics and Health Management Consortium

- Techniques based on data trending, physics-of-failure, and fusion

CALCE

Center for Advanced Life Cycle Engineering for Electronic Products and Systems

Research Contracts

- Large scale programs
- Medium to long-term durations
- Contractual agreements
- Examples:
  Software development,
  testing,
  training programs

Lab Services

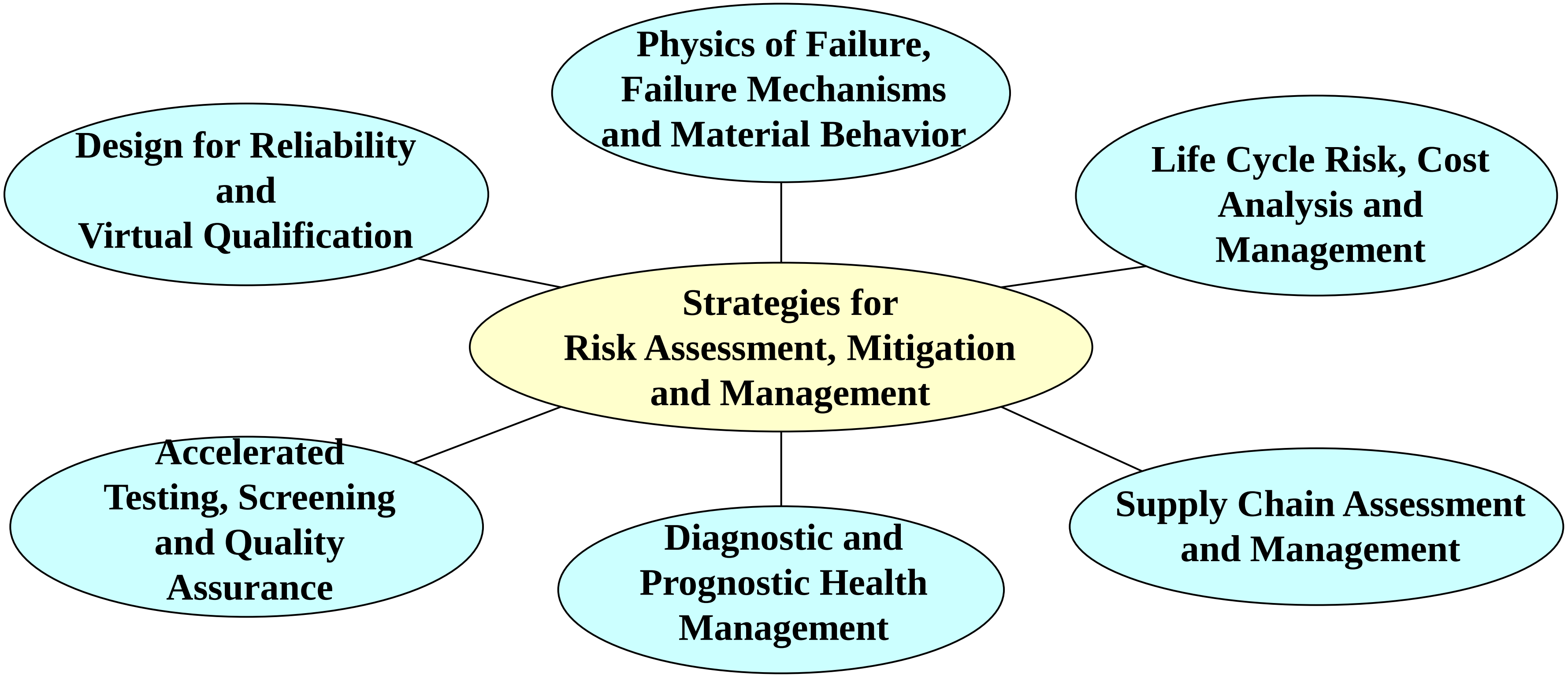
- Small to medium scale
- Rapid response
- Examples:
  Failure analysis,
  measurement,
  design review,
  supplier assessment

Standards

- Putting CALCE research to work for industry
- Examples:
  IEEE
  GEIA
  IPC
  JEDEC
  IEC

CALCE: Our Role

Provide a knowledge and resource base to support the development and sustainment of competitive electronic products and systems in a timely manner.



What is Physics of Failure (PoF)?

PoF is a methodology for building-in reliability, based on assessing:

- the impact of hardware configuration and life-cycle stresses;
- the materials at potential failure sites;
- root-cause failure mechanisms..

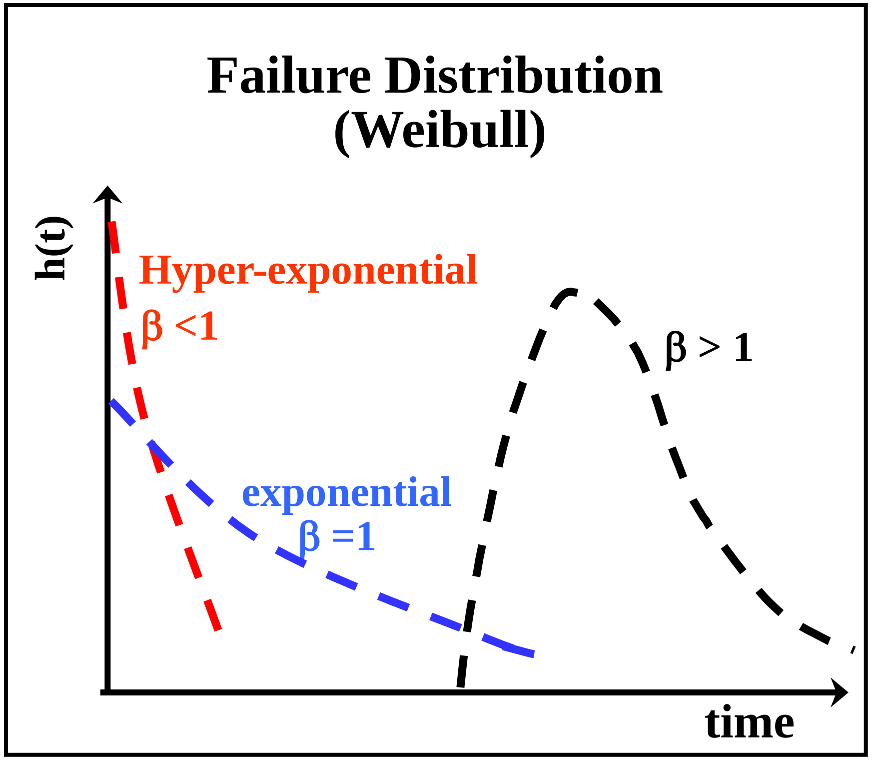
Based on these analyses, the life cycle is managed to minimize failures. Life cycle management includes activities such as:

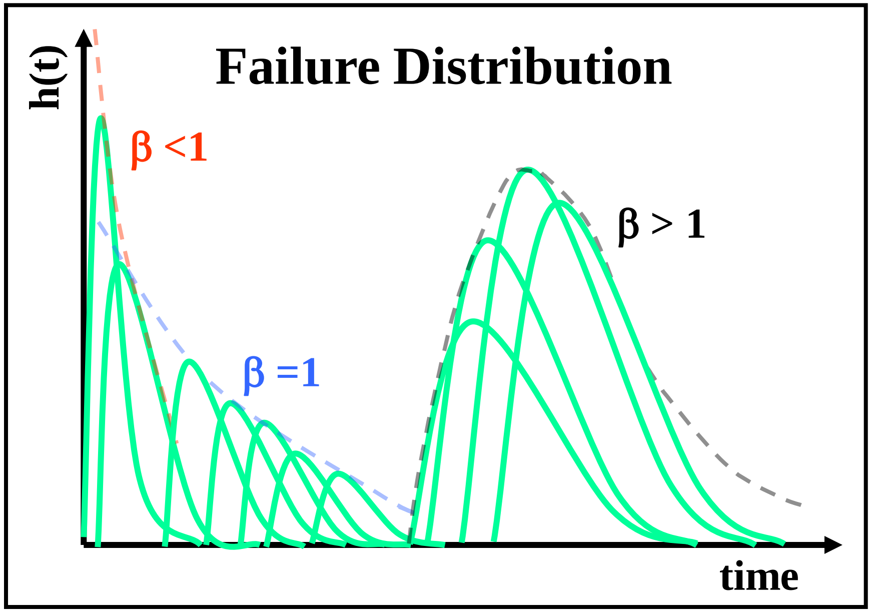
- Design and Qualification
- Manufacture, Assembly, and Quality Assurance
- Supply chain management
- Stress Management & Health Management
- Warranty management, Service and Logistical Support

PoF is just good engineering……PoF is not new !!!!!

Before We Discuss PoF……

Consider the system-level view of failures: 'Bathtub' curve

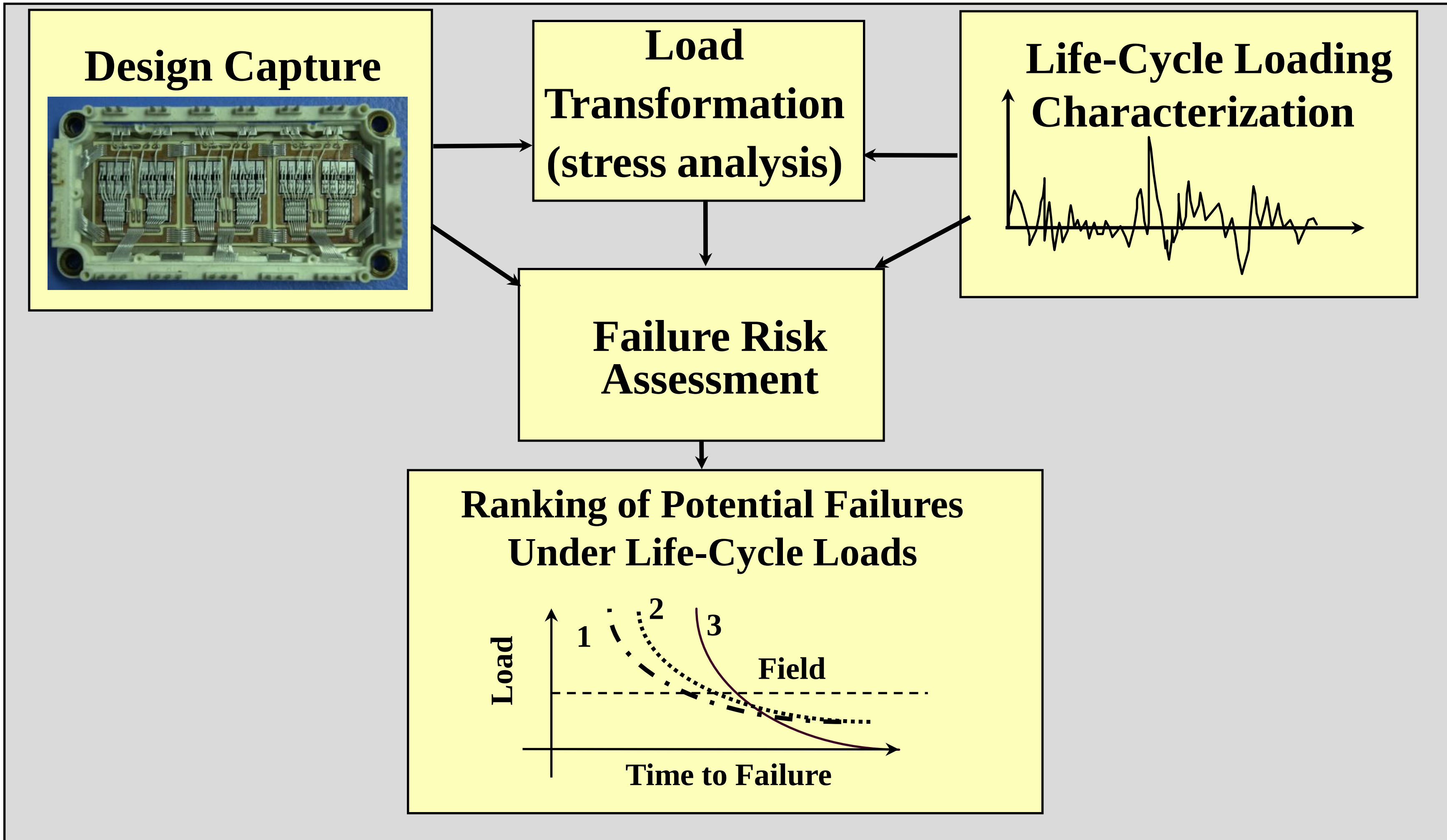




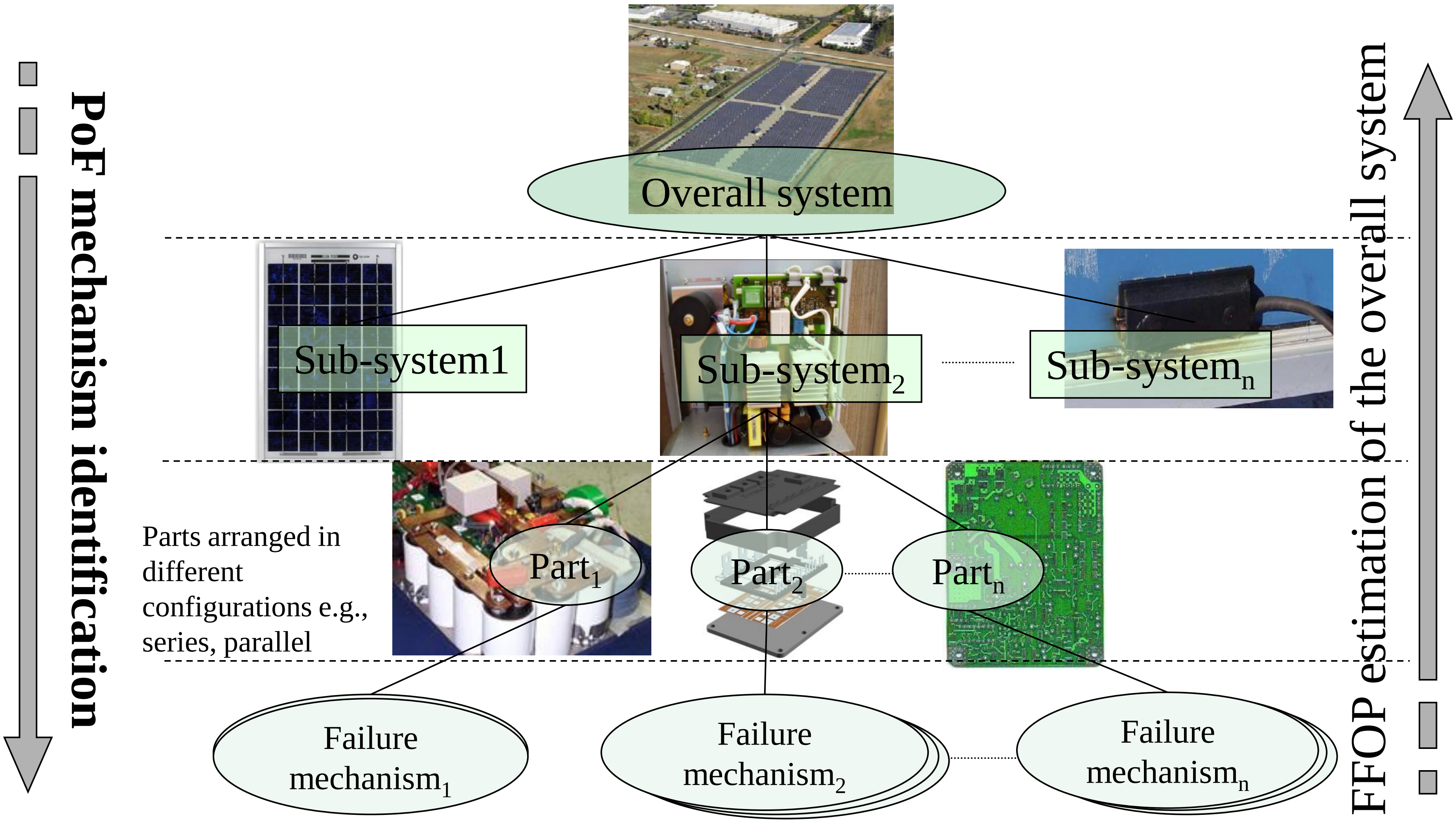
Reliability statisticians are interested in tracking system level failure data for logistical purposes, and in determining how the bathtub curve looks. Causes: infant mortality, "random" failures and wearout

PoF reliability engineers and designers want to figure out why the product's bathtub curve looks the way it does, what the root-causes of failures are, and how to reduce failures.

PoF Reliability Assessment Methodology



Comprehensive System Reliability Assessment



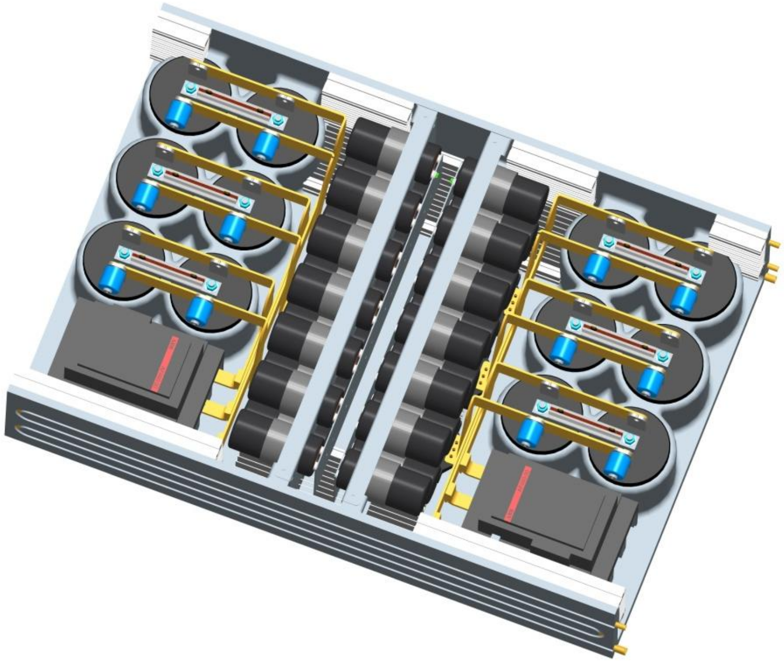
$$L = L_r \left(\frac{V_r}{V_0}\right) \times 2^{\left(\frac{T_r - T_A}{10}\right)}$$

$$\varepsilon = \frac{(R-\rho_f)d\psi}{\rho_i\psi_i} \approx \frac{(\bar{r}-\rho_f)d\psi}{\rho_i\psi_i} = \frac{r(\psi_i-\psi_f)}{\rho_i\psi_i}$$

$$Nf = 0.5\,(\Delta\gamma/2\varepsilon_f)^c$$

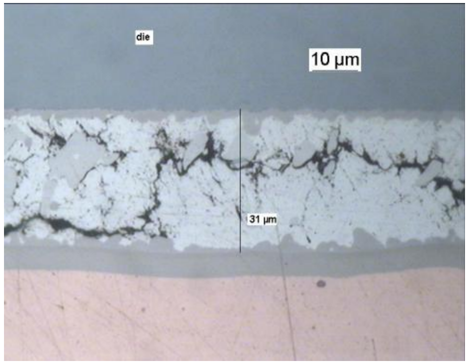
Power Electronic Inverter

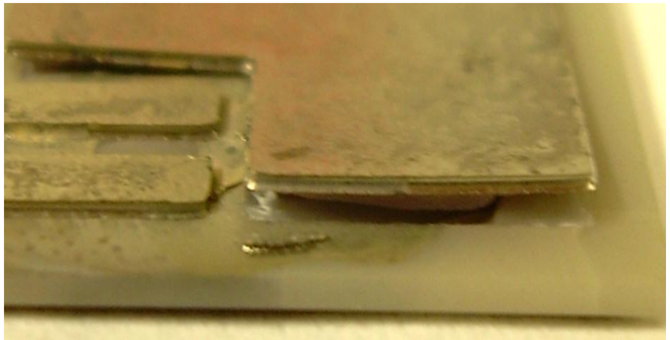
- One of the most common elements of power electronics is the inverter.
- An inverter system combines a number of known power electronic packaging technologies including large IGBT type semiconductor modules; control circuitry with advanced processing, sensors, and communication capabilities; and large passive components.



Packaging Failures in Power Modules

- Wirebonds – main cause of failure under power cycling operation
  - Wire flexure fatigue
  - Wire bond fatigue
- Die attach –main cause of failure under passive thermal cycling operation
  - Attach fracture
  - Attach fatigue
- Substrate – DBC substrates can fracture at the copper to ceramic interface
  - Substrate fracture
  - Substrate fatigue
  - Copper delamination





Inverter Passive Component Failure Mechanisms

Passive components

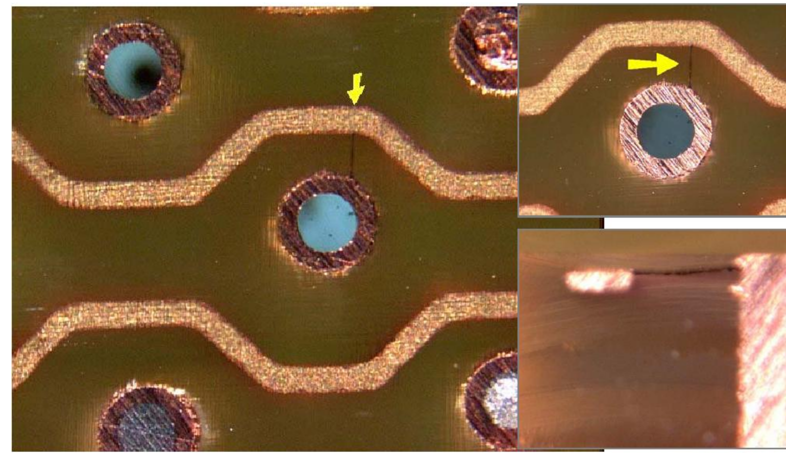
- Capacitors, coils and inductors used for energy storage
- Comprises most of the volume and weight of the inverter; consists of a few components

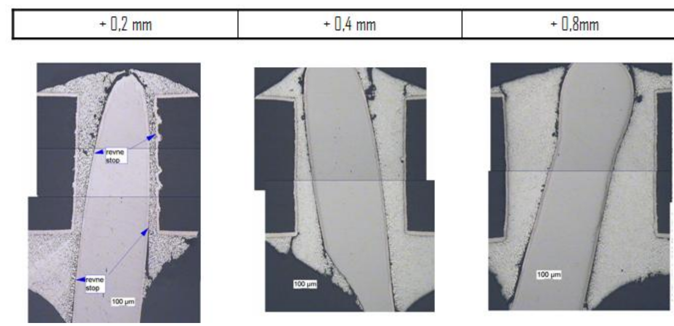
Failure Mechanisms/Reliability

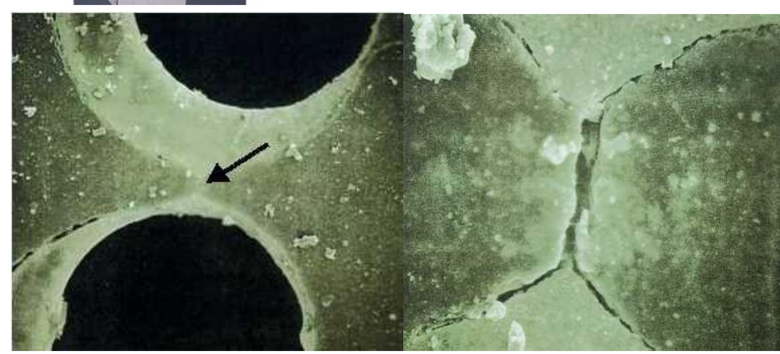
- Electrolytic capacitors
- Ceramic capacitor cracking
- Insertion mount cracking/fatigue
- Film capacitor
  - Dielectric breakdown
  - Electrochemical migration

Inverter Power Board Failure Mechanisms

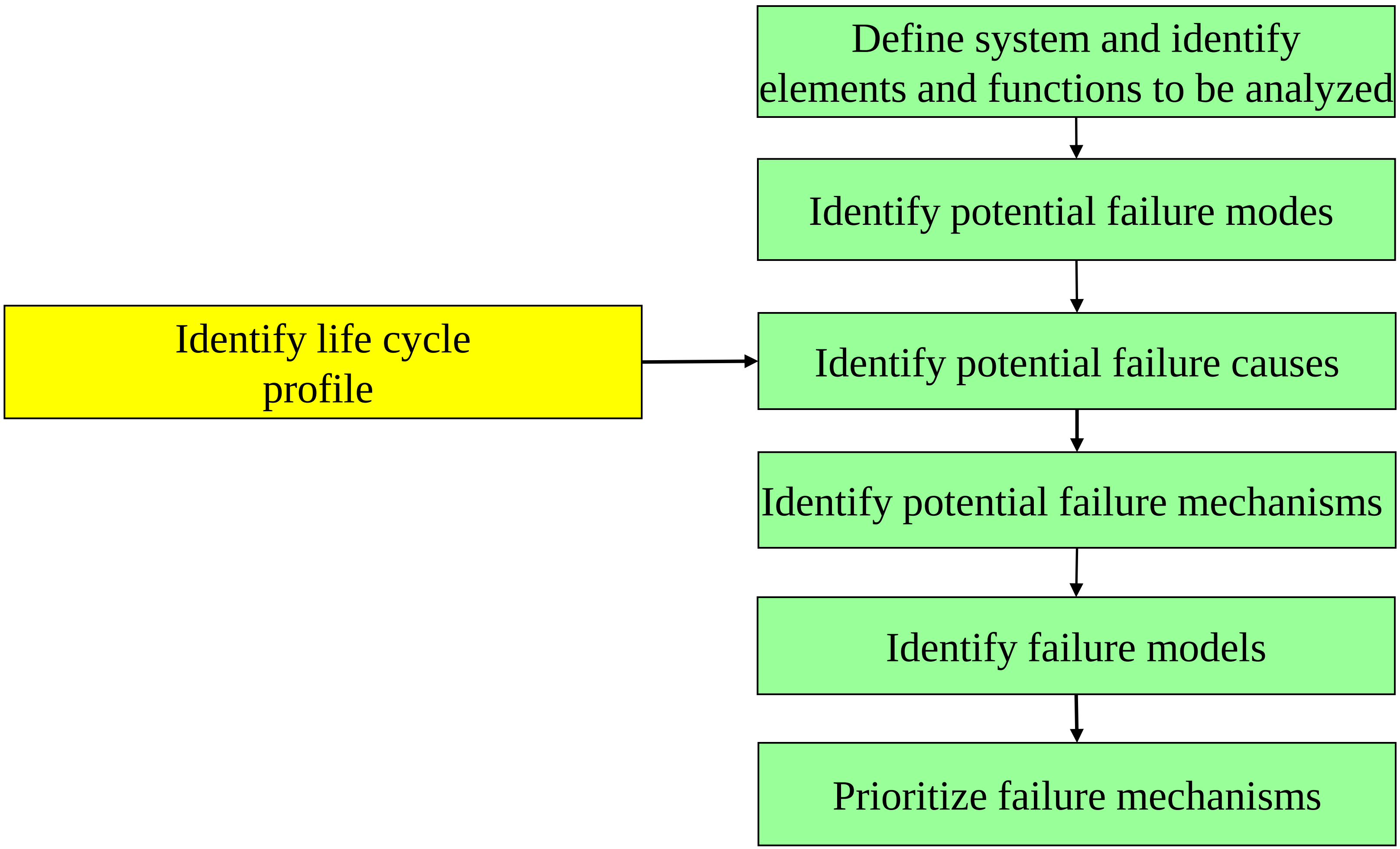
- Conductive Filament Formation
  - Creation of thin metal conducting filaments between traces and vias on the board at high voltage when subjected to thermal cycling and humidity
- Solder Fatigue
  - PTH and SMT components
- PTH/Via Fatigue
  - Fatigue cracking the walls of a plated through hole or via as a result of thermal cycling. Crack can propagate around the circumference of the PTH or Via due to cyclic stresses that exceed the fatigue strength of the copper wall
- Corrosion
  - Electrochemical degradation of metallization





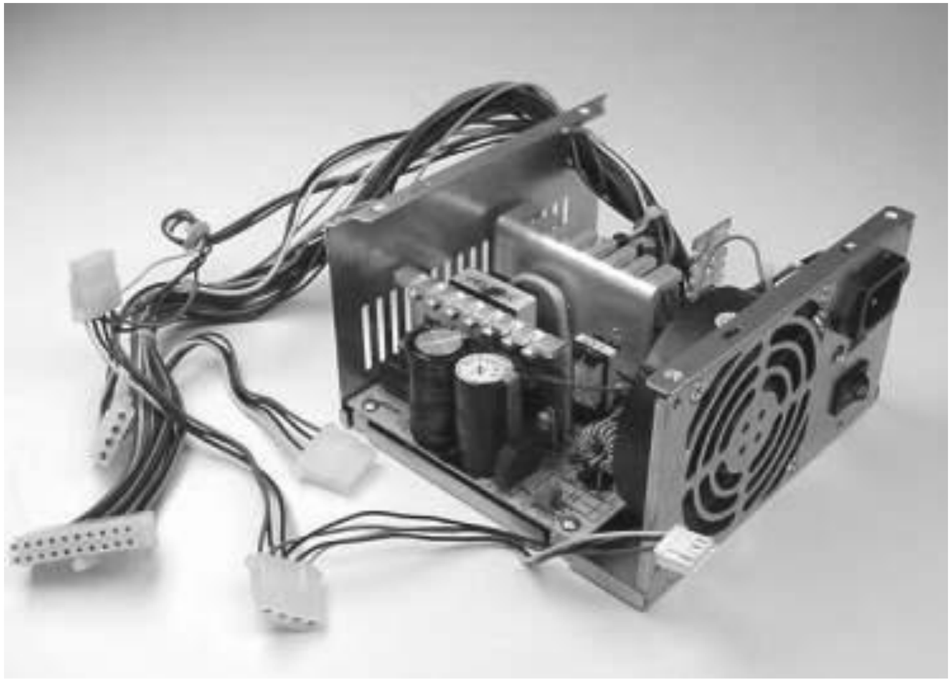


Failure Modes, Mechanisms and Effects Analysis (FMMEA) Methodology



Example: Switch Mode Power Supply for PCs

Subsystems of SMPS
- Voltage regulation unit
  - PCB
  - Resistors
  - Capacitors
  - Diodes
  - Power MOSFET
  - ICs
  - Wires
  - Solder Joints
  - Metallization on the PCB
- Cooling unit
  - Motor
  - Fan blades
  - Bearings



Life cycle loads

- Current

- Temperature

- Humidity

- Vibration

- Shock

FMMEA for Voltage Regulation Unit of SMPS (1/3)

Element	Potential Failure Mode	Potential Failure Cause	Potential Failure Mechanism	Mechanism Type	Severity	Occurrence	Risk
Resistor	Open Circuit	High Temperature	Over voltage	Overstress	Low	Remote	Low
Capacitor	Drop in Capacitance	Electrolyte leakage	Aging of Electrolyte	Wearout	High	Reasonably Probable	High
	Short Circuit	High Voltage	Dielectric Breakdown	Overstress	Moderate	Remote	Low
Inductor	Short/Open between windings and the core	High Temperature	Wearout of Winding Insulation	Wearout	High	Remote	Moderate
Input/ Output Fuse Wire	Open Circuit	High Temperature	Wire Melting due to Current Overload	Overstress	High	Reasonably Probable	High
Diode	Die Fracture	Temperature Cycling	Thermal fatigue	Wearout	High	Reasonably Probable	High
	Short Circuit	High Temperature, Current Density	Contact Migration	Wearout	High	Reasonably Probable	High
	Thermal Runaway	High Temperature due to Resistive Heating	Thermal Runaway	Overstress	High	Remote	Moderate

FMMEA for Voltage Regulation Unit of SMPS (2/3)

Element	Potential Failure Mode	Potential Failure Cause	Potential Failure Mechanism	Mechanism Type	Severity	Occurrence	Risk
Power MOSFET	Gate Oxide Short	High temperature and voltage	Time Dependent Dielectric Breakdown	Wearout	High	Reasonably Probable	High
	Gate Oxide Breakdown	High Voltage	EOS, ESD	Overstress	High	Remote	Moderate
	Change of Leakage Current	High Current Density	Hot Carrier	Wearout	High	Remote	Moderate
	Thermal Runaway	High Temperature because of resistive heating	Thermal Runaway	Overstress	High	Remote	Modarate
Transformer	Short/Open between windings and the core	High Temperature	Wearout of Winding Insulation	Wearout	High	Unlikely	Unlikely
Metallization	Electrical Short/Open, Change in Resistance in metallization traces	High Temperature	Electromigration	Electrical Wearout	Moderate	Unlikely	Low
		High Relative Humidity	Corrosion	Chemical Wearout	Moderate	Unlikely	Low
		Ionic Contamination	Contamination	Chemical Overstress	Moderate	Unlikely	Low

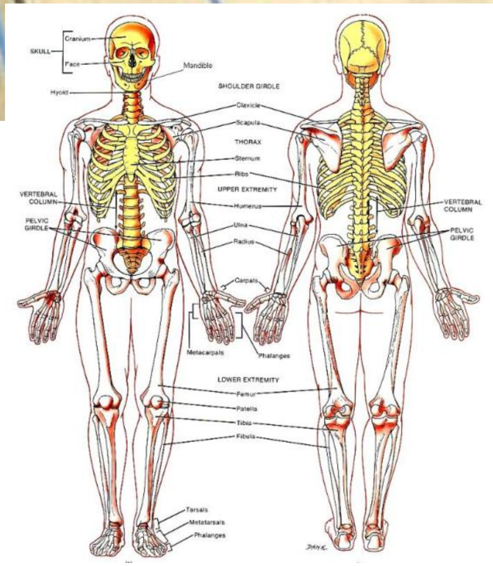
FMMEA for Voltage Regulation Unit of SMPS (3/3)

Element	Potential Failure Mode	Potential Failure Cause	Potential Failure Mechanism	Mechanism Type	Severity	Occurrence	Risk
Integrated Circuit	Open Circuit in Wirebond	High Temperature	Wire Melting due to Current Overload	Overstress	High	Remote	Moderate
		Temperature Cycling	Wire breakage due to thermal cycling	Wearout	High	Remote	Moderate
	Open Circuit/Short Circuit in Die Metallization	High Temperature	Resistive Heating	Overstress	High	Unlikely	Low
		High Temperature	Electromigration	Wearout	High	Unlikely	Low
	Change of Leakage Current	High Electric Field	Hot Carrier	Wearout	High	Remote	Moderate
	Gate Oxide short circuit	High Voltage	Time Dependent Dielectric Breakdown	Wearout	High	Reasonably Probable	High
	Die Fracture	Temperature Cycling	Crack Initiation and Propagation	Wearout	High	Reasonably Probable	High
Printed Circuit Board	Crack/ Fracture	Sudden Impact	Shock	Overstress	Low	Unlikely	Low
		Random Vibration	Fatigue	Wearout	Low	Unlikely	Low
	Loss of Polymer Strength	High Temperature	Glass Transition	Overstress	Low	Unlikely	Low
	Short circuit	Humidity and current	Conductive filament formation	Electrical Wearout	High	Unlikely	Low

Failure Mechanism Models – PV Module

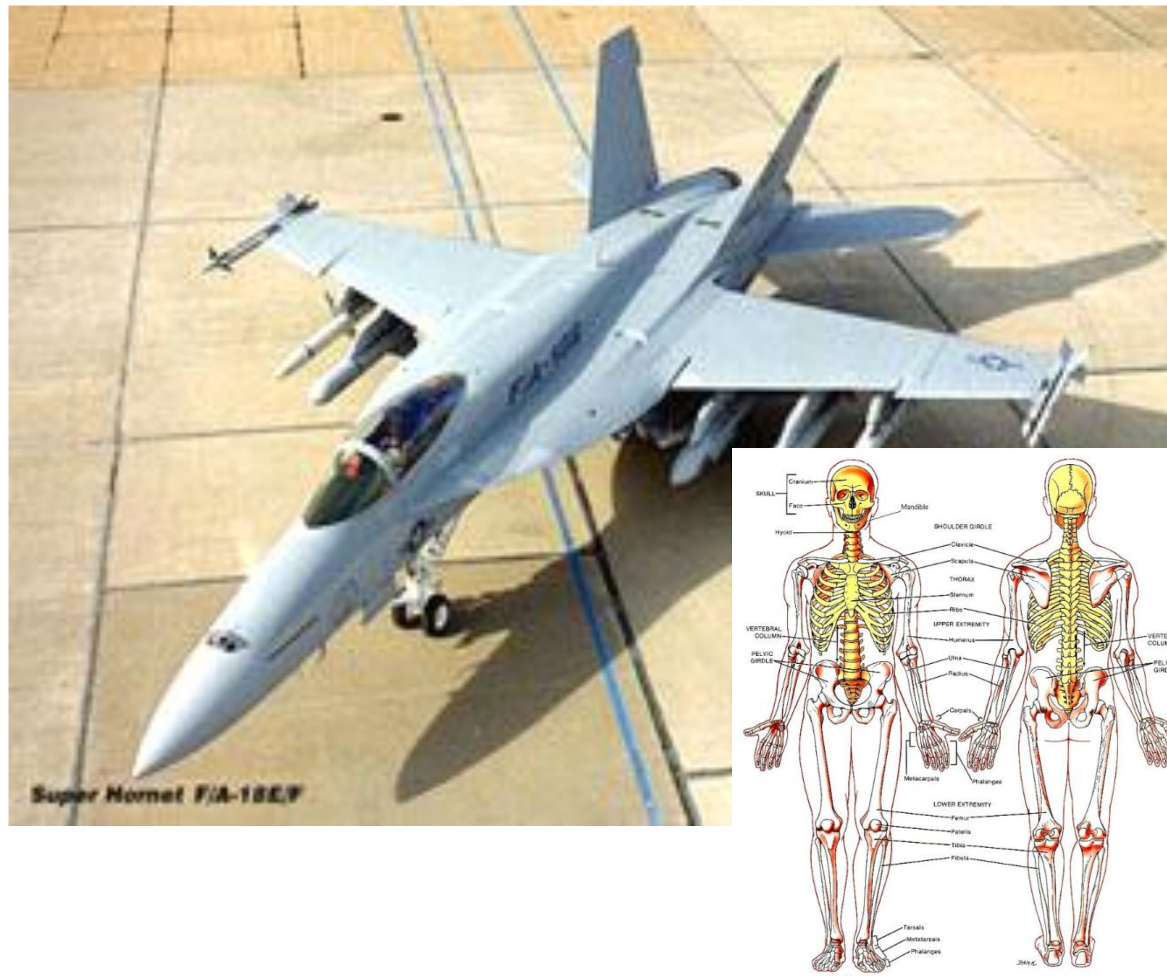
Failure Mechanism	Failure Site	Failure Mode	Relevant Stresses	Environment Test	Model
Dielectric Breakdown	EVA Encapsulation	Leakage Currents	V, T	Powered Temp Aging	Eyring $V^n e^{-Ea/kT}$
UV Reaction Discoloration	EVA Encapsulation	Lower light efficiency	T, Intensity. Frequency	UV Exposure at Temp	Arrhenius Exp (-Ea/kT)
Deadhesion	Front Surface	Electrical Open	ΔT, H, ΔH	Damp heat Temp cycle	Coffin-Manson $N = C(\gamma)^n$
Deadhesion	Back Surface	Poor Heat Transfer	ΔT, H, ΔH	Damp heat Temp cycle	Coffin-Manson $N = C(\gamma)^n$
Corrosion	Front Surface Interconnects	Open Circuit Incr. Resist.	M, ΔV, T, impurities	Powered damp heat at Temp	Eyring $(V)^n(RH)^n e^{-Ea/kT}$
Fatigue Disintegration	Backsheet Lamination	Cracking	ΔT, ΔH, ΔV	Damp Heat Temp cycle	Coffin-Manson $N = C(\gamma)^n$
Fracture	Glass	Cracking	Mech Load	Mech Load	Paris Law (LEFM)
Fatigue	Edge Sealing	Cracking Voiding	ΔT,ΔH, ΔV	Damp Heat Temp cycle	Coffin-Manson $N = C(\gamma)^n$
Metal Segregation	Solder Connection	Voiding Intermetallic	T, J	Powered Temp Aging	Eyring (Black) $J^n e^{-Ea/kT}$
Fatigue	Solder or Cell Connection	Loss of connection	ΔT, ΔV	Powered Temp cycle	Coffin-Manson $N = C(\gamma)^n$

Health is the extent of deviation or degradation from an expected normal condition.



Prognostics

Techniques utilized to trend health and to determine the remaining useful life with a defined level of confidence for a specified coverage of anticipated events



2003: US Military Requires Prognostics to be Included in All New Weapon Systems

2007
Prognostics Introduced
to
ITRS: Semiconductor Roadmap

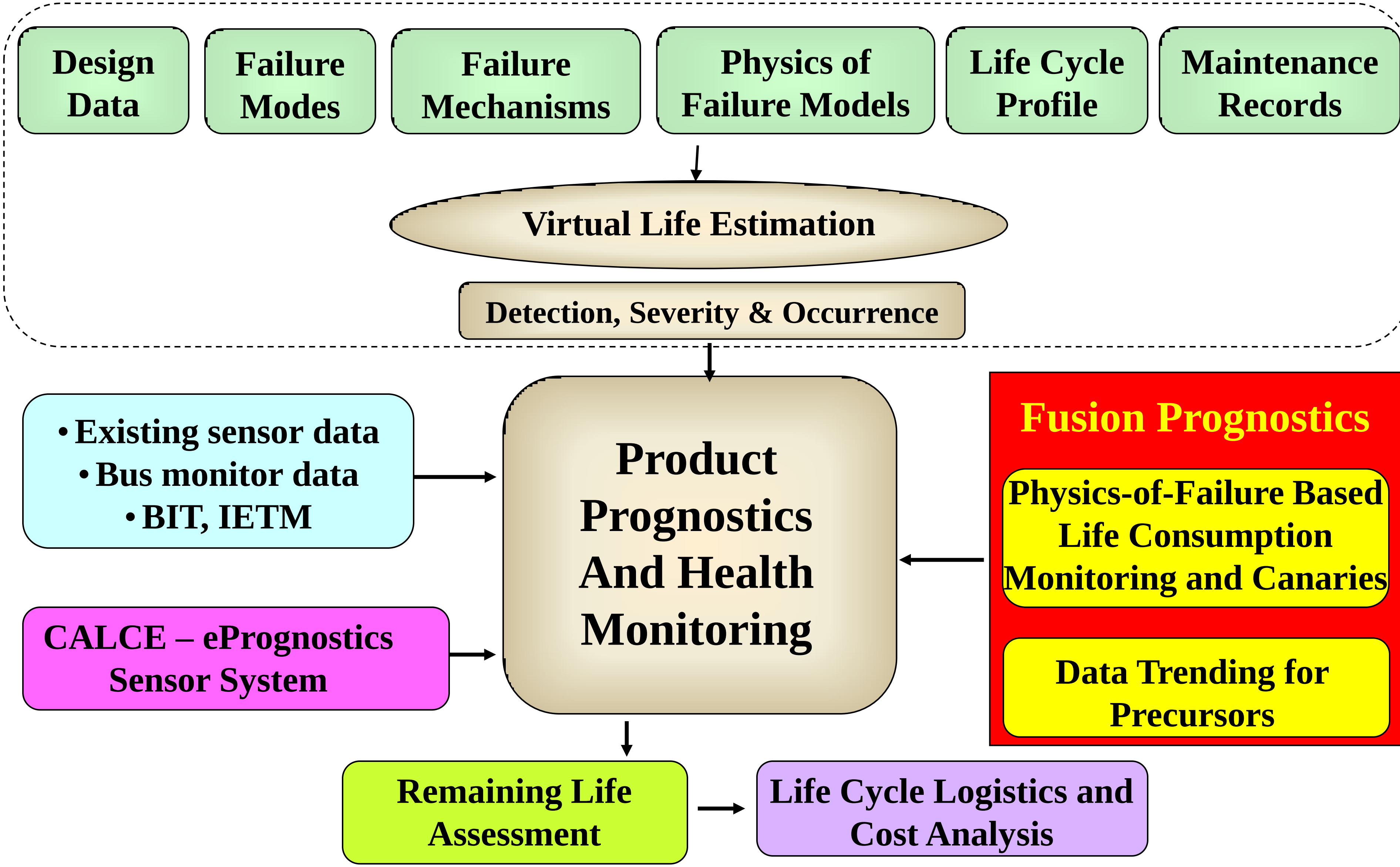
PHM Implementation Benefits

- Provide an early warning of failure
- Provide guidance to extend warranties
- Optimize qualification tests
- Provide efficient fault detection (CND)
- Forecast maintenance as needed
- Improve designs

Approaches to Prognostics

- Physics-of-failure (PoF) based prognostics utilizes knowledge of a product's life cycle loading conditions, geometry, material properties, and failure mechanisms to estimate its remaining useful life.
- Data-driven prognostics use statistics and probability for analyzing current and historical data to estimate remaining useful life.
- Fusion approach combines the advantages of the PoF and data driven approaches.

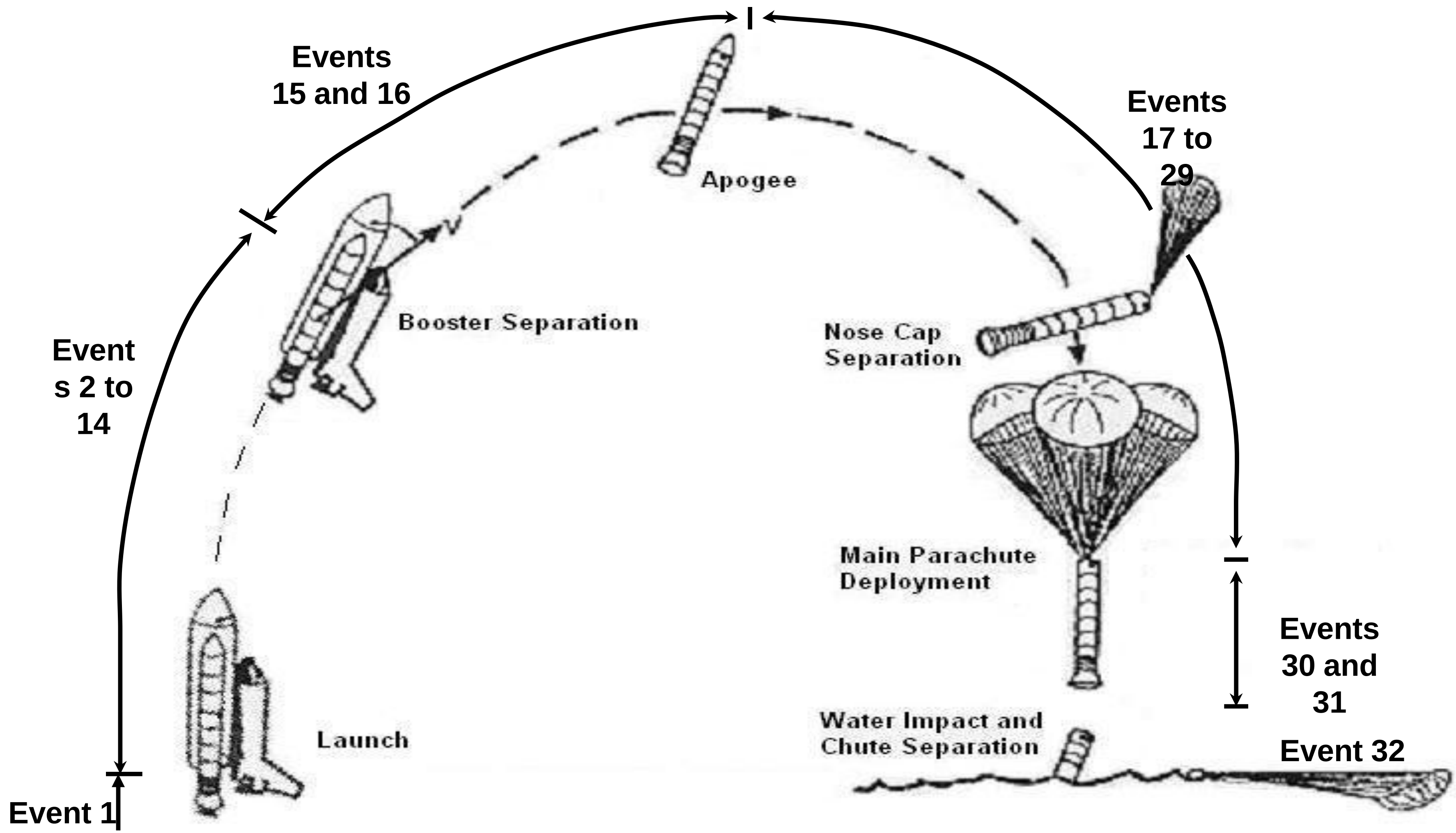
CALCE PHM Methodology



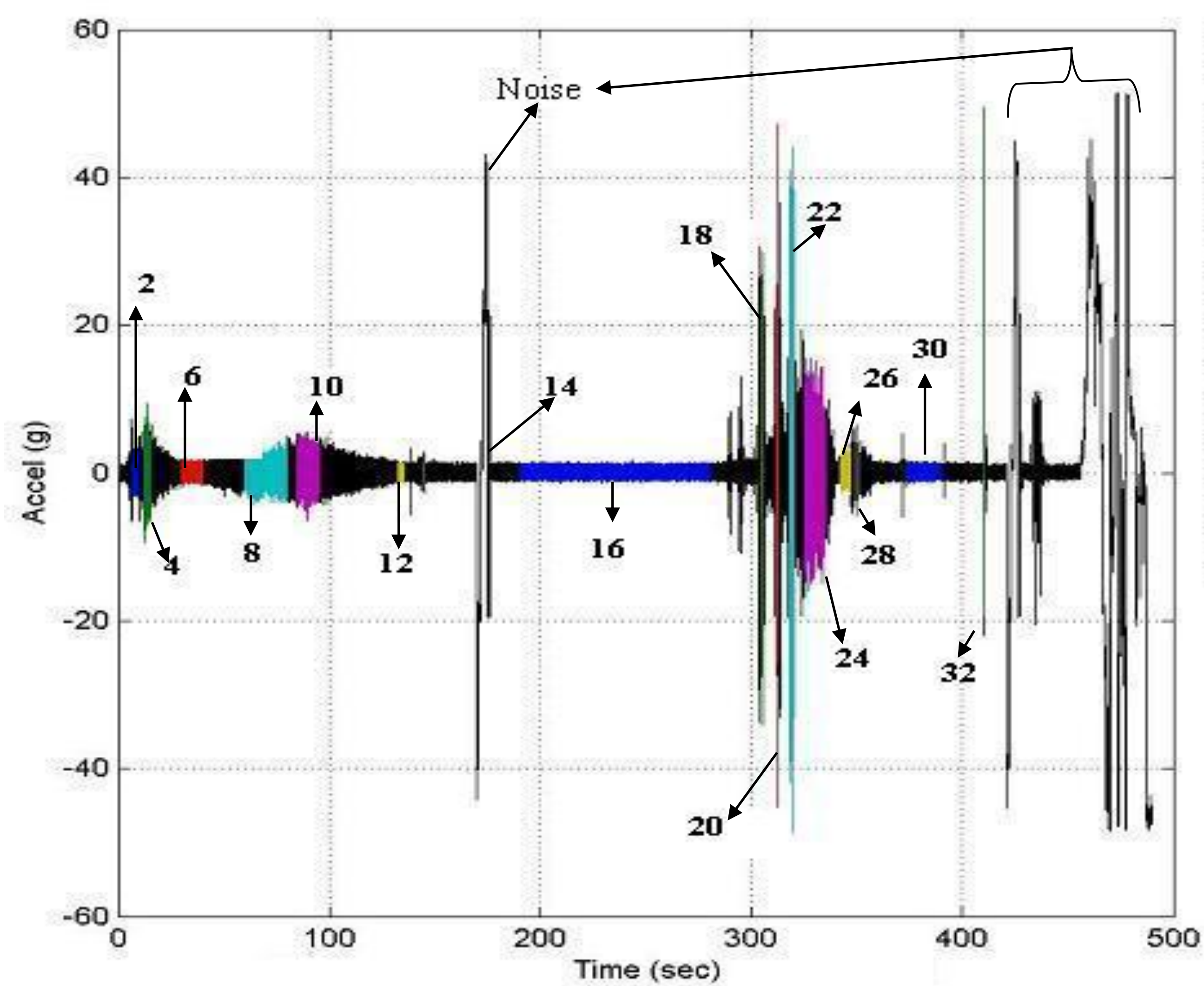
Remaining Life Assessment of NASA Solid Rocket Booster (SRB) Electronic Hardware

- The space shuttle solid rocket booster (SRB) was designed for a 20 year life.

LCP : SRB Flight Segments



LCP: Vibration History from One Flight

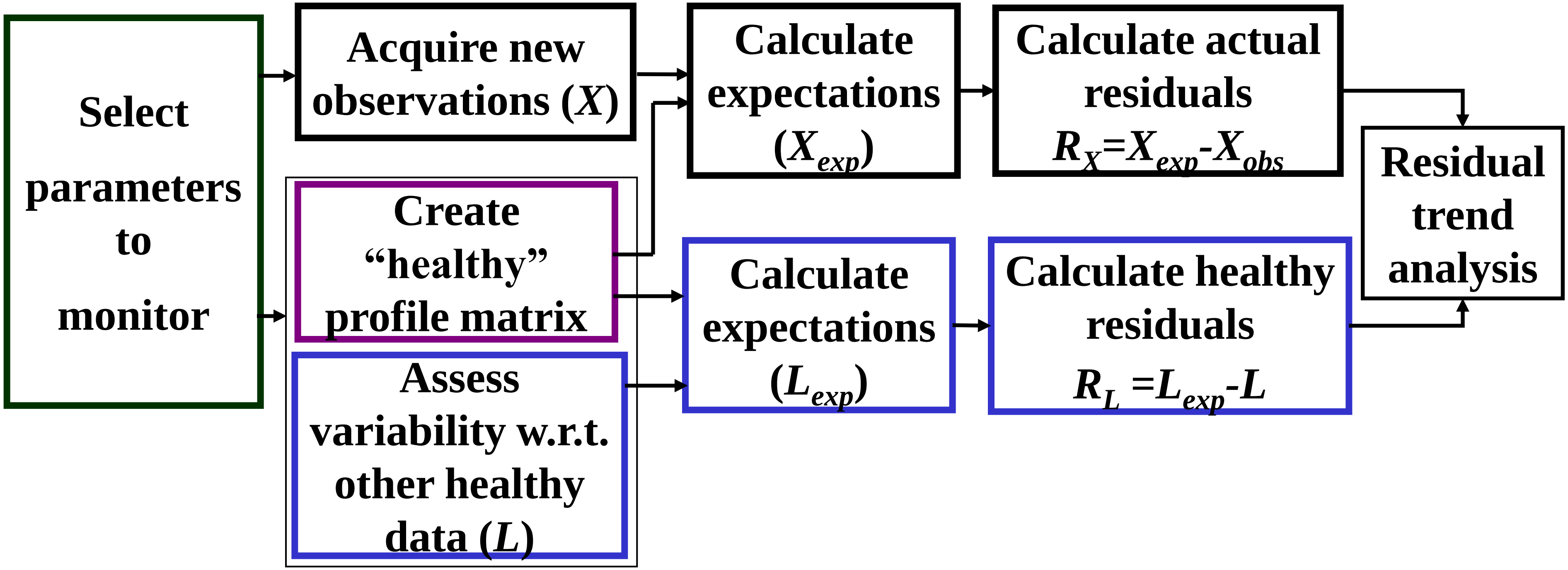


2, 4 – LiftOff
6, 8, 10 – Ascent
12 Pre Separation
14 Separation
16 Apogee
18, 20, 22, 24, 26, 28 – Re-Entry
30 Parachute
32 Water Impact

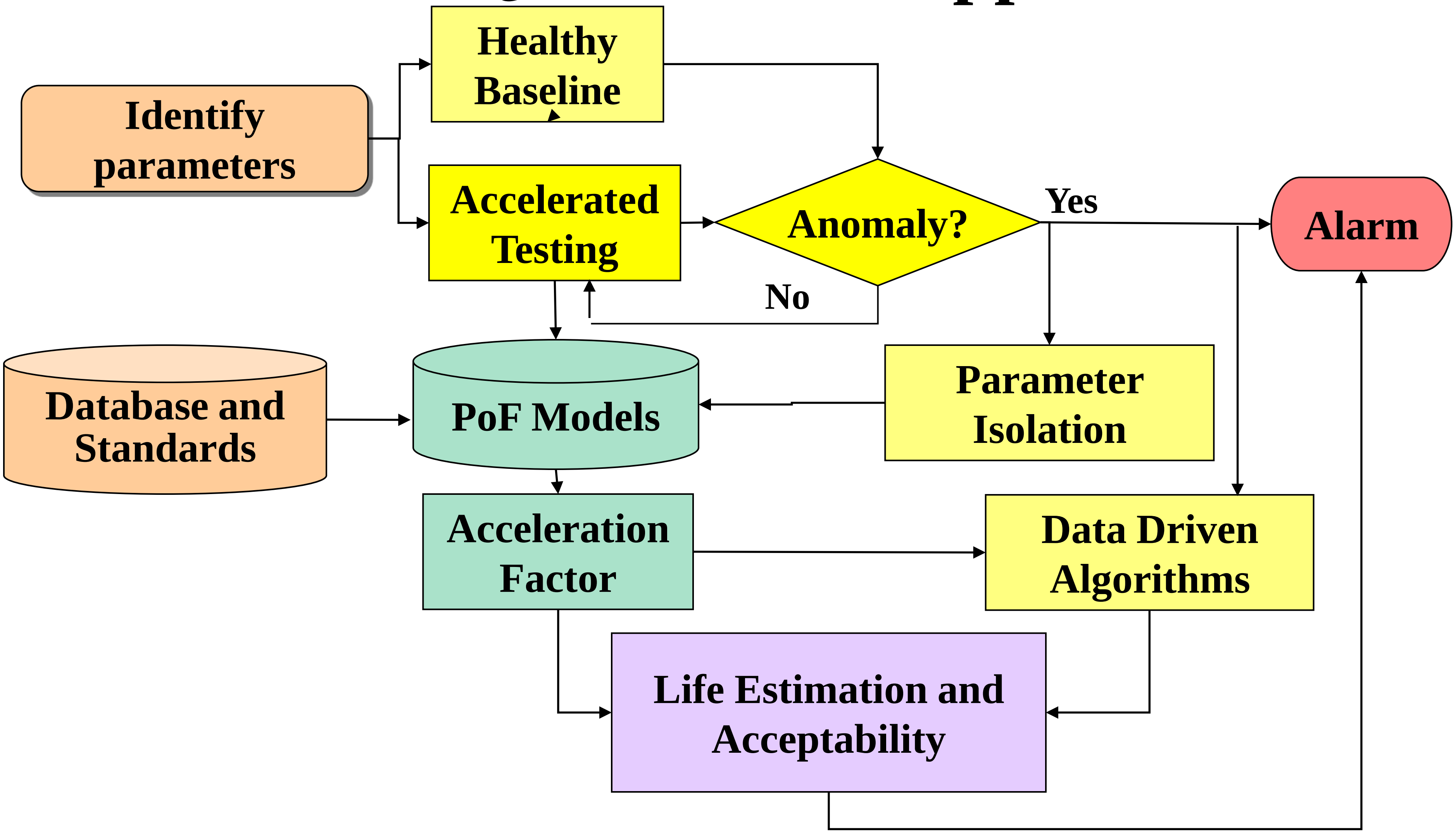
How Do We Learn (Know) What We Don't Know

- New defects
- New failure mechanisms
- Intermittent failure mechanisms

Data Driven Approach (simplified)
- Machine Learning & Artificial Intelligence -



Fusion Prognostics Based Qualification Approach



The Future

- **Prognostics will be incorporated into all electronics**
- **Prognostics will be used for qualification, screening, in-situ health monitoring, and continuous remaining life assessment**

CALCE Research Focus in PHM

- Developing the capability to learn from data, **detect changes in real-time and predict the future performance** of electronic systems.
- **Integrating the center's expertise in reliability and physics of failure (PoF)** of electronic components into hybrid data driven models for autonomous system prognostics and diagnostics.
- Researching and developing prognostic and health management technologies that will **enable autonomous fault diagnostics and prognostics** in electronic systems such that reliability mitigations can be implemented.

Ongoing CALCE Research in Electronics Prognostics (1/2)

- **Sensor Systems: ePrognostics Sensor System**
- **Component level:**
  - Data Driven Approach
    - Prognostics for multilayer ceramic capacitors (MLCCs)
    - Detection of degradation in Ball Grid Arrays (BGAs) under thermal cycling
  - Physics of Failure Approach
    - Evaluation of resistors under thermal cycling
    - Evaluation of surface mount MLCCs
    - Evaluation of embedded planar capacitor laminates
    - Evaluation of reliability of PBGAs
    - Identification of failure precursor parameters in IGBTs
- **Board level:**
  - Prognostics for power supplies
  - Canaries to detect electrochemical migration in electronic circuits
  - Detection of conductive filament formation for printed circuit boards

Ongoing CALCE Research in Electronics Prognostics (2/2)

- **System Level:**
  - Data Driven Approach
    - Prognostics for aging systems
    - Degradation monitoring of electronic products using non-parametric techniques
    - Health monitoring of systems with both continuous and step function parameters
    - Approaches to assess health of field returned electronic products
    - Analysis of army vehicles usage monitoring data for prognostics
    - Laptop computers
    - Anomaly detection for multivariate centroid clustering using nonparametric hypothesis tests
  - Fusion Approach
    - Early detection of interconnect degradation
    - Detection of wearout failure in cooling fans
    - LED lighting system
- **PHM cost and return-on-investment modeling**