PHM for Electronics Panel

at the PHM Society Conference

Lou Gullo, IEEE, Panel Moderator
October 31, 2023

Introduction of the Panelist

- Sony Mathew, SDF, previous Vice-Chair of the IEEE 1856 Working Group (WG)
- Rex Sallade, LMC retired, Chair of IEEE P1856.1 WG, previous member of the IEEE 1856 WG
- Kenney Crooks, NGC, Technical Fellow, Enterprise lead for CBM+/PHM

Overview

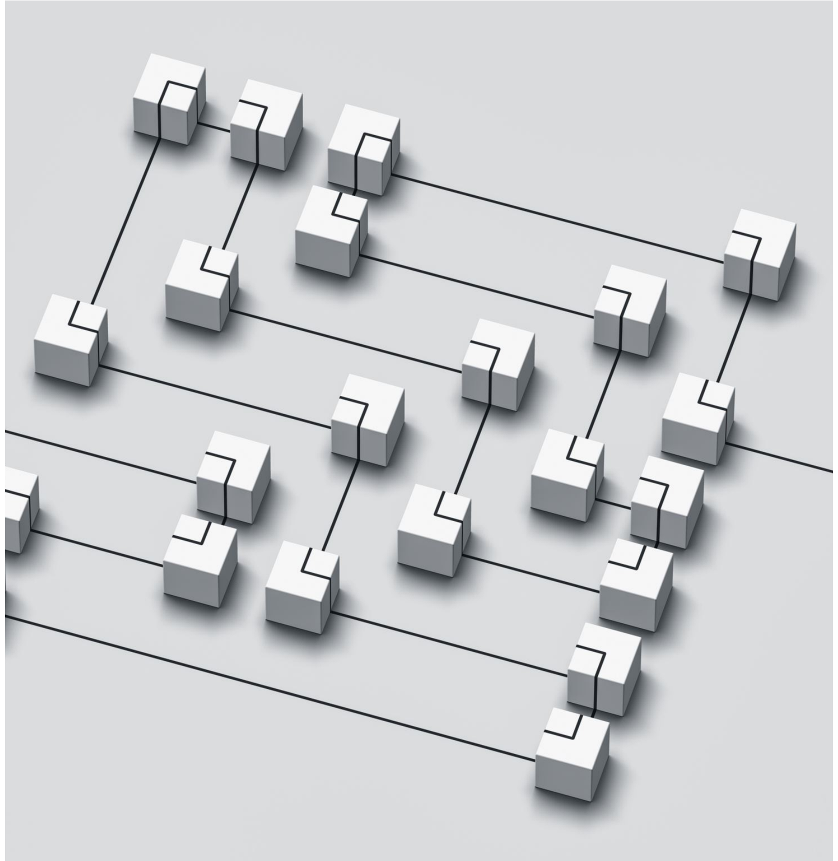
1. Evolution of Prognostics and Health Management (PHM)
2. Plans to collaborate on standards between IEEE and SAE
3. Discussion of existing IEEE and SAE standards
4. Building technology capability for AI/ML for RAMS/PHM
5. IEEE plans for development of PHM for Electronics standards
6. Path to Condition-Based Maintenance Plus (CBM+) and Reliability Centered Maintenance (RCM)
7. Future of PHM/CBM+
8. Closing Remarks

Evolution of PHM

- PHM is evolving from application-specific and program-specific technologies to business-level and enterprise-level technologies to impact multiple industries and programs
- PHM is expanding into a new era of electrification in the mobility sector, which warrants the need to develop predictive analytics technologies for condition-based maintenance and imminent failure alerts for power electronic devices, energy storage systems, and power transmission and usage.
- IEEE Reliability Society has begun collaborating with the IEEE Power and Energy Society to enable this expansion.

IEEE RS TA Vision to Initiate Collaboration

- Research areas where IEEE Reliability Society (RS) Standards Committee (SC) portfolio can benefit other Organizational Units (OUs), such as the IEEE Power and Energy Society (PES)
- Propose projects to transfer technology from RS generalized application to specific OU technology applications
- Stand up projects in terms of an SC group of standards, or a single WG, Study Group, or Subgroup sanctioned by IEEE Standards Association (SA)
- Collaborate on existing Project Authorization Requests (PARs), or future PAR creation
- If successful in this collaboration, write and publish papers in newsletters and present at each others' events/conferences/ podcasts
- Leverage IEEE Steering Committees, Future Direction (FD), and IEEE Roadmap Users Group (IRUG)
- Initiated collaboration agreement between IEEE SA and SAE



Why Are Standards Important?

- From device to device, network to network, across borders and around the world, standards touch almost all products, services and technologies in use today
- They help ensure connectivity, interoperability, and security so we can live, work and communicate in easier, safer, and more sustainable ways
- IEEE SA offers an open platform for global volunteers (> 34k) to collaborate and explore market needs, share industry knowledge, and develop standards
- Currently, IEEE SA maintains over 2,100 standards and projects across a wide range of industries and technologies.

IEEE Collaboration with SAE

- IEEE and SAE have an agreement to jointly develop standards
- Plan joint PHM standards development with SAE
  - SAE invited IEEE RS to join SAE G-31 Committee with HM-1 WG and others
  - IEEE RS is connected to SAE G-33 for Configuration Management (CM) led by Bob Aiello (IEEE CS S2ESC)
  - Potential to connect with G-11 for Reliability Standards
- IEEE RS attended SAE HM-1 virtual call on Feb 28, 2023
- Interfacing with members of the SAE IVHM Steering Group (SG) and the SAE Health Management Committee (HM-1)

IEEE and SAE Joint Development Agreement

- SAE HM-1 and the IEEE Reliability Society Standards Committee are empowered to develop joint standards
- Collaborate on roadmaps for the prognostics and health management of all electrical systems and components used in the electrified mobility and related sectors (e.g., low-power electronics, high-power electronics, power transmission systems, electromechanical systems such as generators and motors, etc.)
- SAE HM-1 and the IEEE Reliability Society Standards Committee may also review existing SAE and IEEE standards and suggest improvements if they do not cover critical high-level aspects of PHM system design, testing, deployment, and maintenance.
- The standards development process will be based on a joint set of agreed procedures that satisfy the requirements of each organization.
- The standard shall be numbered as "IEEE XXXX-20XX / SAE XXX-20XX”.

IVHM Steering Group

- Started in 2010, along with HM-1.
- Coordinating the work of G11 (G11-SHM later renamed AISC-SHM), E32, and HM1 TCs.
- Invited membership based on balancing representation from various disciplines and sectors.
- TC chairs ex-officio members.
- The SG takes on special initiatives from time to time.

IVHM-SG

E-32 | AISC-SHM | HM-1 | G11s

AE-7D, G-41 | Other SAE TCs | Other SDOs

1905

2023

- SAE established: 1905
- SAE charter expanded to incorporate aeronautics: 1916
- 1st SAE Aerospace Standard: 1917
- SAE E-32 – EHM committee: 1975
- G-11 SHM (now AISC-SHM) formed and work on ARP6461 begun: 2008
- IVHM Steering Group and HM-1 committee: 2010
- SAE AeroTech with IVHM track and first SAE IVHM book: 2011
- ARP6461 Published: 2013
- Reliability Maintainability and Health Management Systems Group: 2016
- DDSG and G31 committees. Standards for digital transactions: 2018
- ARP5987 Published: 2018
- G34 committee on AI in aviation: 2019
- G35 committee on modeling and simulation and training: 2021
- More than 12 books on IVHM and related topics published to date

SAE HM-1 Organization

- HM-1 belongs to the Reliability, Maintainability, and Health Management Systems Group under Aerospace Council which also includes the following committees:
  - Aerospace Industry Steering Committee on Structural Health (AISC-SHM)
  - E-32 Aerospace Propulsion Systems Health Management (Engine Health Monitoring)
  - G-11 Probabilistic Methods and Uncertainty Quantification
  - G-11 Reliability Maint Support and Probabilistic Methods
  - G-11 Reliability, Maintainability, Supportability and Logistics Software Committee
  - G-11M, Maintainability, Supportability and Logistics
- The HM-1 Committee serves as a forum to gather, develop, record and publish expert information in the discipline of IVHM.
- Membership comes from across the mobility sector (primarily aerospace and automotive)
- HM-1 is the parent to the HM-1R Rotorcraft Integrated Vehicle Health Management Subcommittee
- The following classes of vehicles and related equipment and platforms may be considered:
  - Military and Civil fixed wing and rotary wing air vehicles
  - Unmanned fixed and rotary wing air vehicles
  - Data processing equipment, systems and software; and Air vehicle maintenance platforms.
- 19 published standards on topics ranging from overview, systems engineering processes, and sensors

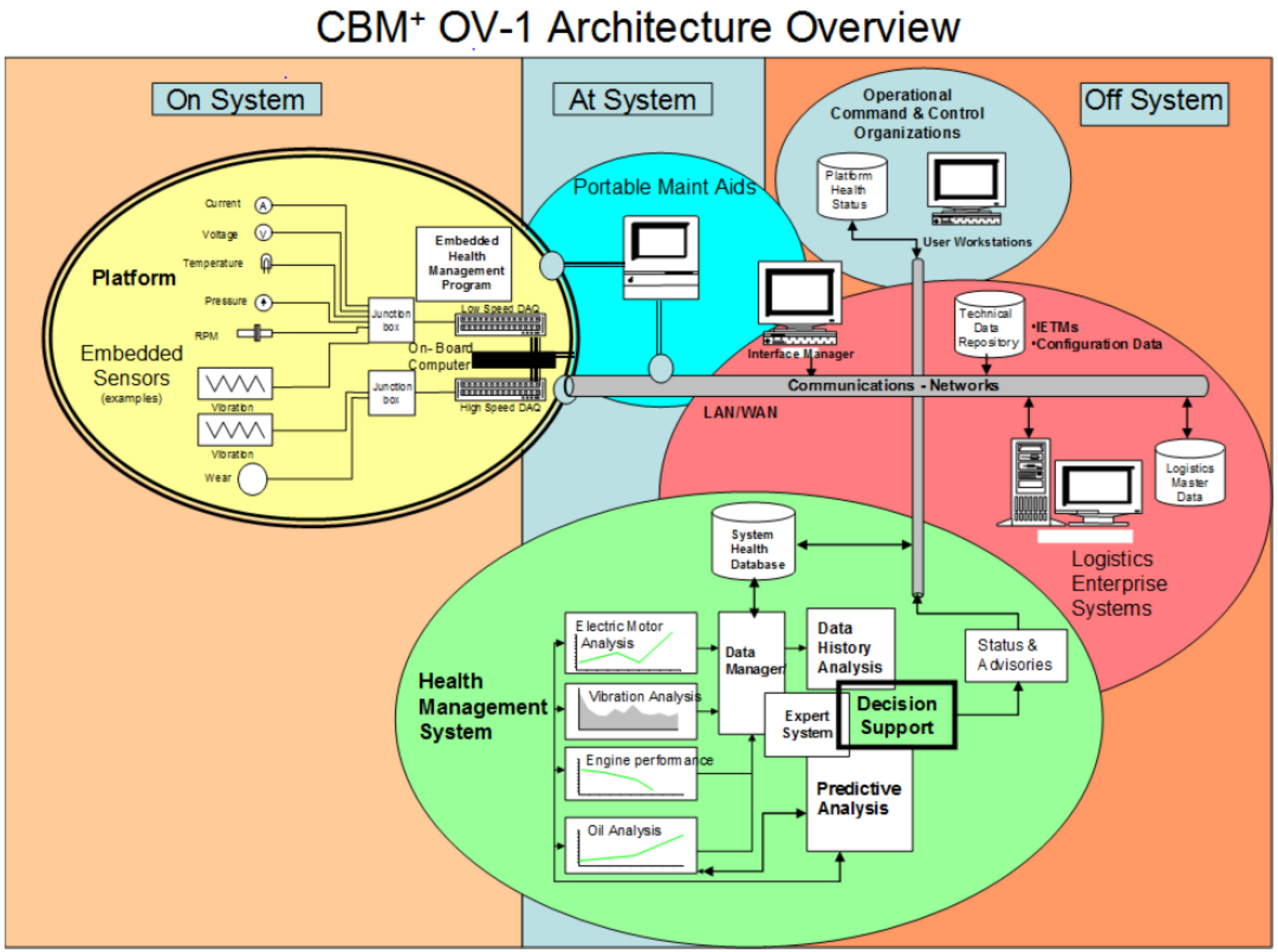
Published Documents

Document	Title
ARP6290	Guidelines for the Development of Architectures for Integrated Vehicle Health Management Systems
JA6268_202303	Design and Run-Time Information Exchange for Health-Ready Components
AS5391A	Helicopter Health and Usage Monitoring System Accelerometer Interface Specification
AIR6212	Use of Health Monitoring Systems to Detect Aircraft Exposure to Volcanic Events
ARP6275A	Determination of Cost Benefits from Implementing an Integrated Vehicle Health Management System
AIR8012	Prognostics and Health Management Guidelines for Electro-Mechanical Actuators
AIR6334	A Guide to Extending Times Between Overhaul for Rotorcraft Power Train Transmissions Using Monitoring Data
AS5394A	Health and Usage Monitoring System, Advanced Multipoint Interface Specification
AS5392A	Health and Usage Monitoring System, Rotational System Indexing Sensor Specification
AS5393A	Health and Usage Monitoring System, Blade Tracker Interface Specification
AIR6915	Human Factor Considerations in the Implementation of IVHM
ARP6883	Guidelines for Writing IVHM Requirements for Aerospace Systems
ARP6407	IVHM Design Guidelines
JA6097_201905	Using a System Reliability Model to Optimize Maintenance Costs A Best Practices Guide
AIR6900	Applicable Aircraft Integrated Vehicle Health Management (IVHM) Regulations, Policy, and Guidance
ARP5783	Health and Usage Monitoring Metrics, Monitoring the Monitor
AS5395	Health and Usage Monitoring System Data Interchange Specification
AS4831A	Software Interfaces for Ground-Based Monitoring Systems
ARP6803	IVHM Concepts, Technology and Implementation Overview

CBM+ PHM Architecture from DoD

CBM+ is Condition-Based Maintenance Plus

PHM is Prognostics and Health Management



Reference:
CBM+ DoD Guidebook

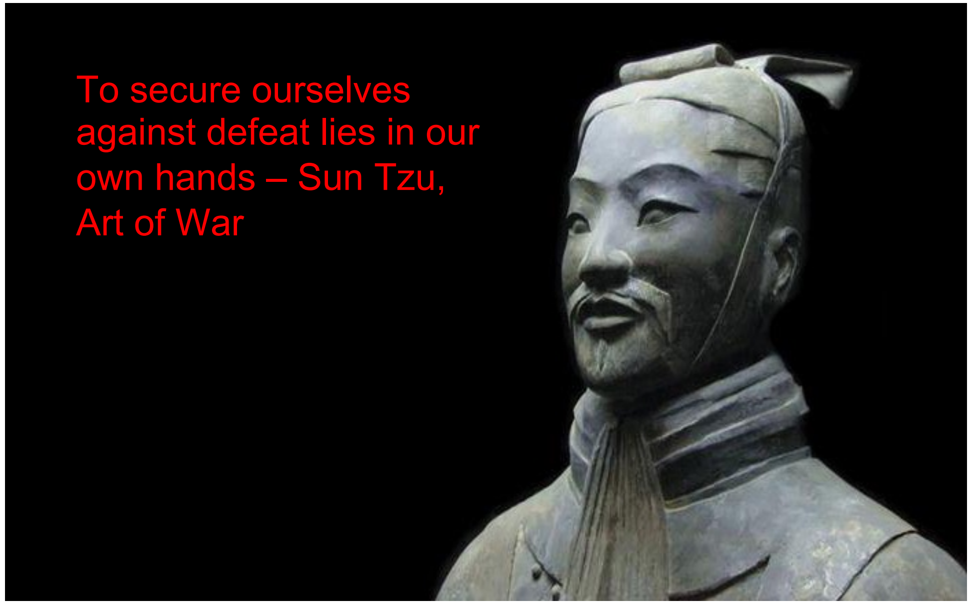
Date: May 2008

Link:
https://www.acqnotes.com/Attachments/CBM+%20DoD%20Guidebook%20May08.pdf

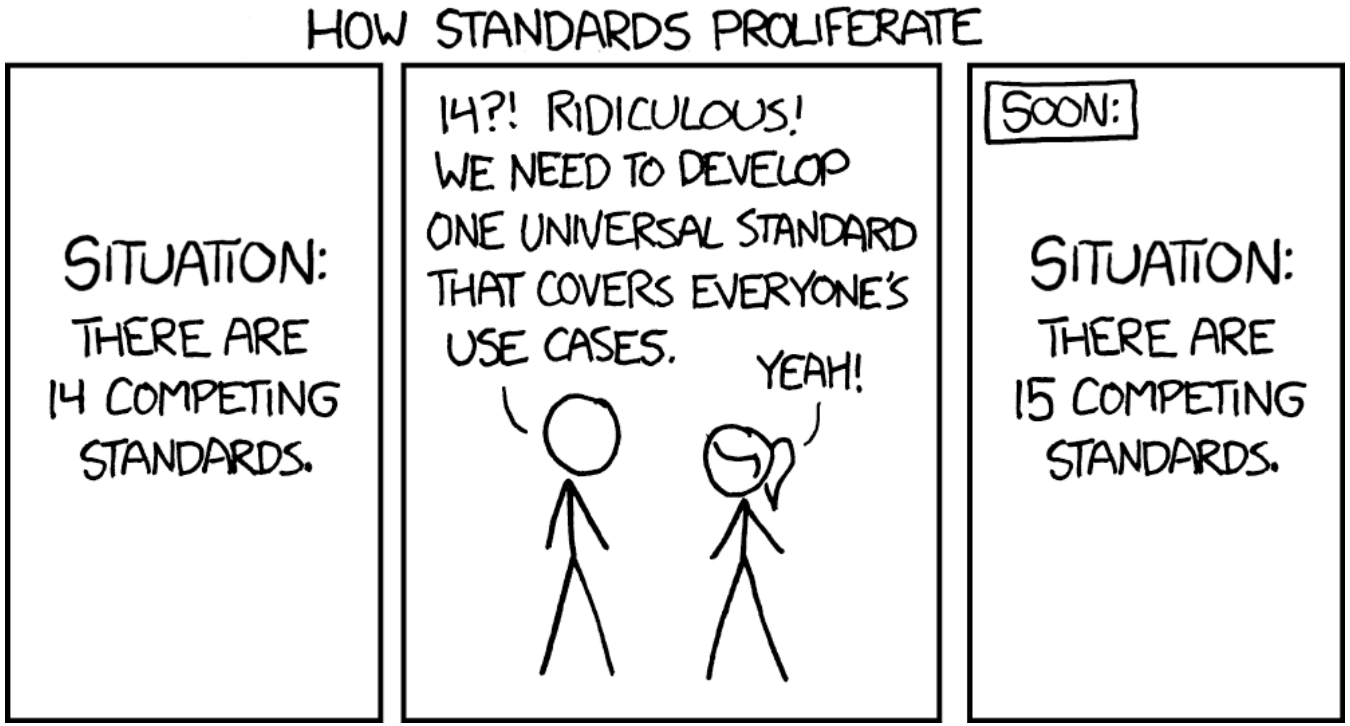
Sony slides

The Need to Know

- Engineers always want to know the root cause of the failure.
- Reliability is "The ability of a product to function as intended, without failure, within specified performance limits, for a specified period of time, under the life cycle application conditions."
- Prognostics and health management (PHM) is an enabling discipline consisting of technologies and methods to assess the reliability of a product in its actual life cycle conditions to determine the advent of failure and mitigate system risk.
- PHM is an enabler for reduced life cycle cost and better health management of systems.



PHM Standards

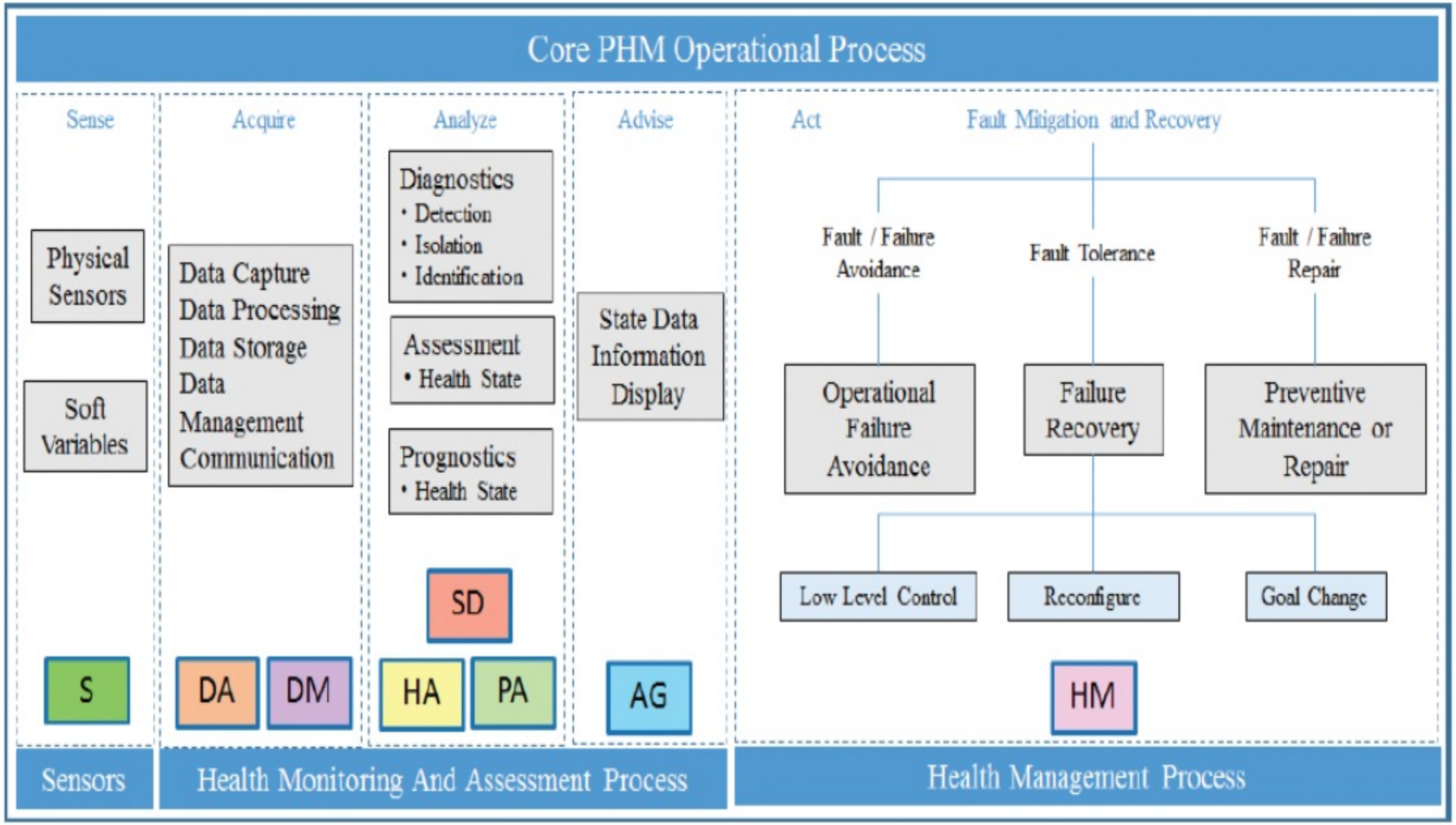


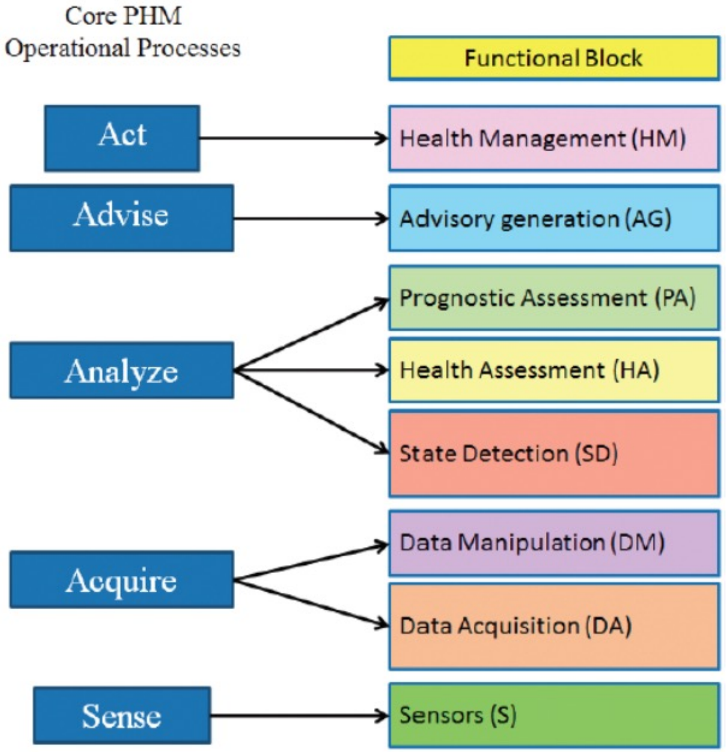
- IEEE 1856: IEEE Standard Framework for Prognostics and Health Management of Electronic Systems. (2017)
- ISO Standards – ISO 13381-1: 2015:Condition Monitoring and diagnostics of Machines – Prognostics – Part 1: General guidelines.
- SAE: ARP6290 - Guidelines for the Development of Architectures for Integrated Vehicle Health Management Systems
- SAE AIR 8012: Prognostics and Health Management Guidelines for Electro-Mechanical Actuators

System Health Management (SHM)

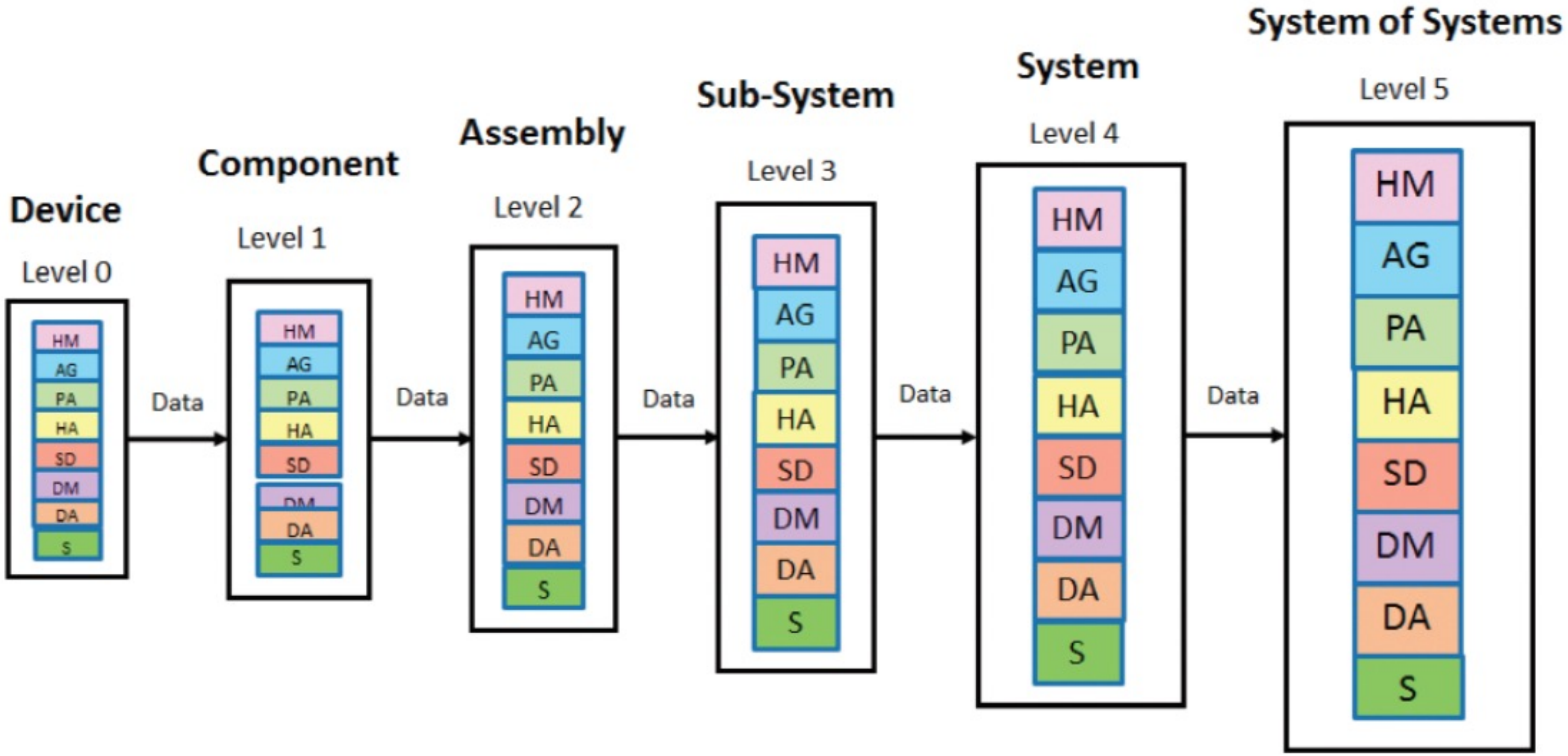
- Health management includes the decision of what response actions to take and the actions themselves, which may include:
  1. Continued operation – state of health is sufficient for further operation.
  2. Reset/ Repair - using on-board capabilities
  3. Replace – sub-systems to proceed with operation.
  4. Re-allocate resources - divert resources to make optimal use of RUL
  5. Re-prioritize function/change system goals - - adjust mission profile based on RUL
  6. Remove/ shutdown.
- These actions may be taken individually or in some combination based on the health and future mission information available.
- These steps enhance survivability and minimize unplanned down-time (increase availability).

IEEE 1856 Operational View





Levels of Implementation in Electronics



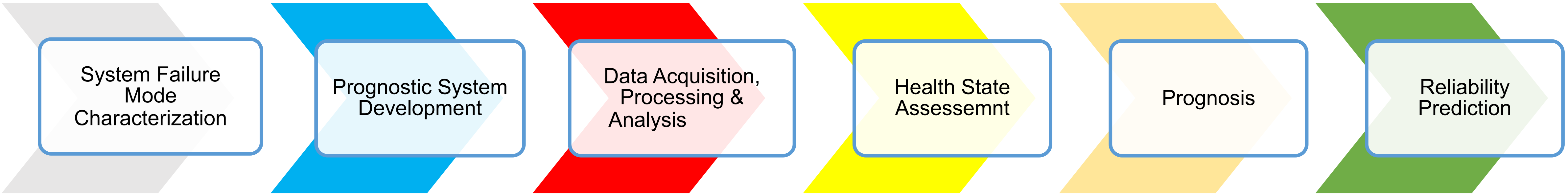
S – Sensors, **DA** – Data Acquisition, **DM** – Data Manipulation, **SD** – State Detection, **HA** – Health Assessment, **PA** – Prognostics Assessment, **AG** – Advisory Generation, **HM** – Health Management

Prognostics-based Reliability Predictions

- Prognostics-based reliability prediction of a given system involves the processing of data to produce an estimate of the degradation of the system's structural and functional attributes, and, thereby estimate the probability of the system achieving its operational goals, i.e. performing its functions within the desired specifications and for the required length of time.

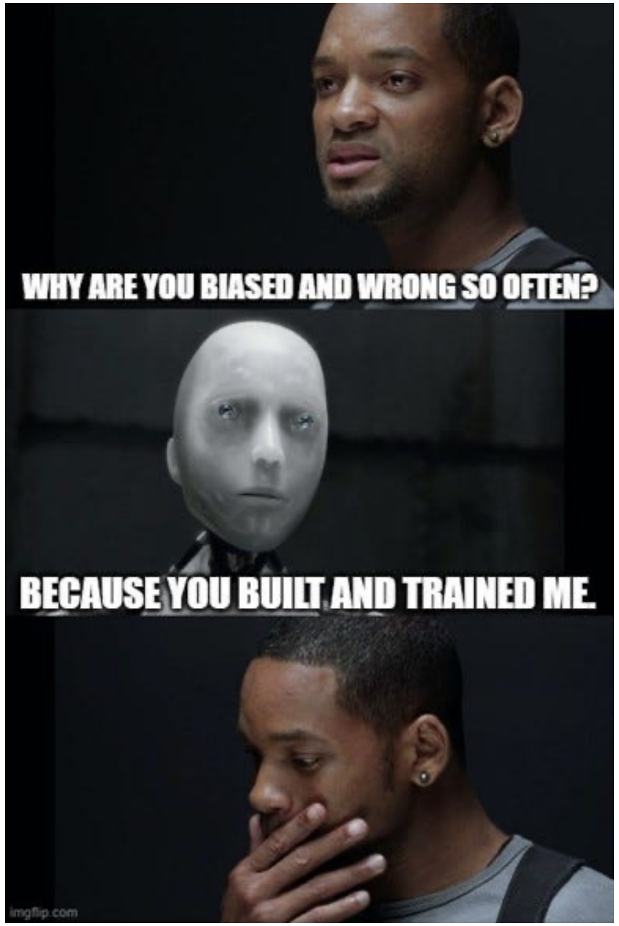
- The outcome of prognostics is an input to the system health management effort, which seeks to use the prognosis conclusions to decide on and implement operational and maintenance actions that will reliably extend the period of operation of the system.

- Reference: IEEE P1413.1 New revision under development



Artificial Intelligence and PHM

- AI has come a long way. AI is now a overused term to include any and all computer programs that can automate an a outcome given some basic inputs.
- ***Definition:*** the theory and development of computer systems able to perform tasks that normally require human intelligence, such as visual perception, speech recognition, decision-making, and translation between languages.
- It is all in the learning. Machine learning is the section of AI that gives the computers systems the ability to learn.
- Deep learning as another subset that uses complex algorithms and deep neural nets to train the model to make decisions.
- AI utilize prognosis and manage the outcome.
- What would be the outcome if there are no standards to govern the inputs, the process, and the outcomes of the learning.
- How do we standardize an evolving field?



Need for a Guide that Follows IEEE 1856

- Recommendation for using different approaches for prognostics.
- Recommendation for sensor selection.
- A guide to sensor data acquisition inputs from multiple sources and mining.
- **Performs Health Monitoring:** The function of estimating a system's health state, including measurement of state variables, and identifying if the states of these variables indicate an off-nominal condition.
- **Provides Prognostics:** The process of predicting an object system's RUL by predicting the progression of a fault given the current degree of degradation, the load history, and the anticipated future operational and environmental conditions to estimate the time at which the object system will no longer perform its intended function within the desired specifications.
- **Outputs Remaining useful life (RUL)**: The length of time from the present time to the estimated time at which the system (or product) is expected to no longer perform its intended function within desired specifications.
- **Continuously Calculates Prognostic Distance:** The time interval between the first time instance at which a prediction meets desired performance (accuracy, precision, and/or confidence) and the estimated failure time of the system.
- **Enables Health Management**: The process of decision-making and implementation of actions based on the estimate of the state of health derived from health monitoring and expected future use of the system.

Is There a Chance for Success?

Rex slides

IEEE P1856.1

Recommended Practice for Development and Implentation of Prognostic and Health Management (PHM) Systems In Accordance with IEEE-1856

IEEE 1856.1 PAR

Section 5.2 Scope of proposed standard:

This recommended practice covers the broadest possible range of development and implementation of Prognostics and Health Management (PHM) systems. This recommended practice references IEEE 1856 for PHM definitions, and descriptions of PHM physical and computational elements. Where necessary, additional definitions and descriptions are provided to support accurate understanding of the development and implementation of PHM systems. The main body of this recommended practice provides example systems, including electronic, mechanical, pneumatic/hydraulic, and nuclear. This recommended practice provides methods for evaluating system PHM needs, defining PHM requirements, implementing, integrating and verifying PHM systems, and managing the life cycle of PHM systems. The use of this recommended practice is not required throughout the industry. This recommended practice provides information to aid practitioners in the implementation of PHM that is appropriate and effective in supporting systems with the intent to explicitly understand and address the criticality of systems and cost/benefit provided to the system owner based on total life cycle cost.

Additional note regarding the development of this standard; There will be a focus on electronic system architecture and use cases that have been successfully applied, leveraging key systems from military, space and commercial applications

What Is Success?

For ‘Users’:

- Customer - Procurement
- System Users/Operators
- System Sustainment/Maintainers
- Engineers
- Development/Production

1856.1 Content and Structure - SE for PHM

- Strategy Development
  - Focus on PHM Success (customer and contractor)
  - Coordination with Customer
  - Coordination with Program Management
  - Coordination with Design Teams (Prime System Dsn, Reliability, Maintainability, Supportability and Logistics)

1856.1 Content and Structure - SE for PHM

- PHM System Architecture
  - On-Equipment - Data Capture, Compression, Data Structure/Format…
  - Off-Equipment - Data Interchange, Processing (Big Data), Security…
  - Maturation - Pre-planned System Performance Evaluation and Updates
  - Prime System Design Change Effects PHM System

1856.1 Content and Structure - SE for PHM

- Design Concept - By Phase or by System Type?
  - Preliminary Design - Coordinated with all other design entities to ensure compatibility, Evaluation of design component (HW and SW) maturity
  - Detailed Design - Early testing of less mature design elements…
  - Integration - of the PHM System elements (and PHM support of Prime System Integration and Test)
  - Design Planning for Verification and Validation

1856.1 Content and Structure - SE for PHM

- Verification and Validation
  - Coordination with Customer
  - Metrics for Initial Verification
  - Metrics and Methods for Field Verification and Validation

1856.1 Content and Structure - SE for PHM

- Field Support
  - Initial PHM Operational Support
  - Sustainment - Tracking and Managing PHM System Performance
  - Prime System Design Change Effects on PHM System Accuracy and Performance

Committee Participation Value?

- Influence - Better Outcome for You/Your Organization
- Increase Your PHM Network
- Increase Your PHM Knowledge
- Share Your Experience With Others

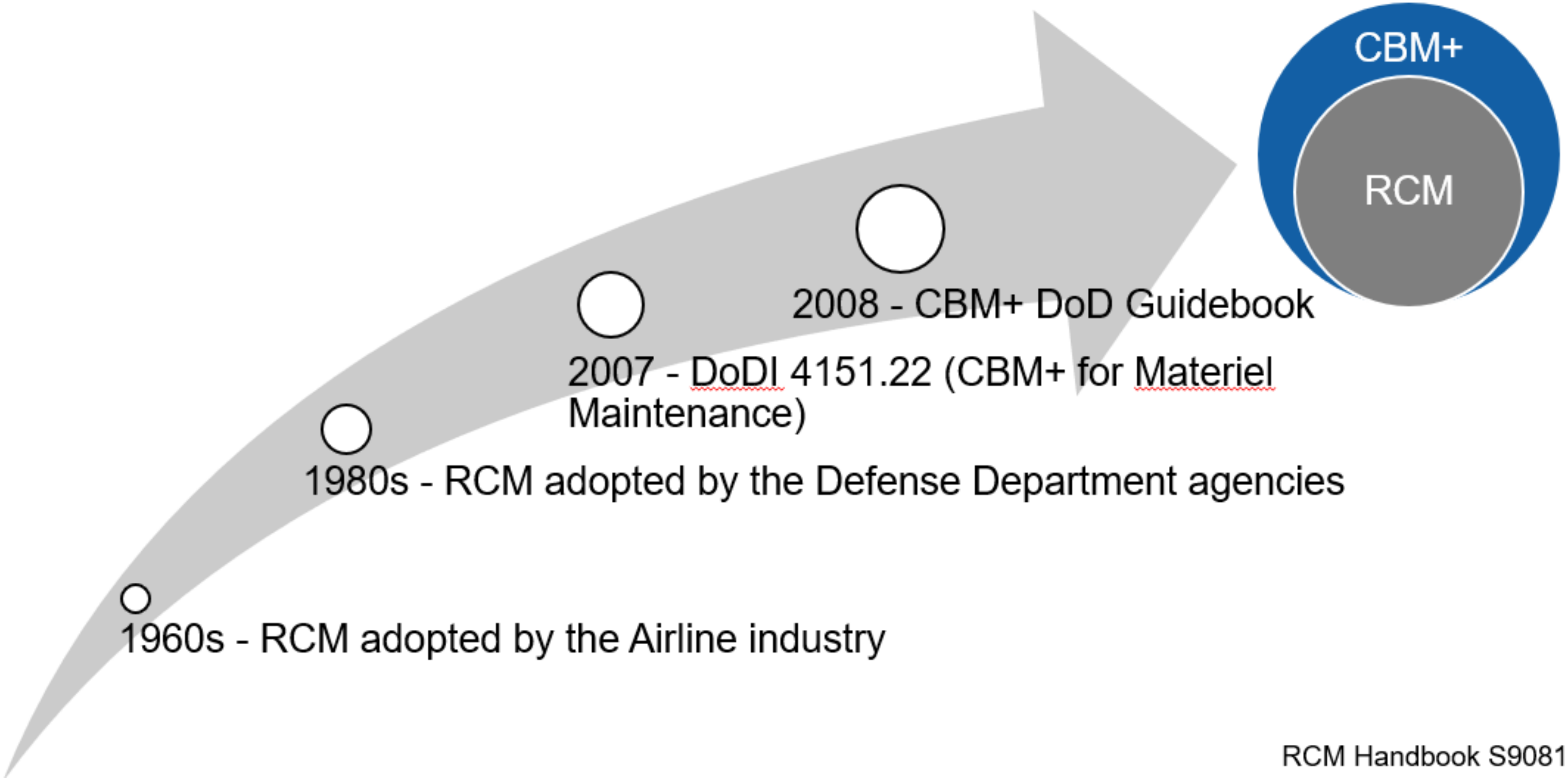
1856.1 Content and Structure (proposed)

For This Panel Discussion:

- Related Standards
- What Is Success For This Standard?
- What Is Your Greatest PHM Challenge?
- What Should We Change?
- What Should We Add?
- Can You Participate in This Standard Development Committee

Kenney slides

Path to CBM+



RCM Handbook S9081-AB-GIB-010

RCM has evolved over time to enable CBM+ methodologies

Reliability-Centered Maintenance (RCM) Approach

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RCM process →

1. Hardware Functional Breakdown
2. Failure Modes, Effects and Criticality Analysis (FMECA)
3. Risk Assessment
4. RCM Logic
5. Task Selection
6. Monitor for Effectiveness

Preventive Maintenance (PM) Tasks				
Condition Directed	Time Directed	Failure Finding	Servicing	Lubrication
Restore/replace based on measured condition compared to a standard	Restore/replace regardless of condition	Determine whether a functional failure has already occurred	Add/replenish consumable	Oil, grease, or otherwise lubricate

MIL-STD-3034

A robust FMECA is required for effective RCM implementation

RCM/CBM+ Relationship

RCM Activities

- System partitioning
- **Functional FMECA to identify individual failure mode causes, severity, and frequency**
- Evidence based selection of PM tasks to preserve function
- Determine optimal failure management strategies
- Continuous evaluation of PM task effectiveness

NAVAIR 00-25-403
MIL-STD-3034

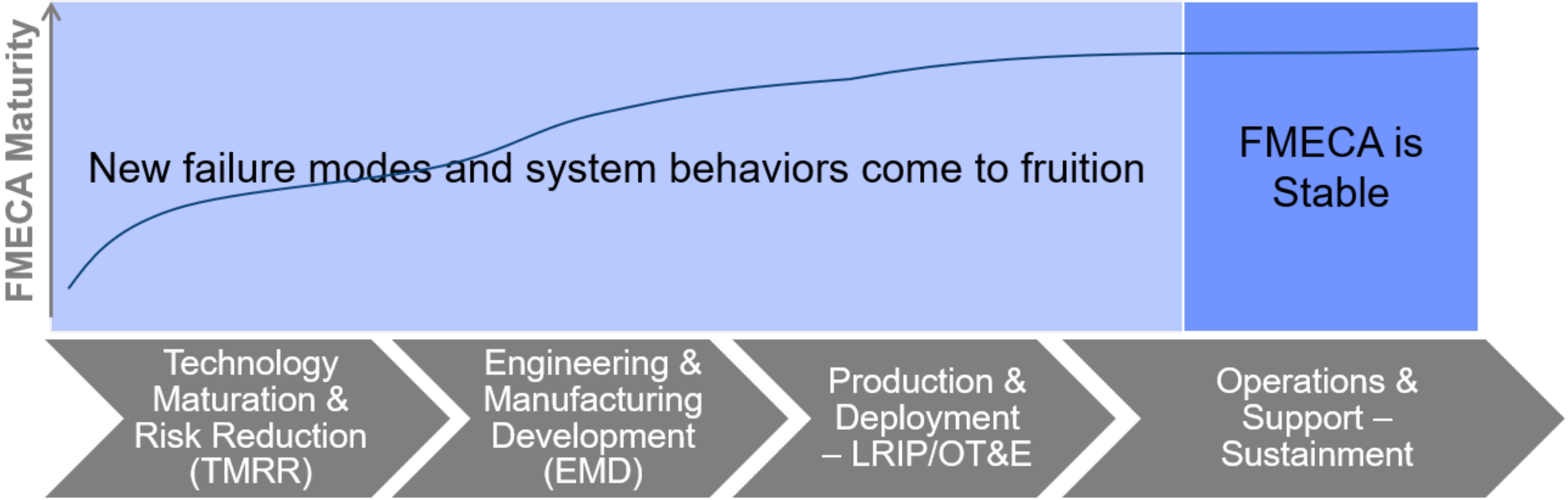
→

CBM+ Activities

- Pursue and incorporate maintenance technologies and processes to more effectively support the warfighter
- Assess available technologies to augment PM tasks
- Provide Business Case Analysis (BCA) to implement cost effective CBM+ strategies
- Transition to predictive/prognostic tasks to improve readiness
- Continuous evaluation of CBM+ implementation

Condition Based Maintenance Plus - DoD Guidebook
MIL-STD-3034

FMECA is Critical



- The FMECA is fluid prior to the sustainment phase in the program life cycle
- Unexpected system behaviors will come to fruition during development testing and flight test
- Limited data to substantiate the extra cost for CBM+ Implementation
- Most of the CBM+ programs we see today are of a “backfit” approach to existing designs as failure modes and system behaviors have been well defined and observed

Gap Analysis Approach

IEEE Reliability Society

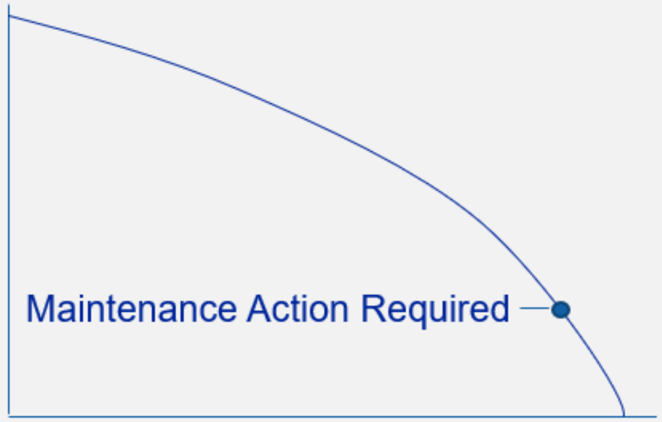
- **Step 1** – CBM+ Candidate Selection
- **Step 2** – Model the System
- **Step 3** – Perform a CBM+ sensor gap analysis
- **Step 4** – Down select CBM+ candidates

Governing Requirements

- The CBM+ implementation SHALL not introduce a new hazard to the platform
- The CBM+ implementation SHALL not reduce the reliability of the target CBM+ candidate
- The CBM+ implementation SHALL not alter the target system behavior

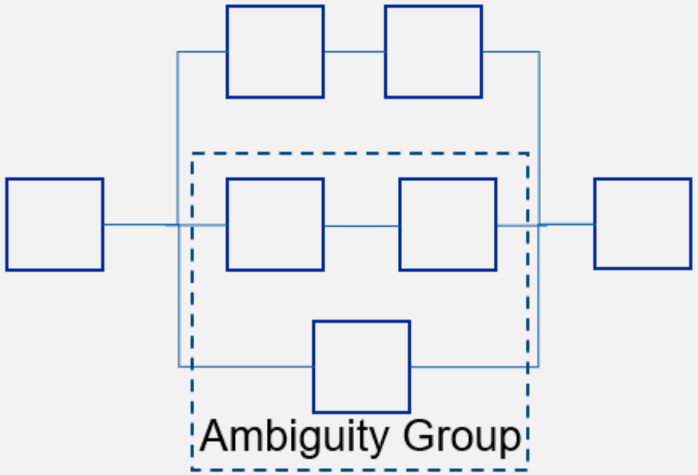
Step 1 – Identify Candidate Systems

Can I improve readiness of Safety/Mission Critical LRUs?



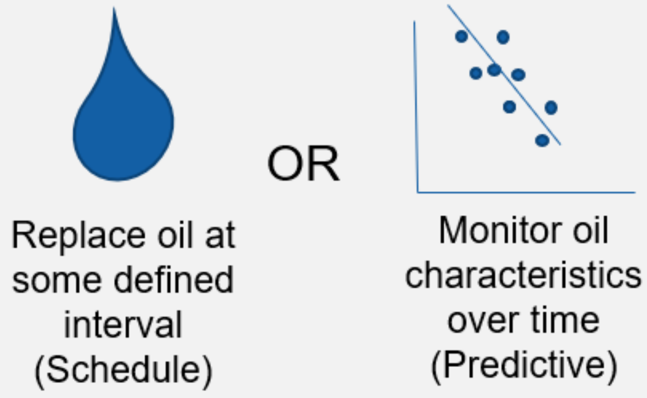
Identify Safety/Mission Critical LRUs that lack failure detection capability or leverage existing sensor suite

Can I improve fault isolation?



Review systems to understand ambiguity groups and foster a holistic view of CBM+ implementation

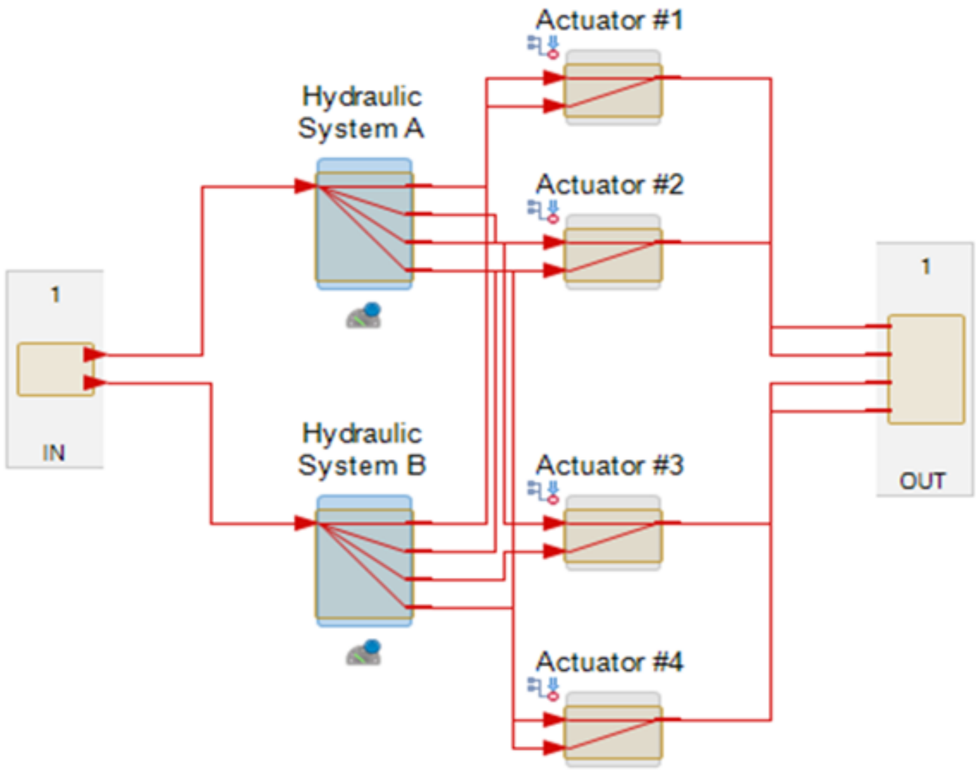
Can I improve Preventive Maintenance?



Investigate Safety/Mission Critical LRUs for opportunities to alleviate preventive maintenance tasks

Step 2 – Functional System Modeling

- Functional System Modeling supports:
  - Visualization of complex system topology and functions
  - Assessment of impacts to diagnostics, reliability, availability, and maintainability
  - Immediate feedback on the capability of the diagnostic system and fault permutations
  - Fault injection with visual representation of the downstream effects to the system for optimization and evidence for recommendations of changes



Maintenance Aware Design (MADe)

Step 3 – Perform a CBM+ Sensor Gap Analysis

- If the RCM analysis is ongoing; perform a tailored MIL-STD-3034 approach with existing FMECA that identifies PM tasks
- Utilize the Functional FMECA preformed at the platform level
- First leverage existing sensor capabilities already designed in the system, i.e. temperature, flow, and pressure sensors
- Identify additional sensors that will not effect the system behavior or impact safety

Analyze Failure Modes

- For each failure mode identify:
  - Existing monitoring/recording capabilities
  - Preventive maintenance task(s) that preserves function
  - Hidden or evident failure characteristics

CBM+ Selection

- Does CBM+ implementation improve readiness?
- Does CBM+ implementation alleviate a hidden failure characteristic?
- Does CBM+ implementation replace or enhance a PM task?

CBM+ Gap

- Identify monitoring/recording opportunities that support CBM+ methodologies
- Identify HW/SW needed to implement CBM+ methodologies

Step 4 – Select CBM+ Candidates

CBM+ Candidate Feasibility

- Identify the feasibility for CBM+ implementation for each candidate
- Work with the design integration team to ensure system behavior and safety is not impacted

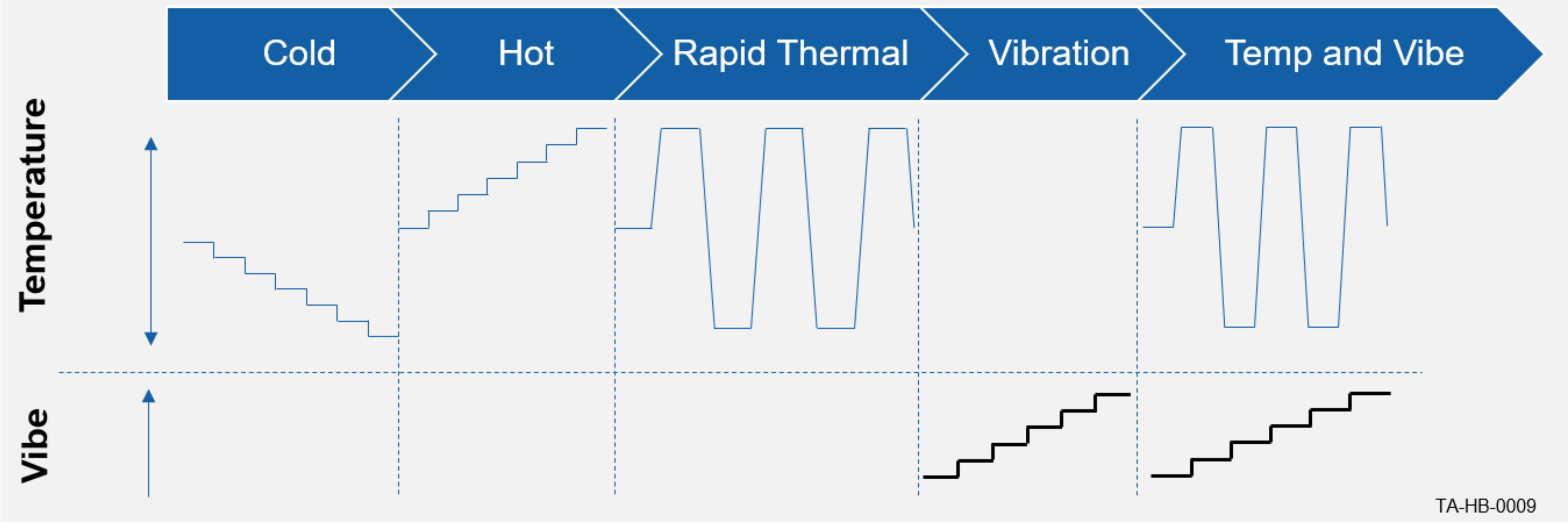
Rank CBM+ Candidates

- Rank CBM+ Candidates that will improve fault detection/isolation capabilities
- Rank CBM+ Candidates that will alleviate PM tasks
- Utilize criticality and probability in the FMECA to substantiate selection

Down Select with the End User

- Present potential candidates to the end user with supporting data to build the CBM+ story (include cost and design trades)
- Ensure the end user will support the technology throughout the program life cycle

Perform HALT on Candidate LRUs



- Perform Highly Accelerated Life Testing (HALT) to define degrading characteristics
- Utilize data for initial predictive capabilities until enough confidence is derived from fielded data

Lou slides

Future of PHM/CBM+

- There is a need for a secure and resilience framework involving Dev/Ops with PHM/CBM+ to ensure continuous, uninterrupted, and reliable system operations
- Exploring the use of PHM/CBM+ for Software System Security, Cybersecurity, Reliability, and Resilience
- Working with industry to consider development of software tools as PHM/CBM+ enablers to accelerate development of practical applications and capabilities

Closing Remarks

With the confluence of Artificial Intelligence (AI), Machine Learning (ML), Big Data Analytics, smart sensors supplemented by Internet of Things (IOT) technologies, 5G and beyond networks for secure and reliable enterprise solutions, software systems with ever increasing complexity, and the constantly growing cyber threat environment, PHM/CBM+ technologies will continue to evolve.

We hope that this panel entices you to explore the concepts of predictive analytics, reliability, maintainability, availability, resilience, security, and system safety using a holistic PHM end to end architecture with machine learning and data management operations (DataOps) and the value of creating standards that provide a roadmap for future direction.

Reference:

RS Standards Committee website: https://sagroups.ieee.org/rs-sc/

Questions