REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED *(From - To)*
07 October 2019	Briefing Charts	09 May 2019 - 07 October 2019

4. TITLE AND SUBTITLE
2nd Cooperative Demonstration of Technologies for Munitions Health Management

5a. CONTRACT NUMBER
FA9300-16-C-0003

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
Q1FT

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RQRM
4 Draco Drive
Edwards AFB, CA 93524-7160

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

AFRL-RQ-ED-VG-2019-133

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A: Approved for Public Release; Distribution is Unlimited. PA Clearance Number: 19299 Clearance Date: 31 May 2019 - VG
Distribution Statement A: Approved for Public Release; Distribution is Unlimited. PA Clearance Number: 19319 Clearance Date: 13 June 2019 - Posters

13. SUPPLEMENTARY NOTES
For presentation at NATO STO AVT-292; Brussels, Belgium; 7 October 2019.
The U.S. Government is joint author of the work and has the right to use, modify, reproduce, release, perform, display, or disclose the work.
Accompanying posters: AFRL-RQ-ED-PS-2019-184.

14. ABSTRACT
Viewgraph/Briefing Charts

15. SUBJECT TERMS
N/A

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			James Singleton
Unclassified	Unclassified	Unclassified	SAR	16	19b. TELEPHONE NUMBER *(Include area code)* N/A

THE VALUE OF PERFORMANCE.
NORTHROP GRUMMAN

2nd Cooperative Demonstration of Technologies for Munitions Health Management

NATO STO AVT-292 at NATO HQ
7-10 October, 2019

Farid Rafla
Air Force Research Laboratory, Edwards AFB

Scott Hyde, Heath Dewey and Derek DeVries
Northrop Grumman Innovation Systems, Promontory, UT

Objectives of Munition Health Management

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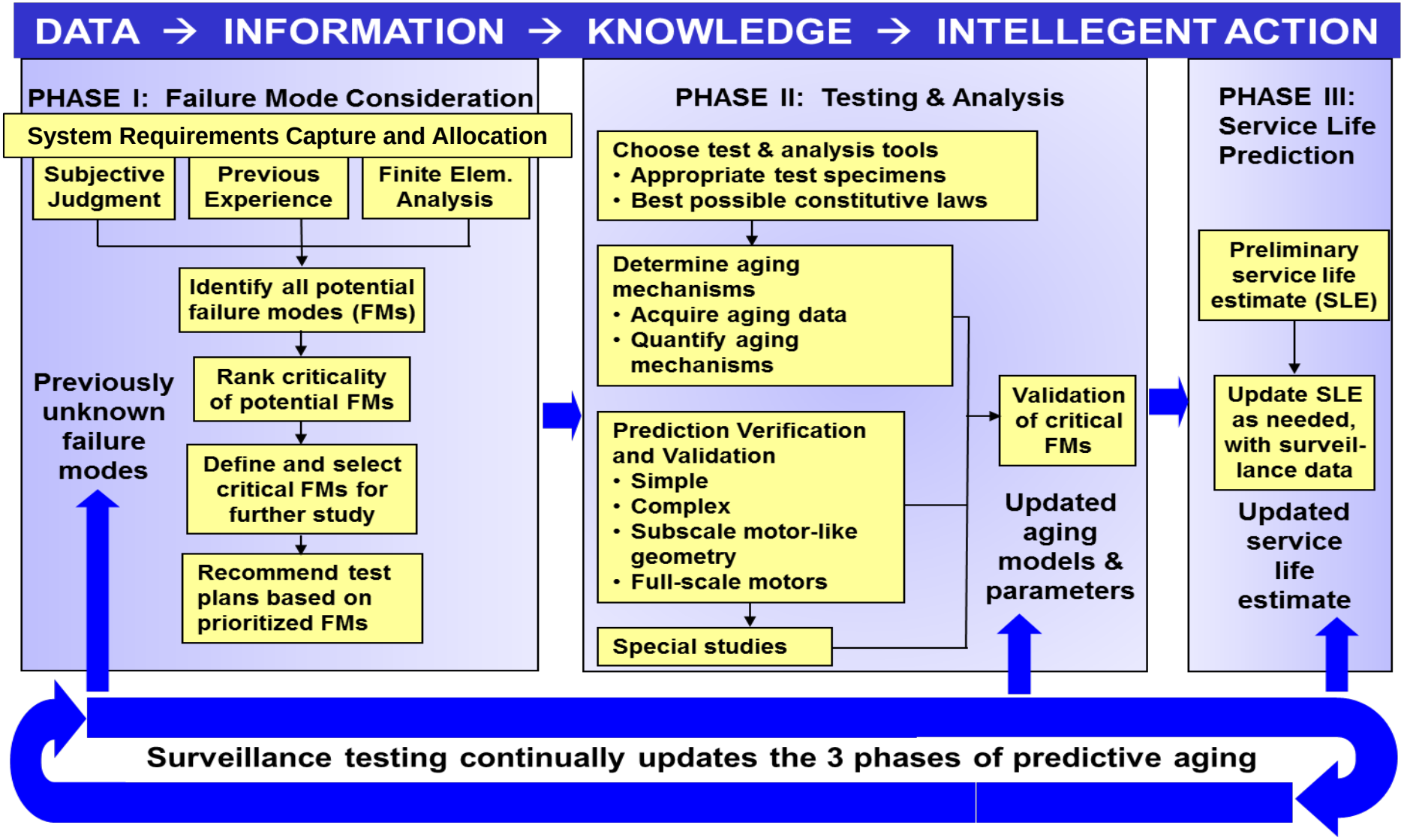
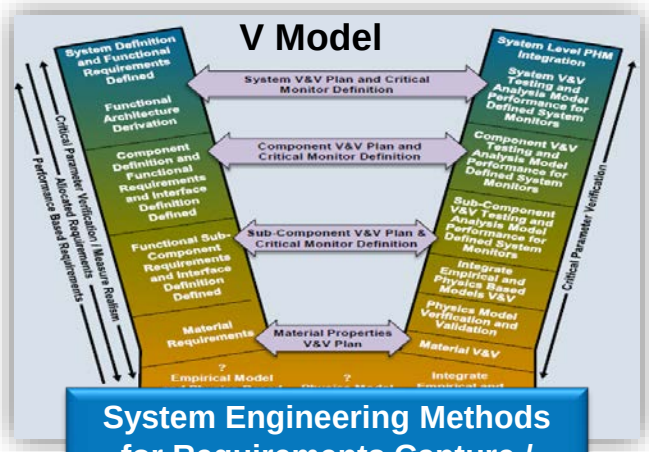
- **Dramatically Reduce Cost** → through use of "Internet of Things" (IoT), Augmented Reality (AR), Digital Twin, and advanced data analysis and management
- **Assure Safe and Reliable Performance** → by monitoring environments and using Advanced Mechanistic Models to link environmental exposure to munition degradation
- **Reduce Risk** → by detecting degradation early allowing for removal of the munition from service

Technology Development Over the Past 20+ Years Enables Integrated System Health Management (ISHM) of Munitions

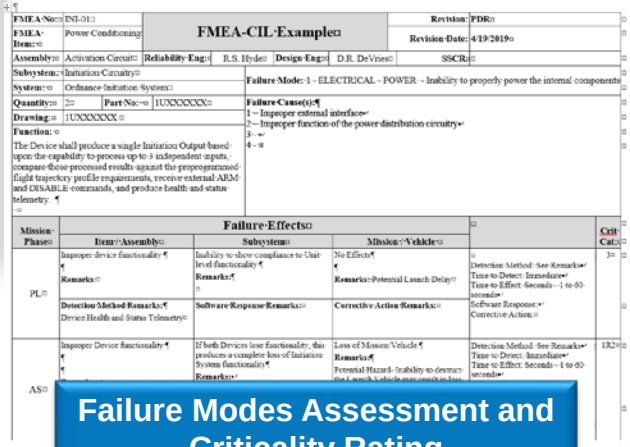
3-Phase IMHM A&S Approach



Defined System Engineering Approach



System Engineering Methods for Requirements Capture / Allocation and Verification/ Validation (V&V).[1,2]



FMEA-CIL-Example

FMEA-No:	INI-01			Revision:	PDR		
FMEA-Item:	Power Conditioning			Revision-Date:	4/19/2019		
Assembly:	Activation Circuit	Reliability-Eng:	R.S. Hyde	Design-Engr:	D.R. DeVries	SSCR:	
Subsystem:	Initiation Circuitry						
System:	Ordnance Initiation System						
Quantity:	2	Part-No:	1UXXXXXX				
Drawing:	1UXXXXXX						
Function:	The Device shall produce a single Initiation Output based upon the capability to process up to 3 independent inputs, compare those processed results against the preprogrammed flight trajectory profile requirements, receive external ARM and DISABLE commands, and produce health and status telemetry.						

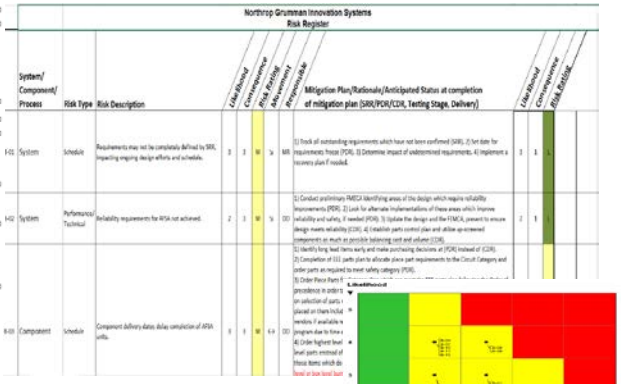
Failure Mode: 1 - ELECTRICAL - POWER - Inability to properly power the internal components

Failure Cause(s):
1 – Improper external interface
2 – Improper function of the power distribution circuitry
3 -
4 -

Failure Effects

Mission Phases	Item/Assembly	Subsystem	Mission/Vehicle	Crit Cat.
PL	Improper device functionality Remarks:	Inability to show compliance to Unit-level functionality Remarks:	No Effect Remarks: Potential Launch Delay	3
	Detection Method Remarks: Device Health and Status Telemetry	Software Response Remarks:	Corrective Action Remarks:	
			Detection Method: See Remarks Time to Detect: Immediate Time to Effect: Seconds – 1 to 60 seconds Software Response: Corrective Action:	
AS	Improper Device functionality Remarks:	If both Devices lose functionality, this produces a complete loss of Initiation System functionality Remarks:	Loss of Mission/Vehicle Remarks: Potential Hazard- Inability to destruct	1R2
			Detection Method: See Remarks Time to Detect: Immediate Time to Effect: Seconds – 1 to 60 seconds	

Failure Modes Assessment and Criticality Rating

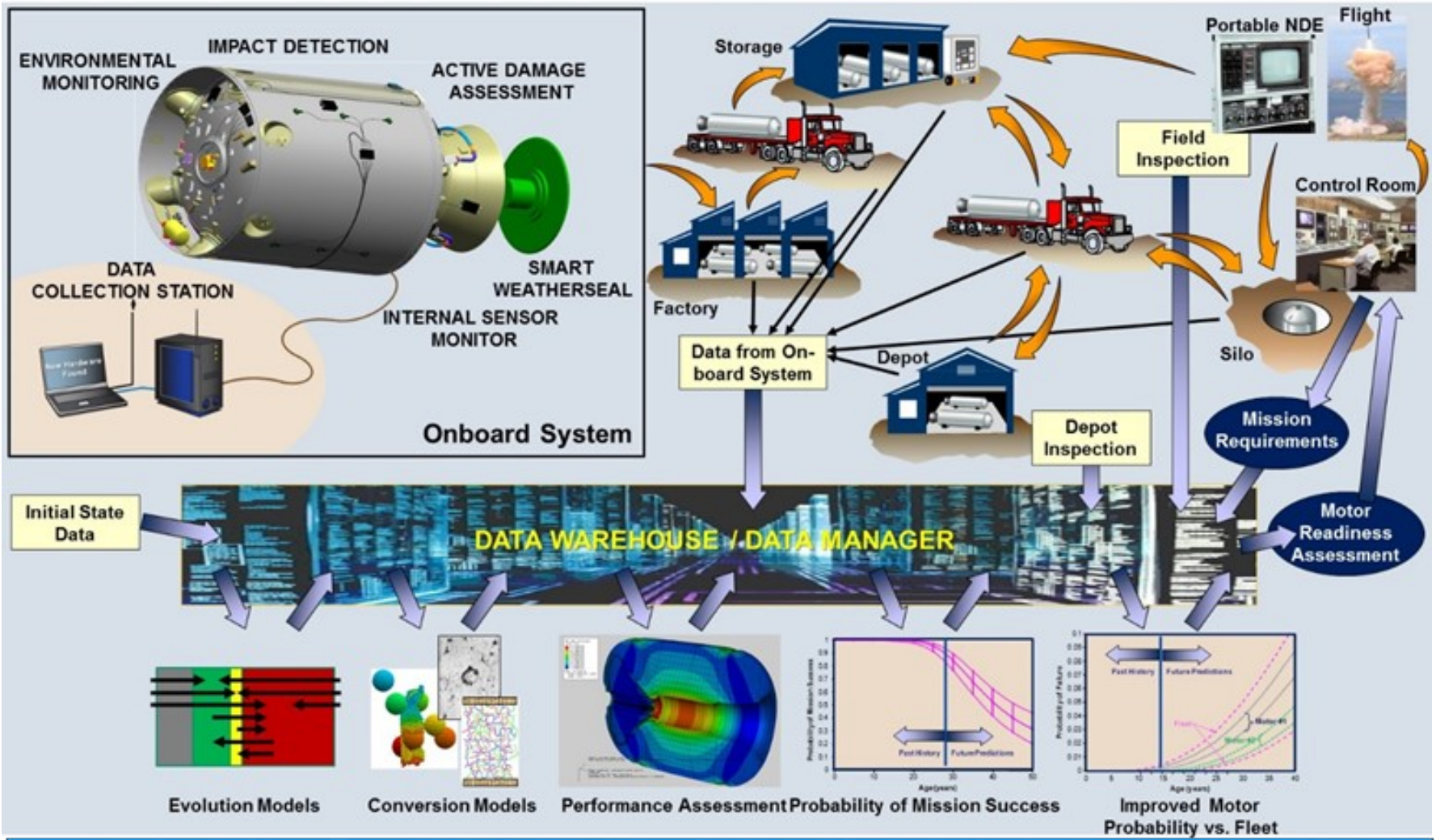


Risk Management and Mitigation Processes

Active System Engineering Processes to Capture Requirements, Identify and Rank Failure Modes, and Manage Program Risk

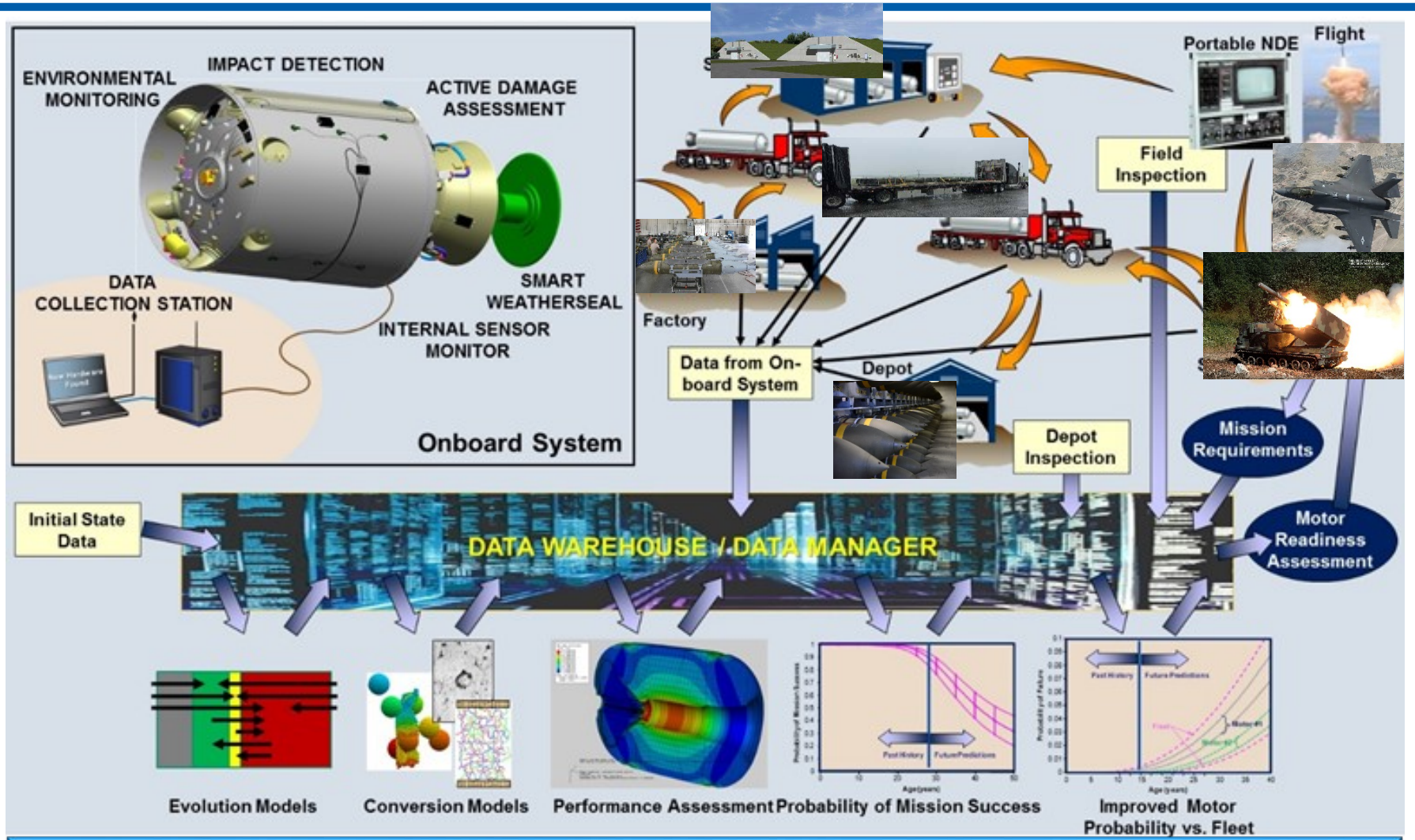
1. Derek R. De Vries, Bryan De Hoff, et.al, "Systems Engineering approach to IMLM DAAS goal achievement," JANNAF 61st JPM, Charleston, SC, May 2014.
2. SE Handbook Working Group International Council on Systems Engineering (INCOSE), INCOSE Systems Engineering Handbook v. 3.2.2, Oct 2011.

Munition Health Management



Ability to Link Munition Environments to Munition Health is Key

Munition Health Management

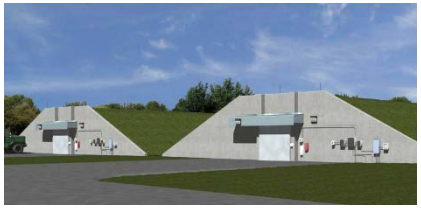


Ability to Link Munition Environments to Munition Health is Key

Munition Health Management Images

http://www.thedrive.com/the-war-zone/11871/the-u-s-air-force-wants-to-buy-more-reliable-bunker-buster-bombs

http://www.osan.af.mil/News/Article-Display/Article/640053/no-mission-without-ammo-muns-airmen-epitomize-fight-tonight-readiness/



https://hardenedstructures.blogspot.com/2013/07/hardened-structures-military.html

https://military-photoshops.blogspot.com/2012/04/f-35-joint-strike-fighter-for-raf-uk.html

http://www.tanks-encyclopedia.com/coldwar/US/M270-MLRS.php

http://armyrecognition.com/march_2018_global_defense_security_army_news_industry/lockheed_martin_s_pac-3_successfully_intercepted_2_ballistic_missile.html

Ability to Link Munition Environments to Munition Health is Key

Difference Between SHM and ISHM

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Data

- Requires subject matter expertise
- Gathered from many sources
  - Utilize COTS technologies
  - Establish sources if necessary

Information / Knowledge

- Requires subject matter expertise
- Historically people convert data into information / knowledge
- Automated processes are desired
  - Enable real-time visual analysis
  - Sophisticated data processing algorithms

Action

- Focus is on applying risk management
- Historically labor intense & error prone
- Automated algorithms
  - Decision support
  - Risk management

Historically

- Manual data capture and data processing
  - Slow – months/years
  - Labor intensive – costly
  - Managed fleet not individual assets
- Prone to errors
  - Human
    - Typos/transpose
    - Duplicate
    - Interpretation
  - Lost paper
  - Complacency

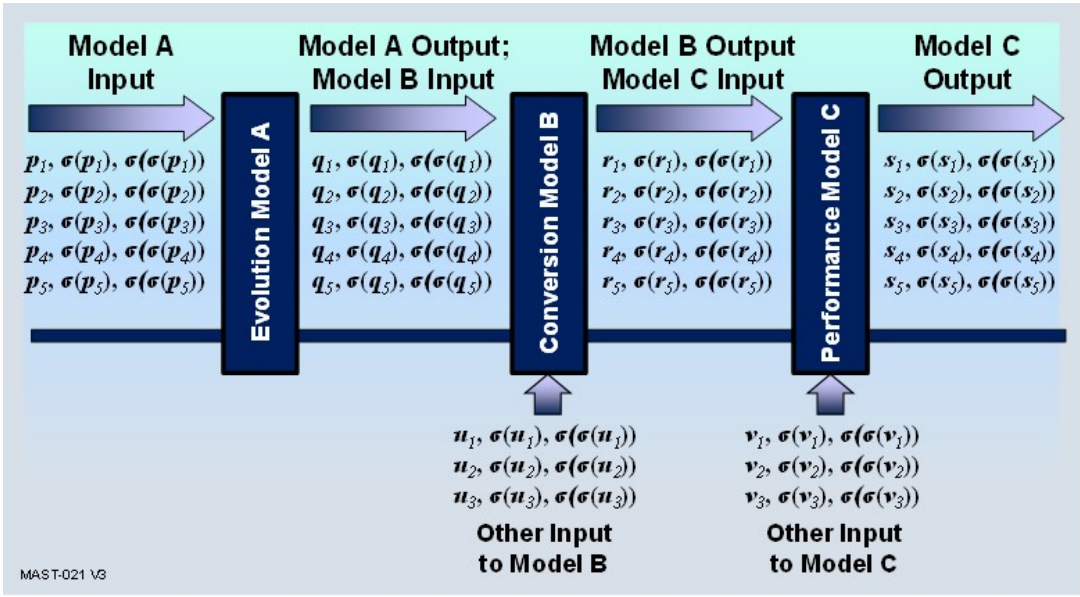
Currently

- Integrated system-level solution
  - Automated software enabling near real-time SLE's
  - Digital twin and augmented reality enabling efficient processes / cost savings
- Improved accuracy
  - Individual munition management
  - Automated data capture

SHM is labor intense and costly. NGIS ISHM automates most of the process lowering cost and improving response and efficiency

Identification and Reduction of Uncertainty Is Key to MHM Effectiveness

MHM Methods Identify, Track and Reduce Uncertainties Throughout the 50+ Year Life-Cycle of the Munition at Less Cost and Higher Reliability Than Historical Methods



Munition Service Life Estimates

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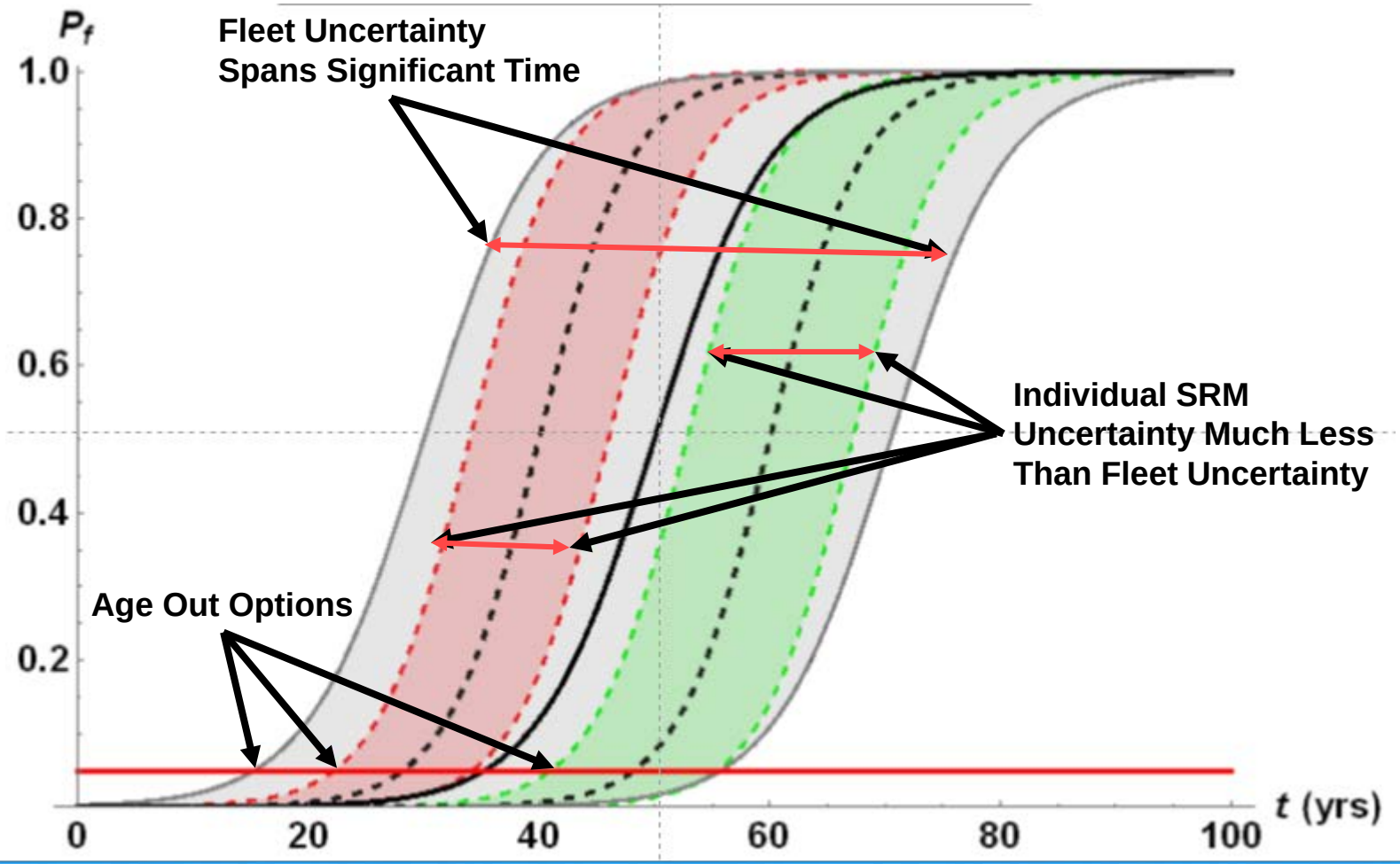
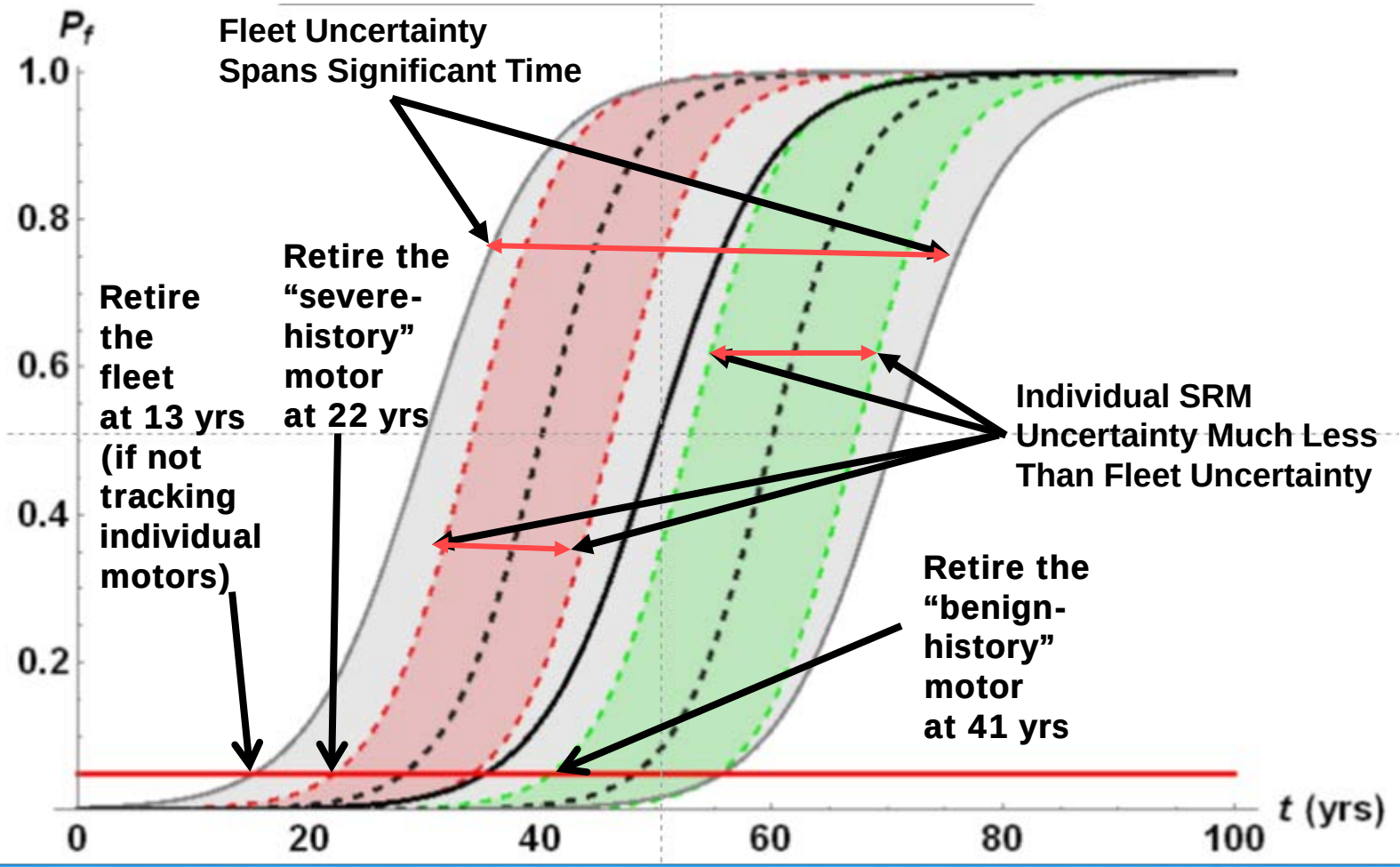


MHM Enables the Near Real-time SLE of Individual Assets to Be Determined And Culled If Necessary To Maintain Fleet Reliability

Munition Service Life Estimates

NORTHROP GRUMMAN



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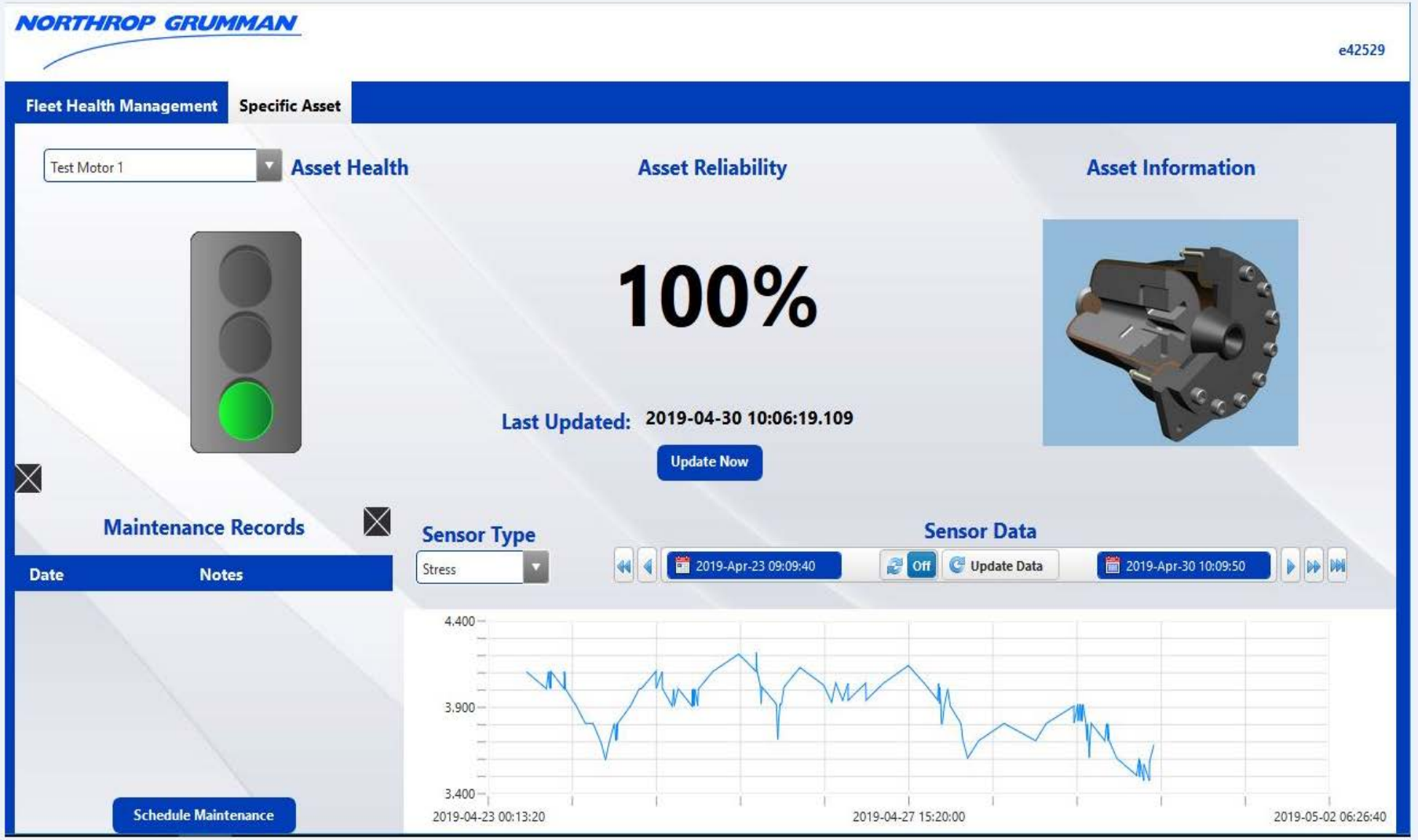
IMHM Asset Monitor Panel Example



THE VALUE OF PERFORMANCE.

NORTHROP GRUMMAN

- Munition's exposure to diverse environments affects performance over time

Benefits of CBM+/IMHM Approach

- Retirement of less assets due to greater understanding of aging mechanisms: Predictive uncertainty reduced by 20% to 50%
- Reduction in procurement cost by over 20% over the system life facilitates a level buying strategy.

DoD systems and compo

… At its core, CBM+ is

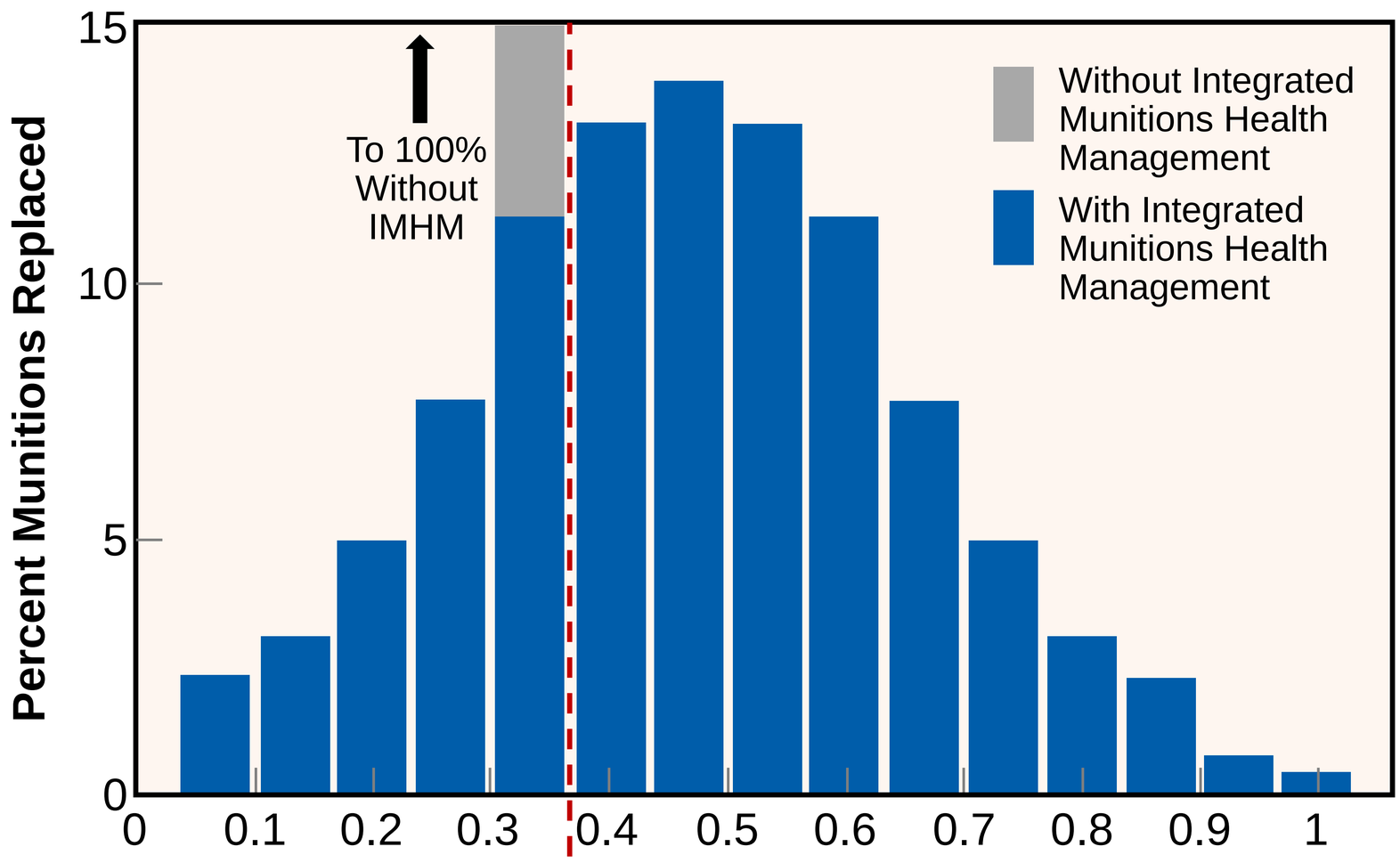
evidence of need …

CBM+ uses a systems e

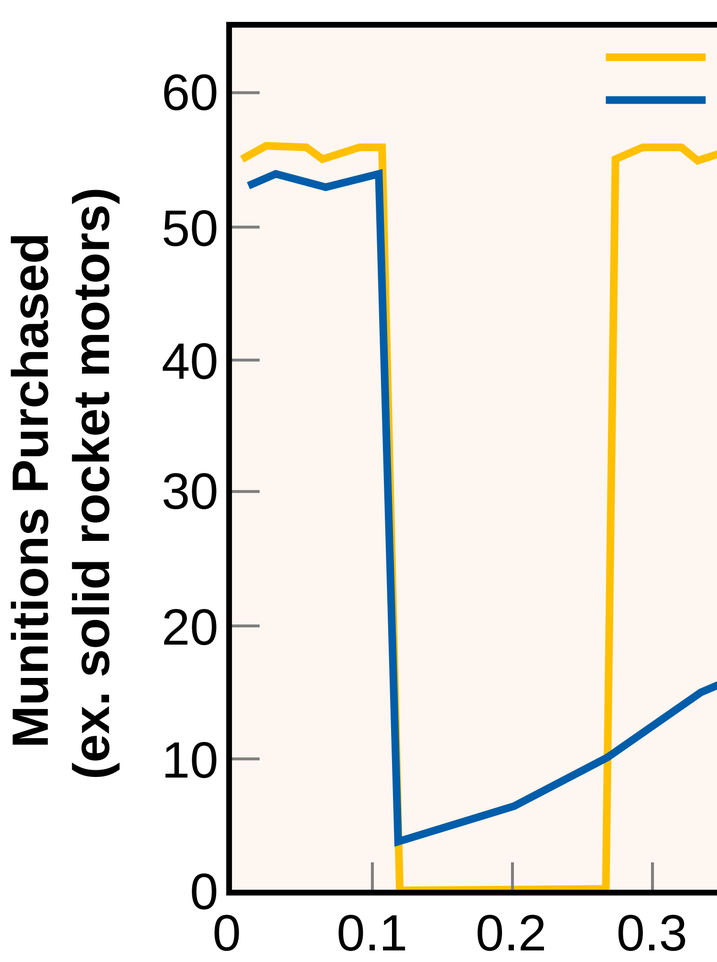
system acquisition, mod

operations.

Benefits of CBM+/IMHM versus Legacy Approaches from AFRL Study



CBM+/IMHM Approa Strategy and Reductio



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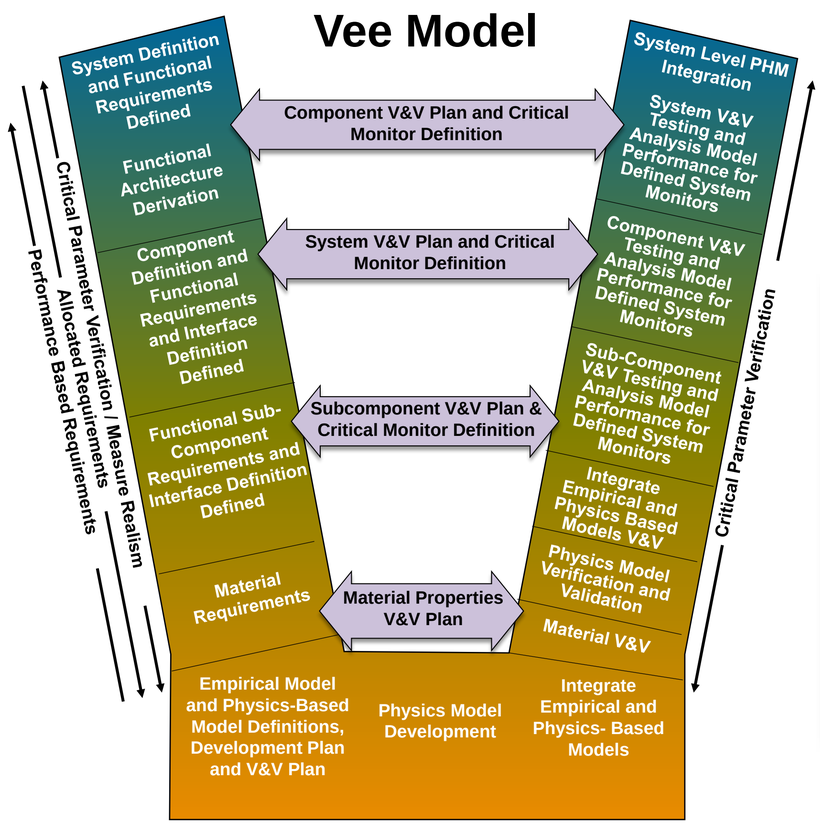

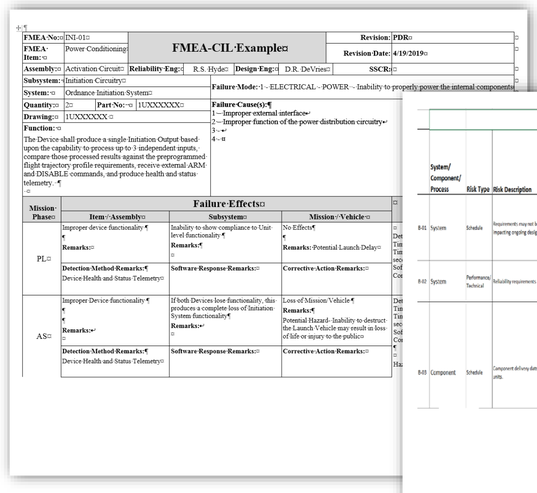

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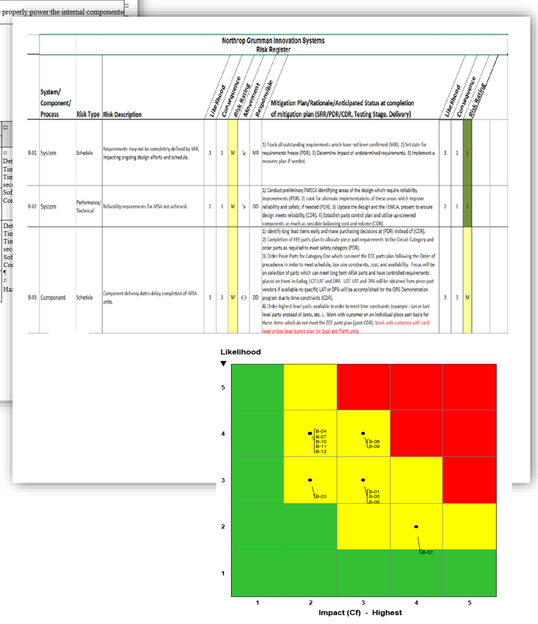
AS	Improper Device functionality Remarks:	If both Devices lose functionality, this produces a complete loss of Initiation System functionality Remarks:	Loss of Mission/Vehicle Remarks: Potential Hazard- Inability to destruct the Launch Vehicle may result in loss of life or injury to the public
	Detection Method Remarks: Device Health and Status Telemetry	Software Response Remarks:	Corrective Action Remarks:



Northrop Grumman Innovation Systems
Risk Register

System/ Component/ Process	Risk Type	Risk Description	Likelihood	Consequence	Risk Rating	Responsible	Mitigation Plan/Rationale/Anticipated Status at completion of mitigation plan (SRR/PDR/CDR, Testing Stage, Delivery)	Likelihood	Consequence	Risk Rating
B-01	System	Schedule	3	3	M	VL	1) Track all outstanding requirements which have not been confirmed (SRR). 2) Set date for requirements freeze (PDR). 3) Determine impact of undetermined requirements. 4) Implement a recovery plan if needed.	3	1	L
B-02	System	Performance, Technical	2	3	M	N	DD	1) Conduct preliminary FMECA identifying areas of the design which require reliability improvements (PDR). 2) Look for alternate implementations of these areas which improve reliability and safety, if needed (PDR). 3) Update the design and the FEMCA, present to ensure design meets reliability (CDR). 4) Establish parts control plan and utilize up-screened components, as much as possible balancing cost and volume (CDR).	2	1	L
B-03	Component	Schedule	3	3	M	H	DD	1) Identify long lead items early and make purchasing decisions at (PDR) instead of (CDR). 2) Completion of EEE parts plan to allocate piece part requirements to the Circuit Category and order parts as required to meet safety category (PDR). 3) Order Piece Parts for Category One which can meet the EEE parts plan following the Order of precedence in order to meet schedule, box size constraints, cost, and availability. Focus will be on selection of parts which can meet long term ATEA parts and have controlled requirements placed on them including ECP LAT and DRA. LOT LAT and DRA will be obtained from piece part vendors if available no specific LAT or DPA will be accomplished for the CRS Demonstration program due to time constraints (CDR). 4) Order highest level parts available in order to meet time constraints (example : Use or last level parts instead of parts, etc.). Work with customer on an individual piece part basis for these items which do not meet the EEE parts plan (post-CDR). Work with customer with card level or box level burnin plan for Quad and Flight units.	3	3	M

CBM+/IMHM Approa Strategy and Reductio

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  - Establish sources if necessary

Information Knowledge
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Action
- Focus is on applying risk management
- Historically labor intense & error prone
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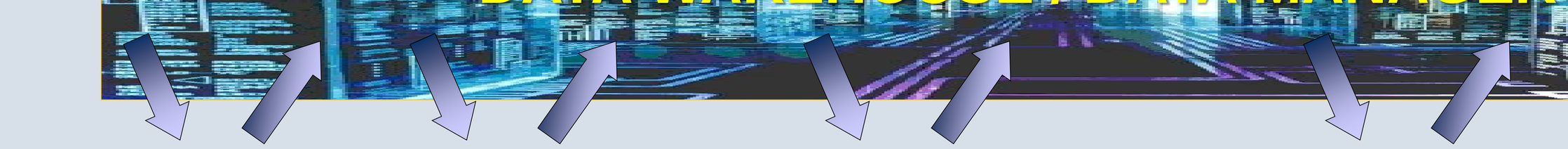
  - Decision support
  - Risk management

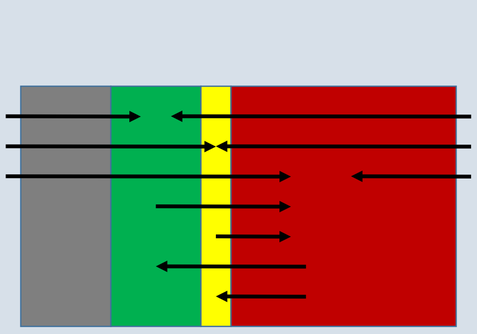
System Engineering Methods for Requirements Capture / Allocation and Verification/ Validation (V&V).[1,2]

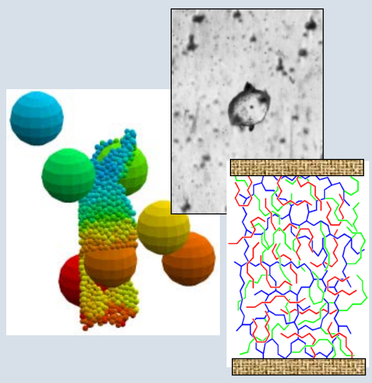
Failure Modes Assessment and Criticality Rating

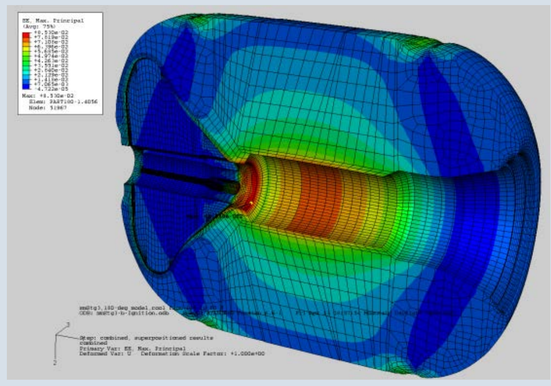
Risk Management and Mitigation Processes

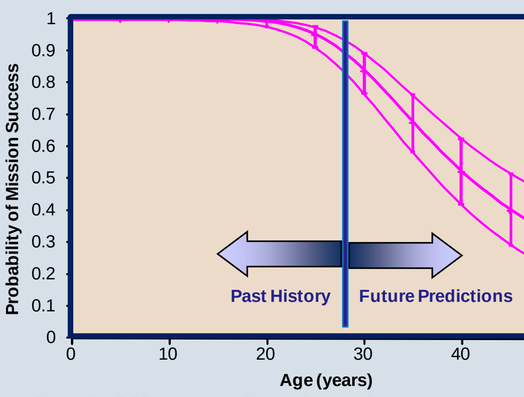
Active System Engineering Processes to Capture Requirements, Identify and Rank Failure Modes and Manage Program Risk











Evolution Models | **Conversion Models** | **Performance Assessment** | **Probability of Mission Suc**

NGIS three Phase IMHM Approach

DATA → INFORMATION → KNOWLEDGE → INTELLEGENT ACTION

PHASE I: Failure Mode Consideration

- System Requirements Capture and Allocation
- Subjective Judgement / Previous Experience / Finite Elem. Analysis
- Identify all Potential Failure Modes (FMs)
- Rank Criticality of Potential FMs
- Define and Select Critical FMs for Further Study
- Recommend Test Plans Based o Prioritized FMs

Previously Unknown Failure Modes

PHASE II: Testing and Analysis

- **Chose Test and Analysis Tools**
  - Appropriate test specimens
  - Best possible constitutive laws
- **Determine Aging Mechanisms**
  - Acquire aging data
  - Quantify aging mechanisms
- **Prediction Verification and Validation**
  - Simple
  - Complex
  - Subscale motor-like geometry
  - Full-scale motors
- **Special Studies**
- **Validation of Critical FMs**

Updated Aging Models and Parameters

PHASE III: Service Life Prediction

- Preliminary Service Life Estimate (SLE)
- Update SLE as Needed, with Surveillance Data

Updated Service Life Estimate

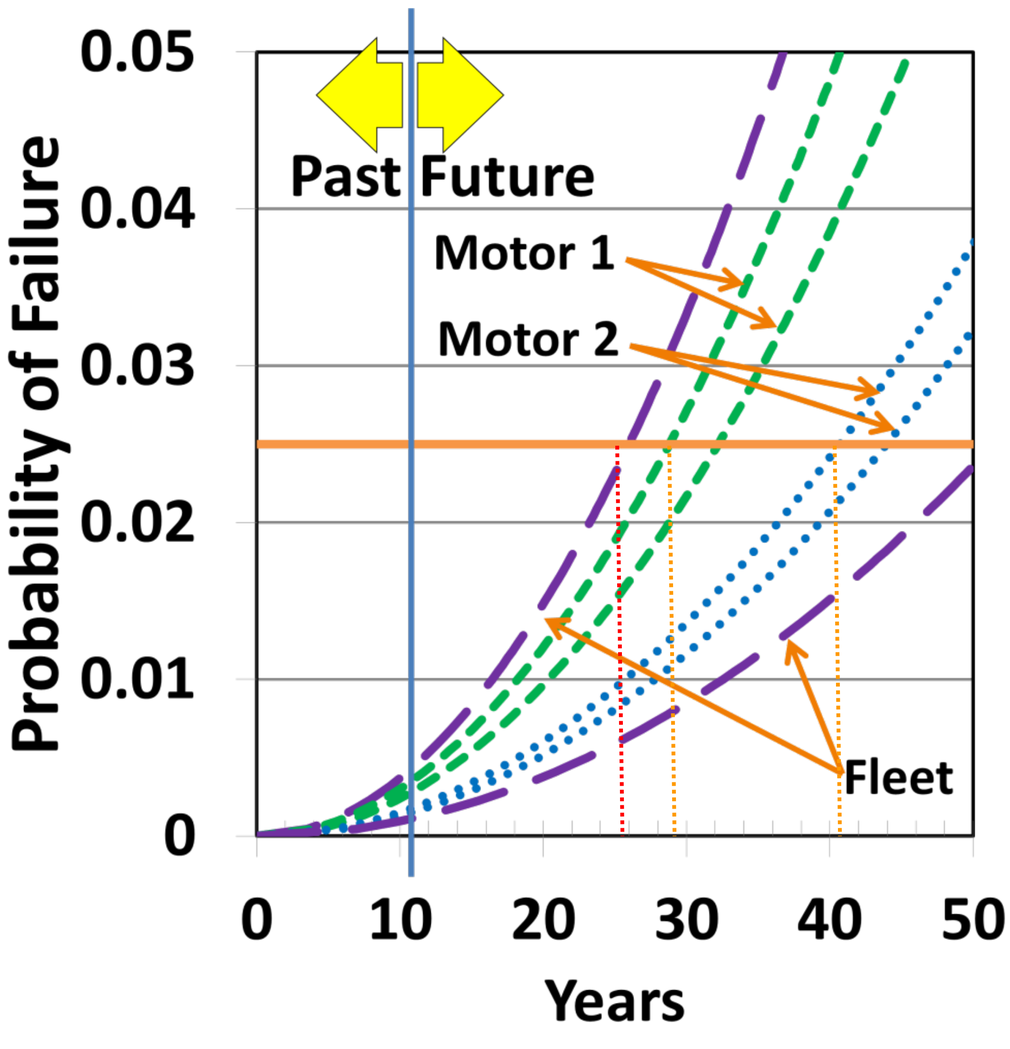
Surveillance Testing Continually Updates the 3 Phases of Predictive Aging

IMHM Methods Identify, Track and Reduce Uncertainties Throughout the Life-Cycle of the Munition at Less Cost and Higher Reliability Than Historical Methods

Model A Input

$p_1, \sigma(p_1), \sigma(\sigma(p_1))$
$p_2, \sigma(p_2), \sigma(\sigma(p_2))$
$p_3, \sigma(p_3), \sigma(\sigma(p_3))$
$p_4, \sigma(p_4), \sigma(\sigma(p_4))$
$p_5, \sigma(p_5), \sigma(\sigma(p_5))$

Munition Service Life Estimates



Fleet-wide estimate has a large uncertainty, leading to early withdraw of service (red dotted line); individual motors still have uncertainty but stay in service longer before reaching minimum probability of failure (orange dotted line)

IMHM Enables the Near Real-time SLE of Individual Assets to Be Determined And Culled If Necessary To Maintain Fleet Reliability

IMHM Asset M