

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 21-09-2011		2. REPORT TYPE Briefing Charts		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Health Management and Service Life for Air Force Missiles				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Greg Ruderman, Eric Weber, and Andrew Sincock				5d. PROJECT NUMBER	
				5f. WORK UNIT NUMBER 48470524	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/RZSB 4 Draco Drive Edwards AFB CA 93524-7160				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/RZS 5 Pollux Drive Edwards AFB CA 93524-7048				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S NUMBER(S) AFRL-RZ-ED-VG-2011-389	
12. DISTRIBUTION / AVAILABILITY STATEMENT Distribution A: Approved for public release; distribution unlimited. PA #11806-M.					
13. SUPPLEMENTARY NOTES For a briefing in Korea, 26 Sep 2011.					
14. ABSTRACT This briefing was about health management and service life for Air Force missiles.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 27	19a. NAME OF RESPONSIBLE PERSON Andrew Sincock, Maj USAF
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code) N/A



Air Force Research Laboratory



Integrity ★ Service ★ Excellence

Health Management and Service Life for Air Force Missiles

Date: 26 09 2011

**Major Andrew Sincock
Chief**

Motor Branch

Air Force Research Laboratory



Agenda



- **Introduction**
- **Motivation**
- **Background / Previous Successes**
- **Current Work**
- **Tech Needs**
- **Summary and Conclusions**



Introduction



- **Solid motors are:**
 - **Simple:** few moving parts, provide rapid response
 - **Storable:** no costly cryogenic or pressure systems required
 - **Reliable:** ready when needed, even after extended deployment
- **However, solid rocket motors are:**
 - **Mechanically and chemically complex**
 - **Designed with small margins**
 - **Dynamic, changing with age and environmental exposure**
 - **Often required to function long beyond the design life**
 - **Often subjected to unexpected environments**
 - **Generally not capable of maintenance/repair**

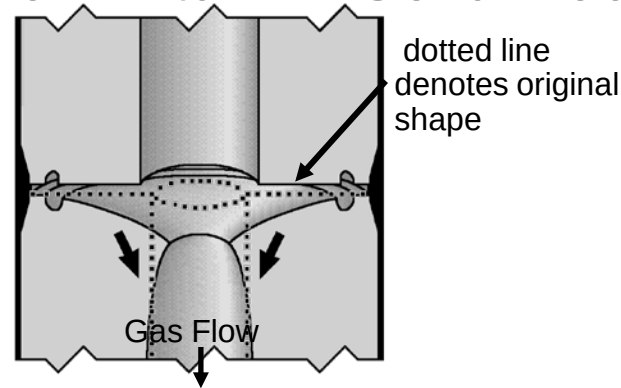


Motivation



Structural-Ballistic Interaction: Titan IV Solid Rocket Motor failure

Soft propellant deflects into flow, causes unexpected overpressure



Cost: Test stand damaged, Titan SRM destroyed, ~14 month program delay

Aging Failure: AIM-7 Sparrow explodes on launch from F-15

Chemical reaction of insulation curative degrades bondline to zero strength
Resulting structural-ballistic interaction causes missile to explode off wing



Cost: F-15 damaged, failure investigation



Background

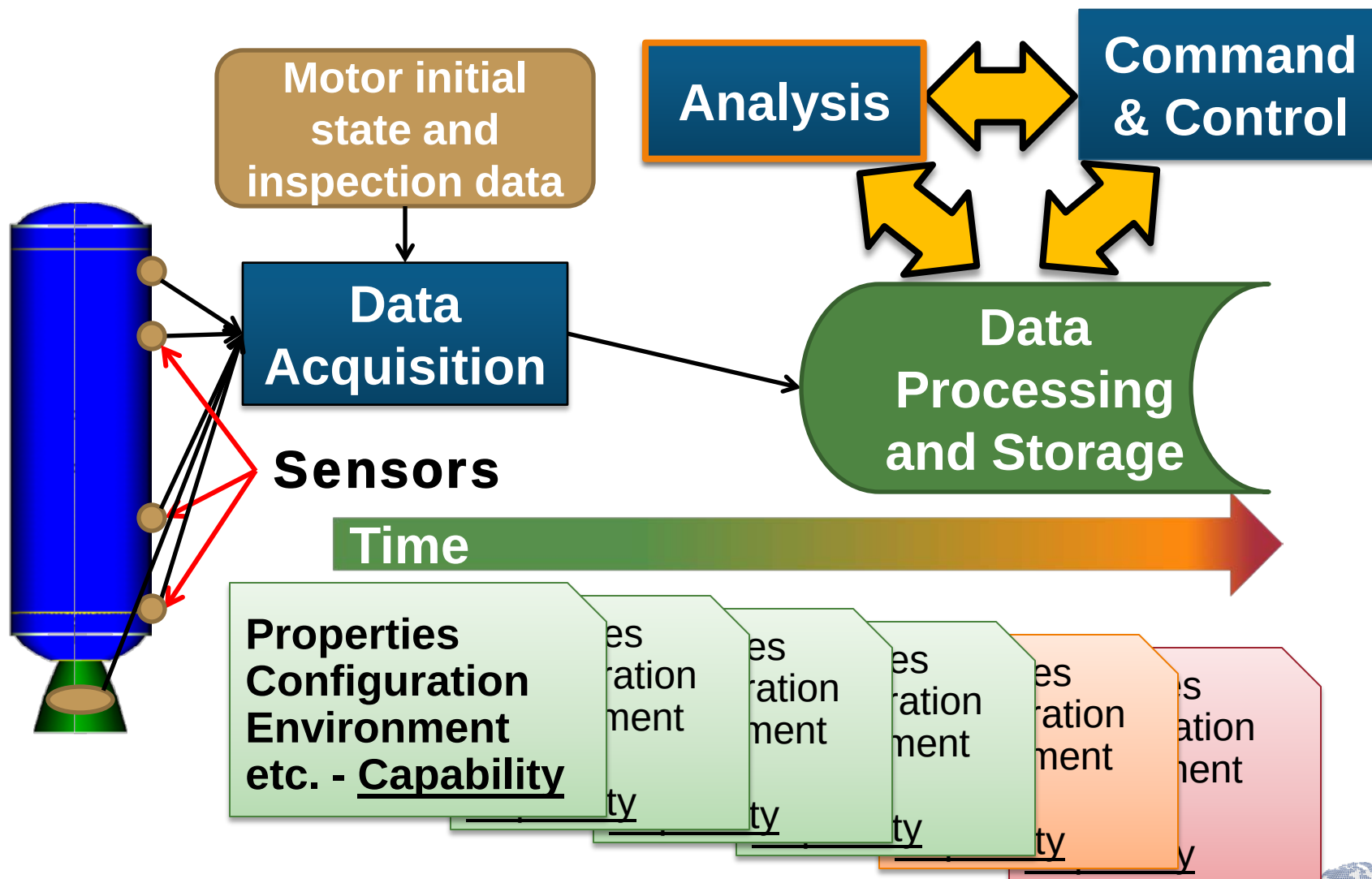


- In 1994, industry and government addressed the issue of service life prediction of rocket motors
- Consensus of the community was that the best predictions could be trusted to at most five years
- Only way to accurately improve predictions was to move to a mechanistic (first-principles) methodology
- Doubling the “look-ahead” window gives sufficient time to replace system without dramatically impacting readiness

Accurate method of predicting motor life prevents unnecessary replacement of good motors based on conservative service life predictions



AFRL Missile System A&S



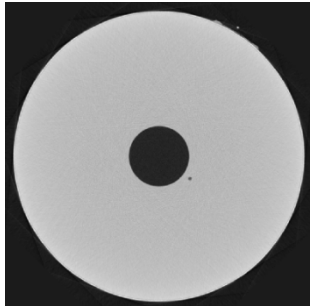


Analysis Programs Overview

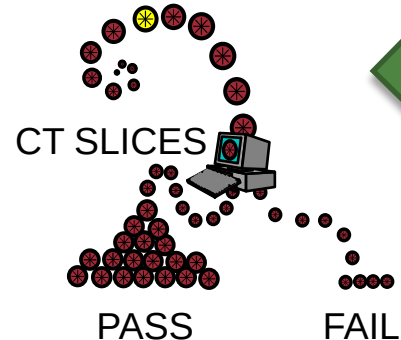


NDE Data Processing Program (1997)

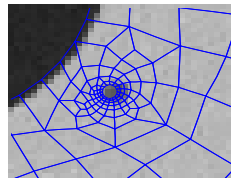
CT Flaw Detection



Automated Flaw Evaluation

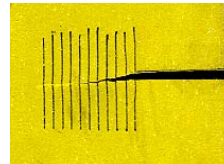


Critical Defect Assessment Program (1998)

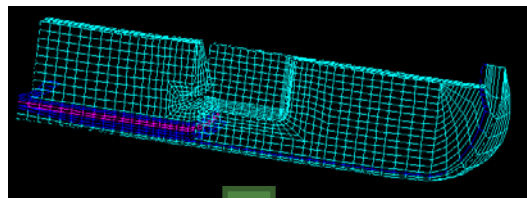


Automated 2D Flaw Meshing

Automated Fracture Propagation



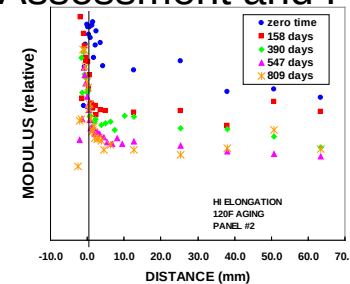
3D Structural/Ballistic Modeling



SRM Service Life Estimate

Service Life Prediction Technology Program (1997)

Chemical/Mechanical Property Assessment and Prediction

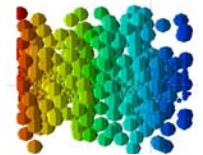


Polymer Mechanics



Nonlinear Viscoelastic Constitutive Modeling

Particle Packing

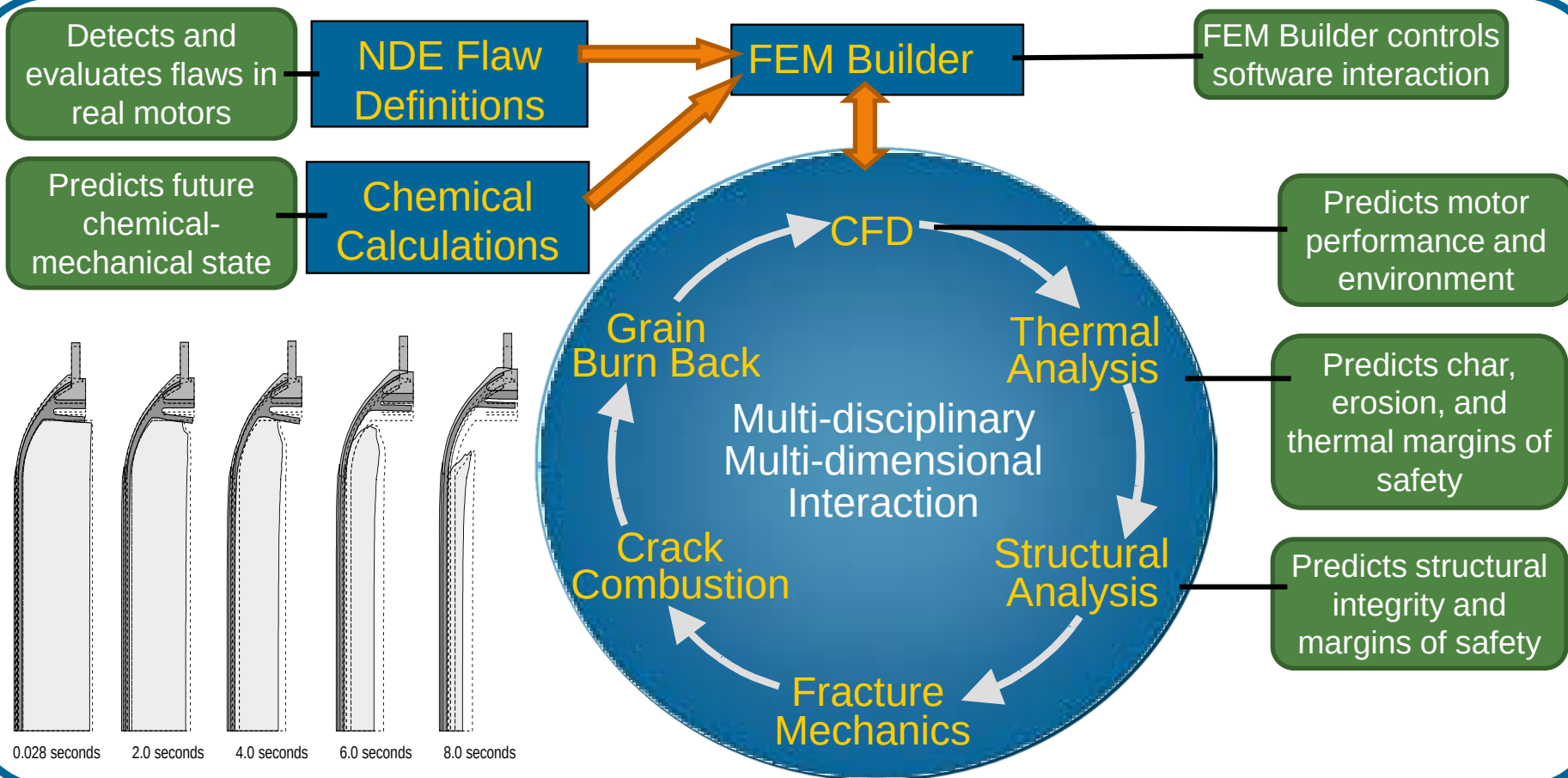


AMPT Task Order 4 (2006)

Dewetting, and multi-scale crack coalescence



Automated Multidisciplinary Solution Framework



Analysis software developed transitioned to industry — used on operational and development programs



Sensor Development



Instrumented, non-destructive life determination is the next step

Questions that must be answered:

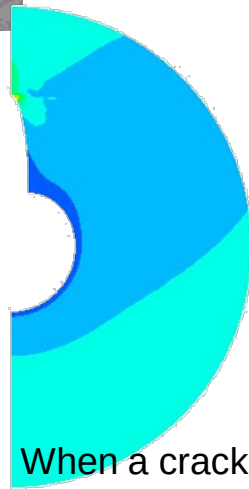
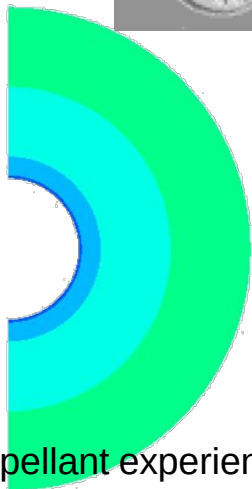
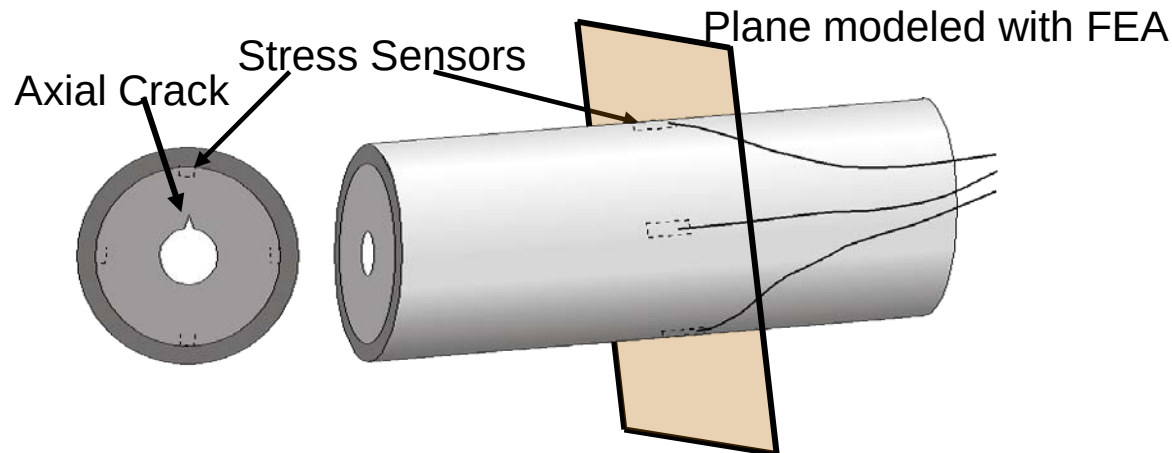
- Effects of sensor on system safety and reliability
- Sensor optimization and placement
- Data acquisition, storage, transfer, and security
- Determination of minimal set of valuable data



Sensor Number and Location Optimization

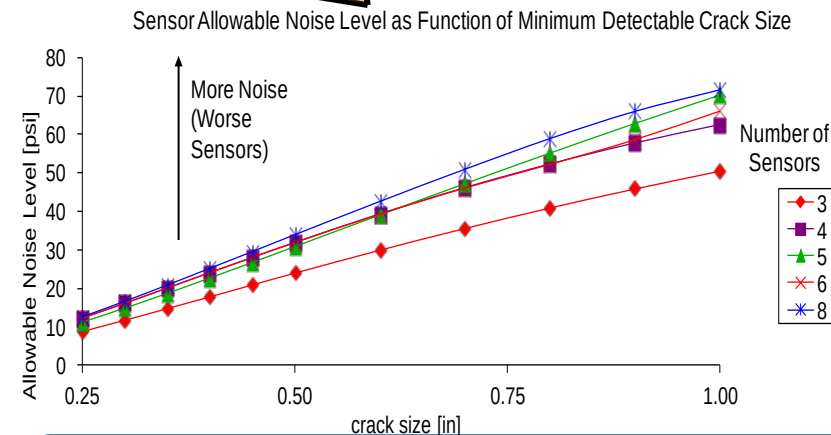


Analysis of sensor location, sensitivity requirements – Dr. Timothy Miller



Propellant experiences tensile radial stresses as it tries to pull away from the case

When a crack develops, the stresses are released near the crack.



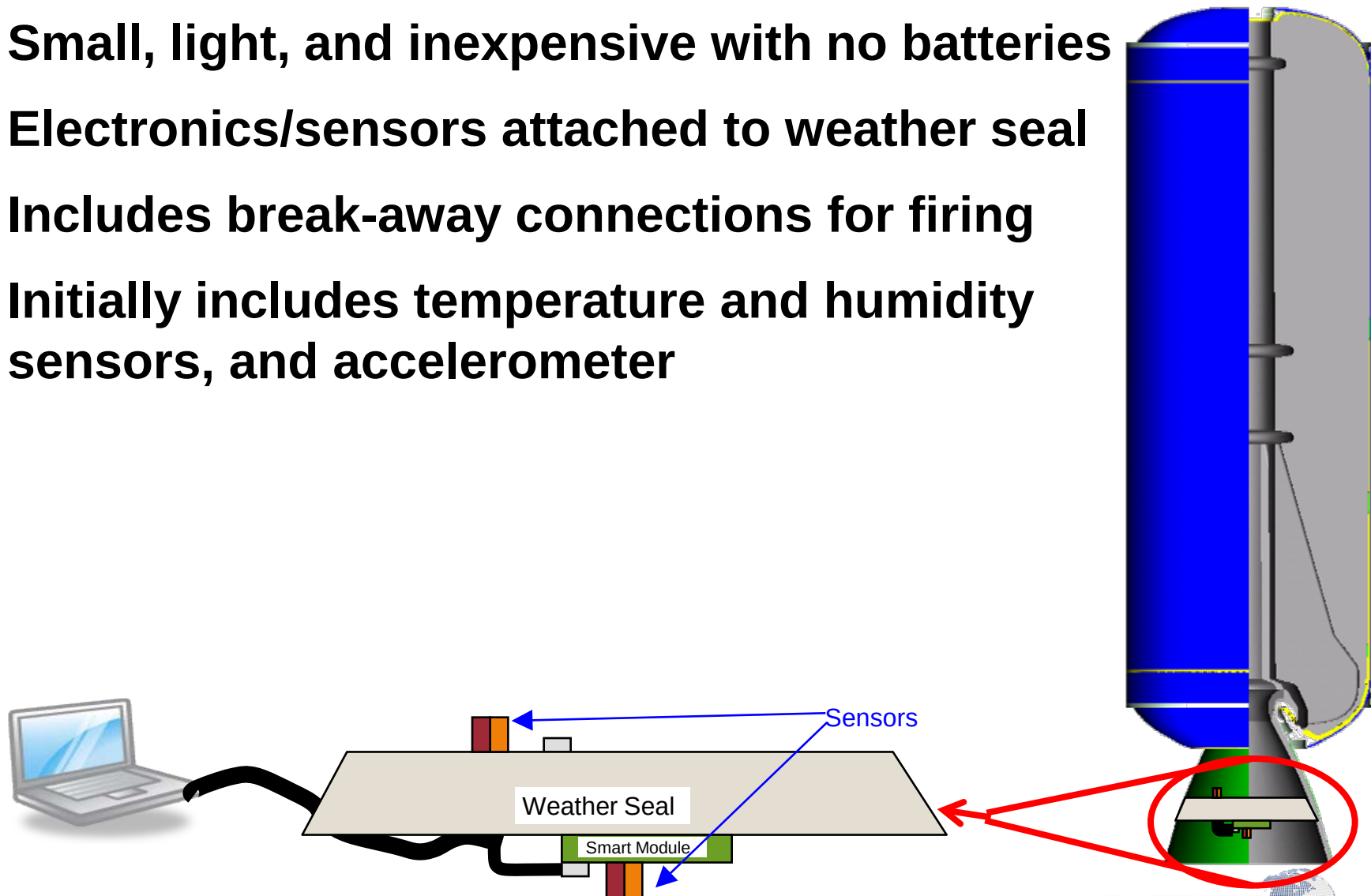
Relationship between crack size, number of sensors, sensor sensitivity



Smart Weather Seal

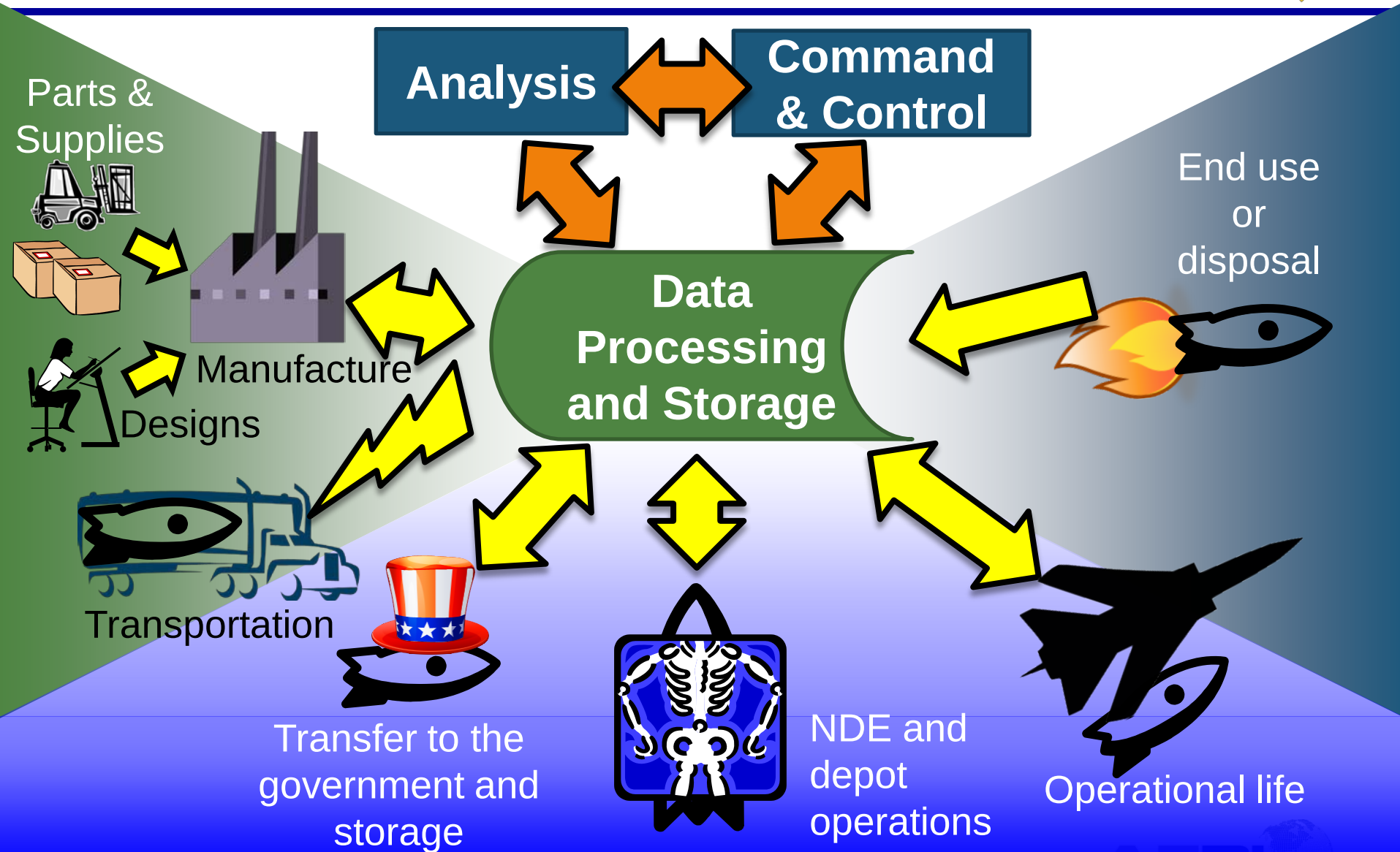


- Small, light, and inexpensive with no batteries
- Electronics/sensors attached to weather seal
- Includes break-away connections for firing
- Initially includes temperature and humidity sensors, and accelerometer





Lifecycle Data Management





Sensor Tech Needs



- **Modulus sensors:**
 - Method to determine various mechanical moduli throughout the asset
- **Chemical sensors:**
 - A method to measure the chemical changes in the PLI are driven by chemical diffusion-reaction processes
 - Field measurements would be of substantial benefit
- **Non-contact sensors**
 - Compact, transportable systems to replace depot inspections with CT, UT, X-ray, or other techniques
 - External sensors to replace embedded sensors



Analysis Tech Needs



- **Flaw behavior during operation**
 - Physics based models
 - Addition of new physics to modeling framework
- **Enhanced coupling of modeling technologies**
- **Validation Data**
 - Motor firing data
 - Physical property measurement



Summary and Conclusions



- **Solid rocket motors are a unique and challenging environment for health monitoring**
- **Current AFRL aging and surveillance effort addresses analysis, sensors, and data management**
- **Future opportunities exist in the areas of:**
 - **Advanced analysis capabilities**
 - **Validation data**
 - **Sensors**
 - **Technology integration**





Other Possible Slides

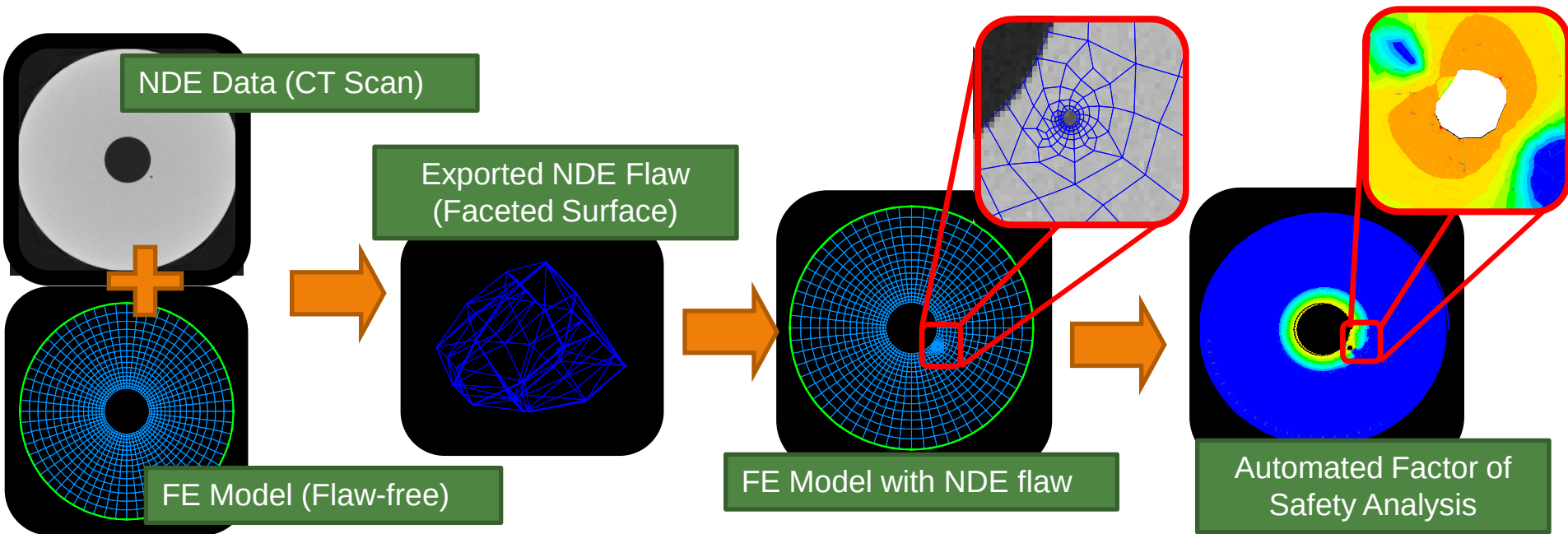




Non-Destructive Flaw Assessment



- ANDES/2 code analyzes X-ray CT scan, detects voids, inclusions, and debonds
- Flaw data automatically incorporated into existing baseline model and analyzed



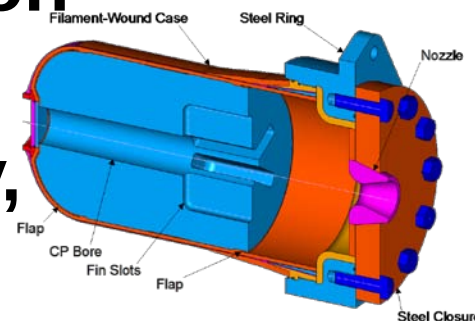
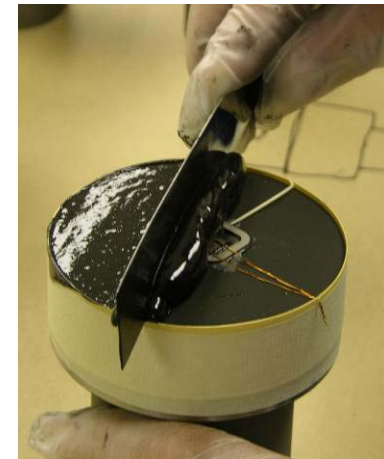
ANDES/2 in daily use for motor inspections



Sensor Application/Modeling



- Demonstrate embedded sensors in near-production environment
- Bond strength test results
 - Multiple sensors embedded in SRM liner, tested in tension and shear
 - No failures through sensors
 - No change in bond system strength
 - No damage to sensors from storage/handling
- Demonstration of bore crack detection with bondline sensors
- 10" analog motors fired successfully, stored for long-term aging study





Aging and Surveillance Relationship to Other Work



1994 SOTA

- Linear elastic constitutive model
- Uncoupled or manually coupled analyses
- 0D or 1D Fluid Mechanics
- Automated Pass/Fail of CT scanned motors
- Flaw resolution of 40 mils
- Flaws, voids, fractures input and propagated by hand
- Material aging assumed to follow Layton (logarithmic) aging law
- Maximum service life look ahead 5-years

A&S Programs Advancements

- NLVE constitutive model
- Mechanistic model for filled polymer constitutive behavior
- Coupled structures-ballistics-burnback analysis, fully 3D
- Automated coupled solution, scriptable
- Automated analysis speed increased 50x
- Flaw resolution increased
- Flaws read from CT data
- Fractures generated from continuum failure analyses
- Automated 3D fracture propagation in mesh-free mode
- Future chemical state prediction from actual chemical processes
- Material property changes from chemical/mechanical link
- Service life look-ahead 10 years with 90% reliability/90% confidence



Integrated Motor Life Management (IMLM)



- **Design a system to accurately predict the ability of a specific solid rocket motor (SRM) to perform its intended mission**
- **Task 1: Baseline the System**
 - **Identify high TRL sensors, analysis software, and other associated components necessary to deploy a prototype**
- **Task 2: Integration and Assembly of Prototype/Breadboard System**
 - **Assemble prototype/breadboard system using the proposed technologies**



Integrated Motor Life Management (IMLM)



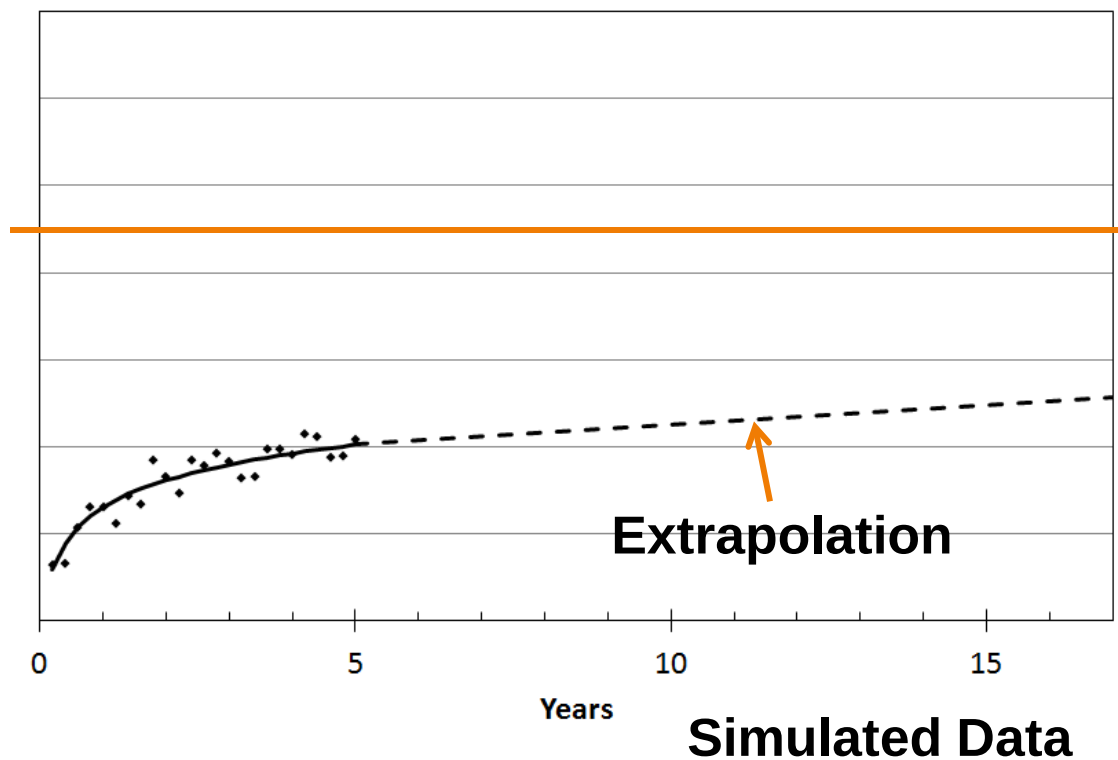
- **Task 3: Demonstrate Integrated Prototype on Motor Analogs**
 - Demonstrate integrated prototype in relevant environments at a laboratory scale – confirm system capabilities
- **Task 4: Demonstrate Integrated Prototype System in Relevant Environments**
 - Subscale motors will demonstrate all aspects of the IMLM system
 - A representative scale motor will be analyzed and monitored while manufactured, aged, transported, transferred to the government, and tested
 - True prediction of performance will be conducted



AFRL Strategic Missile A&S Approach Overview



- Empiricism cannot always predict future state
- Mechanistic method enables enhanced predictions
 - Mechanistic will not be worse than empirical approach

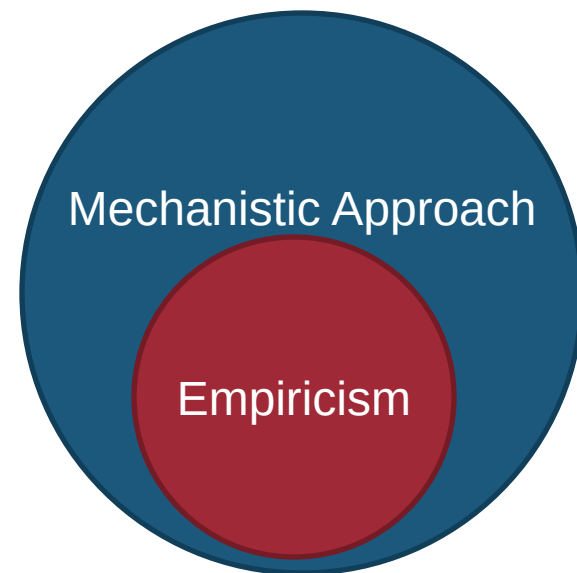
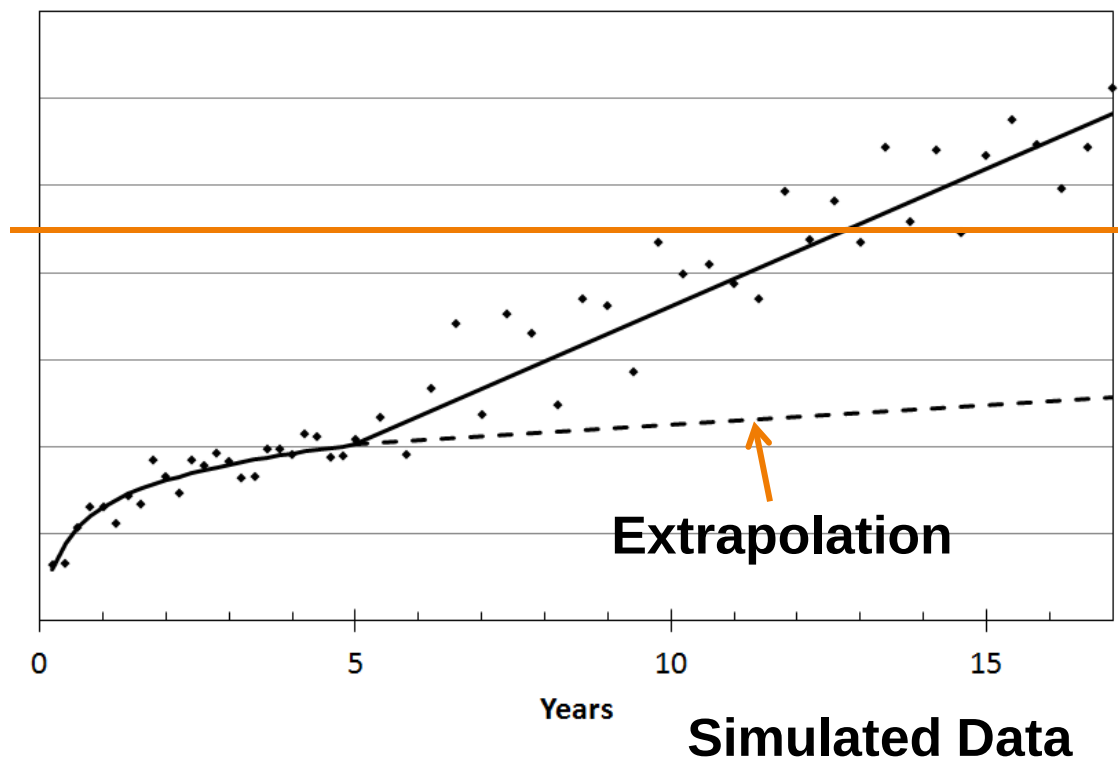




AFRL Strategic Missile A&S Approach Overview

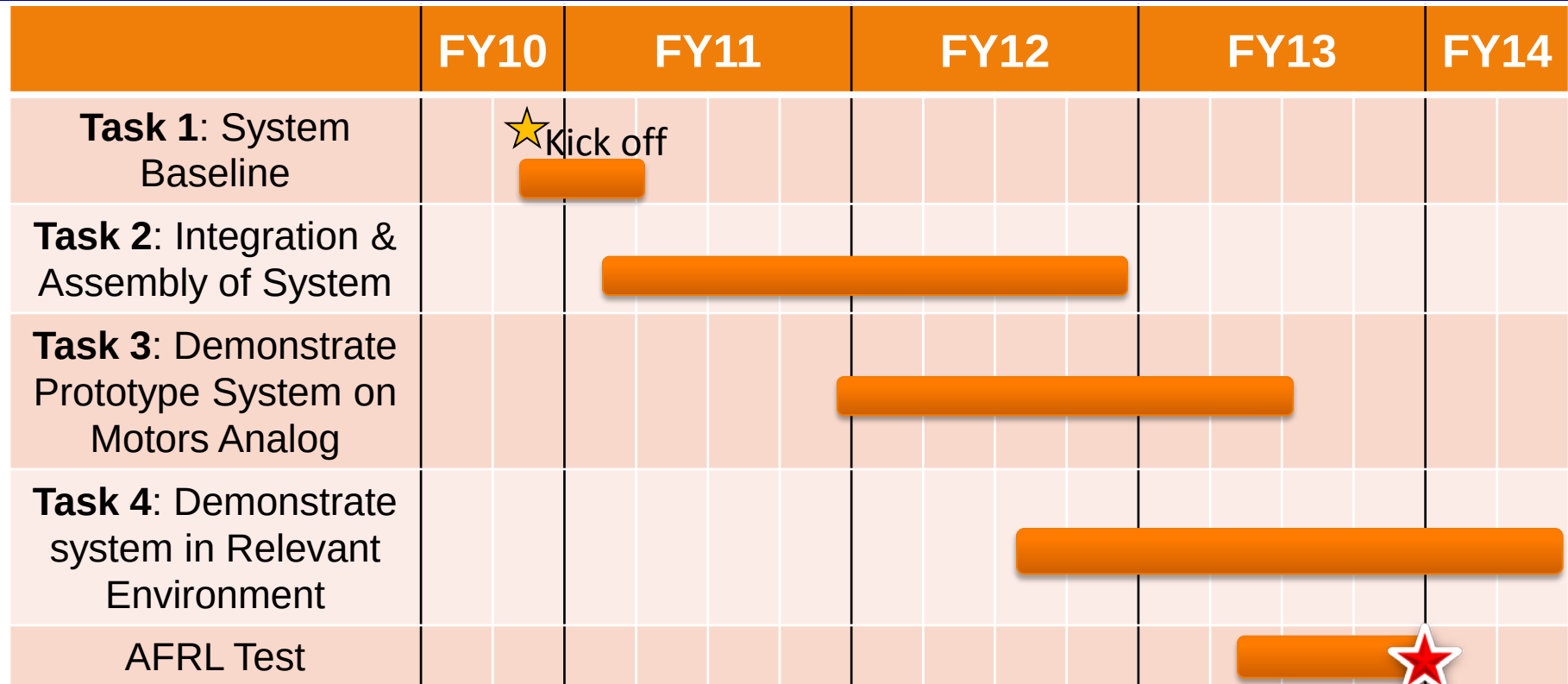


- Empiricism cannot always predict future state
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IMLM Program Schedule



Demonstrate Integrated Prototype System in Relevant Environments