Systems Approach of Energetic Materials Prognostics

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Outline

- Introduction
- Energetic Material Model
- Sensors for Energetic Systems
- Energetic Systems Prognostics – Systems Approach
- Conclusions

Unique Military Requirements

- 9 F to 120 F
Magazine Storage

- 20 F to 130 F
Transportation

- 60 F to <180 F
Field Storage

- Military Energetic System Requirements
  - Reliability
  - Safety
  - Performance
  - Harsh Conditions
    - Storage, Handling, & Use

Persistent Health Monitoring

Operation Iraqi Freedom

4 of 32 Patriots Dropped Several Feet

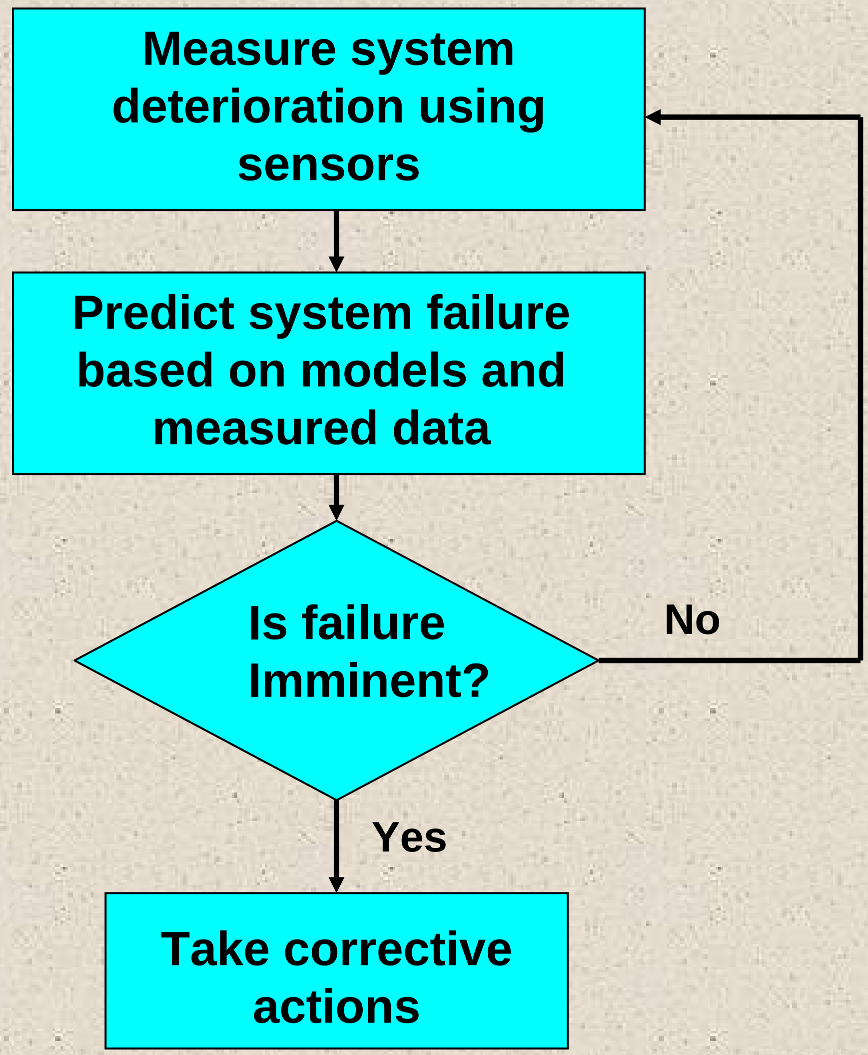
- **Unable to identify dropped assets**
- **No visible damage to outer skin**
- **Possible damage to solid grain propellants**
- **Possible damage to guidance components**

32 Missiles Out of Service
$21.9M
+
Man-hours, Handling, Shipping

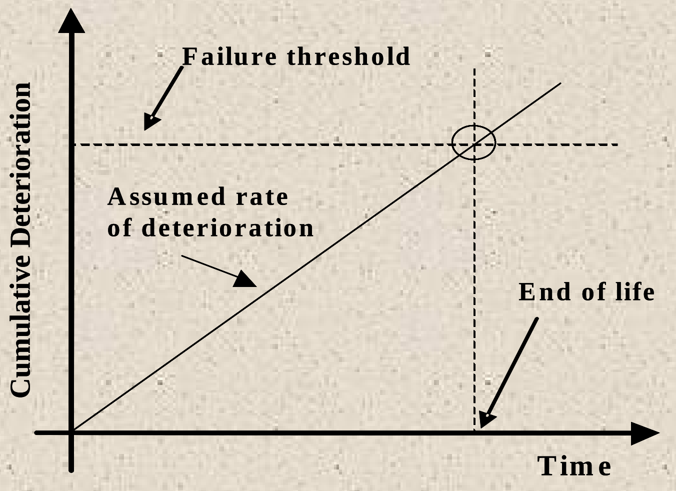
Prognostics of Energetic Materials and Systems

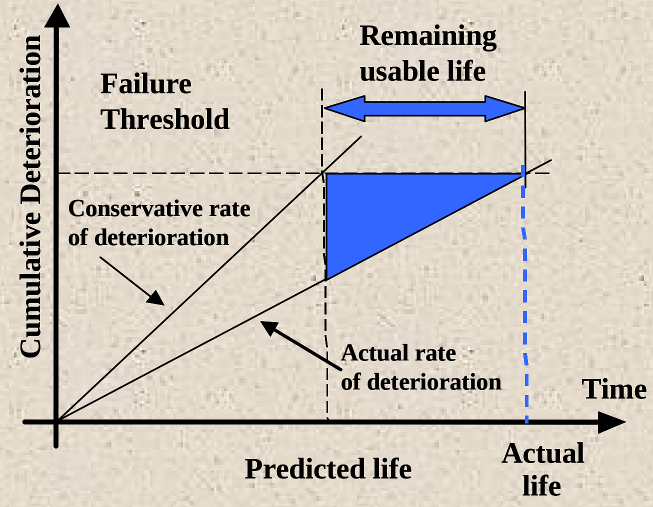
- What is Prognostics?
  - Technique of **detecting oncoming or incipient failure**, before degradation to a non-functioning condition.
    - The condition can also be a functioning condition, but one that is not within the original design or expected operational parameters.
- How is it done?
  - Sensor based persistent health monitoring of the system components
  - Use of modeling and simulation tools to predict incipient failure
  - Take preventive or corrective action

System Prognostics

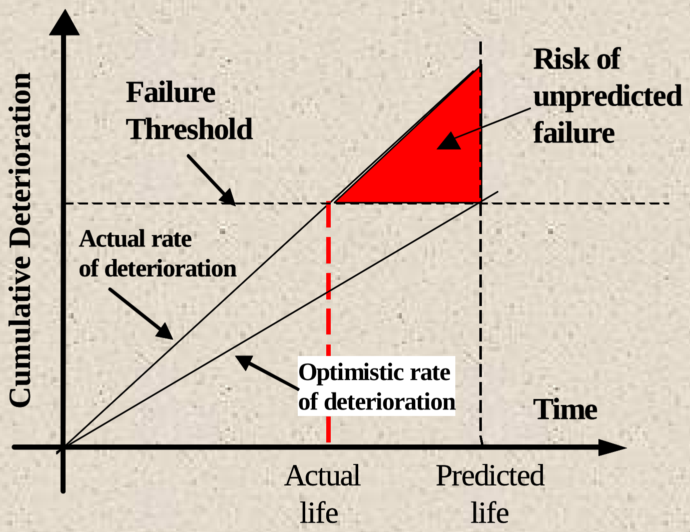


End of Life Prediction





- **Accurate End of Life Prediction can minimize**
  - **Cost**
    - ***"could save as much at 50% in costs over a 50-year life cycle"* [Ruderman, G.A]**
  - **Reduce risk**



Energetic Material Model

- Failure modes of energetics
- Empirical models
- Physics-based models

Failure Modes of Energetics

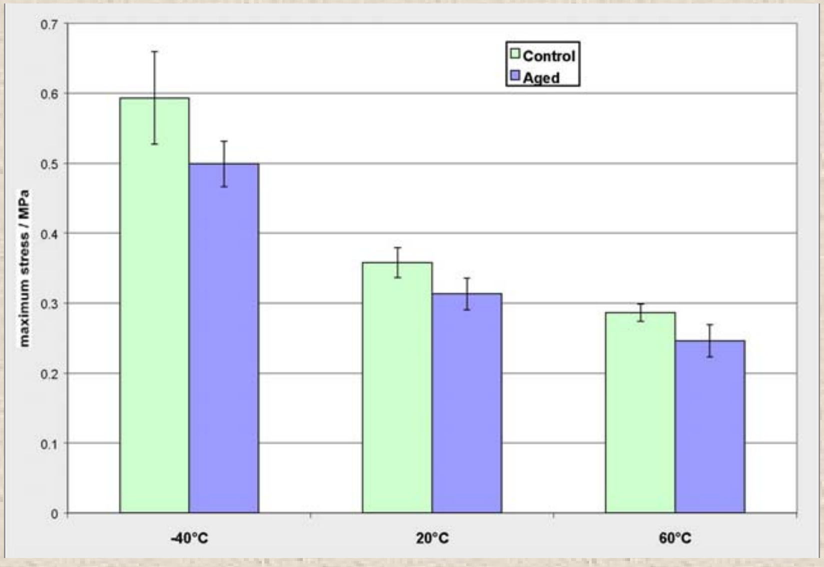
- Change of ignition sensitivity due to chemical aging
  - Cause
    - Chemical Decomposition
  - Increase in sensitivity
    - Autocatalytic ignition
    - Ignition by minor stimuli
  - Decrease in sensitivity
    - Failure to ignite in operation

- Crack formation & debonding
  - Cause
    - Thermally induced stress
    - Shock or vibration loading induced by handling/transit
  - Increase in burn surface area
    - Rocket motor pressure vessel rupture in operation
  - Increase in sensitivity

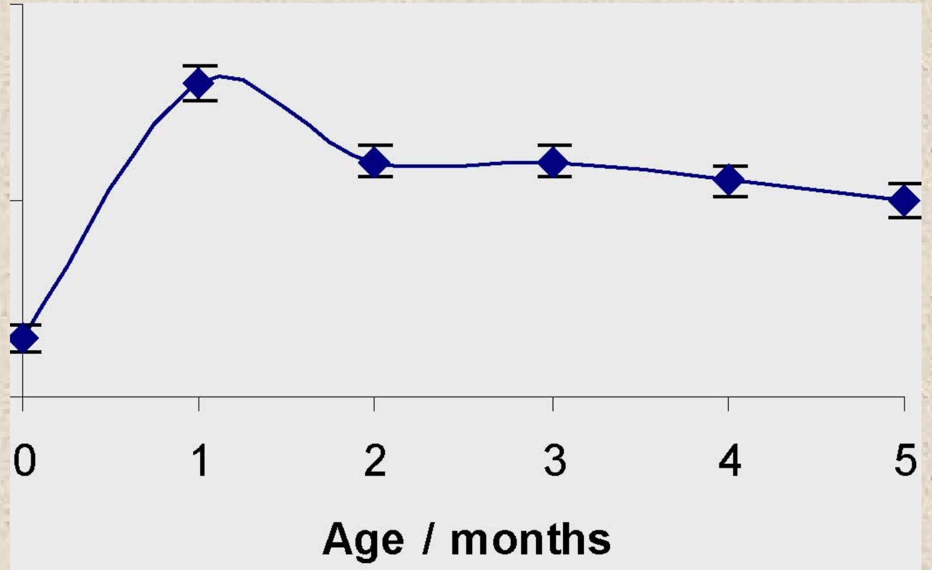
Current Methods of Health Monitoring

- Periodic Testing of Samples From Fleet
  - Performance verification test
    - If samples perform nominally, the remaining life of the fleet deemed viable
    - If not, the entire fleet may be discarded
  - Mechanical and Chemical Property Characterization
    - Laboratory testing
      - modulus of elasticity
      - relaxation modulus
      - material strength

Mechanical Property Measurements



Maximum Stress Level
vs Temperature



Max Failure Load vs Aging

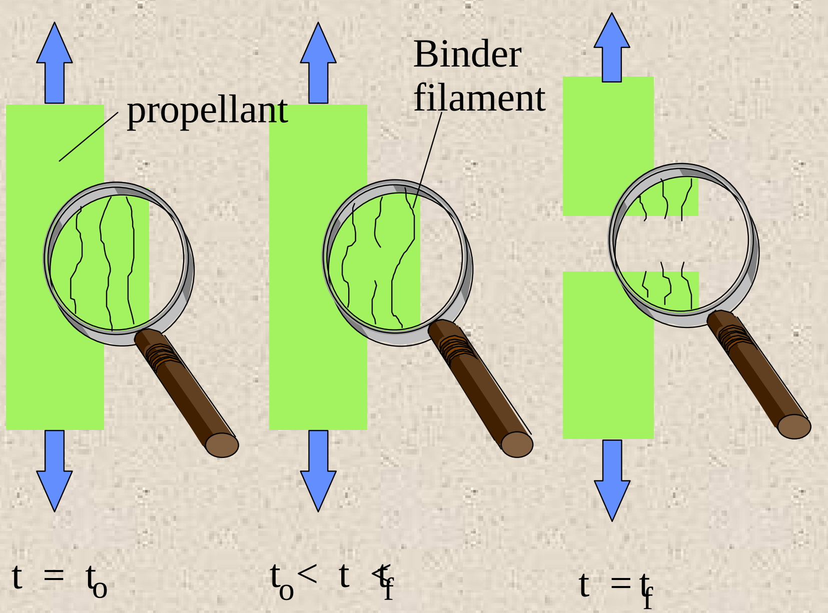
Empirical Models

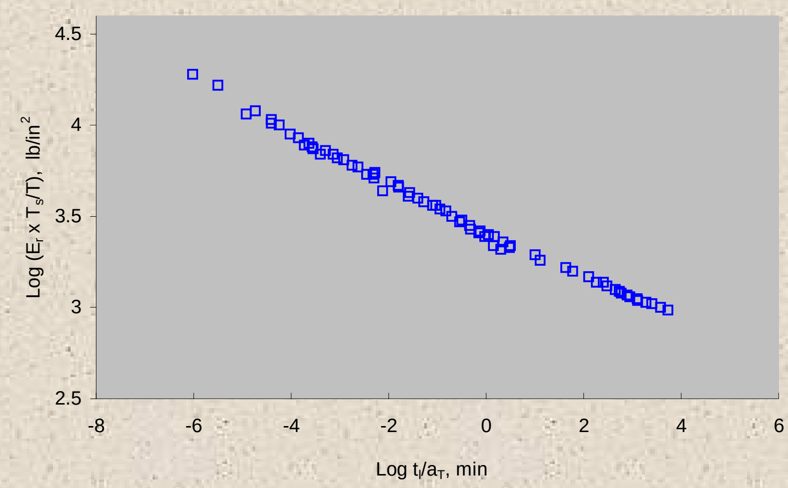
- Model Development
  - Cumulative Damage Model
    - Biggs
  - Kinetic rate correlated mechanical property
    - Craven, Rast, McDonald
  - Others
    - Wiegand, Cheese, etc.

- Advantages
  - With enough test data, validated models can be developed in near term.

- Disadvantages
  - Rely on samples
    - Expensive
    - Hazardous
    - Accelerated aging may not be accurate
    - Applicable to specific formulation/batch

Cumulative Damage Model





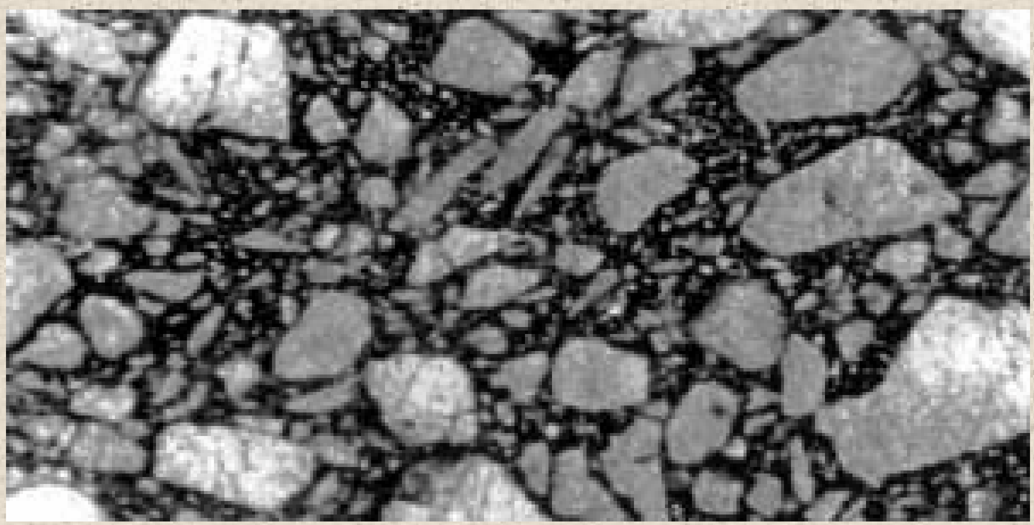
- **Micro-structural failure of the propellant matrix. After some time, *t,* some of the polymeric microstructure has failed. At time *tf*, all of the matrix filaments have failed and a macro-structural failure has occurred.**

Solid propellant relaxation modulus versus reduced time (Log *t//aT*)

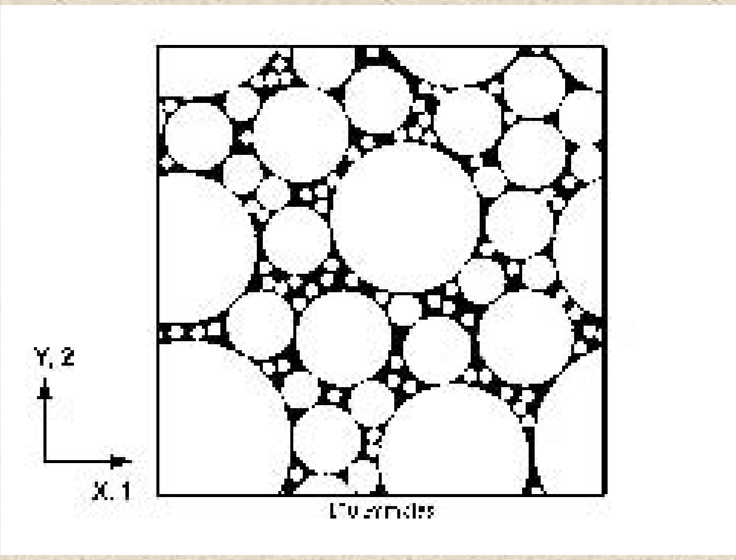
Physics-Based Models

- Model Development
  - Van Duin
  - Brenner
  - Stuart
  - Banerjee
- Advantages
  - Comprehensive characterization of energetic material possible
  - Easier to extend one model to another formulation
  - May provide more accurate methods of accelerated aging
  - May lead to development of new types of sensors for health monitoring
- Disadvantages
  - Computationally expensive
    - Difficulties in modeling composite energetic material:
      - PBX, composite propellants
  - May still need some sample test data

Modeling Composite Material



Micrograph of PBX



Simulated PBX 9501 microstructure

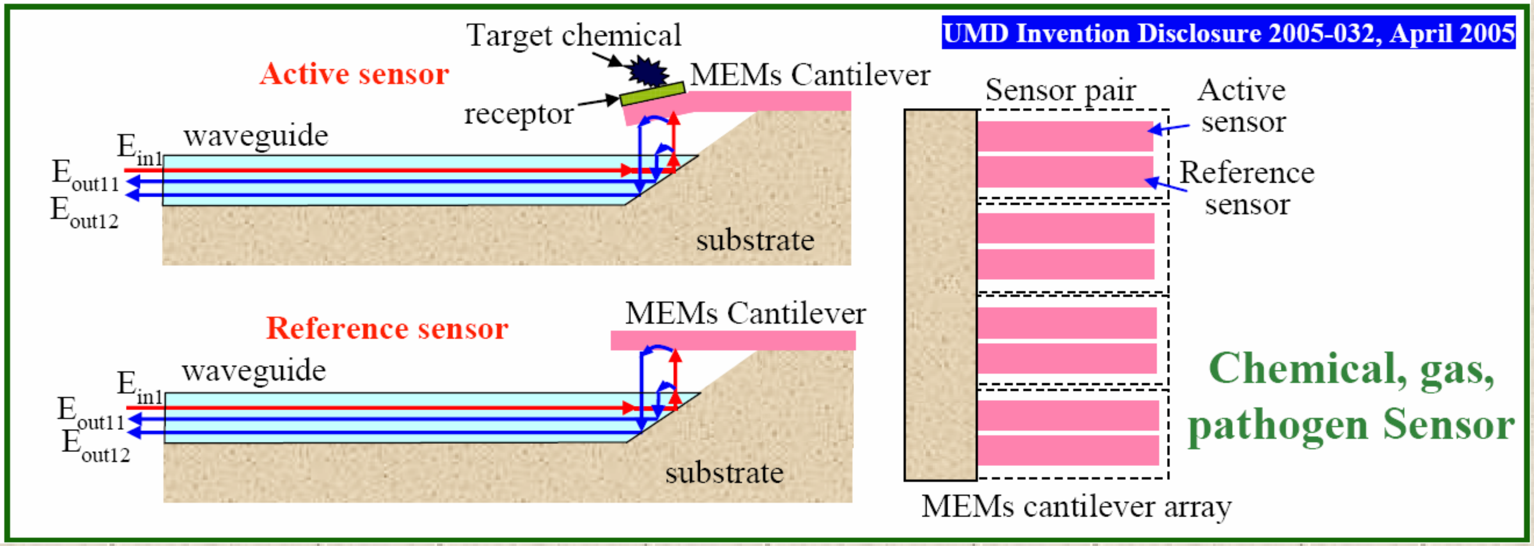
Health Monitoring Sensors

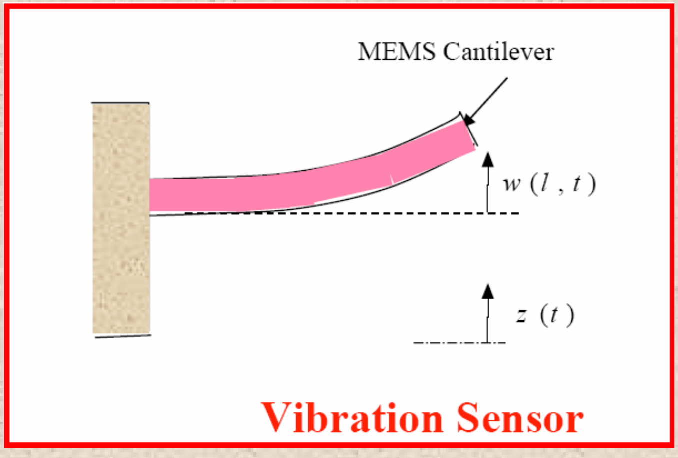
- Embedded Sensors
  - Advantages
    - Can provide direct measurements of energetic material property
    - Sensors would experience near identical loads energetic material receives
  - Disadvantages
    - May influence the material property the sensor is meant to measure
    - May create failure initiation sites if not properly designed and installed
  - Examples
    - Bond-line sensors using embedded diaphragm
    - Bragg-grating fiber optic strain sensor

Health Monitoring Sensors

- External Sensors
  - Advantages
    - Minimally invasive to energetic systems
    - Detachable sensor package possible
  - Disadvantages
    - Does not provide direct measurement of material property
    - May not experience the exact loads energetic materials would experience
  - Example
    - Thermal sensors with RFID
      - Advanced Technology Ordinance Surveillance (ATOS)

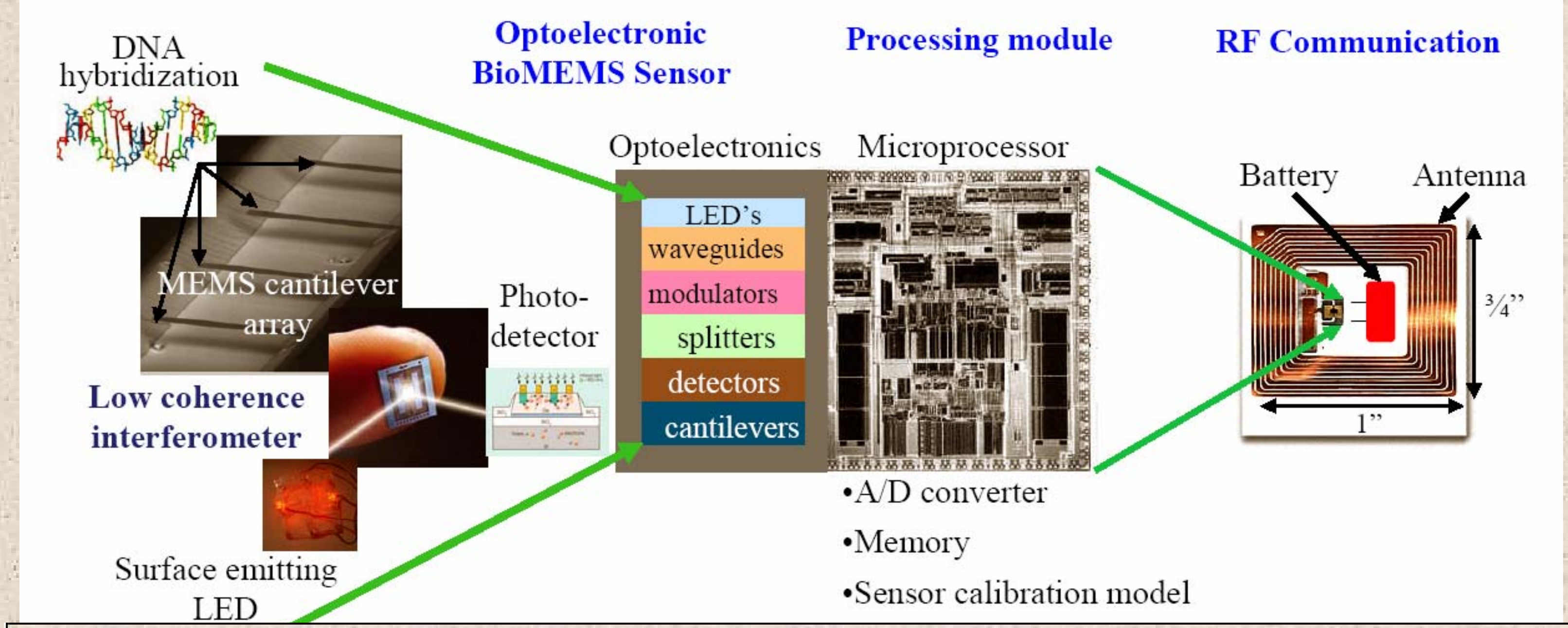
Low Coherence Interferometer Sensor

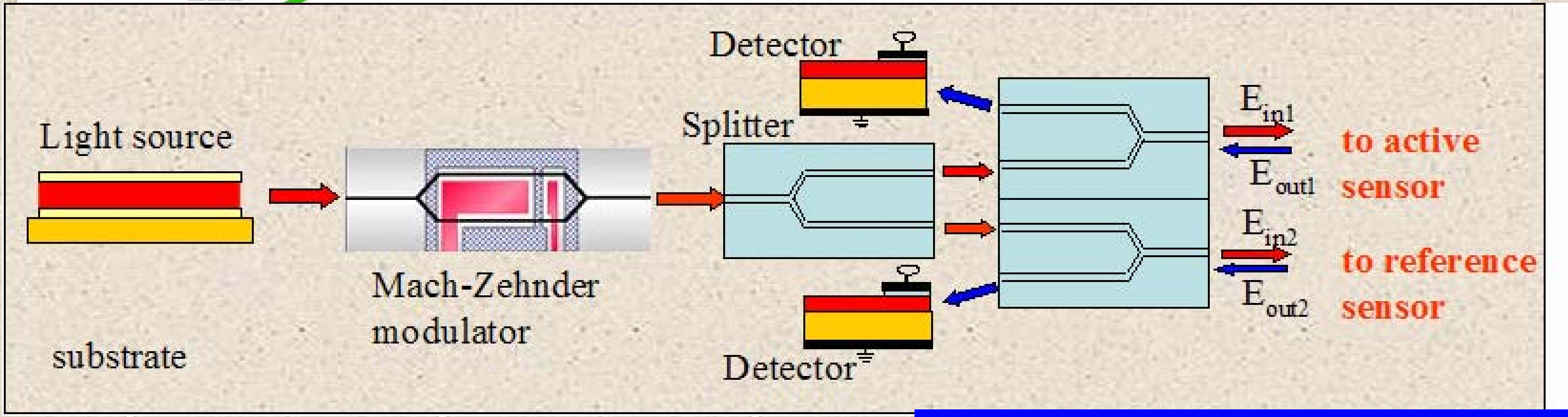




Opto-Electronic MEMS Sensor Chip

Multifunctional OE-MEMS Sensor Chip





UMD Invention Disclosure 2005-032, April 2005

Health Monitoring Sensors

- Canaries
  - Advantages
    - Can predict impending failure in a direct manner
    - Can be applied to legacy systems
    - Detachable packet
  - Disadvantages
    - Difficult to find material with similar properties
    - Requires package design tailored to weapon systems to receive equivalent loads

Systems Approach to Energetic Prognostics

- System Failure / Risk Analysis
  - Determine high risk components
  - Conduct Return On Investment (ROI) of Component Prognostics
- Failure Models Development
  - Imperical models
  - Physics based models
  - Model validation
- Sensor Deployment
  - In-situ sensors
  - External sensors
- Sensor Network
  - RFID
- Decision Making Algorithm

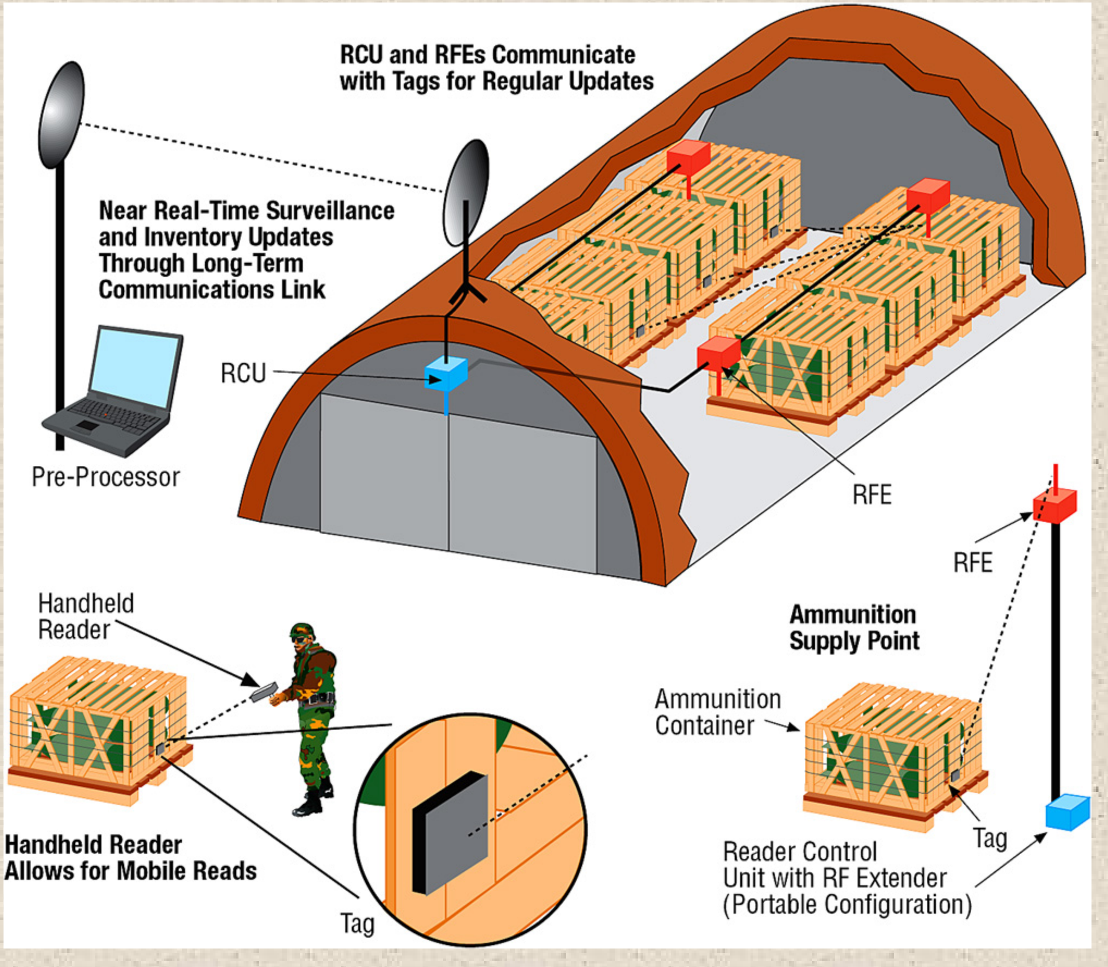
Advanced Technology Ordinance Surveillance (ATOS)

No Infrastructure or Business Process Server.

Benefits can be realized with only HHR and tags.

RCU can be powered by external 24V source – I.e. humvee.

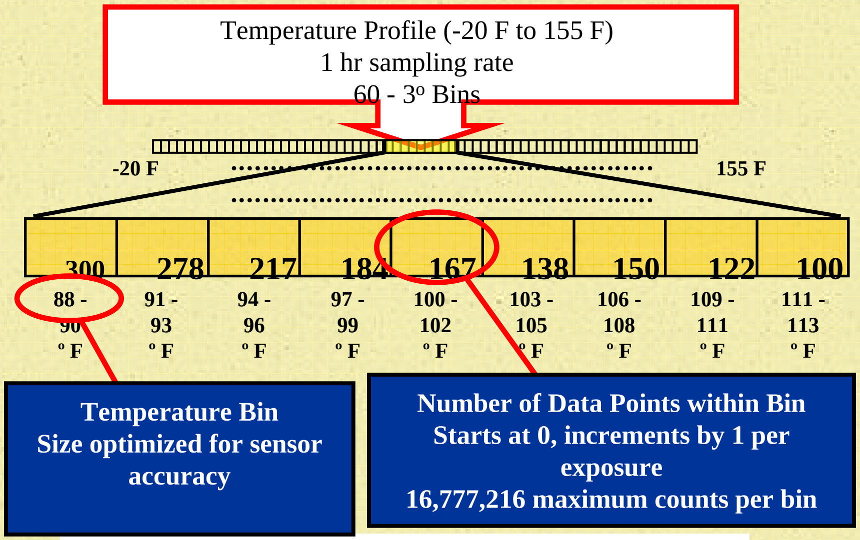
RCU to HHR upload capability.

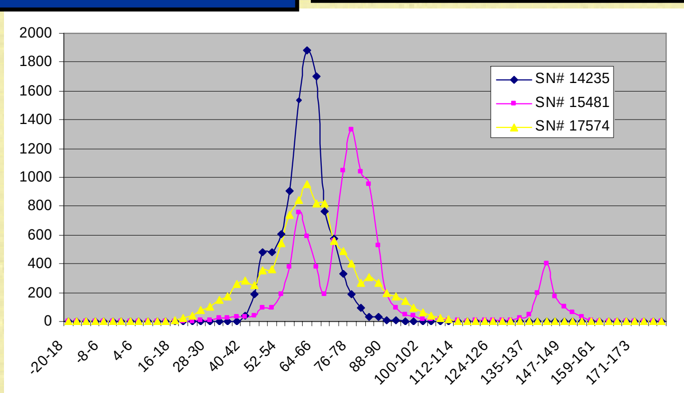


__No__ Separate Business Process Server or infrastructure required!

ATOS

Histogram Data





Serial Data

NSN XXXX-XX-XXX-XXXX Lot#

Tag ID #	Serial#	Date	Temperature Profile Data
00001	14235	0800 hrs, 08/13/01	
00002	14236	1650 hrs, 08/16/01	
00004	15480	0800 hrs, 08/13/01	
00003	15481	1400 hrs, 08/16/01	
00005	15482	1400 hrs, 08/16/01	
00006	15483	0800 hrs, 08/13/01	
00007	16124	0800 hrs, 08/13/01	
00008	16125	0800 hrs, 08/13/01	
00009	17574	1400 hrs, 08/16/01	
00010	17575	1400 hrs, 08/16/01	

$$D = \frac{1}{\left(\sigma(t_0) - \sigma(t_\infty)\right)^\beta \cdot t_0 \cdot a_T} \cdot \int_0^t \left(\sigma(t') - \sigma(t_\infty)\right)^\beta dt'$$

t = time at constant stress

t_0 = reference time

t_∞ = threshold time - no failures occu

a_T = shift factor

σ = true stress

Environmental Data

Strategy for Developing Energetic System Prognostics

- Investment Priorities
  - Short Term
    - Canaries
    - Validated empirical model
    - External sensor and external sensor-material interaction model development
  - Long Term
    - Physics-based model development
    - In-situ sensor development
    - Inverse technique/embedded sensor based health monitoring

Conclusions

- U.S. Military and weapons industries need to find ways to to make the current energetic systems more cost effective and dependable.
  - ***"the right capability for the right cost"*** ("Navy Strategic Plan" by Chief of Naval Operations)
- The method of prognostics can lead to
  - substantial savings in replacement costs
  - highly reliable energetic systems
- Continuous health monitoring not yet possible with current tools.
- Significant investment needed to develop
  - validated models
  - un-intrusive embedded sensors