MECHANISTIC AGING AND SURVEILLANCE OF WARHEAD ENERGETIC MATERIALS

Dr. I. Lee Davis and Dr. Robert Hatch
ATK Aerospace Group
(435) 863-3562, Lee.Davis@ATK.com

October 7-10, 2013

NDIA IMEM Technology Symposium, San Diego, CA

Distribution Statement A: Approved for public release; distribution is unlimited






Outline

Background

Aging effects on warhead performance and safety

Mechanistic versus empirical aging models

Three phases of mechanistic aging predictions

Material analysis tools

Mechanistic and mathematical models

Statistical service life predictions

Background

A known service life of a weapon system is critical to

- Protect the warfighter from catastrophic failure of the weapon
- Maintain a known engagement capability
- Manage, maintain, and enhance defense readiness

Aging and surveillance (A&S) and service life prediction is a recognized requirement of solid rocket motors

- ATK has conducted more than 30 aging and surveillance studies on rocket motors and other munitions for a number of countries and organizations
- A dedicated organization is in place at ATK for this purpose

Less emphasis has been placed on aging and surveillance in warheads

- Not as many catastrophic failure mechanisms as with solid rocket motors
- Nevertheless, many aging mechanism exist to degrade the reliability and/or the IM performance of warheads

Some Aging Effects on Explosives

Decomposition of energetic plasticizers, binders, and solids

- Runaway thermal reactions in warm environments
- Stabilizer depletion in energetic plasticizers and binders is a particular concern
- Void formation for increased shock sensitivity

Plasticizer migration from main explosive fill

- Hardening may enhance sensitivity to impact events
- Migration to booster may desensitize booster
- Shrinkage of explosive fill may create gaps that hinder initiation or increase setback sensitivity in gun launched explosives

Binder hardening due to oxidative crosslinking

- May enhance impact sensitivity and damage from handling

Some Aging Effects on Explosives (cont)

Possible effects of environmental temperature cycling

- Phase changes can cause growth and/or damage (voids)
- Changing solubility of energetic solids in binder may cause growth of energetic particles and increase shock sensitivity

Possible effects of environmental moisture

- Unwanted desensitization of explosives
- Hydrolytic degradation of binder
- Growth of explosive fill

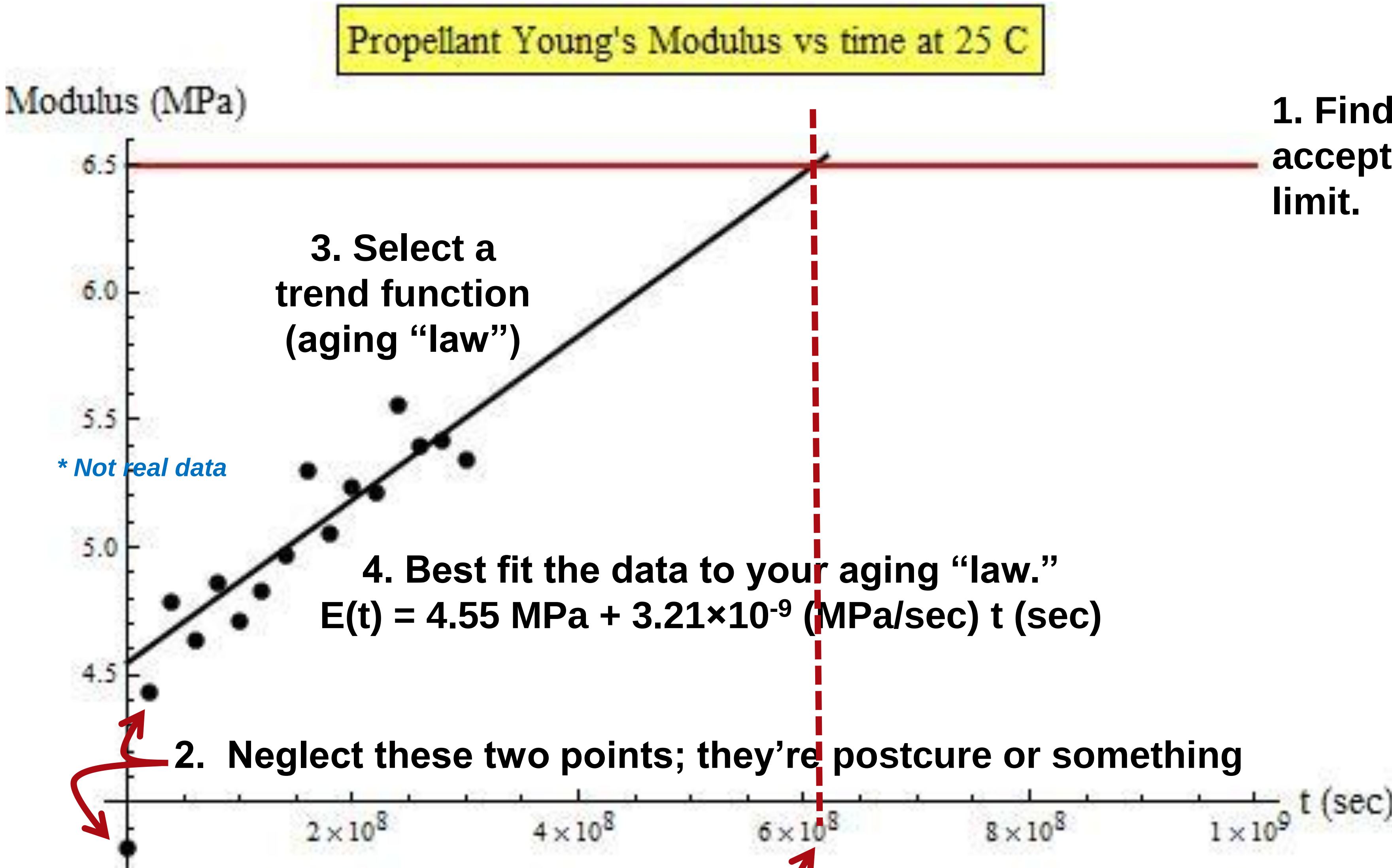
Aging effects on warheads can include IM sensitivity, safety, and reliability

Mechanistic Versus Empirical Aging Programs

The key difference between mechanistic and empirical aging and surveillance programs:

MECHANISMS OF CAUSALITY

Steps for Empirical Service Life Estimate (SLE)*



1. Find the acceptable limit.

2. Neglect these two points; they're postcure or something

3. Select a trend function (aging "law")

4. Best fit the data to your aging "law."

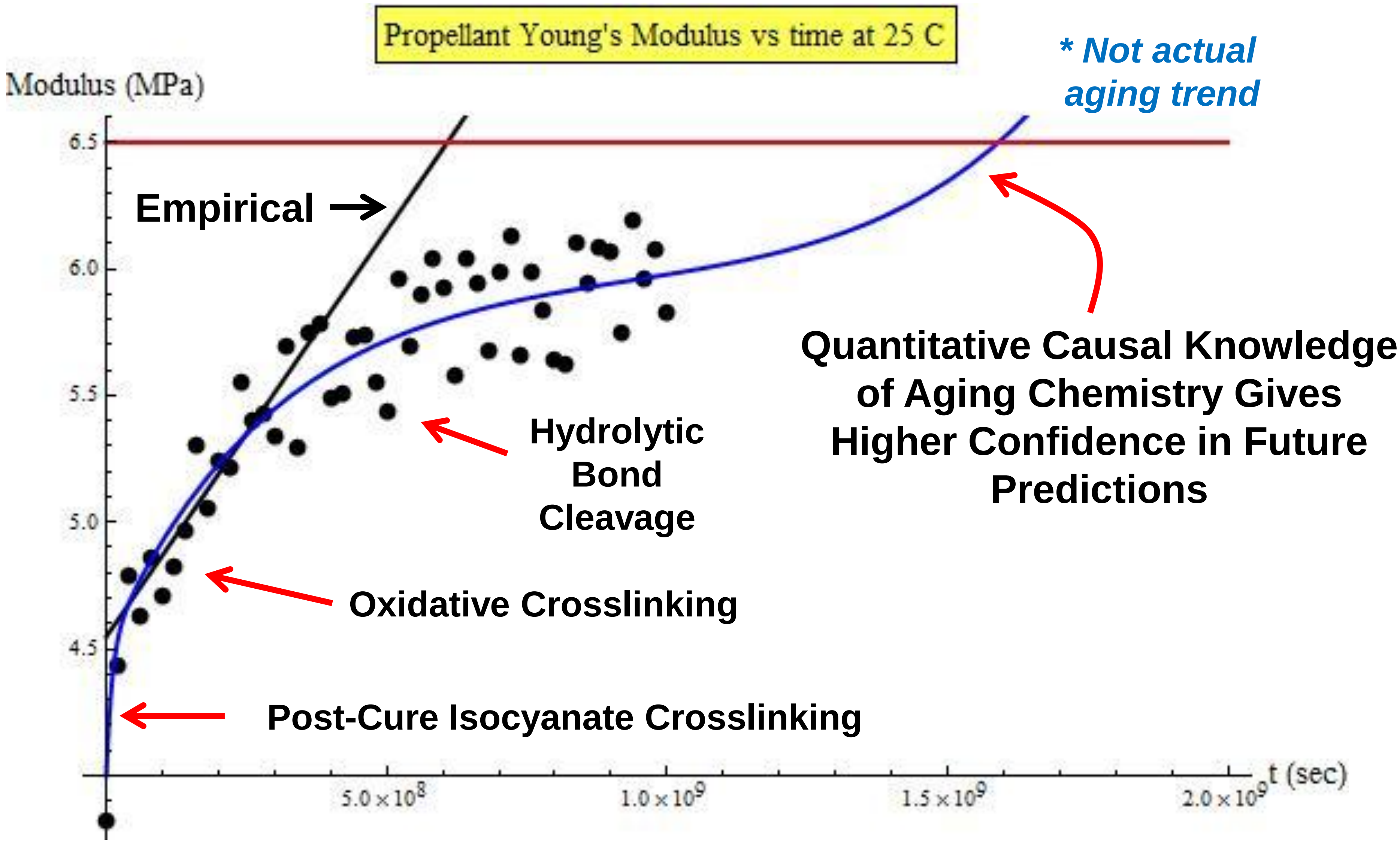
$E(t) = 4.55$ MPa + 3.21×10^{-9} (MPa/sec) t (sec)

5. SLE where trend crosses limit

** Not real data*

Distribution Statement A: Approved for public release; distribution is unlimited

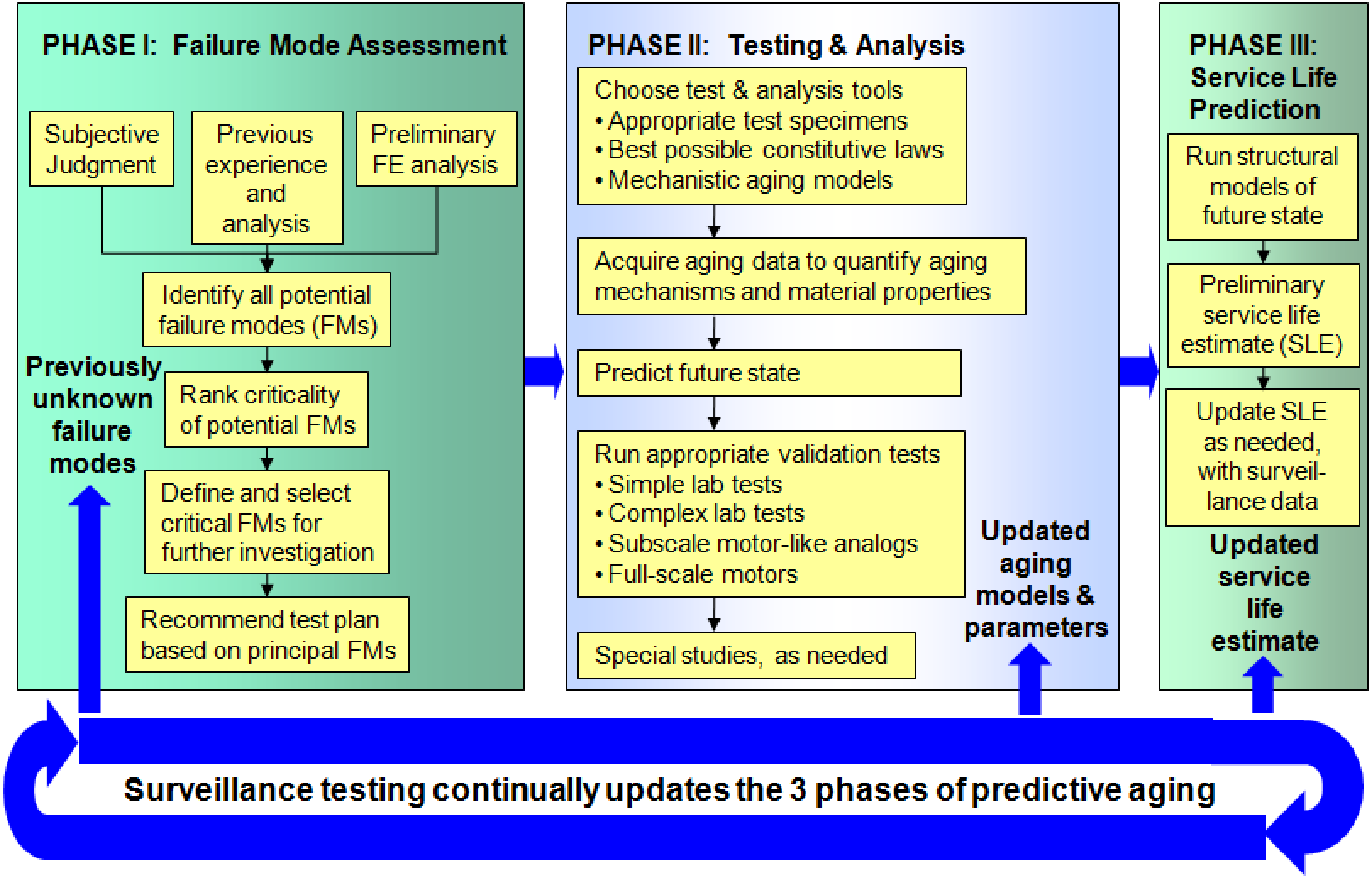
Mechanistic Models Predict into the Future*



** Not actual aging trend*

Distribution Statement A: Approved for public release; distribution is unlimited

Three Phases of Mechanistic Service-Life



Analysis Tools

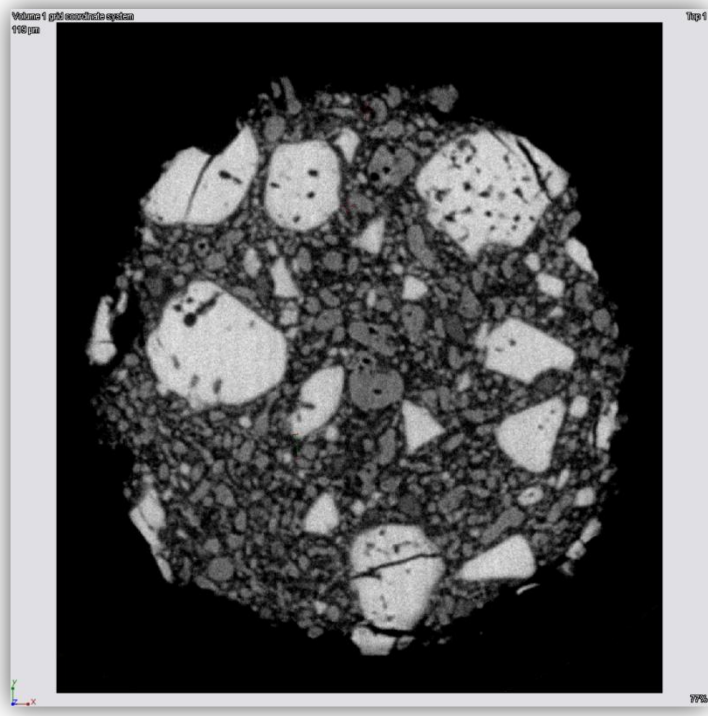
X-ray (gaps in full scale article and voids in energetic material)

Ultrasonics (gaps in full scale article and voids in energetic material)

Full-scale article dissection

High-spatial-resolution analysis of energetic materials

- Micro X-ray tomography (micro voids and damage)
- Mechanical properties
- Chemical Analysis

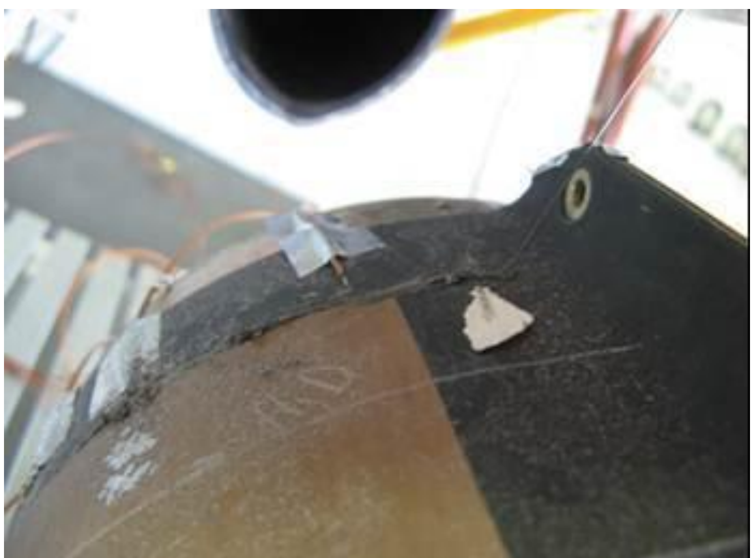


Micro-CT Image

Dissection/Fabrication Tools

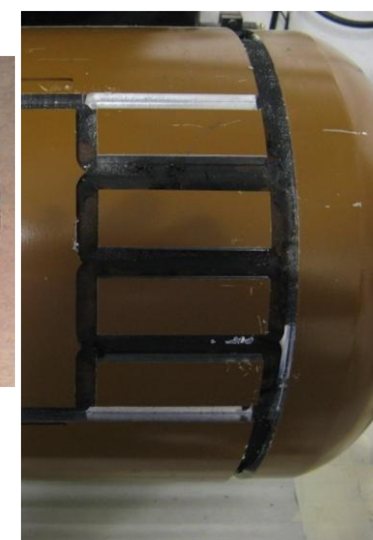
- **2 diamond-wire saws (7” and 18”)**
- **Electro-chemical milling**
  - **Steel**
  - **Aluminum**
  - **Titanium**
- **Milling & lathe cuts**
- **Ban saw cuts**
- **Plugging motors**
- **Grit-blasting (not used much)**
- **Water-jet (not used much)**

Cross-sectional and axial dissections (or anything in between)



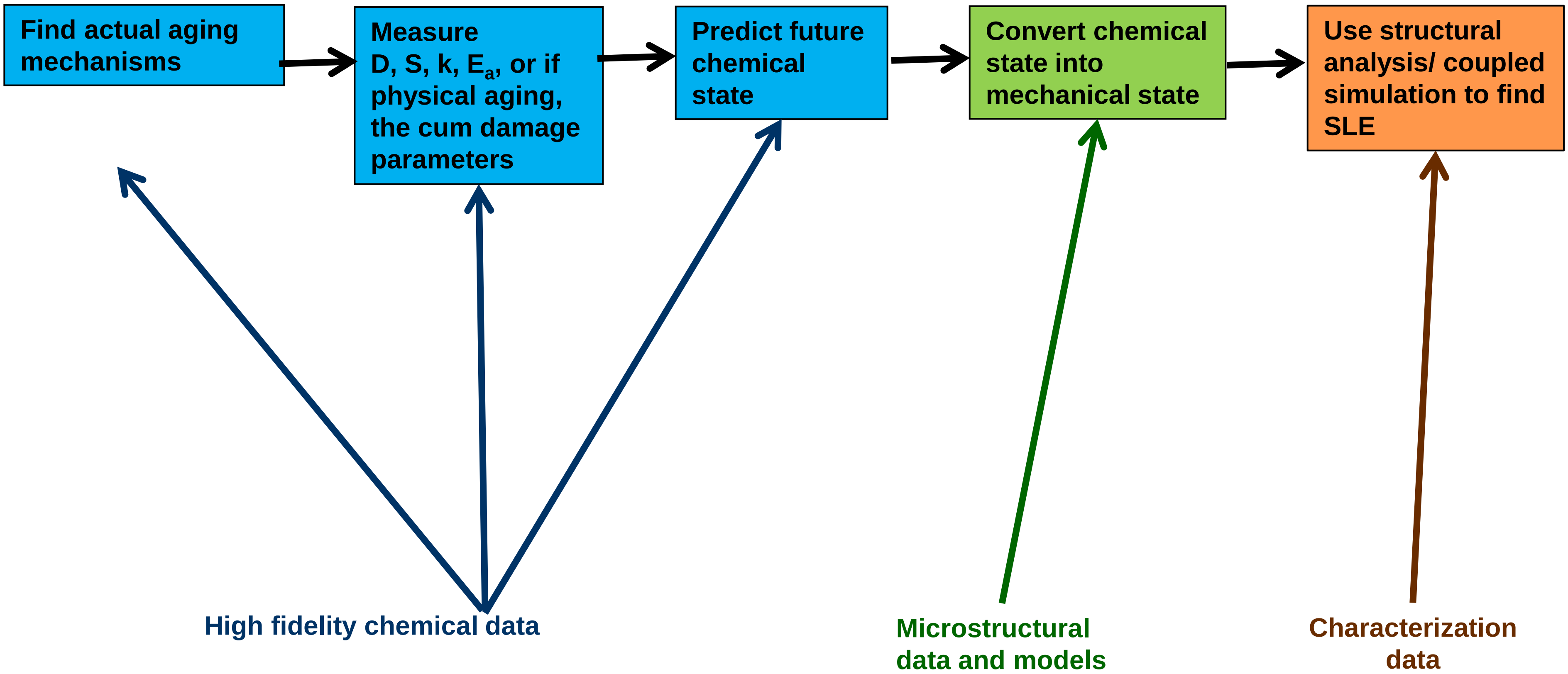
Diamond-wire saw

Electro-chemical milling



Distribution Statement A: Approved for public release; distribution is unlimited

The Heart of Mechanistic A&S: The Predictive Train



Reduce/eliminate empiricism by making sure each model can trace its pedigree to universal law (e.g., Newtonian mechanics, thermodynamics & statistical mechanics, quantum mechanics, etc.)

Example Chemical Aging Mechanisms

Chemical aging mechanisms are ultimately a set of coupled differential equations. Solve with chemical kinetics/diffusion solvers in 1D, 2D, 3D.

1. Plasticizer diffusion

$$\frac{\partial[P]}{\partial t} = D(P)\frac{\partial^2[P]}{\partial x^2}$$

2. Ester hydrolysis

$$\frac{\partial[H_3O^+]}{\partial t} = D(H_2O)\frac{\partial^2[H_2O]}{\partial x^2} - k_{hyd}[eXLD][H_3O^+]$$

$$\frac{d[eXLD]}{dt} = -k_{hyd}[eXLD][H_3O^+]$$

3. Oxidative cross-linking

$$\frac{d[SS]}{dt} = -k_1[SS][O_2]$$

$$\frac{d[V*]}{dt} = k_1[SS][O_2] - k_2[AO][V*] - k_3[V*]^2$$

$$\frac{d[O_2]}{dt} = D(O_2)\frac{\partial^2[O_2]}{\partial x^2} - k_1[SS][O_2]$$

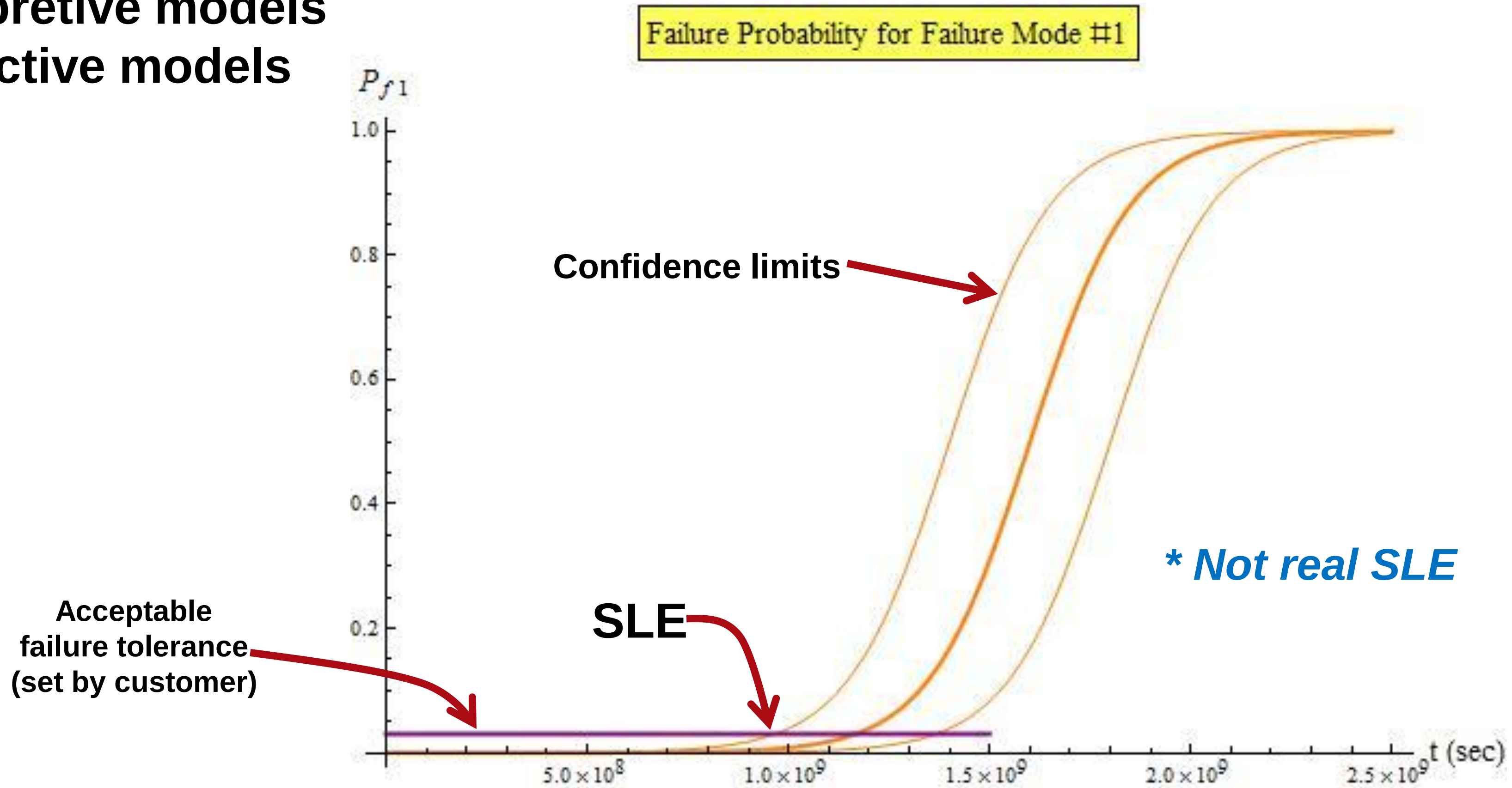
$$\frac{d[AO]}{dt} = D(AO)\frac{\partial^2[AO]}{\partial x^2} - k_2[AO][V*]$$

$$\frac{d[oXLD]}{dt} = k_3[V*]^2$$

Uncertainty: The Error Roll-up*

Must roll up all sources of uncertainty:

- all chemical data sources
- all mechanical data sources
- boundary condition uncertainties
- interpretive models
- predictive models



** Not real SLE*

Multiple failure modes

Suppose the FMEA has several (say, *n*) high-ranked failure modes.
Mechanistic A&S finds failure probability for each:

$$P_{f1}(t), P_{f2}(t), P_{f3}(t), P_{f4}(t), \ldots$$

Overall failure mode is

$$P_f(t) = 1 - \prod_{i=1}^{n} \left[1 - P_{fi}(t)\right]$$

And lastly …
since no one is omniscient, a surveillance program is always necessary for mechanisms that no one suspected.
But surveillance can be done at a reduced rate.
Hence the cost savings from mechanistic A&S.

Summary

- The affects of aging on IM performance of warheads is not well understood
    - Indications are that age may detrimentally change IM response
- New physics-based models are available with capability to predict changes to physical characteristics of emerging IM formulations used in warheads
- These models should be employed in future studies that predict the age life of new and current warheads