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PHM Engineering Perspectives, Challenges and 'Crossing the Valley of Death'

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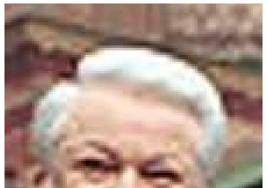
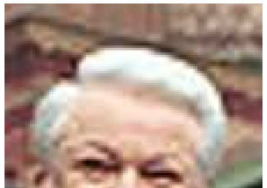
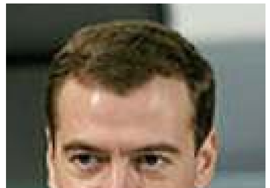
Steve's Prediction Challenge Problem

- Raw data are images ~200 x 265 (53,000 pixels)
- 12 images spanning 92 years (1917 to present)
- Feature "discovered" in 636,000 pixels →
  - Image Feature [B, H]
- Feature trend: B, H, B, H, B, H, B, H, B, H, B, H

Probability that this pattern happens by chance
0.5^{12} → 2.4 times in 10,000

Raw Data With Feature

Image Feature → [Balding, Hairy]

B	H	B	H	B	H
					
Lenin 1917-24	Stalin 1922-53	Kruschev 1953-64	Brezchnev 1964-82	Andropov 1982-84	Chernenko 1984-85
B	H	B	H	B	H
					

Data-Driven Methods Are Very Powerful But…

Understand The Physical Basis of Discovered Features Before Blindly Declaring Success!

Another Key PHM Challenge

- Cannot Duplicate (CND), Retest OK (RTOK), No Trouble Found (NTF), No Defect Found (NDF), No Fault Found (NFF)
  - Symptoms appear in flight…
  - Fault code identifies the culprit…
  - Culprit is exonerated on the ground
- Primary causes:
  - Incorrect isolation
  - False Alarms
  - Real problems that are not reproducible
    - Exact conditions are not known and/or not reproducible on ground
    - Software faults
    - Intermittent failures
- Solution: Prognostics Health Management (onboard & off board)
  - Comprehensive data collection
  - Advanced diagnostics onboard (multi-level reasoning methods)
  - Prognosis (health state prediction)

Given an Indication, What's The Probability That a Defect Truly Exists?

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- Applying Bayes' Theorem: the *probability* that a flaw (F) exists given a positive indication (I) depends on:
  - Sensor's Probability of detection
    - *P(I/F)* → probability that there will be an indication given a qualified flaw exists
  - Sensor's Probability of false positive (false alarm)
    - *P(I/~F)* →probability that there will be an indication given a qualified flaw does not exist
  - A Prior probability $P(F)$ that the qualified flaw exists before indications are considered

Probability of a flaw given an indication

Probability of detection

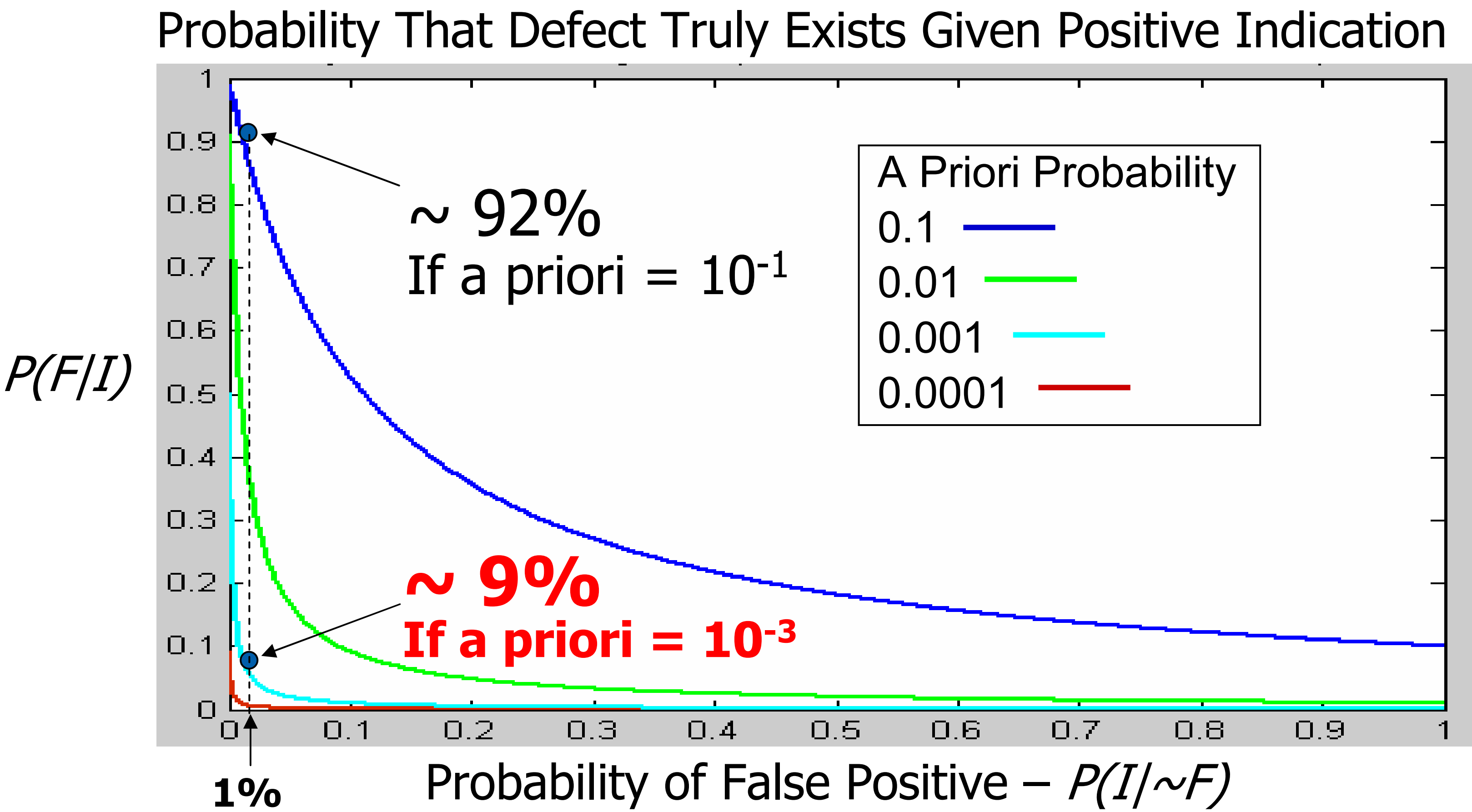
A priori probability of a flaw (from prediction)

Probability of a false positive

$$P(F \mid I) = \frac{P(I \mid F)P(F)}{P(I)} = \frac{P(I \mid F)P(F)}{P(I \mid F)P(F) + P(I \mid \sim F)P(\sim F)}$$

Suppose we have a component with failure probability of 10^{-3} and a fault indication from a test having 100% probability of detection and 1% probability of false alarm.
What is the probability that we really have a failure?

Probability Considering All the Evidence – Highly Dependent on A Priori Probability



A Priori Probability Can Be Provided By Prognosis

Prognosis Is More Than Just Trending

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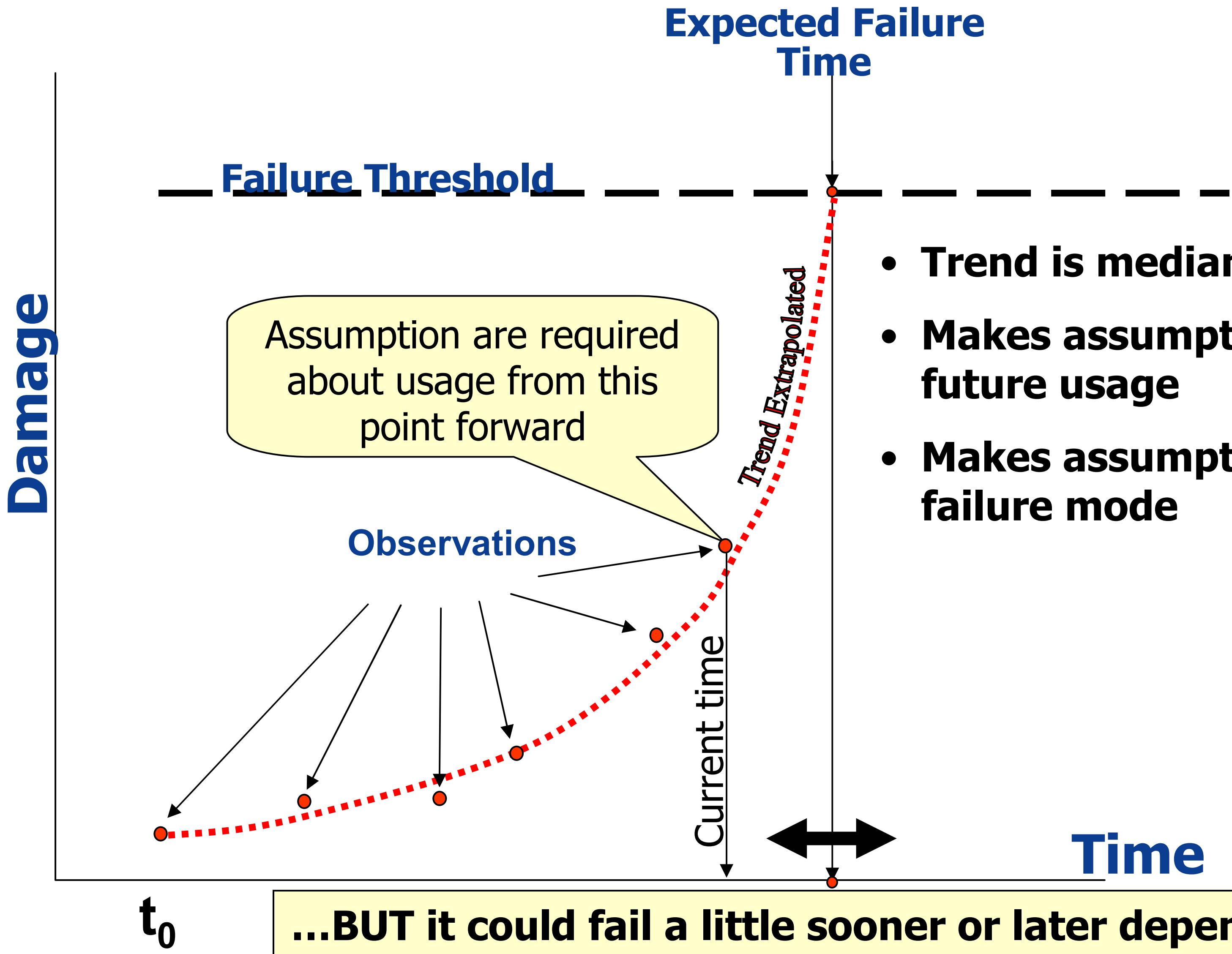
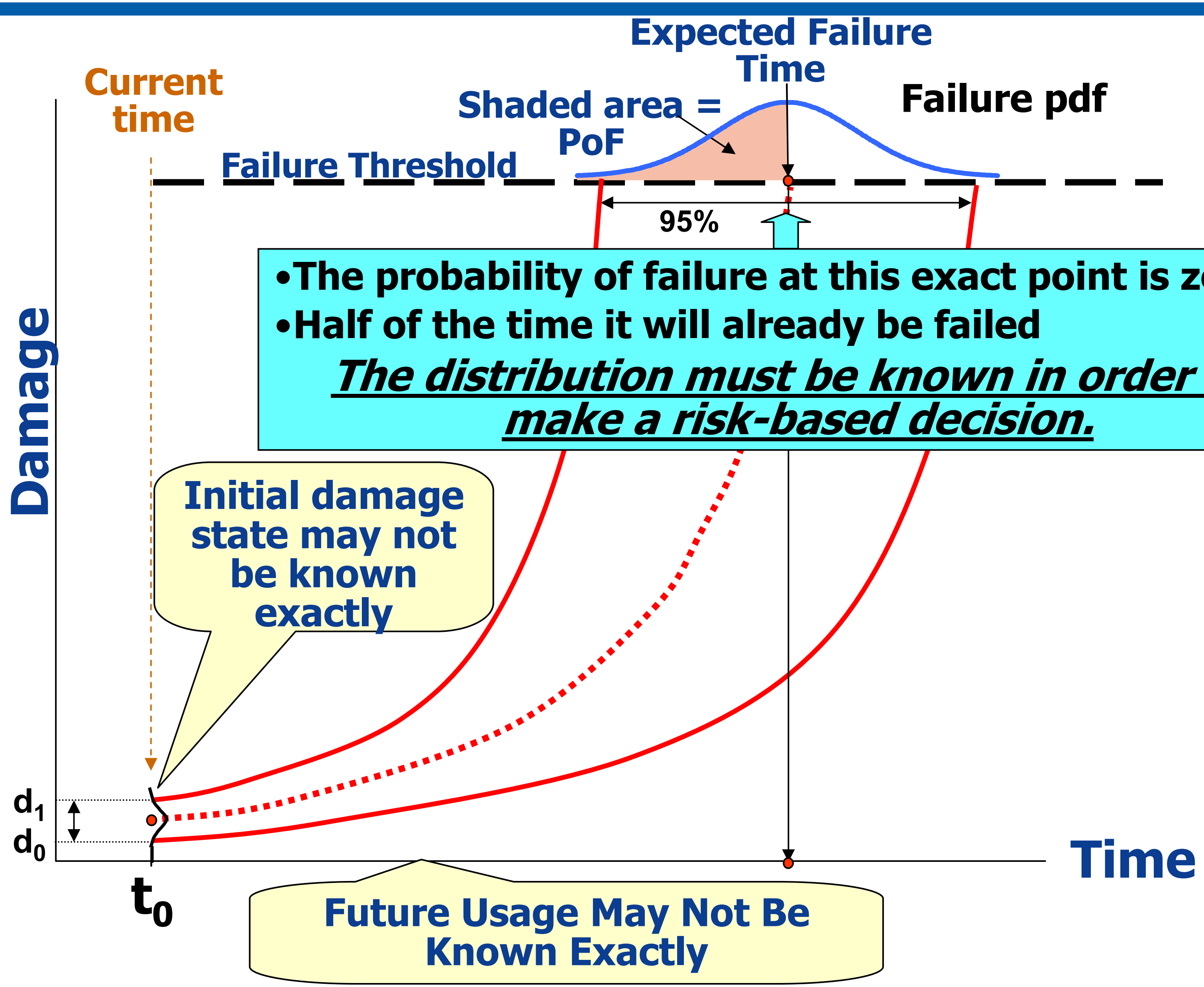


- **Trend is median or average**
- **Makes assumptions about future usage**
- **Makes assumptions about failure mode**

…BUT it could fail a little sooner or later depending on actual usage, model & measurement errors etc

Prediction With Uncertainty Included



Probabilistic Assessments From Deterministic Models

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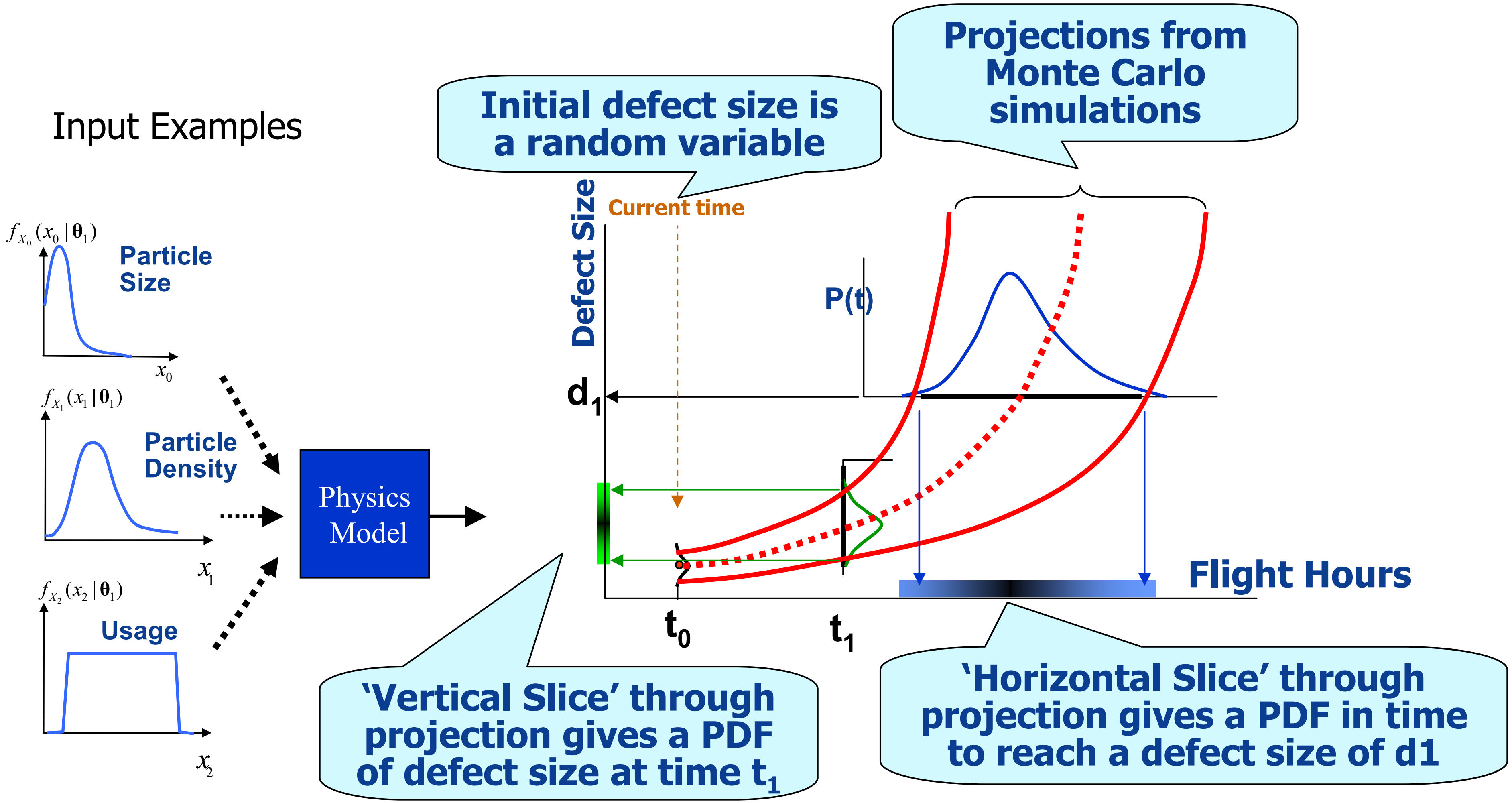

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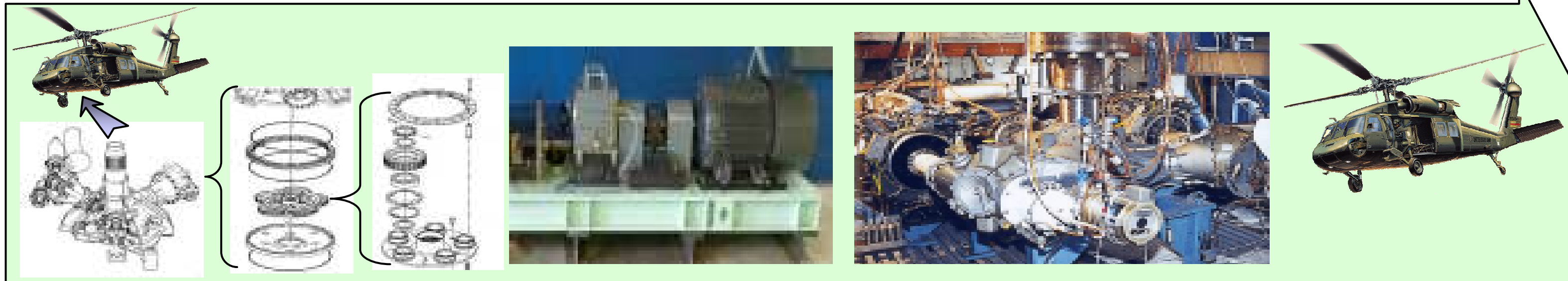
DARPA/Northrop Grumman Corp
Structural Integrity Prognosis System (SIPS)

Power Train Applications



PLANETARY TRANSMISSION | **LAB TESTS** | **NAVAIR HTTF** | **TEST AC** | ***FLEET***

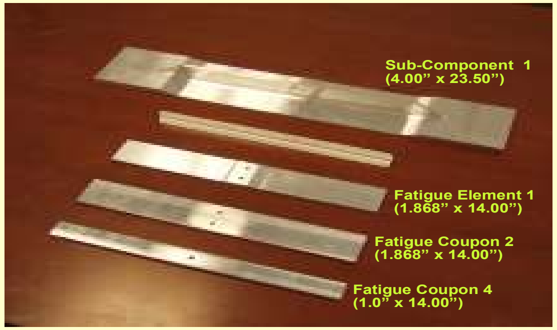
Feature discovery	***Feature validation***	***2 seeded fault tests***	***H-60 AC test***

Sept 2003 → **Sept 2009**

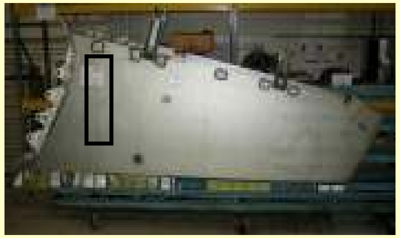
Impact Technologies, Georgia Tech, NAVAIR, Penn State ARL,
Sikorsky, University of Maryland,

DARPA/Northrop Grumman Corp Structural Integrity Prognosis System (SIPS)

Fixed-Wing Structures Application



EA-6B COUPONS, ELEMENTS AND SUBCOMPONENTS



RETIRED WING PANELS

NAVAIR Tests

Active P-3

FLEET

Death Valley

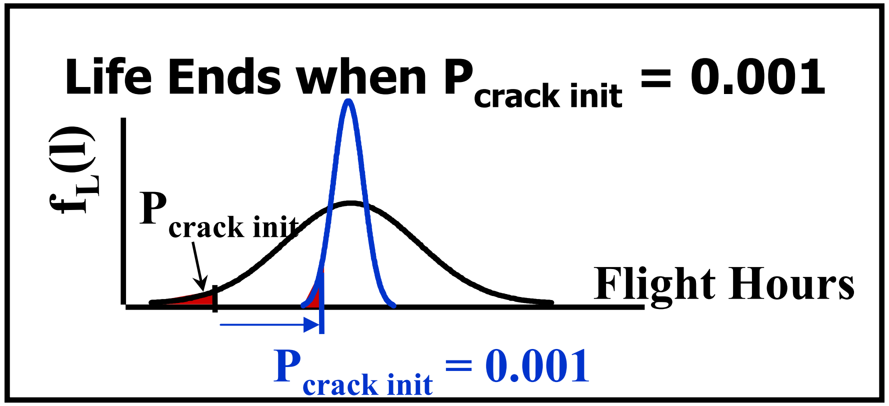
400 lab specimens 10,000 measured cracks	***2 outer wing panel (OWP) teardowns***	***3 full-scale OWP tests***	***24 month P3 flight demonstration***

Sept 2003 → **Sept 2010**

Aero Union Corp, ALCOA, Carnegie Mellon, Cornell, DMI Inc., Impact Technologies, JENTEK Inc., Lehigh, Mississippi State, Oceana Systems, Ohio State, PSI Inc, Rensselaer Polytechnic, Ultra Electronics, University of Pennsylvania, University of Virginia, Vextec, Wash State

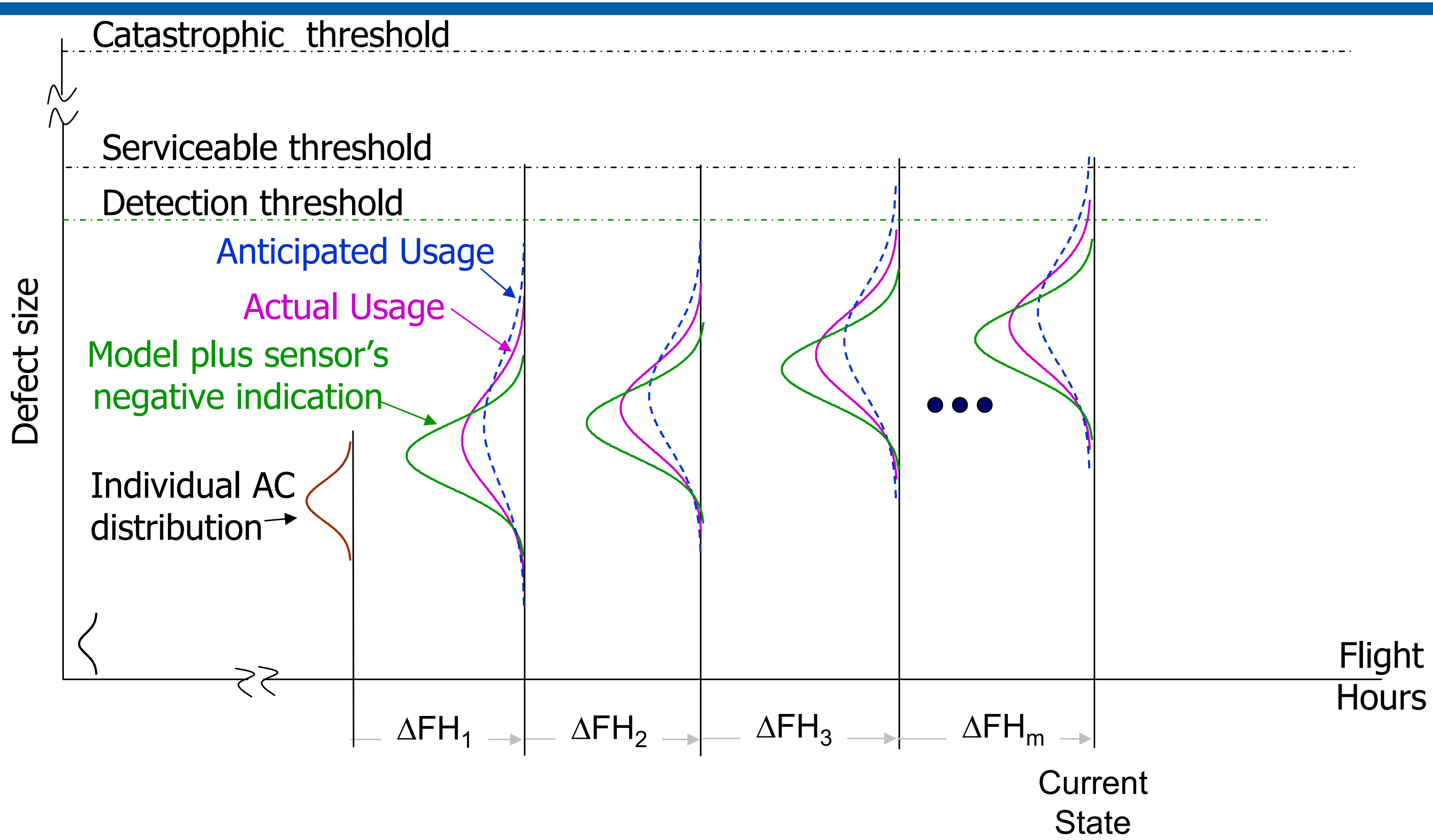
Motivation for Structural Integrity Prognosis System

- Navy Legacy Method - Fatigue Life Expended (FLE)
  - Retirement at initiated crack of 0.01"
  - Coarse Measure of True Condition
  - Does Not Provide Useful Reliability Measures
  - No Longer Applies to Aging Fleet (FLE>100%)
- Conservatism Driven by Uncertainty

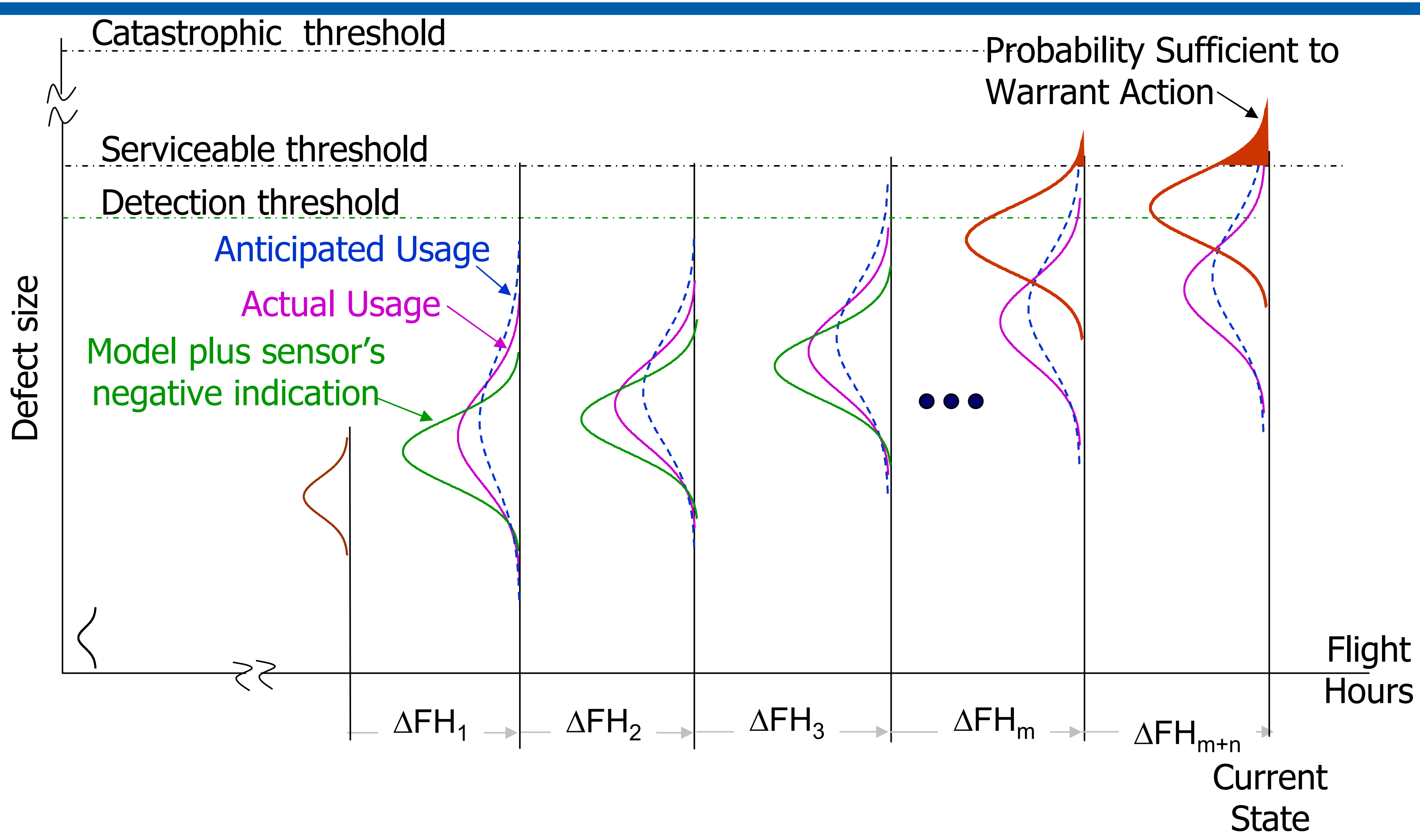


SIPS Provides a More Realistic Assessment of Current & Future Health Condition

Adaptation With Negative Indications



Adaptation With Positive Indications



Engineers Need Requirements!

Four Key Prognosis Requirement Parameters

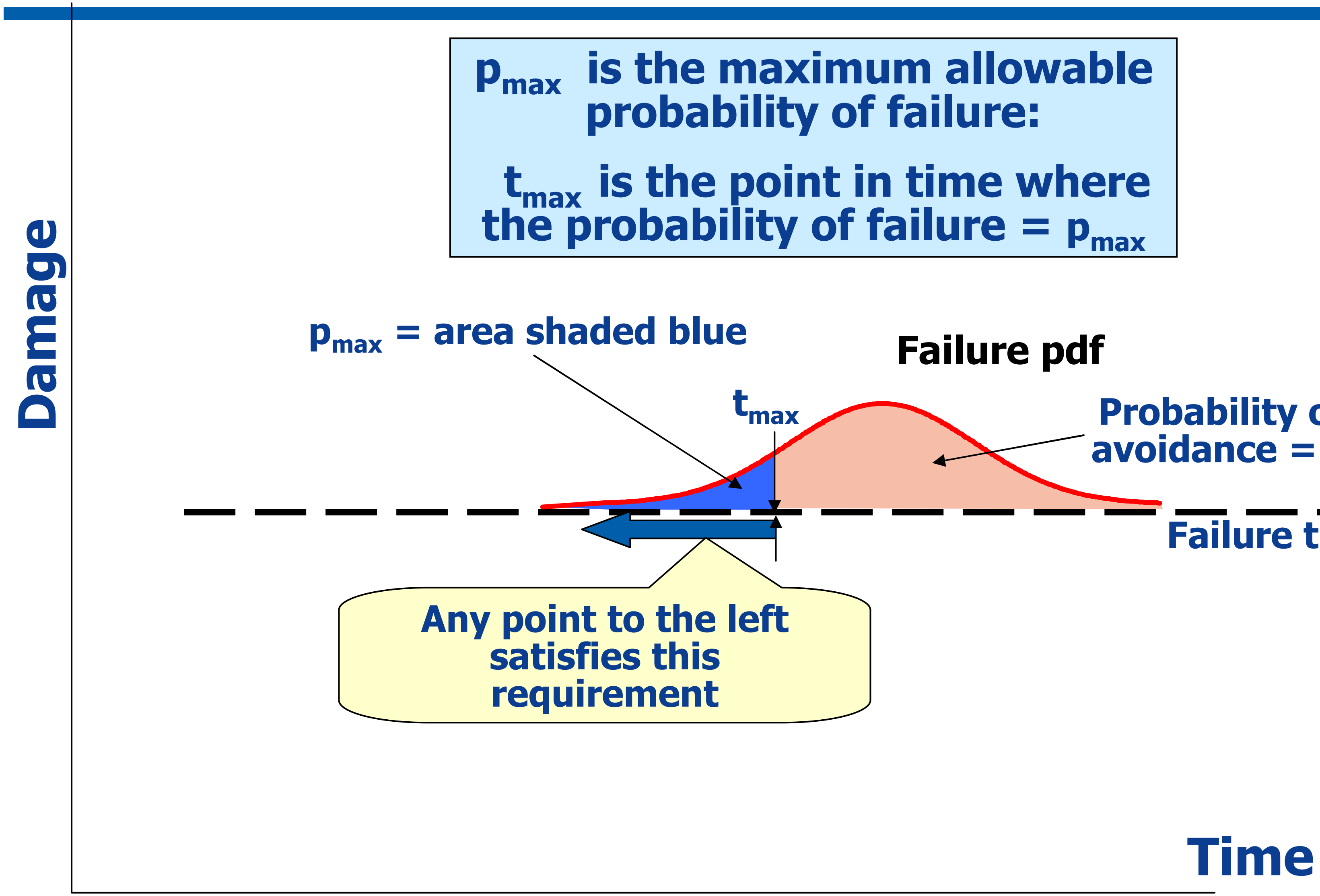
1. Maximum Allowable Probability of Failure
   – Bounds Risk
2. Maximum Tolerable Probability of Proactive Maintenance
   – Bounds Unnecessary Maintenance
3. Lead Time
   – Specifies the amount of advanced warning needed for appropriate actions
4. Required Confidence
   – Specifies when prognosis is sufficiently mature to be used

It is also useful to have a clear definition of failure or end of useful life

Maximum Allowable PoF Limits Risk

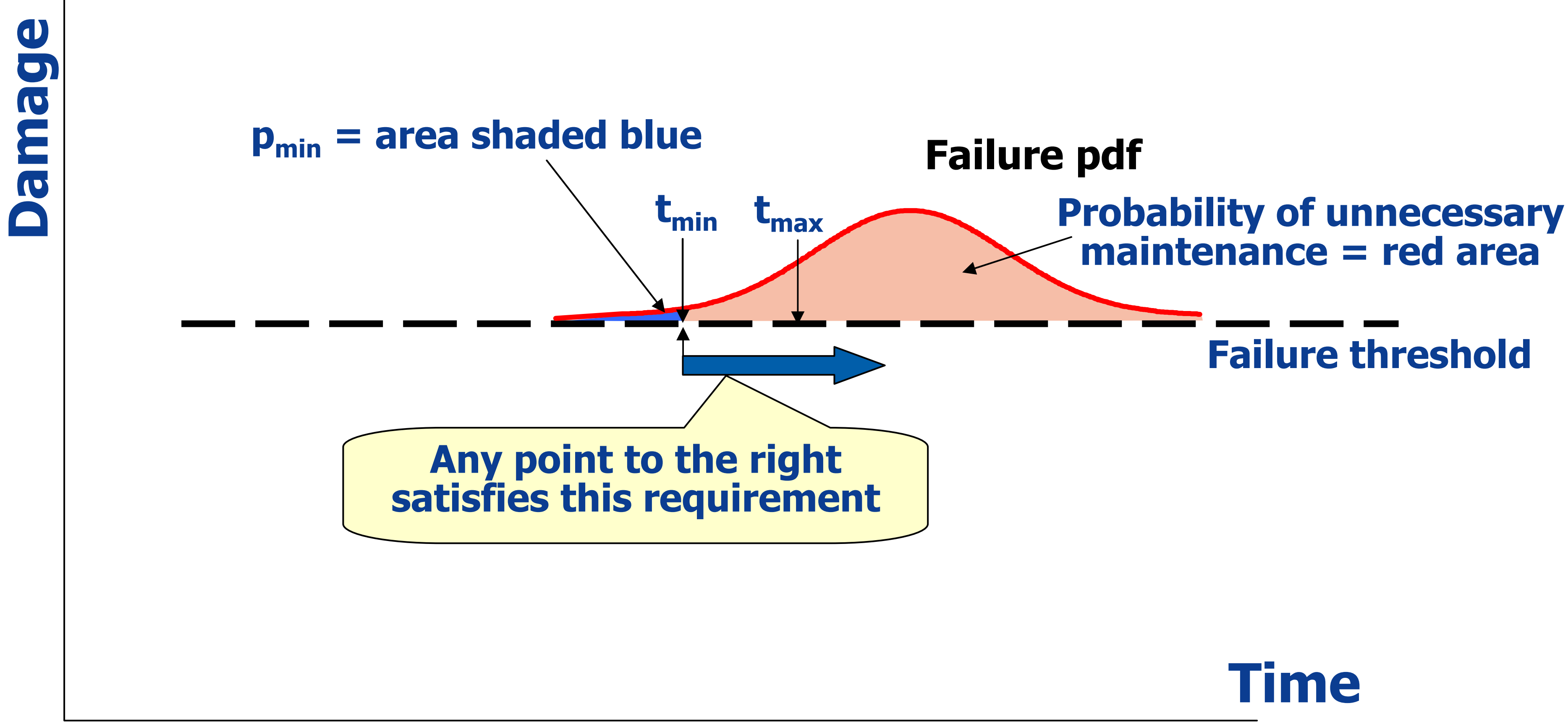
p_{max} is the maximum allowable probability of failure:

t_{max} is the point in time where the probability of failure = p_{max}



Maximum Tolerable Probability of Proactive Maintenance

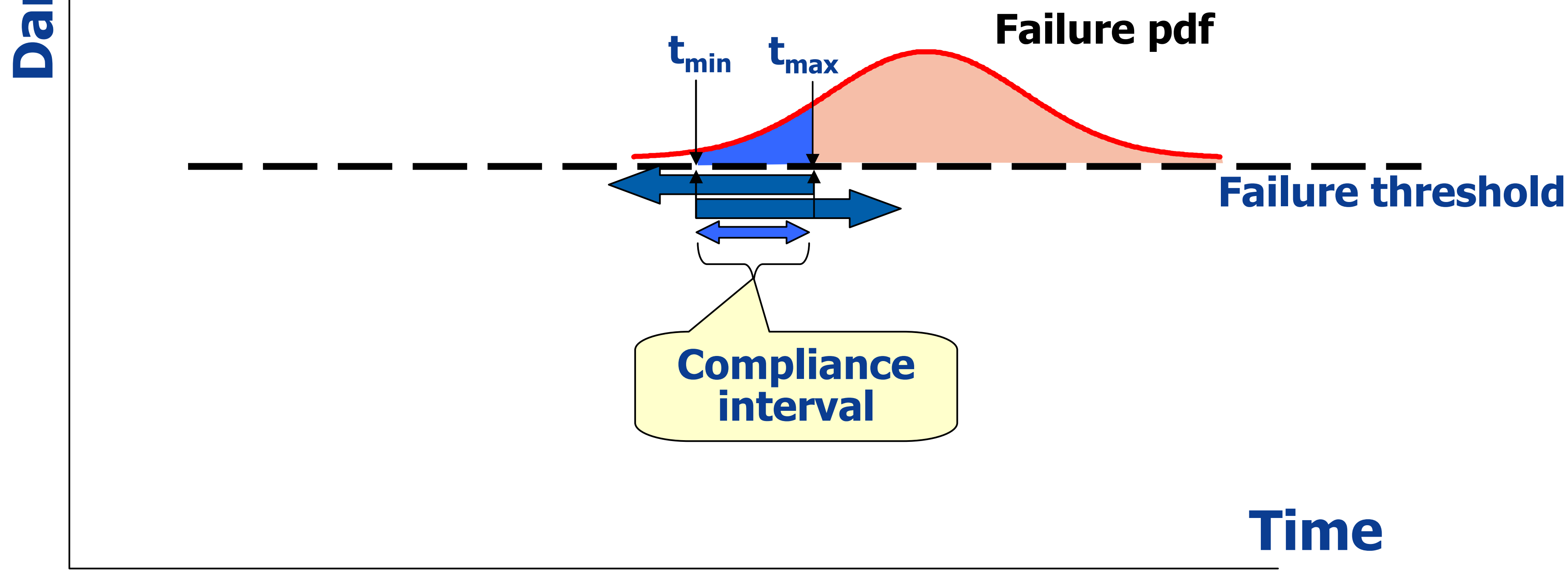
- **[1 - Max Probability of Proactive Maintenance] = p_{min}**
- **t_{min} is the point in time where the probability of failure = p_{min}**



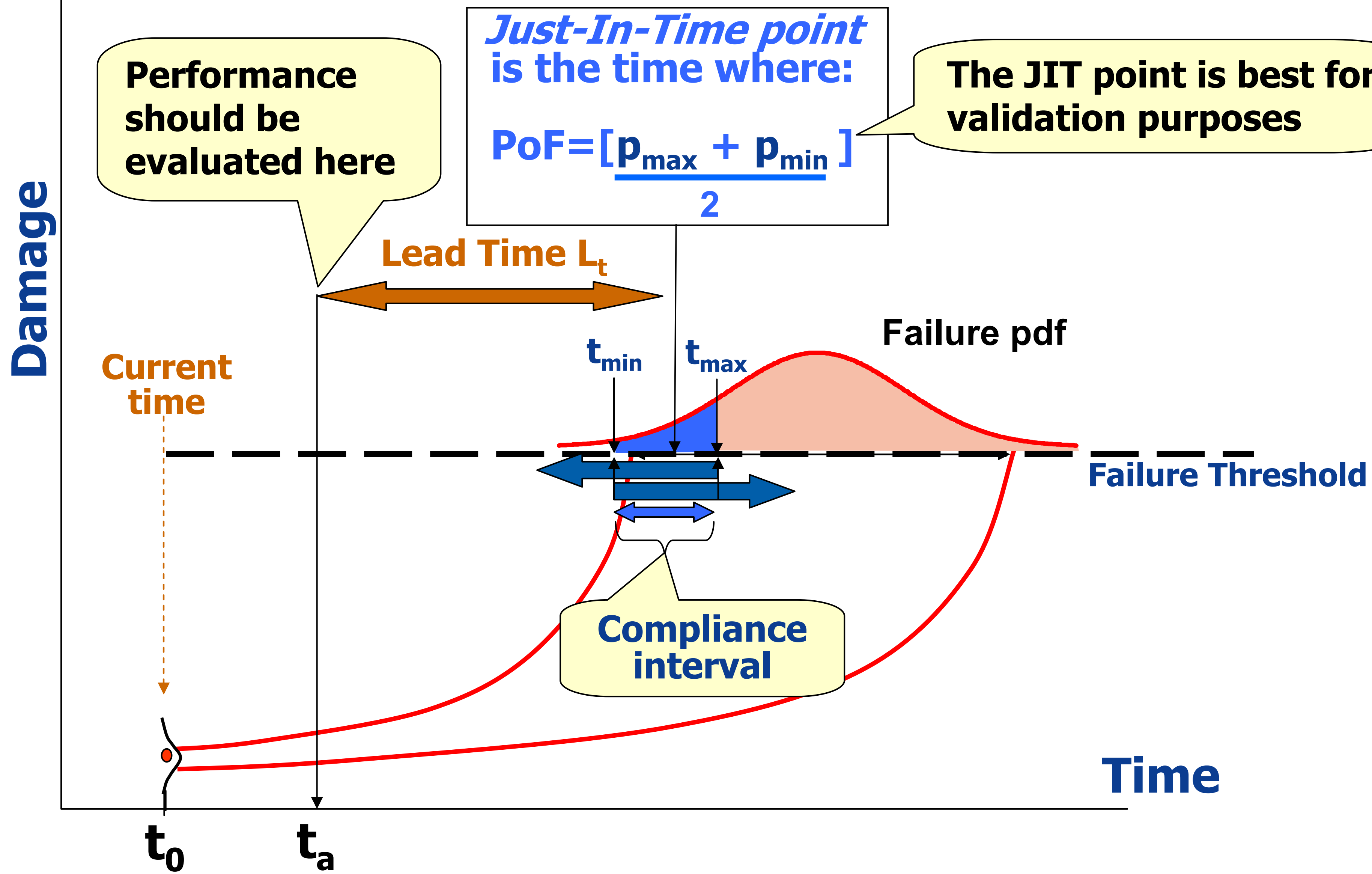
Compliance Interval Satisfies Both

The requirements are satisfied as long as we design our prognosis algorithms to predict any time in the compliance interval.

Is there an ideal point for validation?



Just-In-Time Point & Lead-Time



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Summary

- Discover features in data, but then explain them

- Prognosis / Diagnosis Duality
  - Diagnosis supports prognosis, AND vice versa
  - Together they mitigate false alarms, CNDs, RTOK, NTF… along with a variety of other benefits

- Predicting exactly when a failure will happen is not as useful as predicting when an action should be taken
  - The more precise the failure prediction, the lower the probability of it coming true
  - Don't strive to predict an exact time of failure,
  - Quantify the distribution to enable risk-based decisions

- Well-formed prognostic requirements are the key for transitioning Agnostic Health Managers into PHM practitioners
  1. Maximum Allowable Probability of Failure
  2. Maximum Tolerable Probability of Proactive Maintenance
  3. Lead Time
  4. Required Confidence

Thank You

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