High Cycle Fatigue & Flaw Tolerance

Methods Over View

Fatigue Substantiation Methods Available

- **Safe Life**
  - **Based on <u>crack initiation</u> characteristics.**
  - **Establishes a fixed retirement time.**

- **Fail Safe (Damage Tolerance)**
  - **Based on <u>crack propagation</u> characteristics.**
  - **Establishes an inspection method and interval.**

- **Flaw Tolerance (Flaw Tolerant Safe Life)**
  - **Same as Safe-Life, but assumes all parts have critical flaws.**
  - **Can determine retirement times and inspections.**

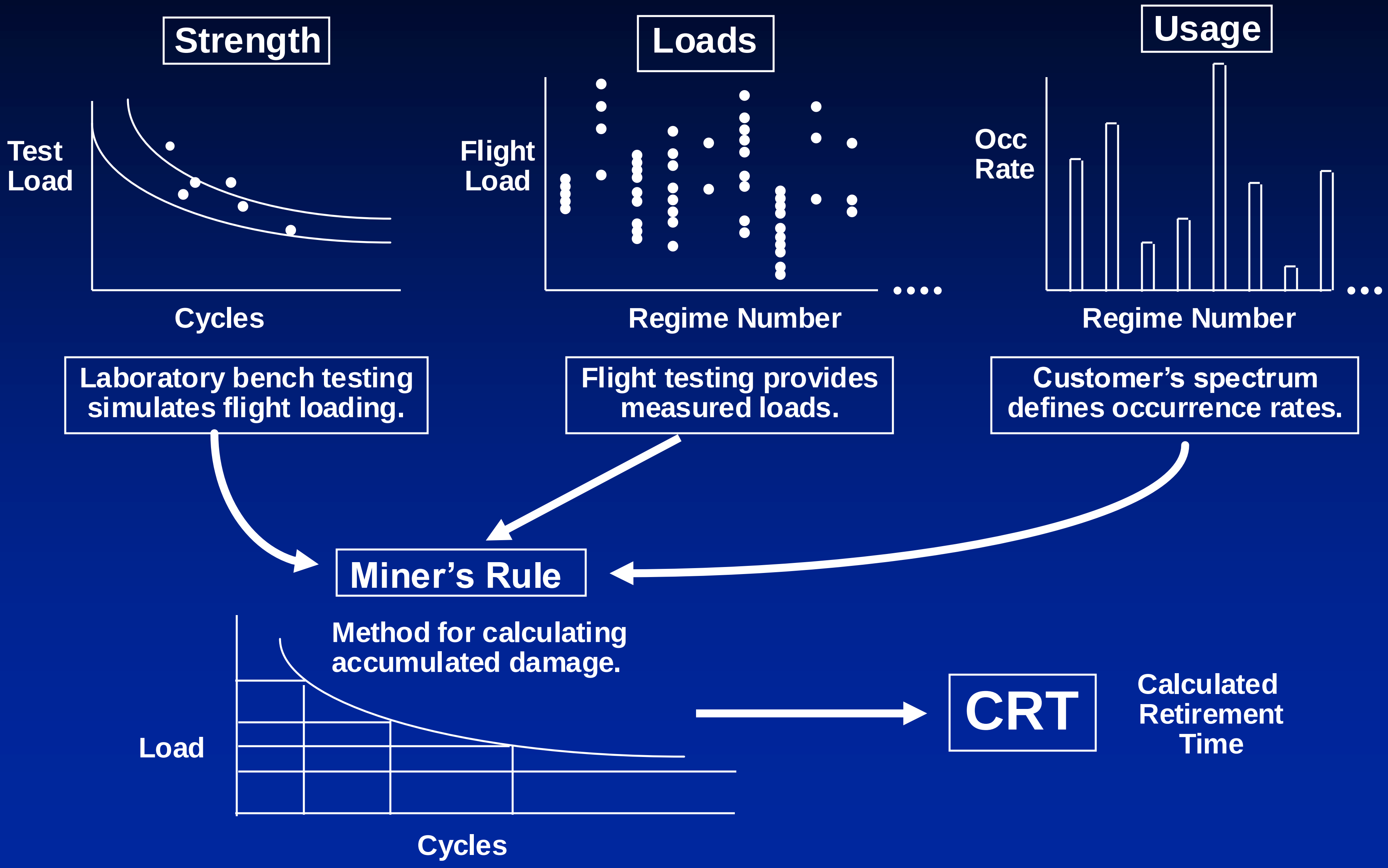
Evolution of Safe Life Fatigue Methodology

- ***Basic Method***
- **First rigorous test-based fatigue.**
  - **Based on prevention of any of fatigue crack initiation.**
  - **Chance of failure was "extremely remote".**

- **Same *Basic Method* used by all manufacturers world-wide.**
  - **Differences only in details, but which can produce large differences in retirement times.**
  - **Certifying Agencies provide only limited direction.**
  - **Approx. 95% of parts in service are safe-life.**

- ***Basic Method* has been validated.**
  - **50 years experience, no "vanilla" fatigue failures.**

Safe-Life Substantiation Process



Strength

Laboratory bench testing simulates flight loading.

Loads

Flight testing provides measured loads.

Usage

Customer's spectrum defines occurrence rates.

Miner's Rule

Method for calculating accumulated damage.

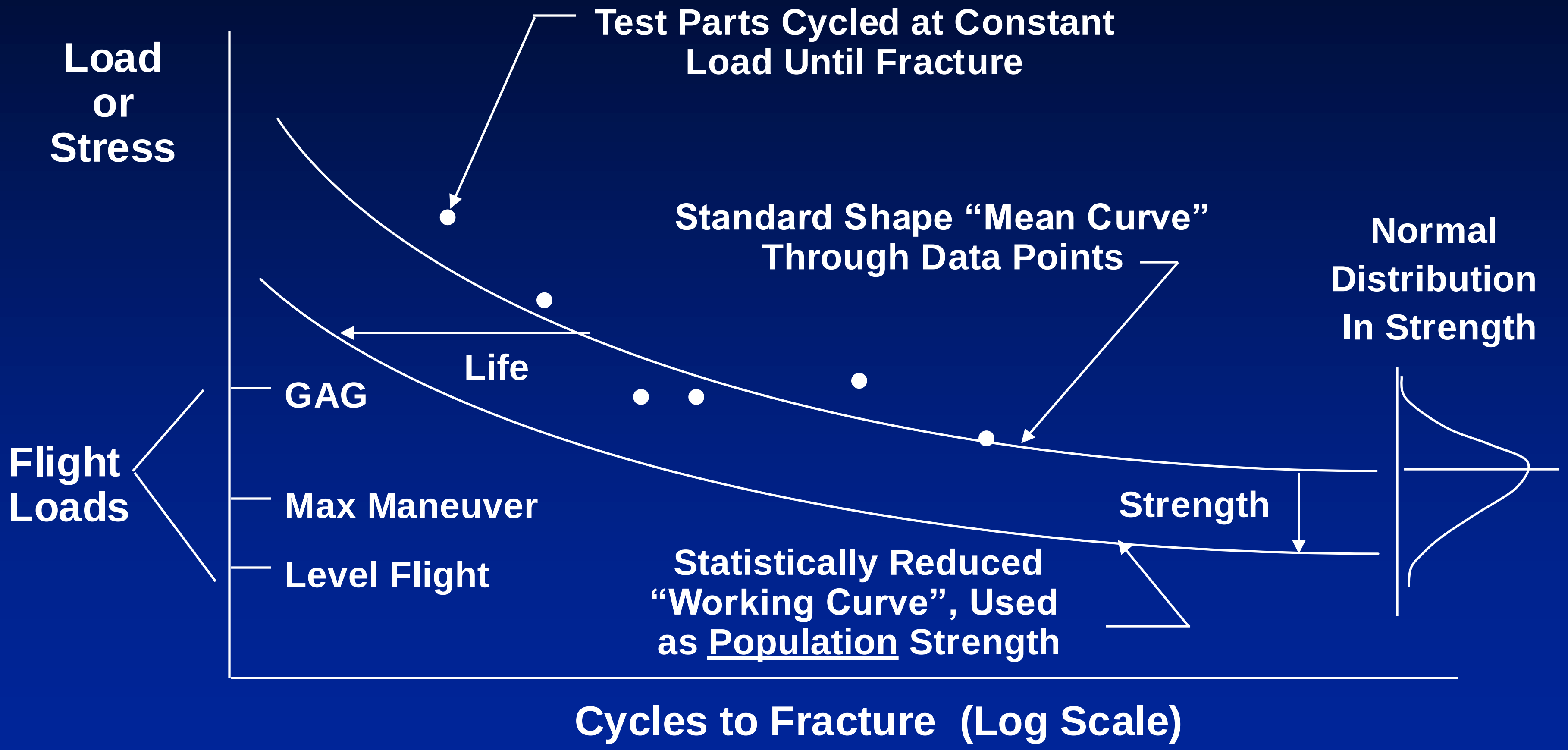
CRT

Calculated Retirement Time

Laboratory Fatigue Testing

- Component Fatigue Strength Determined by Full-Scale Tests.
- Test Set-up Simulates Distribution of Flight Loads and Stresses, both Steady and Vibratory.
- Vibratory Test Load is Accelerated Above Flight Load Levels to Show Required Margin and to Shorten Test.
- Constant Amplitude Cyclic Load Applied Until Fracture.
- Substantiating Parameter (Load or Stress) Chosen Which can be Measured in Both Ground and Flight Tests.
- Multiple Specimens Tested.

S/N Curve Shows Component Fatigue Strength



Load
or
Stress

Test Parts Cycled at Constant
Load Until Fracture

Standard Shape “Mean Curve”
Through Data Points

Normal
Distribution
In Strength

GAG

Life

Flight
Loads

Max Maneuver

Strength

Level Flight

Statistically Reduced
“Working Curve”, Used
as Population Strength

Cycles to Fracture (Log Scale)

Standard S/N Curve Shapes

- **Standard Shape Equation:**

$$\frac{S}{E} = 1 - \frac{\beta}{N^{\gamma}}$$

- **Where:**
  - S is stress or load.
  - N is the number of cycles in millions.
  - E is the endurance limit at $N = \infty$.
  - β and γ are the standard curve shape constants.

- **Typical Curve Shape Discriminators:**
  - Material
  - Mode of Failure (Chafing, Interlaminar Shear, etc)
  - Surface Finish (Shot Peen)
  - Stress Concentration

Sources of S-N Curve Shapes

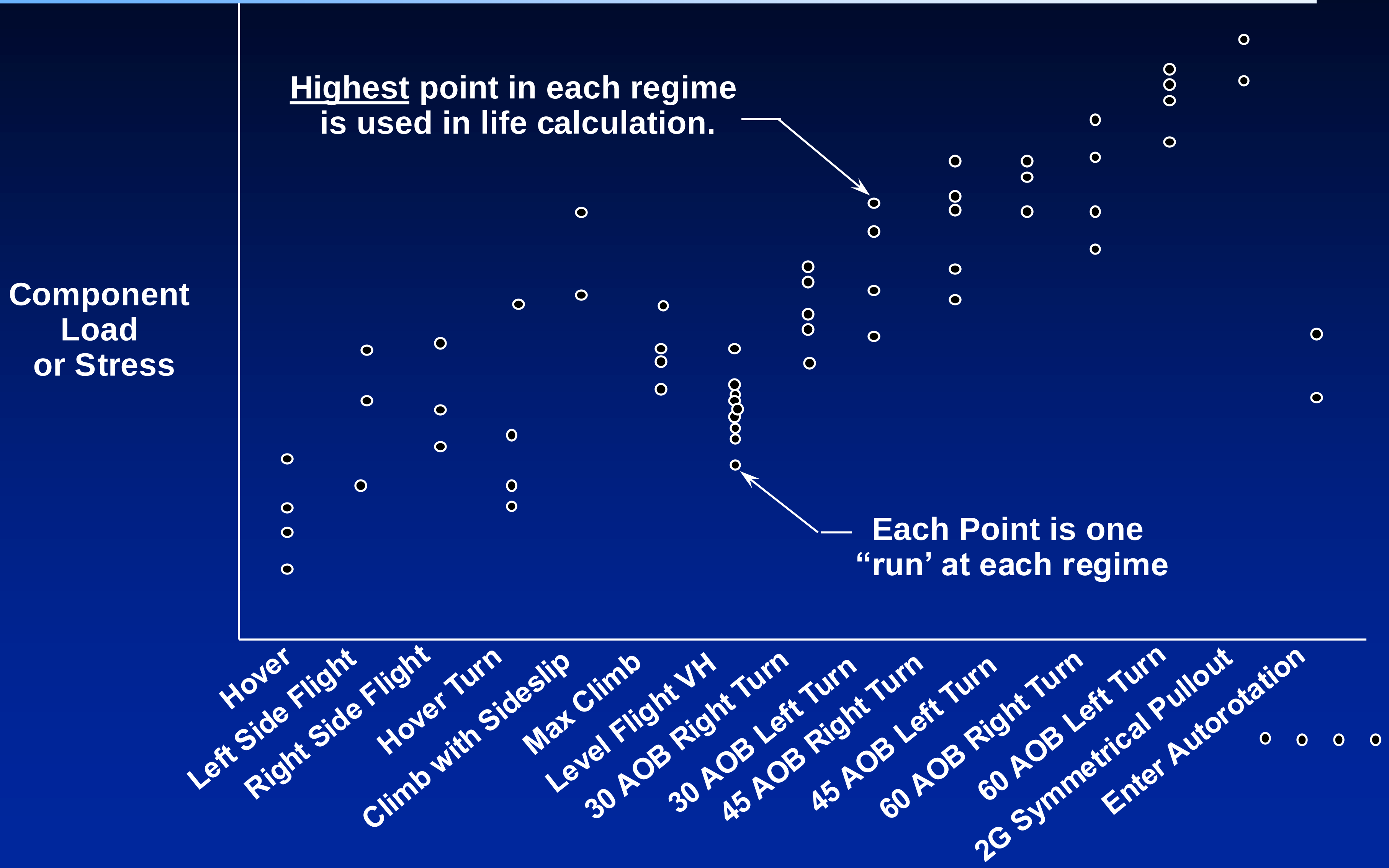
- Original (1950’s) Steel and Aluminum Shapes
  - Royal Air Force Published Data
  - Hamilton Standard Propeller Data
- Titanium
  - Initially (1960’s) used limited coupon and full scale data
  - Supplanted by coupon test programs in early 1980’s.
  - Added high Kt Beta Ti curve as a result of BH Spindle (1985).
- Composites
  - Coupon programs for all fiber and resin systems.
- Any “New” Material
  - Coupon Programs
- Full Scale Data
  - If data set is in obvious disagreement with standard shape, it is “warped” through the test data (common in low-cycle region).

Working Curve Reduction Factors

- Strength Reduction
  - “3-sigma” reduction based on a normal distribution.
  - Approximately 3-9’s reliability by itself.
  - Sigma is based on “population” scatter plus normal variations in material, manufacturing, processing, measurements, and sampling errors.
  - Composites: scatter, plus an environmental factor up to 20%.
  - Further reduction if needed for low points.

- Life Reduction
  - Assures a minimum life margin everywhere.
  - Curve shape uncertainty in low cycle region.

Typical Maneuver Flight Loads Compilation



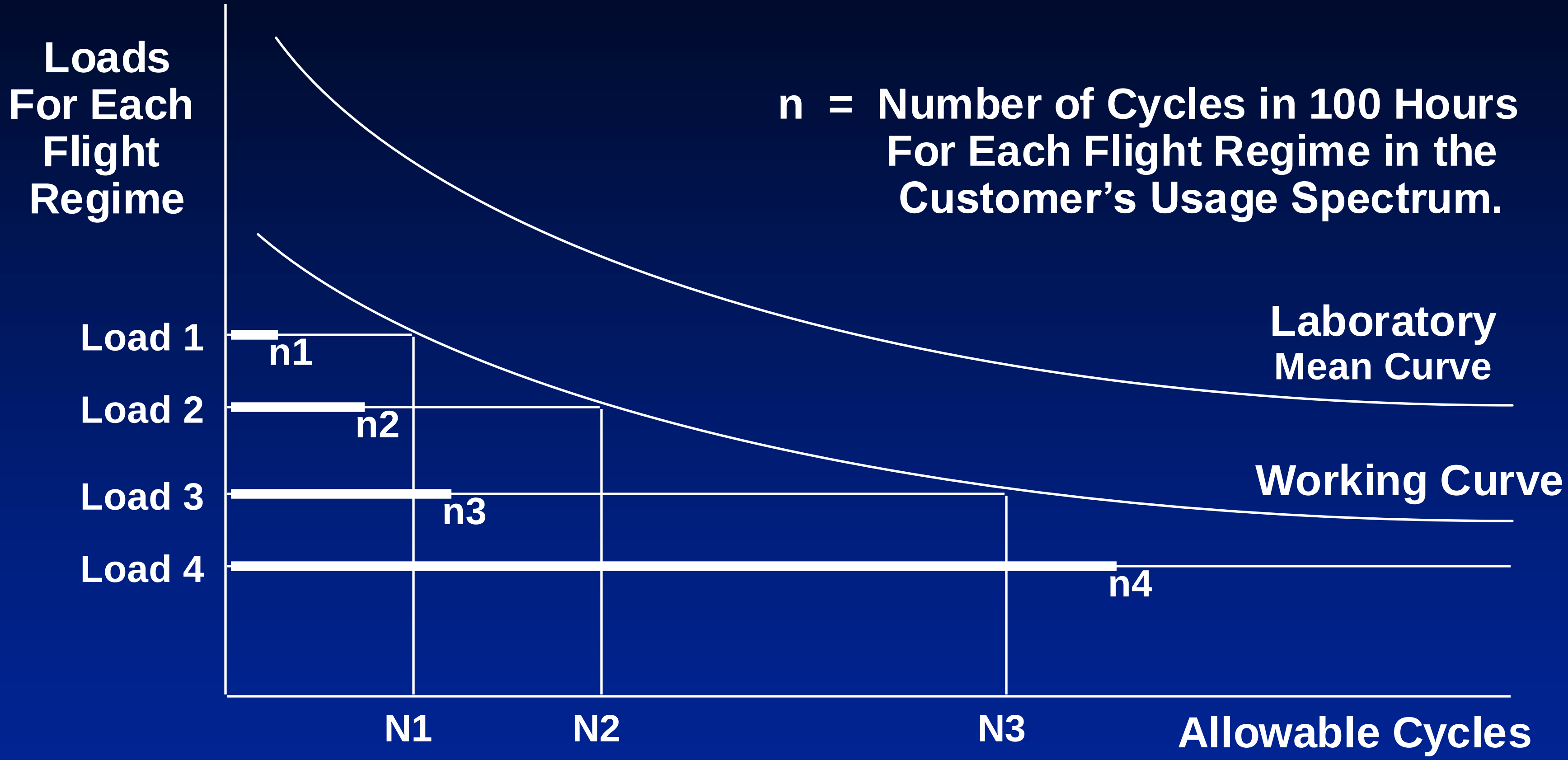
Highest point in each regime is used in life calculation.

Each Point is one “run’ at each regime

Usage Spectrum

- Usage Spectrum is Defined by the Customer.
  - Rates of occurrence or percent times are provided for each flight regime expected to occur in normal service.
  - “Pro-Rates” are provided for gross weight and altitude.
- A “Composite Worst Case” Approach is Preferred:
  - The highest rate of occurrence, from any use or mission of the aircraft, is used for each flight regime.
  - A conservative, mutually exclusive, composite mission results.
- Improving Estimates of Usage:
  - Pilot and squadron surveys.
  - Recognize changing configurations or missions.
  - ***Usage Monitors*** with regime recognition capability

Miner’s Rule of Linear Cumulative Fatigue Damage



n = Number of Cycles in 100 Hours For Each Flight Regime in the Customer’s Usage Spectrum.

$$\text{Damage in 100 Hours} = \frac{n1}{N1} + \frac{n2}{N2} + \frac{n3}{N3} + \frac{n4}{N4} + \cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot$$

Calculated Retirement Time (CRT) = 100/D

Conservatisms in Safe-Life Substantiations

- Low envelope of strength (3-sigma and 5:1 reductions)
- High envelope loads (95th percentile or max. measured)
- Composite Worst Case usage spectrum
- Conservative fatigue test and flight test procedures.
- Conservative prorates for altitude, gross weight, configurations, missions
- No prorate for CG (in general).   Use only extreme CG's.

Simulation Validation of Methodology

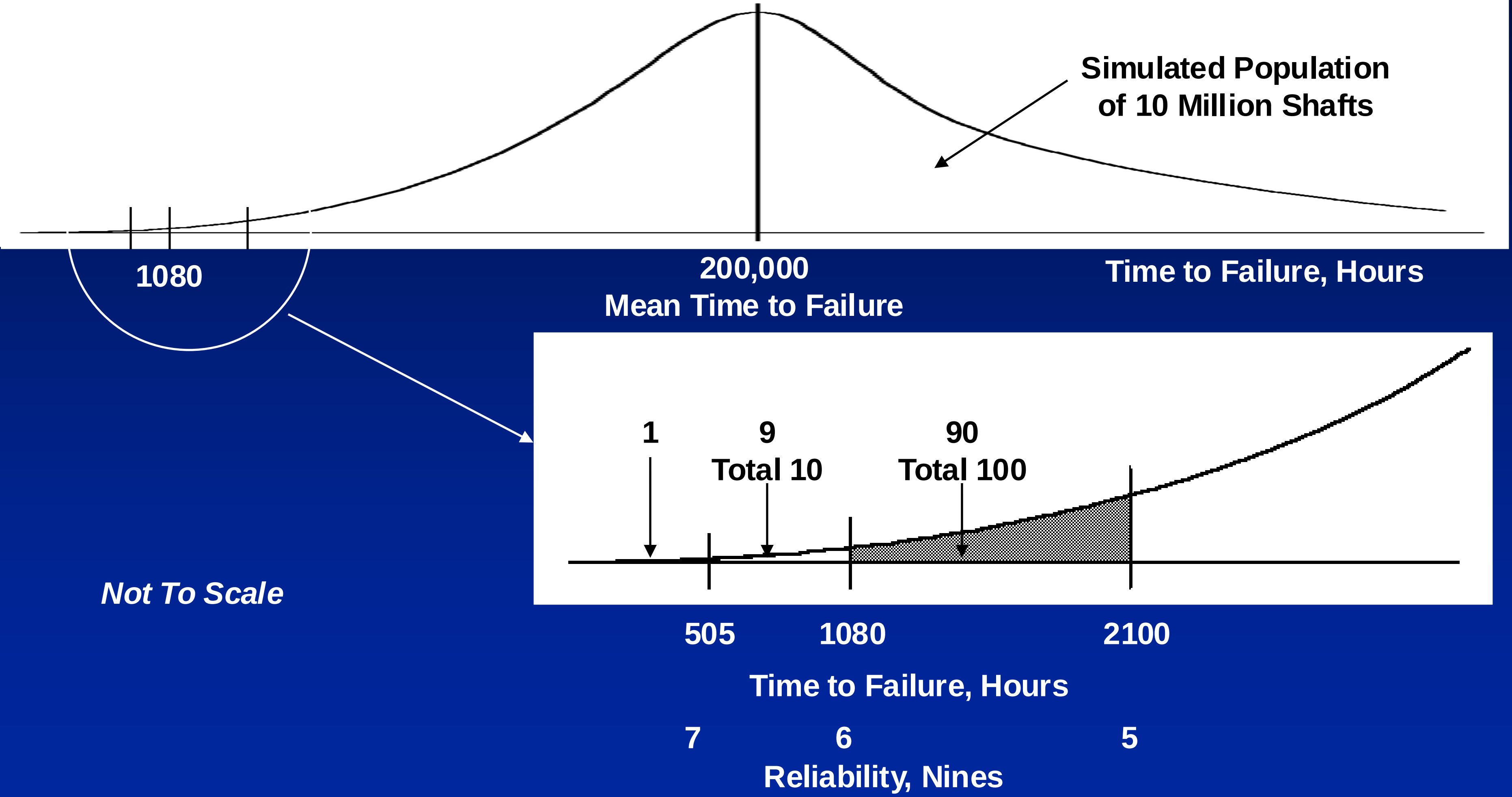
- **Computer Simulation of In-Flight Fatigue Damage Initiated to Demonstrate Requirement for “6-9’s” Reliability.**
  - **Required to show that less than 1 part in a million would have a fatigue failure in service.**
  - **Method used for U.S.Army “Combat Fatigue Lives” study during *Desert Storm*.**

- **Conventional Fatigue Methodology Yields**

  6-9’s Reliability for <u>Conforming</u> Parts.
  - **The old arbitrary conservatisms in strength, loads, and usage produce the required reliability.**
  - **The six nines are made up of: 3 from strength, 2 from loads, 1 from usage**

Simulation Shaft Failure Distribution

Based on Computer Damage Simulation for Nominal Mission, Conforming Parts



Not To Scale

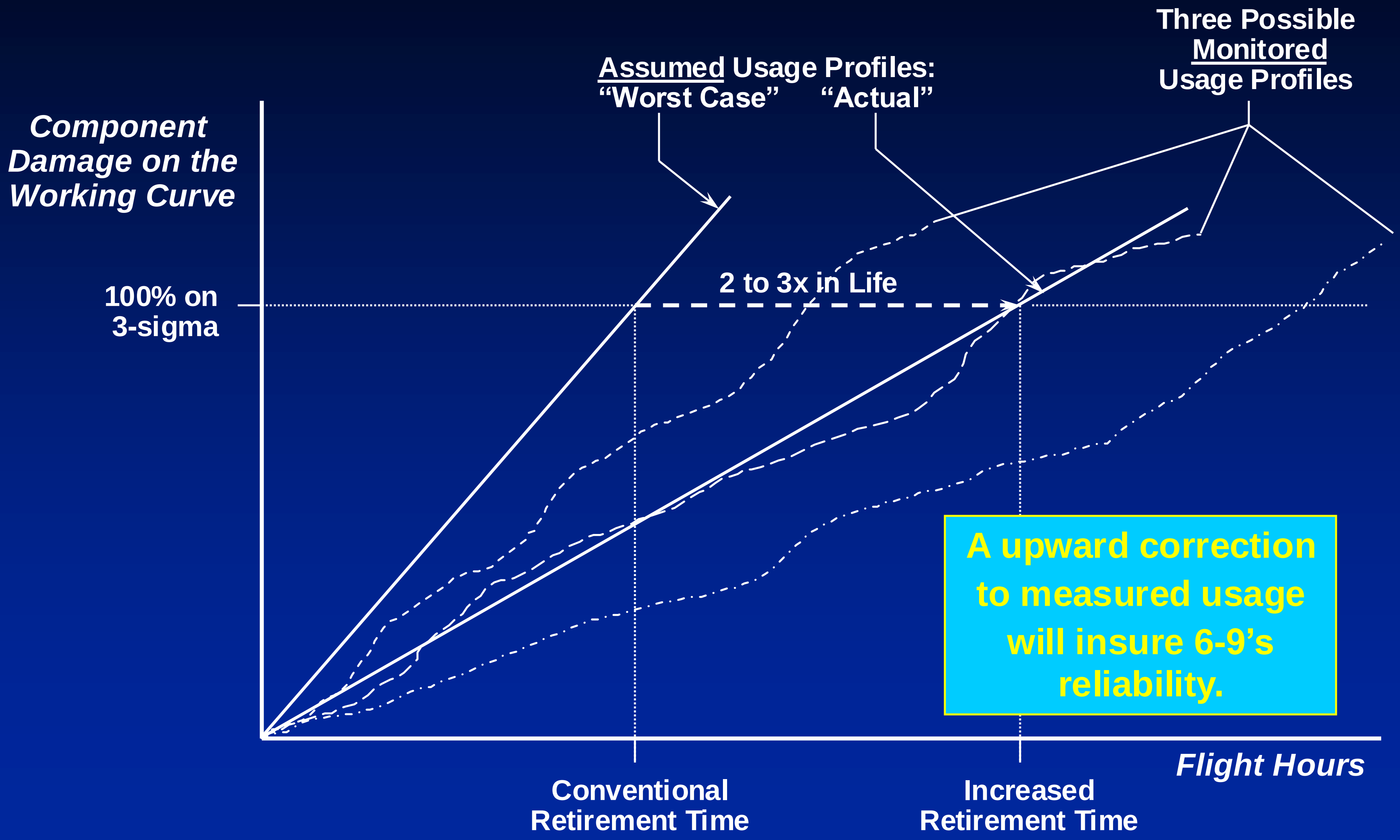
Why Isn’t 6-9’s Achieved in Service?

- In-Flight Fatigue Failures are Very Rare, but Still Occur More Often than 1 Part in a Million.

- Fatigue-Related Accidents Have All Had an Assignable Cause:
  - Lower Strength Than Predicted:
    - Manufacturing and Processing Conditions.
    - Material Discrepancies.
    - Maintenance, Overhaul, and Handling Errors.
    - Service Degradation such as Corrosion and Wear.
  - Higher Flight Loads Than Predicted:
    - Growth - Engine Power, Gross Weight, Configuration Changes.
    - Maneuver Variations not in the Flight Load Survey.
    - Jammed or Degraded Parts.
  - More Severe Usage Than Predicted:
    - Maneuvers not in the Original Spectrum.
    - Rates of Occurrence Higher than Predicted.

- The Retirement Times can only be Based on What is Known.

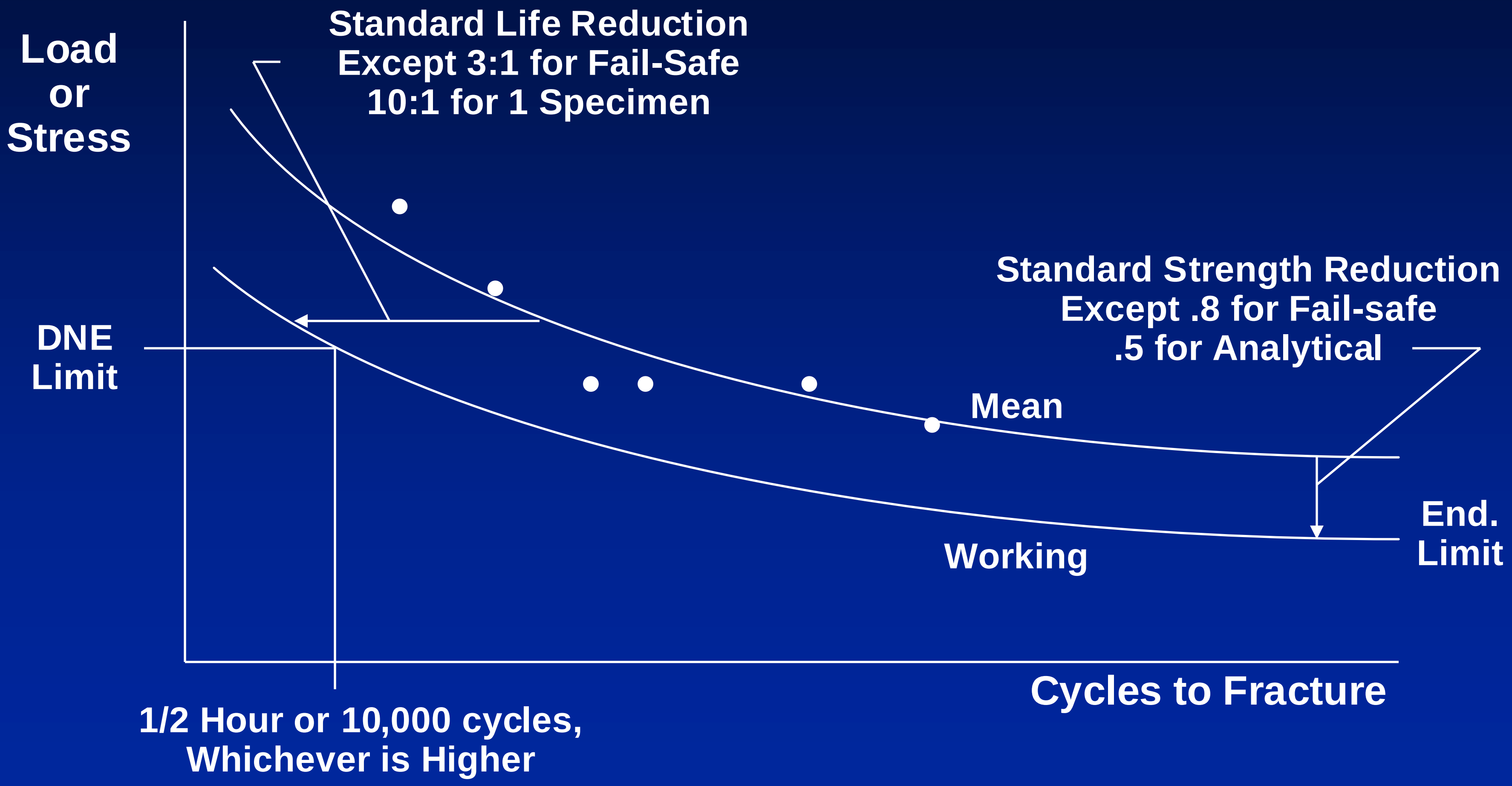
Adding a Usage Monitor, No Corrections



A upward correction to measured usage will insure 6-9's reliability.

Determination of Vibratory DNE

Based on Component S/N Curve



Evolution of Flaw Tolerance Methodology

- **“Enhanced Safe Life” idea started in the eighties.**
  - **Same as conventional safe life except the tested parts have critical flaws in critical locations.**
  - **Addresses the criticism that conventional safe life does not account for the inevitable problems that occur.**

- **FAA Rule 29.571 Amendment 28, 1989**
  - **Required either Fail-Safe or Flaw Tolerant Safe Life substantiations for all flight critical parts for Part 29**

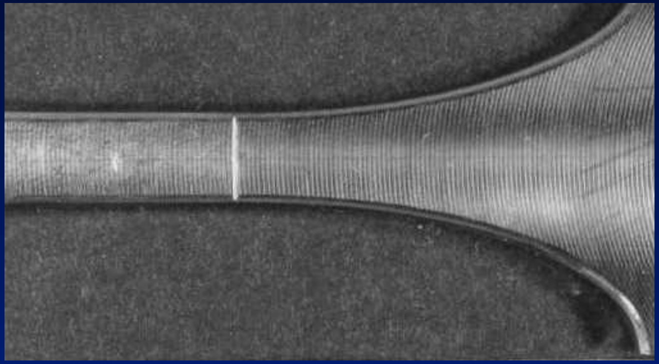
  - **Must show catastrophic failure is avoided even considering the effects of flaws and damage.**

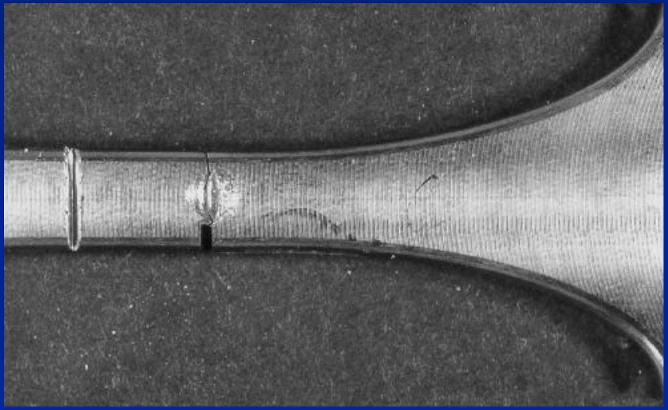
Basics of Flaw Tolerance

- Hazard Assessment
- Coupon evaluation of flaw types and sizes.
- Method for imposing Equivalent Flaws on full-scale test parts.
- S-N Testing
- Safe-Life Damage Calculation
  - Retirement times based on results with “barely detectable” flaws, a worst case of undetectable flaws.
  - Inspection intervals based on results with “clearly detectable” flaws, inspecting for the flaws.

Selection of Flaw Sizes

- “Barely Detectable” Flaws - .005” Deep.
  - Basis for retirement time.
  - Worst case of “undetectable” flaws.
  - Coupon strength reductions:
    - Mechanical: 0 to 5%
    - Corrosion: up to 15%





- “Clearly Detectable” Flaws - .040” Deep.
  - Basis for inspection interval.
  - Low probability of occurrence.
  - High probability of detection.
  - Focus for scheduled directed inspections.
  - Coupon strength reductions up to 56%.

Composites Issues

- Composites tend to have excellent fail-safety - easy inspections and graceful failure modes.

- But can be susceptible to damage
  - Manufacturing flaws – voids, disbonds, delams, fiber misplacement, etc.
  - Environmental degradation due to temperature and moisture exposure.
  - Impact damage – tool drops, runway debris.

- And can be sensitive to loads excursions because of flat S/N curve shapes.