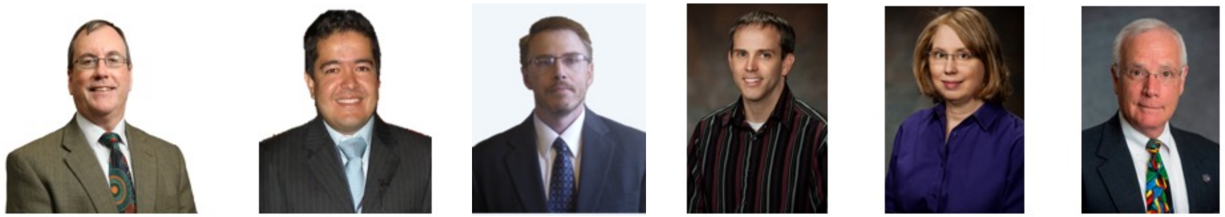
Smart|DT Overview

Aircraft Airworthiness and Sustainment Conference

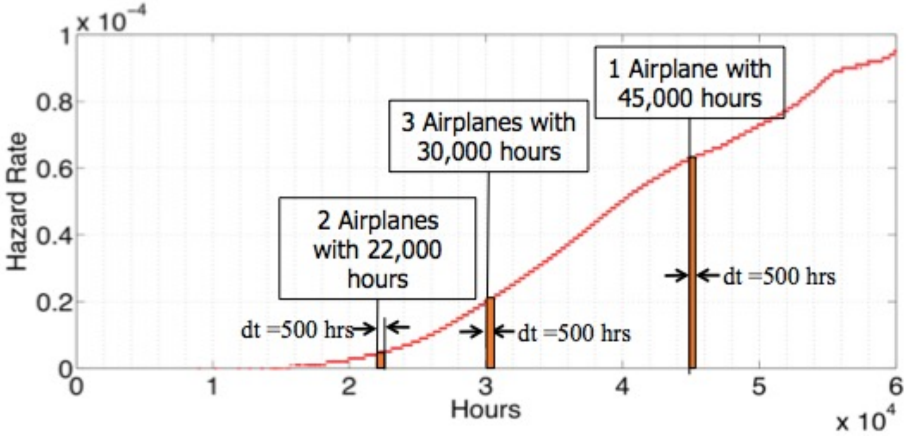
August 29, 2022



AA&S The Aircraft Airworthiness & Sustainment Conference
August 29 - September 1, 2022

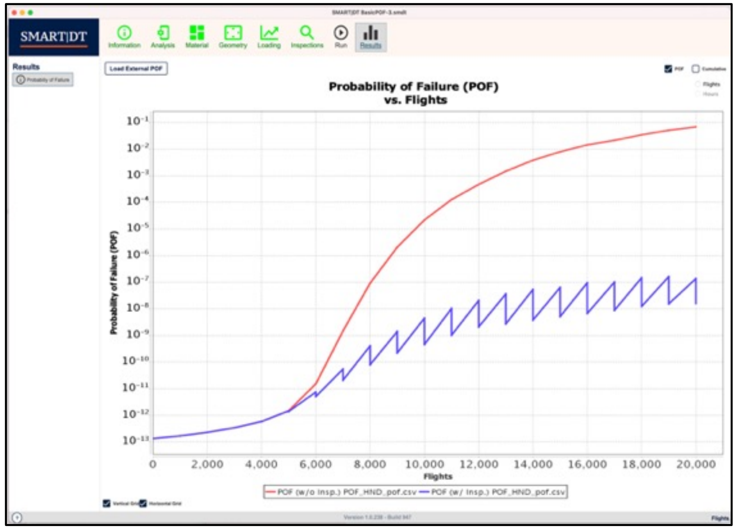
Program Overview

Probabilistic Fatigue Analysis (Smart|LD)

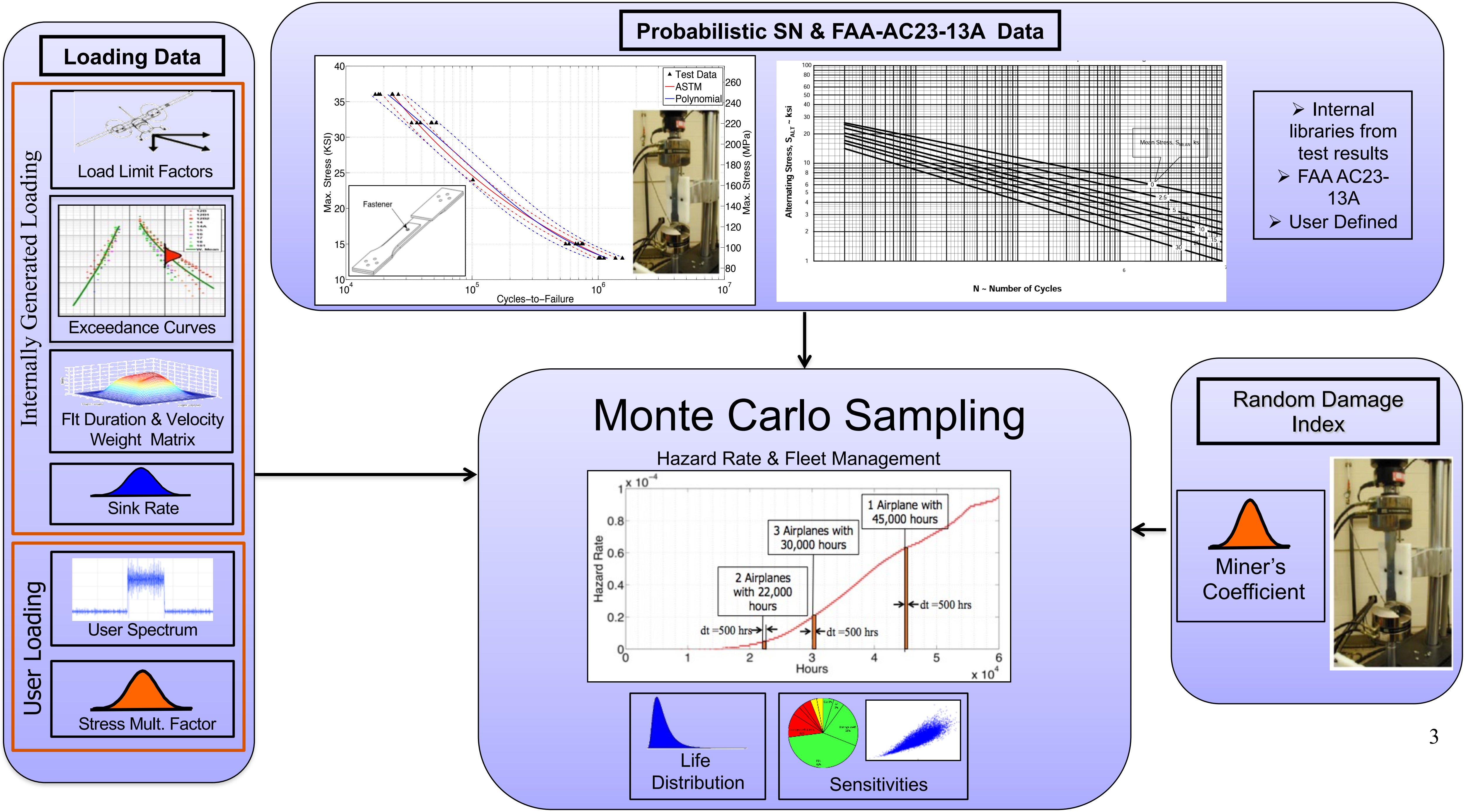


- Miner's rule
- Probabilistic S-N curves
- Exceedance curves
- Sensitivities
- Fleet management

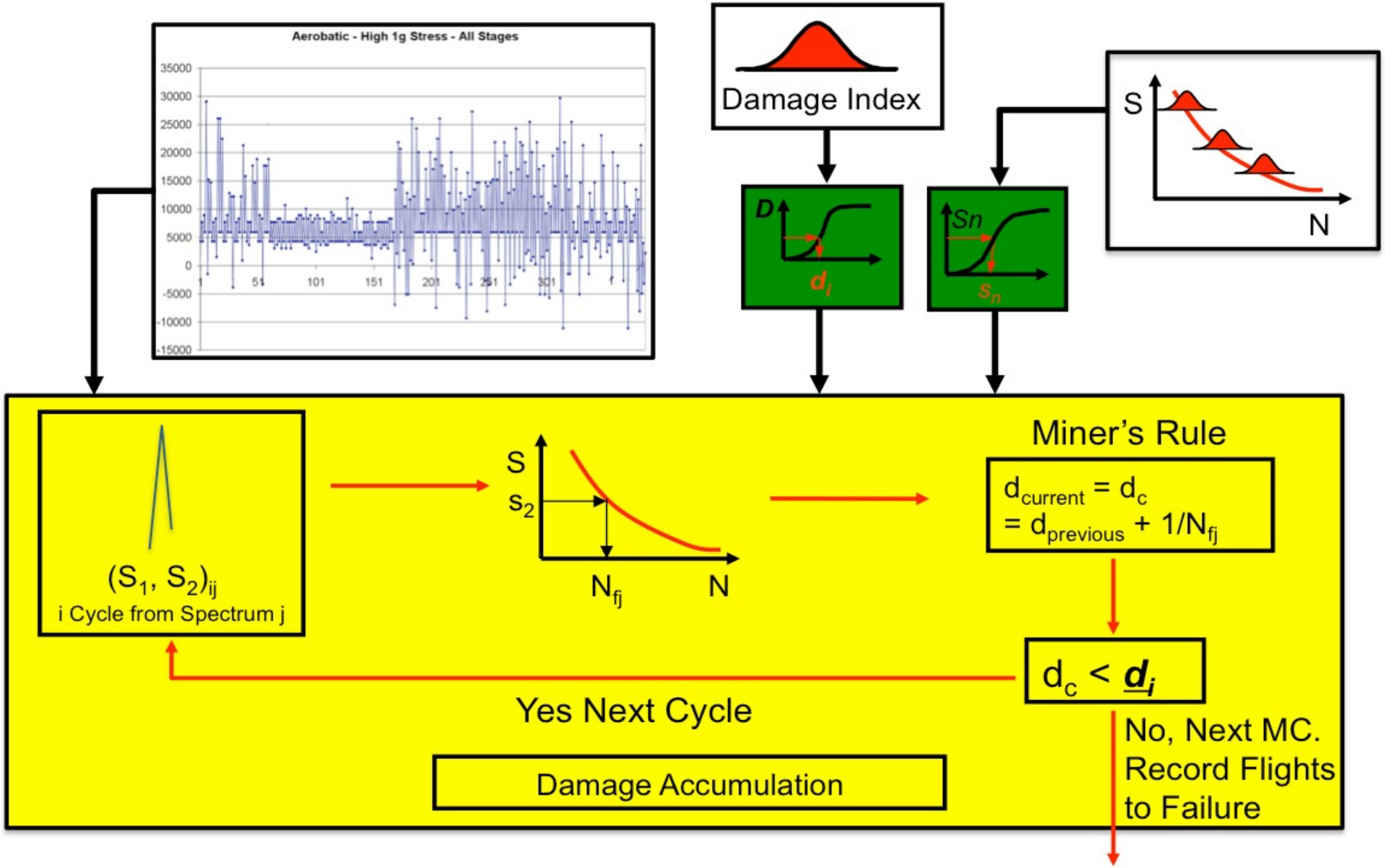
Probabilistic Damage Tolerance Analysis (Smart|DT)



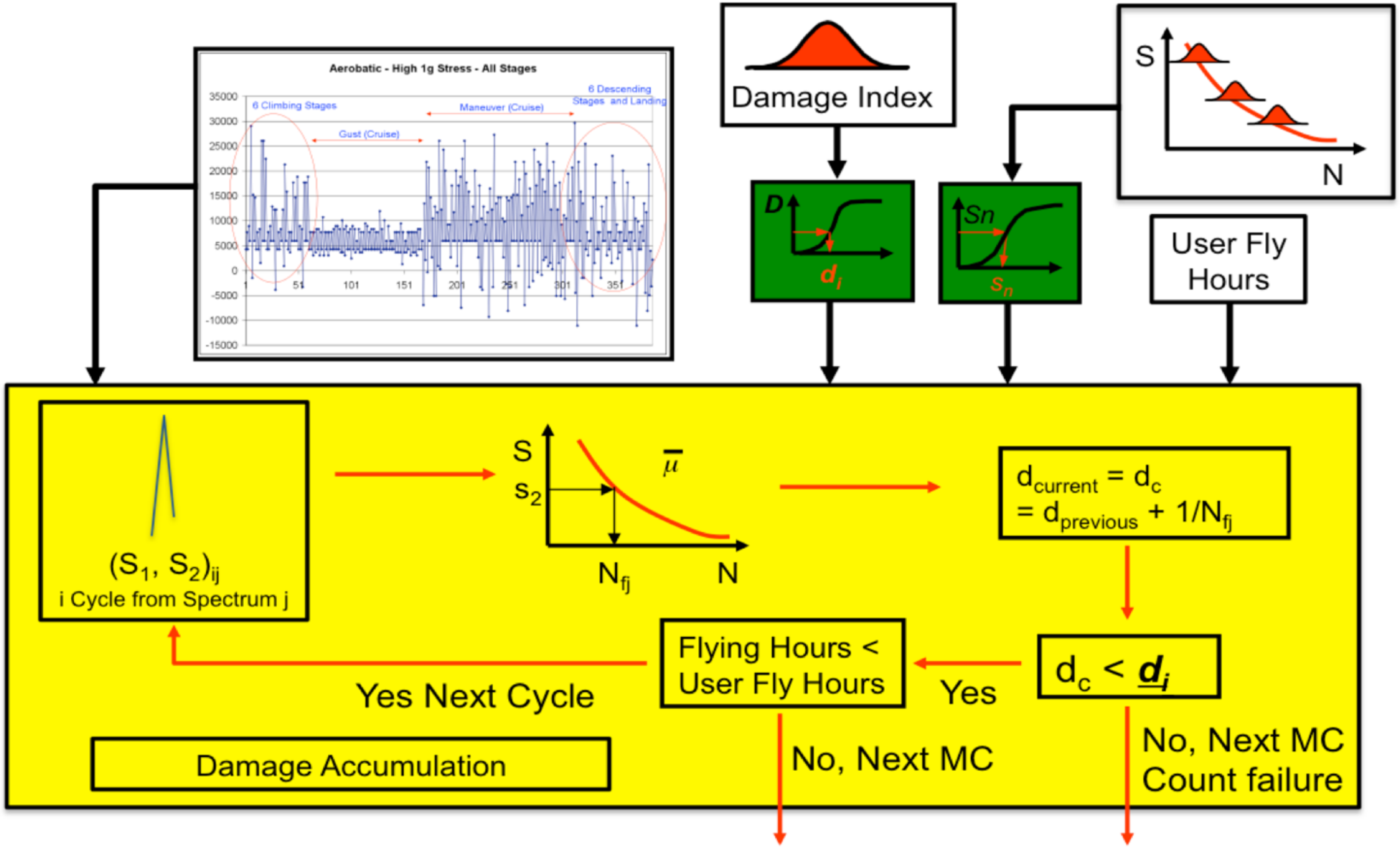
- Crack growth analysis
- Loading
- Single-flight probability of failure
- Inspection/Repair Effect
- Optimized inspections


Loading Data
Internally Generated Loading
Load Limit Factors
Exceedance Curves
Flt Duration & Velocity Weight Matrix
Sink Rate
User Loading
User Spectrum
Stress Mult. Factor
Probabilistic SN & FAA-AC23-13A Data
Max. Stress (KSI)
Max. Stress (MPa)
Cycles–to–Failure
Test Data
ASTM
Polynomial
Fastener
Alternating Stress, S_{ALT} ~ ksi
N ~ Number of Cycles
Internal libraries from test results
FAA AC23-13A
User Defined
Monte Carlo Sampling
Hazard Rate & Fleet Management
Hazard Rate
Hours
1 Airplane with 45,000 hours
3 Airplanes with 30,000 hours
2 Airplanes with 22,000 hours
dt =500 hrs
Life Distribution
Sensitivities
Random Damage Index
Miner's Coefficient

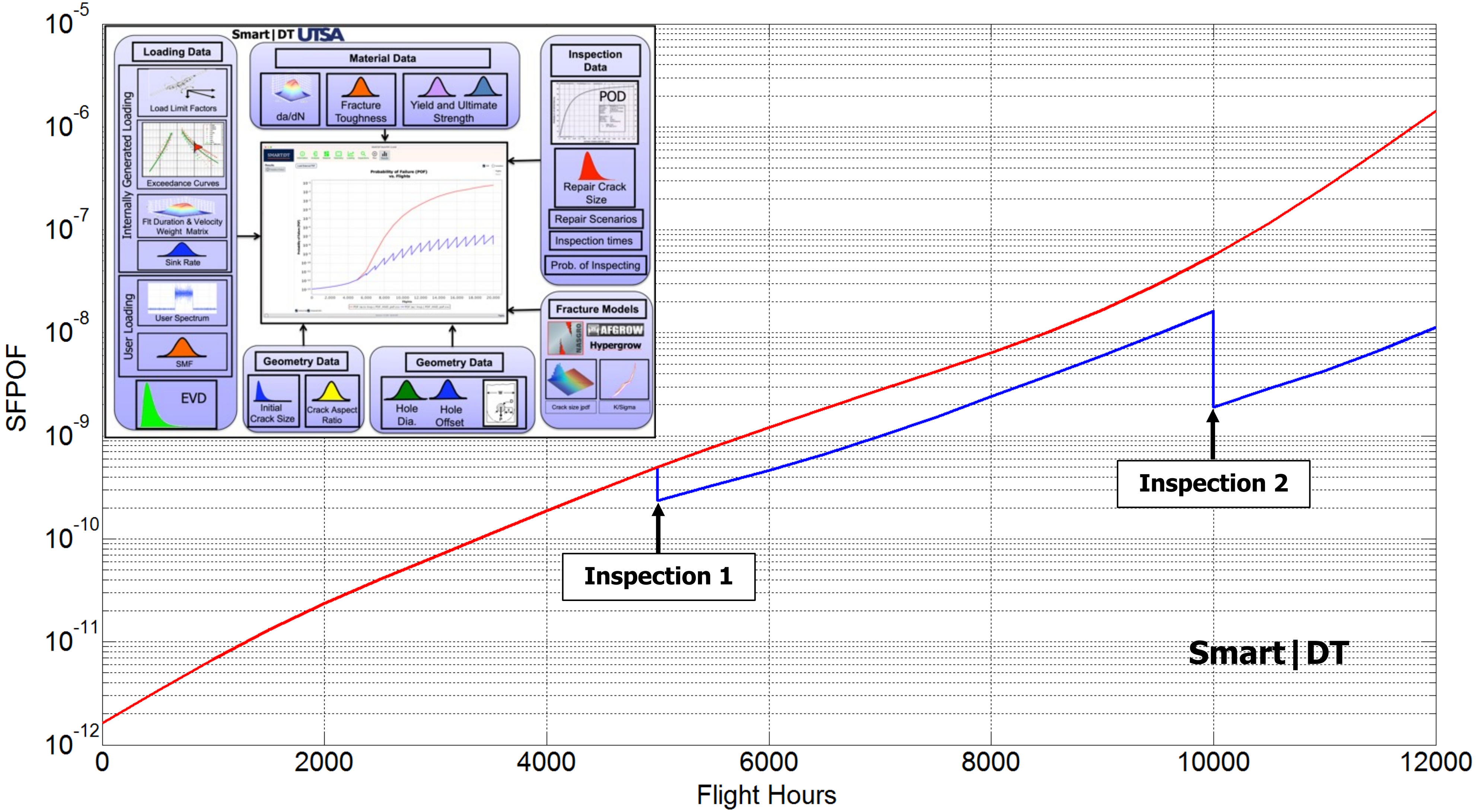
Damage Methodology (Safe Life)



Hours Methodology (Current-Future Risk)



Risk Assessment



Probability Equations

The probability-of-failure is the probability that maximum value of the applied stress (during the next flight) will exceed the residual strength σ_{RS} of the aircraft component

$$POF_{\text{no-surv}}(t) = P\left[\sigma_{Max} > \sigma_{RS}(t)\right] = \int \left[1 - F_{EVD}\left(\sigma_{RS}(t)\right)\right] f_{\mathbf{x}}(\mathbf{x})\, d\mathbf{x}$$

Lincoln formulation

(default in Smart|DT)

$$CTPOF(t) = \int \left[1 - \prod_{i=1}^{t} F_{EVD}\left(\sigma_{RS}(t_i)\right)\right] f_{\mathbf{x}}(\mathbf{x})\, d\mathbf{x}$$

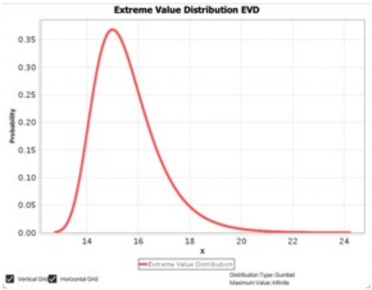
$$Hz(t) = \frac{POF_{\text{surv}}(t)}{1 - CTPOF(t)}$$

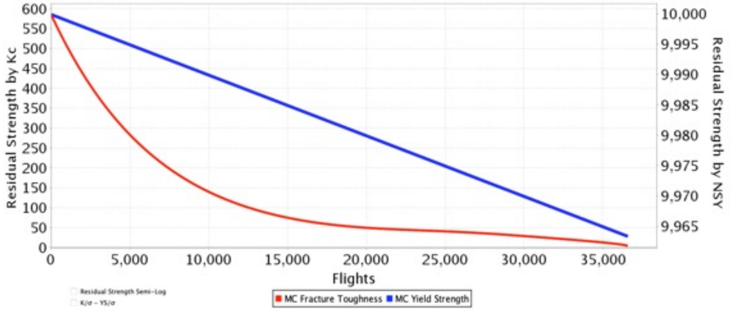
$$POF_{\text{surv}}(t) = \int \left[\prod_{i=1}^{t-1} F_{EVD}\left(\sigma_{RS}(t_i)\right)\right]\left[1 - F_{EVD}\left(\sigma_{RS}(t)\right)\right] f_{\mathbf{x}}(\mathbf{x})\, d\mathbf{x}$$

Freudenthal formulation

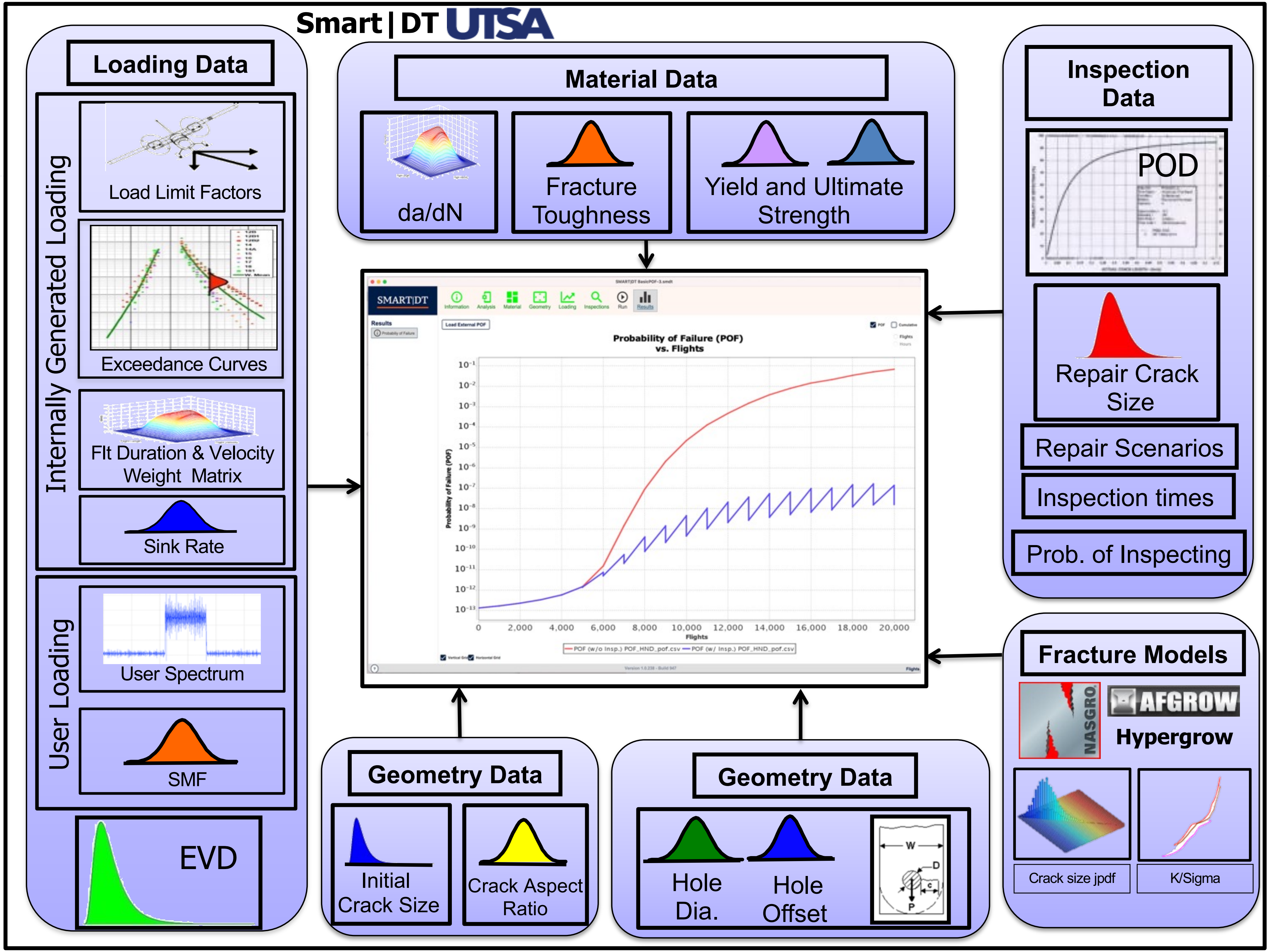
F_{EVD} – CDF of the maximum stress per flight (extreme value distribution)

$\sigma_{RS}(t)$ – residual strength





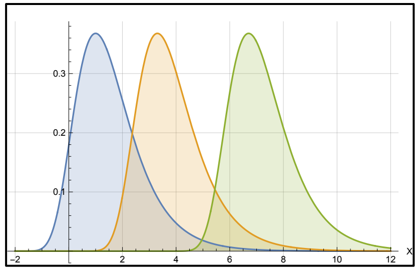
Smart|DT

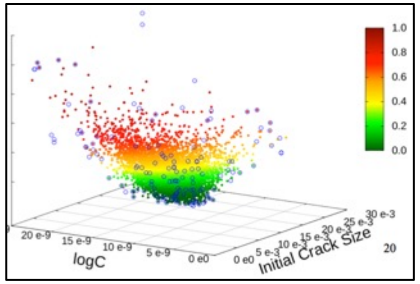

Smart | DT UTSA
Loading Data
Internally Generated Loading
Load Limit Factors
Exceedance Curves
Flt Duration & Velocity
Weight Matrix
Sink Rate
User Loading
User Spectrum
SMF
EVD
Material Data
da/dN
Fracture Toughness
Yield and Ultimate Strength
Inspection Data
POD
Repair Crack Size
Repair Scenarios
Inspection times
Prob. of Inspecting
SMART|DT
Probability of Failure (POF) vs. Flights
Probability of Failure (POF)
Flights
POF (w/o Insp.) POF_HND_pof.csv
POF (w/ Insp.) POF_HND_pof.csv
Fracture Models
NASGRO
AFGROW
Hypergrow
Crack size jpdf
K/Sigma
Geometry Data
Initial Crack Size
Crack Aspect Ratio
Geometry Data
Hole Dia.
Hole Offset

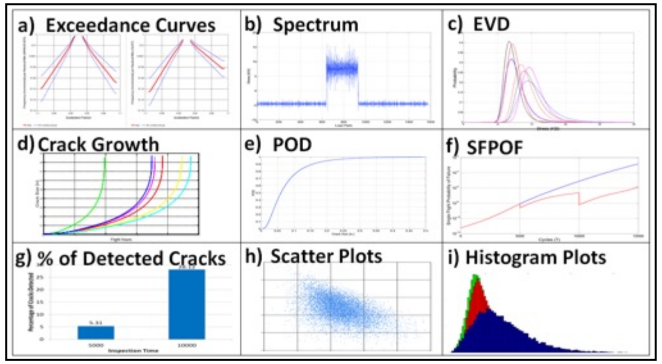
Smart|DT Capabilities

Version 1

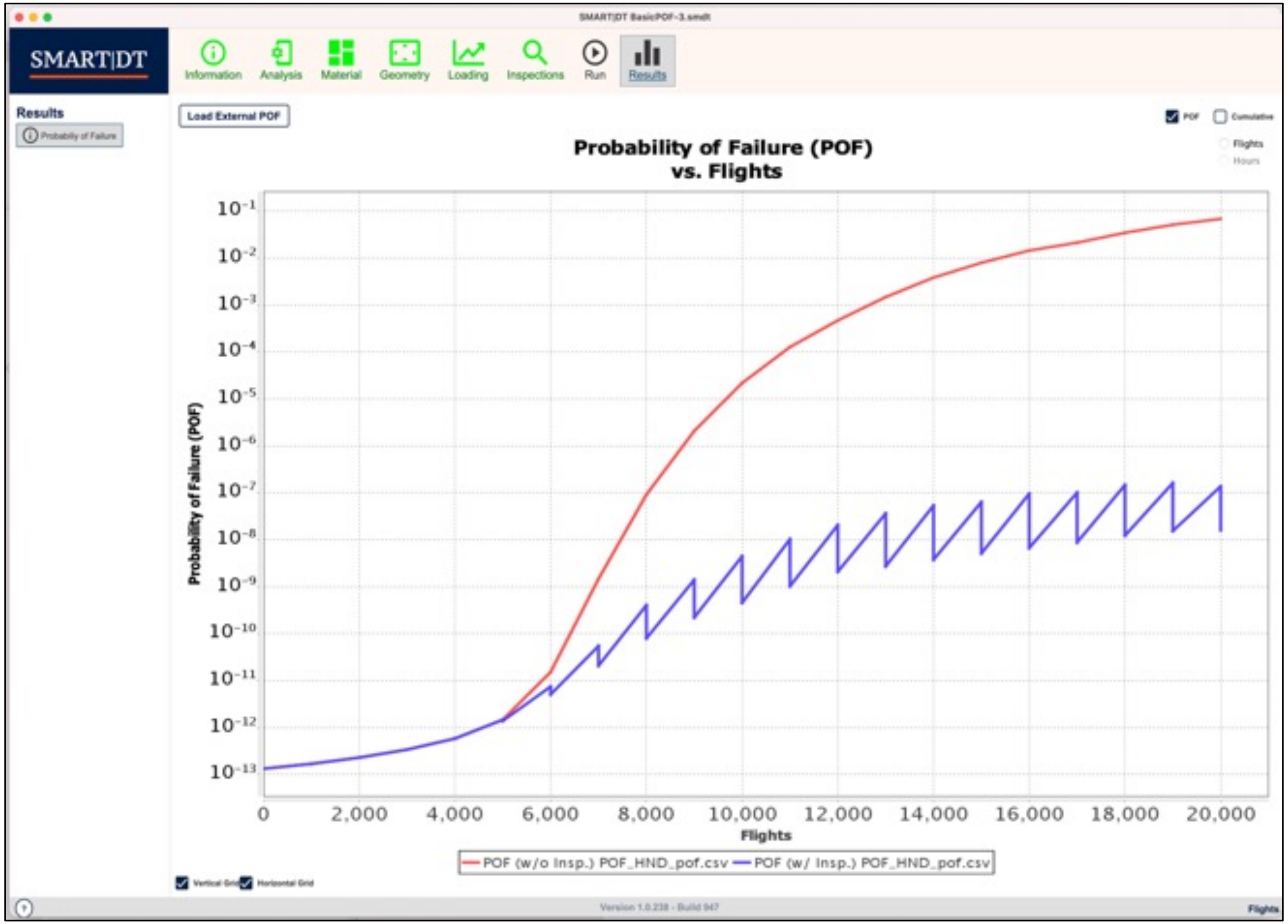
- Loading Generation
  - Computed from exceedance curves (Internal library and user exceedance option) – weighted usage available.
  - Flight duration and weight matrices, design load limit factors, one-g stress, and ground stress as user input.
  - Stresses and/or flights randomizations
  - Spectrum editing option (rainflow, rise/fall, dead band)
  - User-defined spectra (Afgrow format)
- Extreme Value Distribution for Loads
  - User input: Gumbel, Frechet , or Weibull-Max.
  - Ultimate/Limit load (deterministic)
  - Computed from exceedance curves, weight matrix, etc. (Gumbel, Frechet , and Weibull)
- Probability calculations
  - POF (Lincoln & Freudenthal formulations)
  - Cumulative POF
  - Crack size quantiles
  - Remaining useful life
  - Percent of cracks detected
- Crack growth
  - Master curve method for crack growth interpolation (user input)
  - Hypergrow internal crack growth code
  - Direct link to Afgrow, Nasgro (v 7.1)
- Probabilistic methods
  - Standard Monte Carlo
  - Weighted branch integration method
  - Adaptive Importance sampling
  - Numerical integration
- Inspection capabilities
  - Any number of inspections (arbitrary limit set to 40)
  - Arbitrary repair crack size distribution (lognormal, tabular, Weibull, deterministic, perfect)
  - Arbitrary POD (lognormal, tabular, deterministic)
  - User defined probability of inspection
  - Different repair scenarios within/between inspections
  - Database of POD curves (eddy current, FPI, MPI, ultrasonic, visual, x-ray)
- Random variables w probabilistic database
  - Initial crack size, repair crack size, fracture toughness, exceedance curves, POD
  - yield strength, ultimate strength
  - da/dN, hole diameter, hole offset, crack aspect ratio, loading variation
- Computational implementation
  - Standard Fortran 95/03/08, Windows and Unix (Intel ifort compiler)
  - HPC Implementation (parallel: OpenMP and vectorized)







Graphical User Interface



Random Variable Summary

Random Variable	Options	Probabilistic Database
Initial Crack Size	Lognormal, Weibull, Tabular, Tabular joint a and c	✓
Fracture Toughness	Normal, tabular	✓
Extreme Load per Flight	Gumbel, Weibull-Max, Frechet	
da/dN Parameters	Correlated normal	
Crack Aspect Ratio	Normal, Tabular	
Hole Diameter	Normal, Tabular	
Hole Offset	Normal	
Yield Strength	Normal	✓
Ultimate Strength	Normal	✓
Peak Stress	Uniform	
Random variables and distribution options ***expandable***		

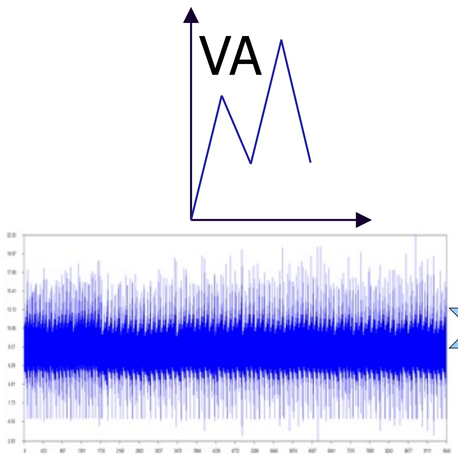
✓ Version 1

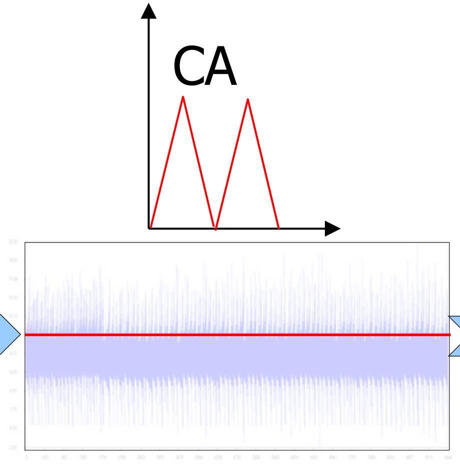
Fracture Mechanics Links

- ✓ User-supplied Master Curve:
  - ✓ User supplies the crack growth and residual strength vs. flights information
- ✓ HyperGrow - Internal crack growth code
- ✓ Link to AFGROW - Users needs to have a version of AFGROW installed on their computer. Com interface.
- ✓ Link to NASGRO - SMART|DT is delivered with NASGRO V7.1 to NASGRO users or FAA employees and contractors. File-based interface.
  - ✓ API link to Nasgro under development

Version 1

HyperGrow - Internal CG Code

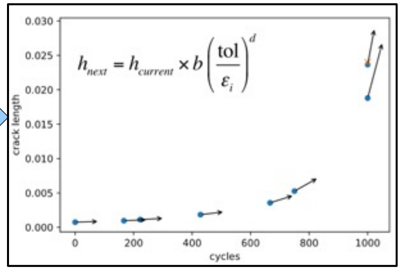




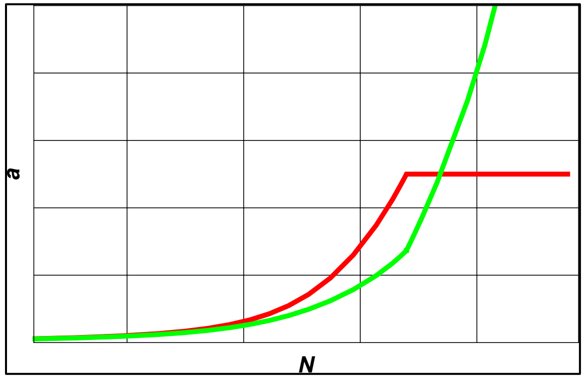
ODE Formulation

$$\frac{da}{dN} - C(\Delta K(a,c))^n = 0$$
$$\frac{dc}{dN} - C(\Delta K(a,c))^n = 0$$
$$Initial\ Conditions: a(0) = a_i, c(0) = c_i$$

RK ODE Solver

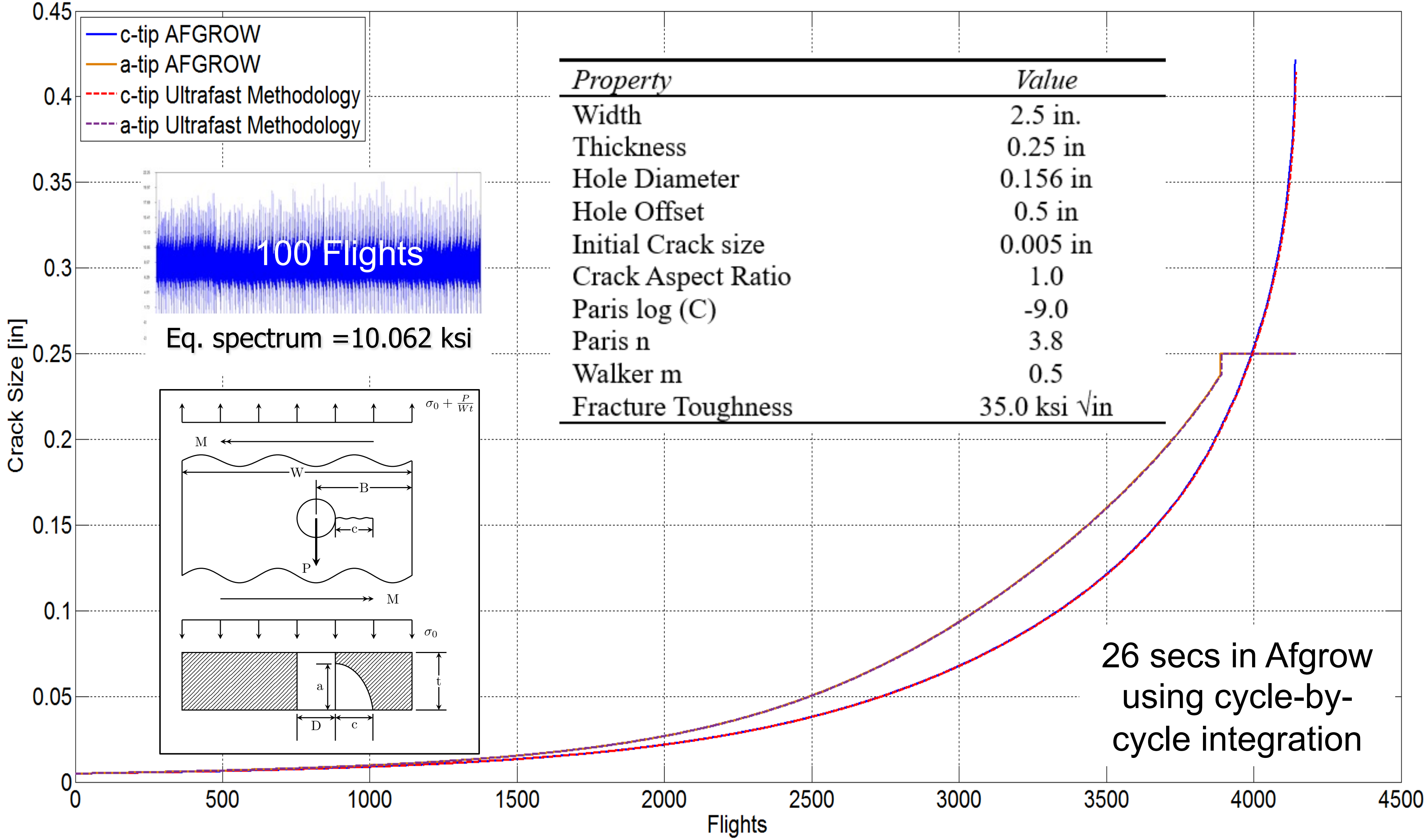


Crack Growth Result



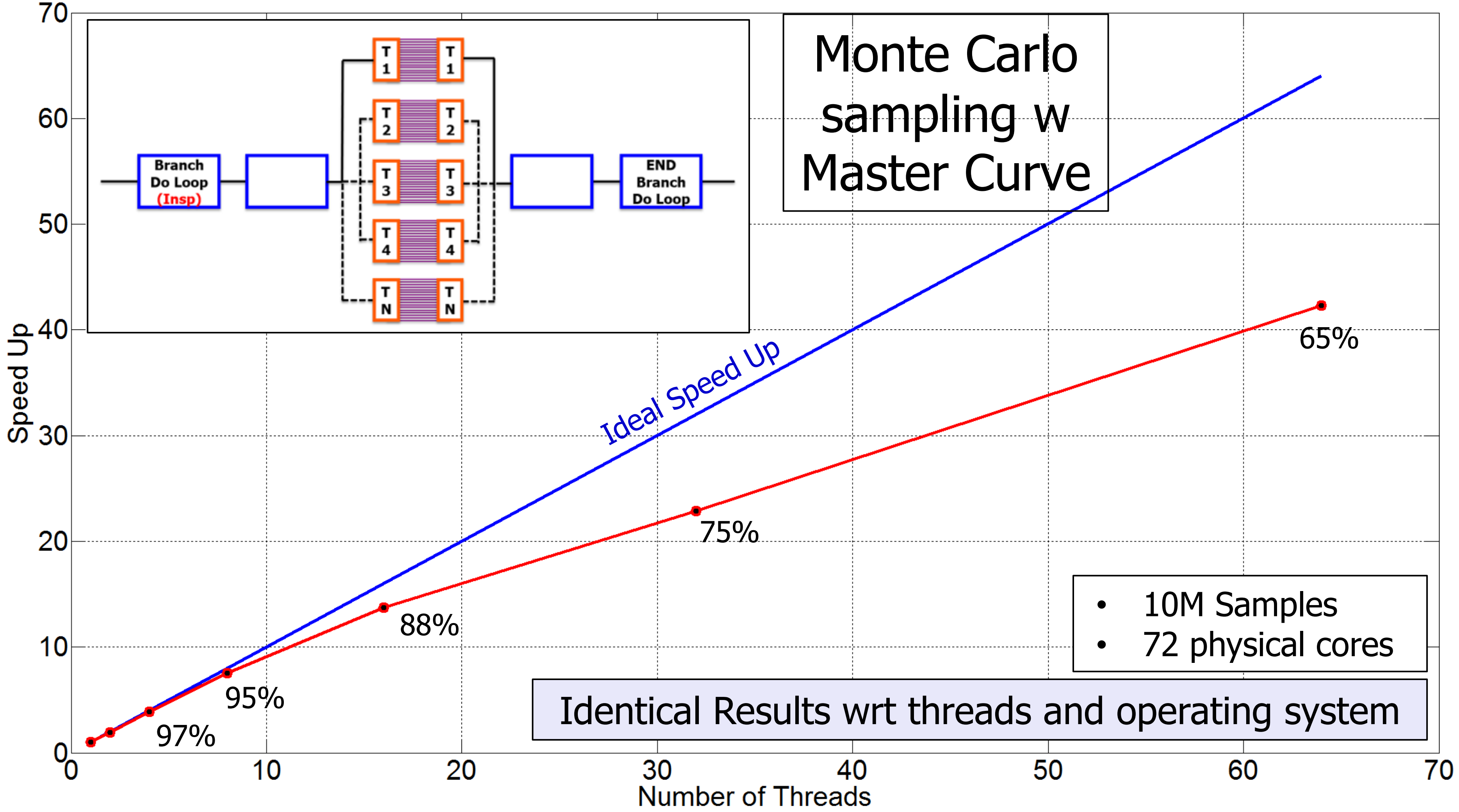
ICG Capabilities	
Method	4-5th order Runge-Kutta
Accuracy	Error controlled by user input
Speed	~10000/sec single proc.
Parallel	95% speedup on 8 proc.
K solutions	Newman-Raju, read beta tables

Corner Crack at Hole
(Tension)



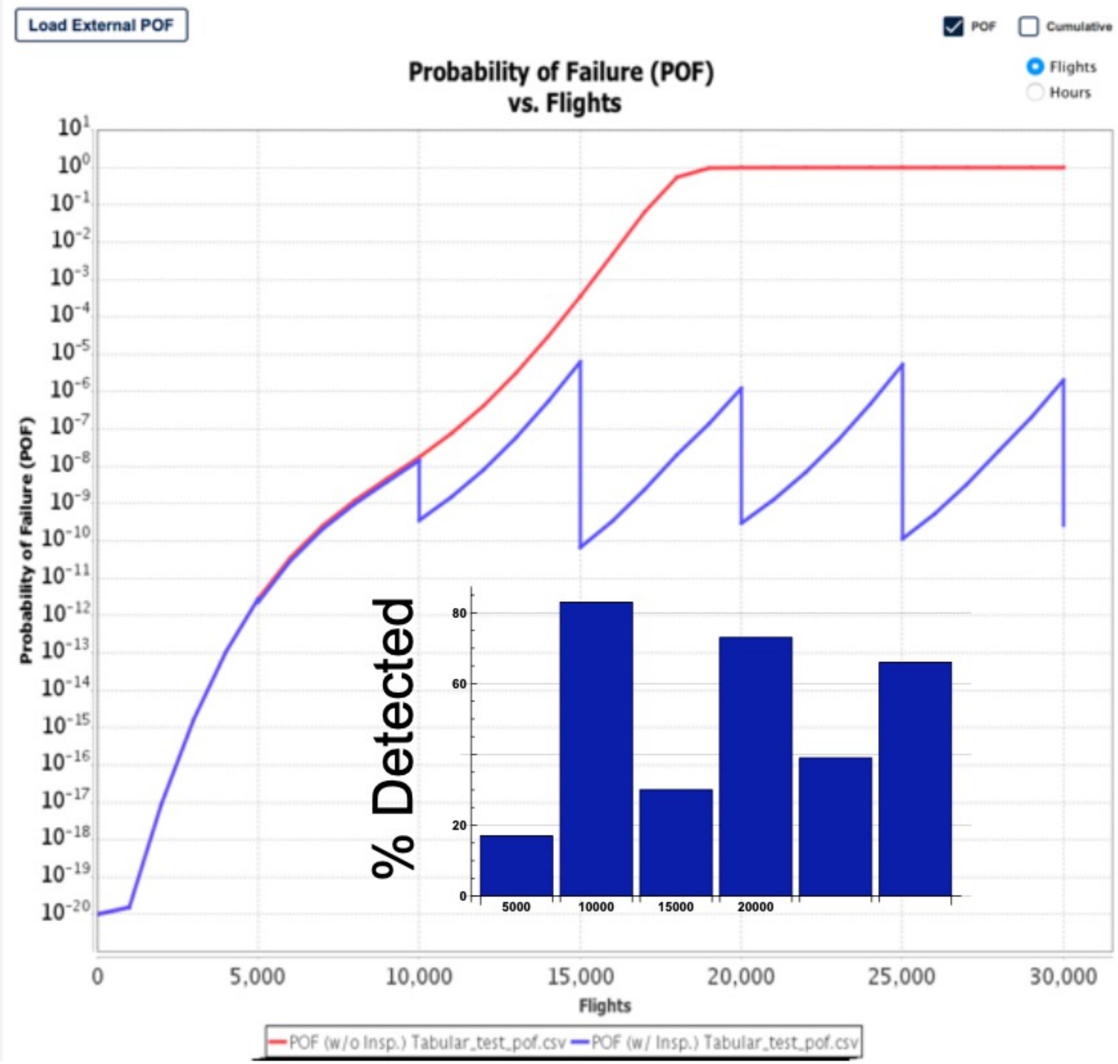
Property	*Value*
Width	2.5 in.
Thickness	0.25 in
Hole Diameter	0.156 in
Hole Offset	0.5 in
Initial Crack size	0.005 in
Crack Aspect Ratio	1.0
Paris log (C)	-9.0
Paris n	3.8
Walker m	0.5
Fracture Toughness	35.0 ksi √in

Parallel & Vectorized



Inspection & Repair

POF



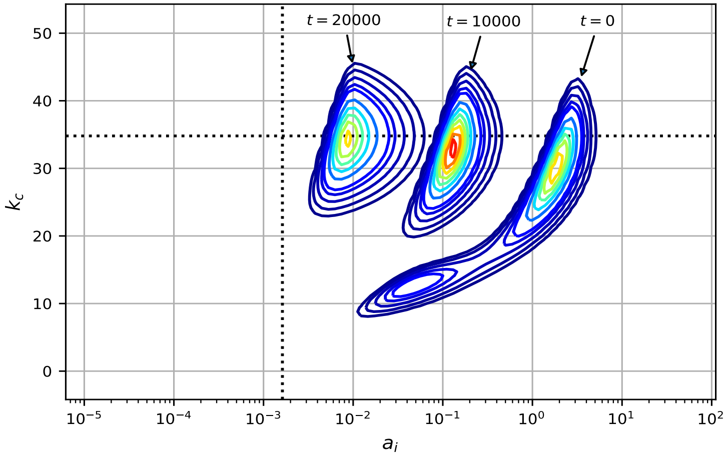
- 100+ built-in POD curves
  - (Visual, eddy current, FPI, X-ray, ultrasound)
- Arbitrary repair crack size
- Probability of inspection

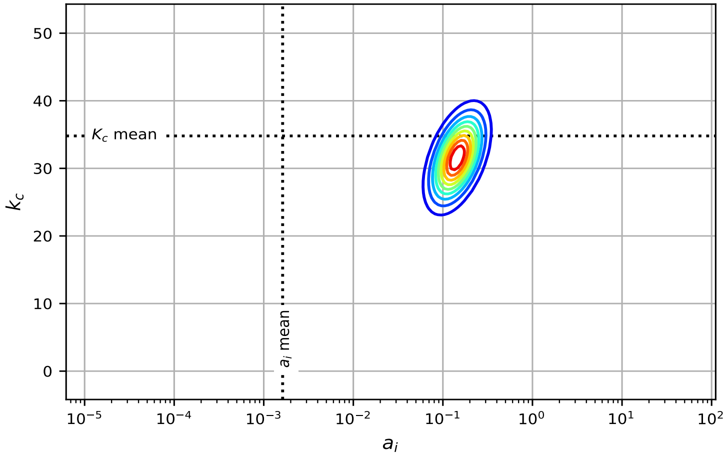
Multiple Adaptive Importance Sampling

Traditional

Important Region(s) | Adapted Sampling Region

Individual Times

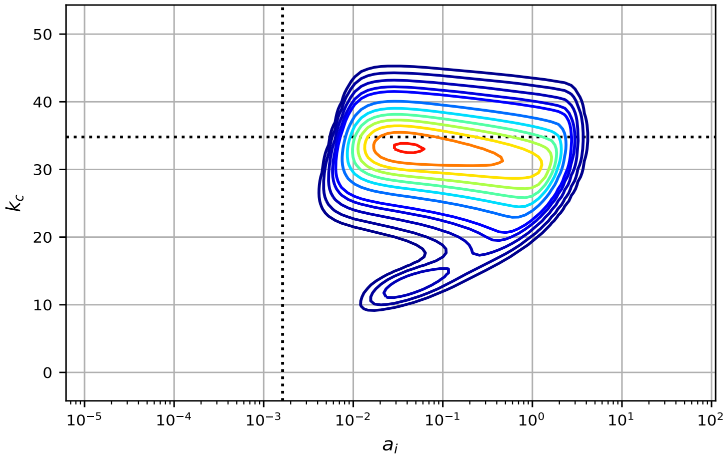


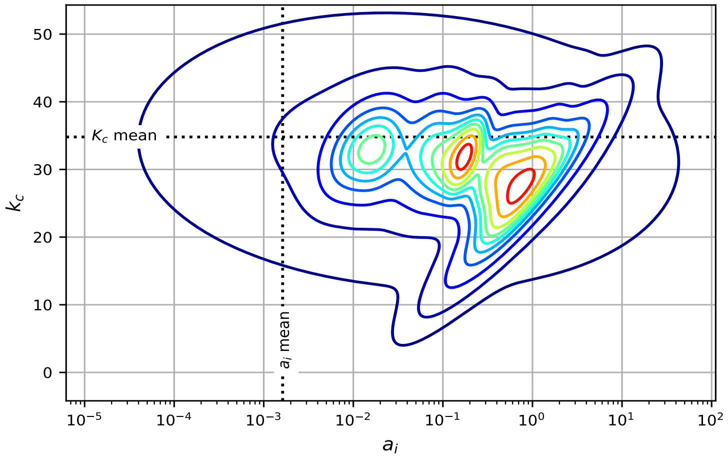


- Basic Importance sampling
  - Adapt single sampling densities for individual evaluation times

AMIS

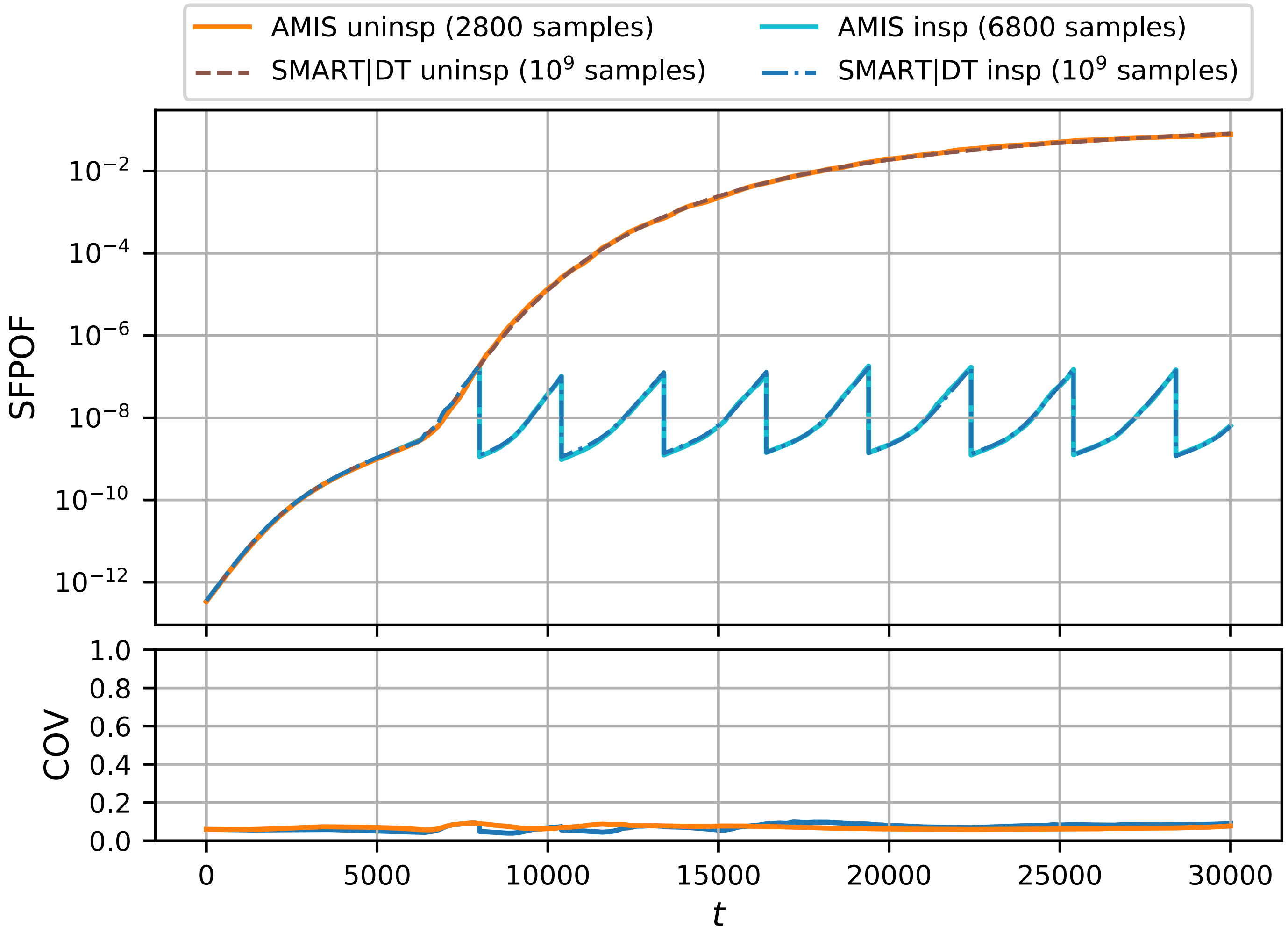
Multiple Times





- Multiple Importance Sampling
  - Adapt a mixture density for a range of evaluation times

POF Results After Adding 8 Inspections



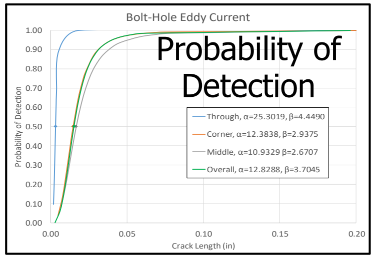
- PDTA AMIS
  - 2800 samples for uninspected POF
  - 6800 samples for inspected POF after adding 8 inspections one-at-a-time

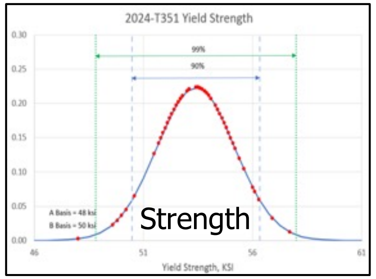
- PDTA AMIS in excellent agreement with SMC using 10^9 samples

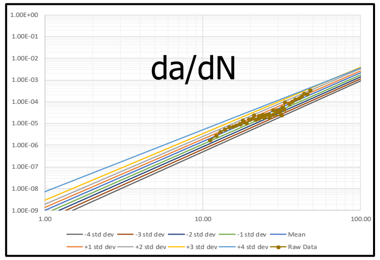
The PDTA AMIS algorithm estimates POF for PDTA using 6 orders of magnitude fewer samples compared to SMC for probabilities of 10^{-7}

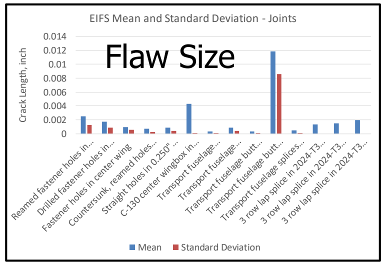
Probabilistic Database

- **Flaw size**: Size (EIFS); Crack aspect ratio (a/c)
  - Commercial transport, military fighter, military transport
- **Geometry: Fastener hole diameter; Edge distance**
- **Inspections: Probability of detection**
  - Eddy current, FPI, MOI, Ultrasonic, visual, x-ray
- **Material Properties: Fracture toughness; Yield/ultimate strength, da/dN**
- **Al: 8 groups, 35 treatments**
    - 2014(3 treatments), 2024(7), 2124, 7050(7), 7075(10), 7150, 7175, 7474(3)
  - Steel: 9 groups, 18 treatments
    - 300, 4130(2), 4330, 4340(4), AMS 6526, Aeromet(4), D6AC(4), Ph13
  - Ti: 1 group, 2 treatments
    - 6Al-4V(2)









Analysis Sequence

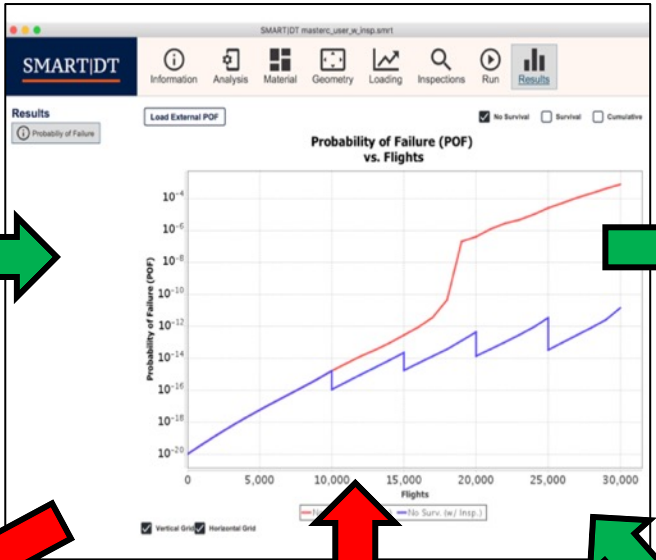
GUI

.dat input file

.exe engine

Crack growth curve

- job.avsn




```
! EXAMPLE PROBLEM 6a ASIP 16 TRAINING
! RANDOM AI, and Kc, GUMBEL EVD,
! MONTECARLO, INSPECTIONS, DETERMISTIC
! POD, POF
                FRACTURE MECHANICS
 -----------------------------------------
CRACK_GROWTH_CODE = MASTERC_USER
MasterCurve_e100.avsn 34.8D0
INITIAL_CRACK_SIZE = LOGNORMAL 5.0D-3 3.0D-3
FRACTURE_TOUGHNESS = NORMAL 34.8D0 3.4D0
```

```
************************************************
********* Beginning PDTA analysis *********
************************************************

Finished reading input data

  Branch Number =     1 (Samples =    10000000)    32 Threads
  Sample no.       1000000      10 % complete.
  Sample no.       2000000      20 % complete.
  Sample no.       3000000      30 % complete.
  Sample no.       4000000      40 % complete.
  Sample no.       5000000      50 % complete.
  Sample no.       6000000      60 % complete.
  Sample no.       7000000      70 % complete.
  Sample no.       8000000      80 % complete.
  Sample no.       9000000      90 % complete.
  Sample no.      10000000     100 % complete.
  Branch Number =     2 (Samples =     7600000)
  Sample no.        760000      10 % complete.
  Sample no.       1520000      20 % complete.
  Sample no.       2280000      30 % complete.
  Sample no.       3040000      40 % complete.
  Sample no.       3800000      50 % complete.
  Sample no.       4560000      60 % complete.
  Sample no.       5320000      70 % complete.
  Sample no.       6080000      80 % complete.
  Sample no.       6840000      90 % complete.
  Sample no.       7600000     100 % complete.
  Branch Number =     3 (Samples =     8200001)
  Sample no.        820000      10 % complete.
  Sample no.       164000       20 % complete.
  Sample no.       24600        30 % complete.
```

Input & output json file

- job.smdt

<u>Database (json files)</u>

- Material properties
- POD curves
- Initial crack size

`job.pof` **(pof results)**

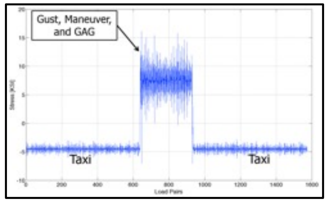
`job.out` **(all output results)**

Scriptability

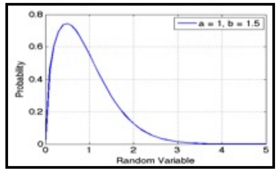
- Engine is callable from scripts to facilitate new analyses:
  - Automating a large number of analyses
  - Modifying crack growth input due to, e.g, microstructure
  - Connecting with other computer codes
  - Optimization applications
  - Adding additional random variables

Smart|DT

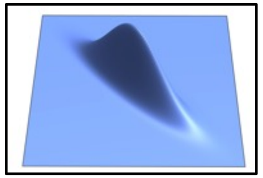
Loading Generation



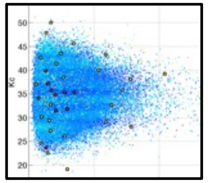
EVD Dist



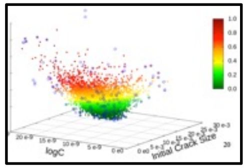
dadN variability



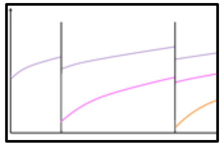
Monte Carlo



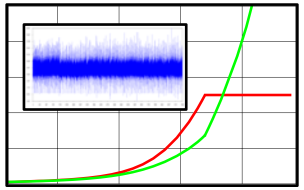
Kriging surrogate



Inspection and repair



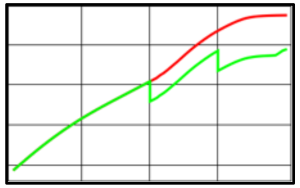
HyperGrow



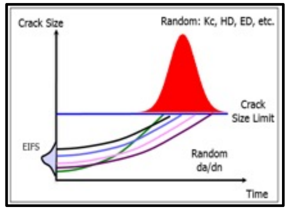
Nasgro interface

Afgrow interface w COM

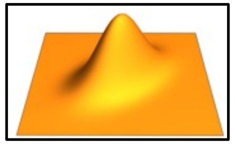
POF



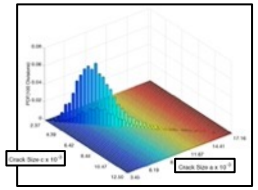
RUL



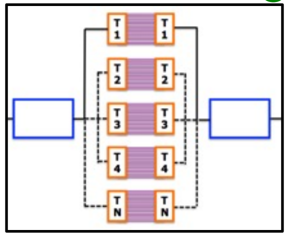
Numerical Integration



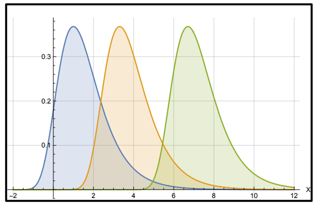
Joint a & c interpolation



HPC - multithreading



Importance sampling



GPU MPI/Cloud

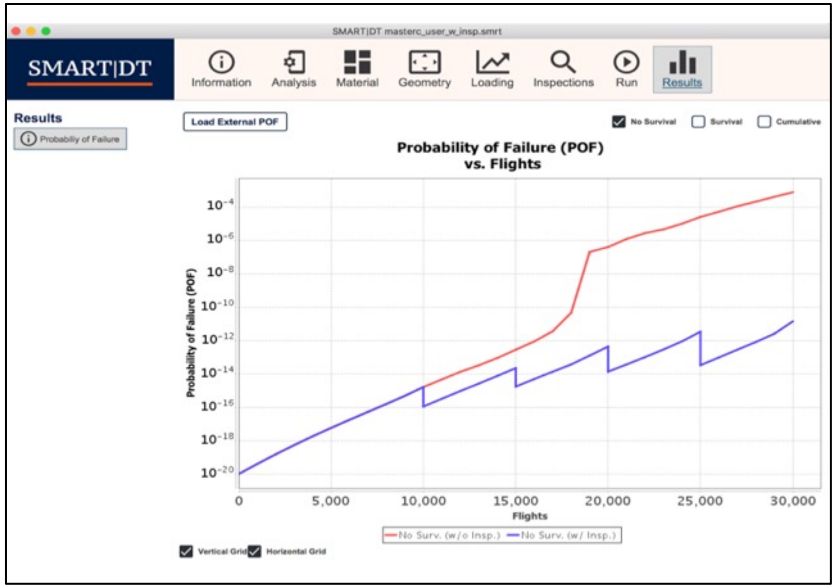
Interoperability

Scriptable

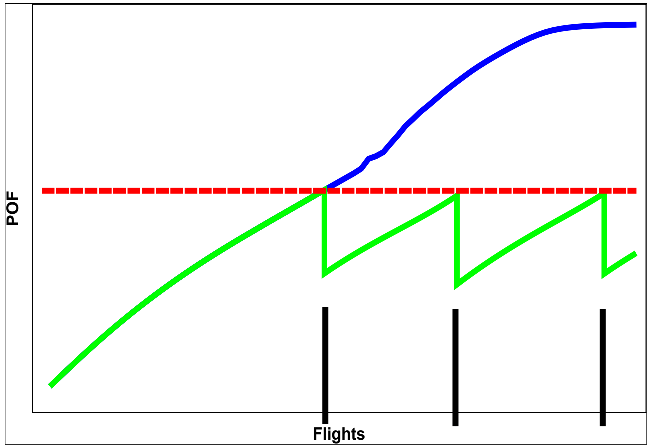
SMART|DT Current Development Activities

- Enhanced graphical user interface
- Optimized risk-based inspection schedules
- Fleet management

Graphical User Interface

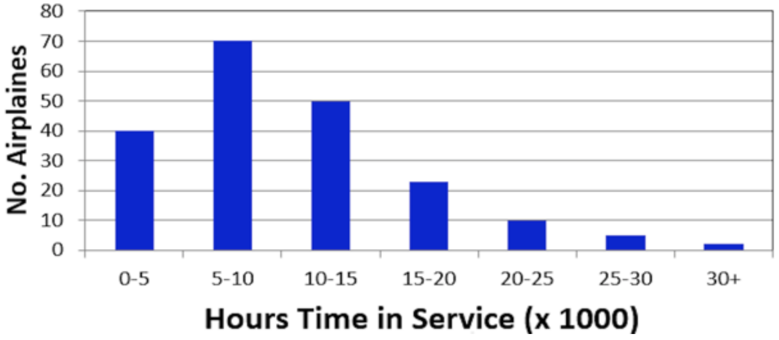


Risk-based inspections



Optimum inspection times

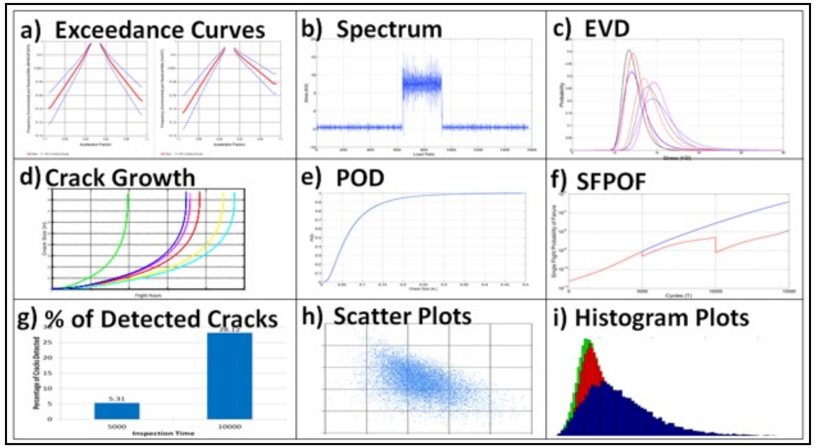
Fleet Management



Code Availability

- Code available by download.
- For more information contact:
  - harry.millwater@utsa.edu
  - jocampo@stmarytx.edu

https://smartdtsoftware.wixsite.com/smart



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