Introduction to Probabilistic Methods with Applications to Probabilistic Damage Tolerance Analysis

Inspection Overview

Harry Millwater - University of Texas at San Antonio,

Juan Ocampo, St. Mary's University,

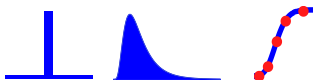
Nathan Crosby, AeroMatter Inc.

Beth Gamble, Chris Hurst, Textron Aviation (Cessna)

Marv Nuss, Nuss Sustainment Solutions

August 29, 2022

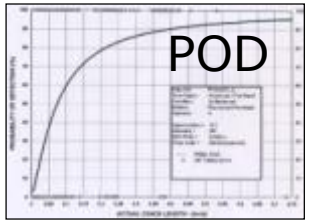
Inspection Capabilities

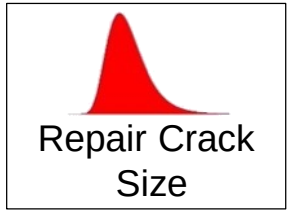
Feature	Possible Values	Notes
Inspection times	User-defined list of flight times & inspection types	Each inspection becomes a separate "branch" in the analysis
For each inspection type:		
Probability of Inspection (POI)	Range [0-1]	Weighted sum of POF w and w/o inspection
 POD	Deterministic Lognormal Tabular	Monotonic function between 0 & 1
 Repair Crack Size	Deterministic Lognormal Weibull Tabular (CDF) "Perfect"	Independent of initial crack size

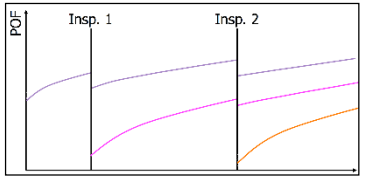
Perfect repair assumes all repaired cracks will never cause failure

Inspection Process

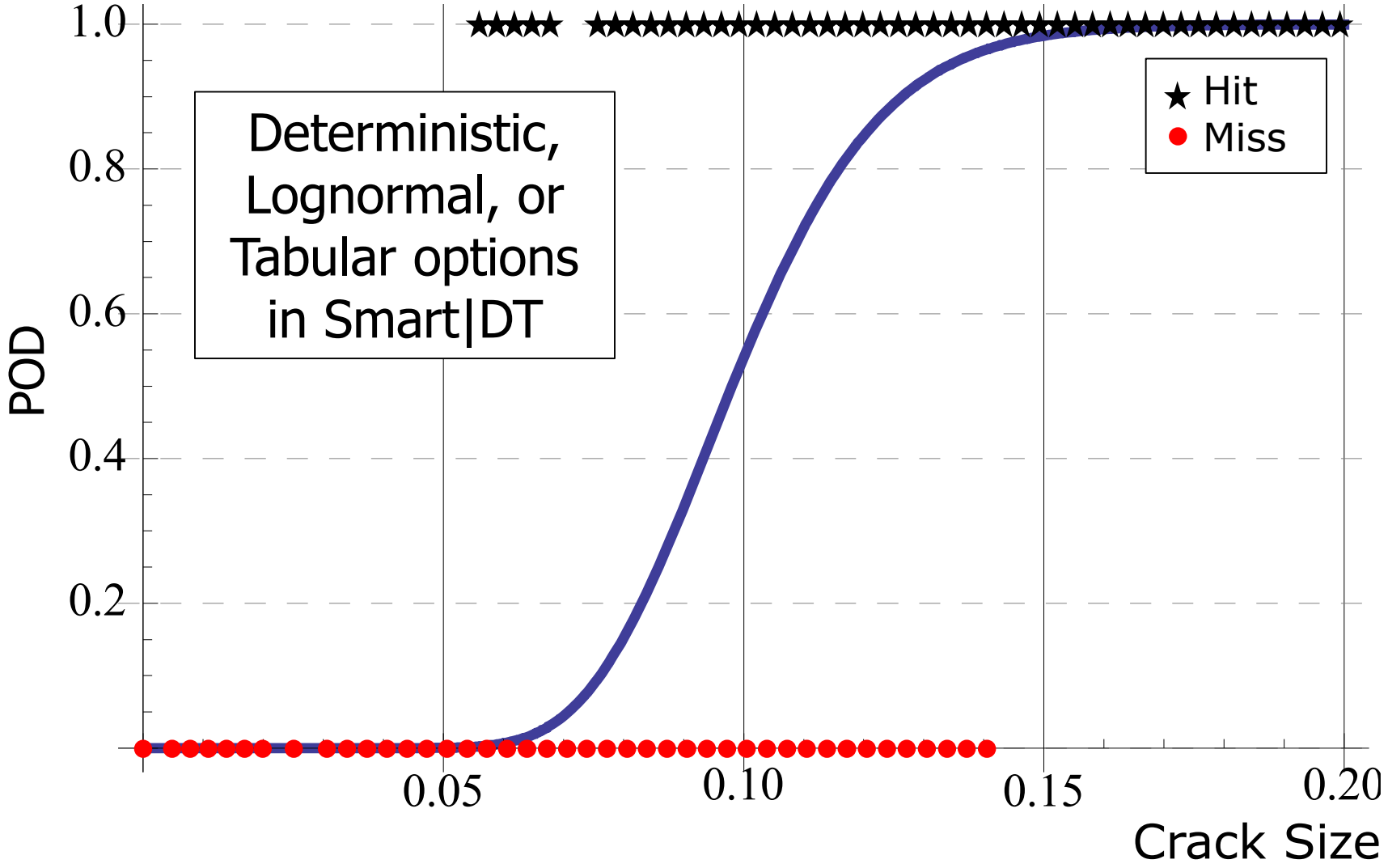
1) The crack size is passed to a POD curve which provides the probability of detecting that crack. A random number is used to decide if the crack is detected or not.
2) If detected, the crack is removed from the population and replaced with a crack from the "repair" crack size distribution.
3) The risk of all "replaced" cracks is then computed using a new "branch" and added back to the main branch.





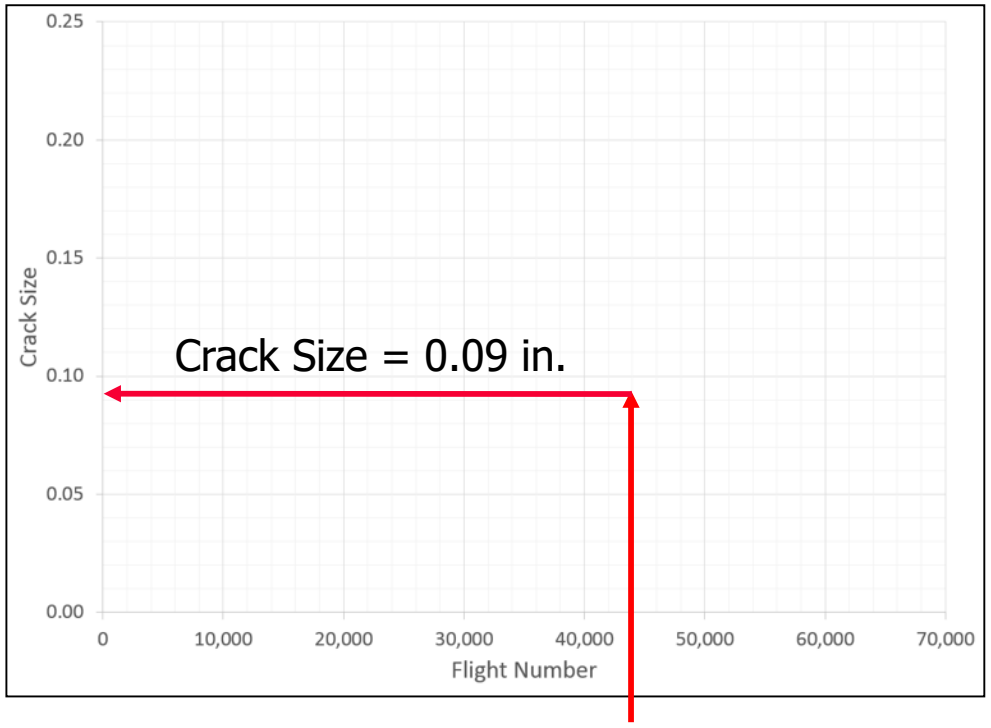


POD (Probability of Detection)

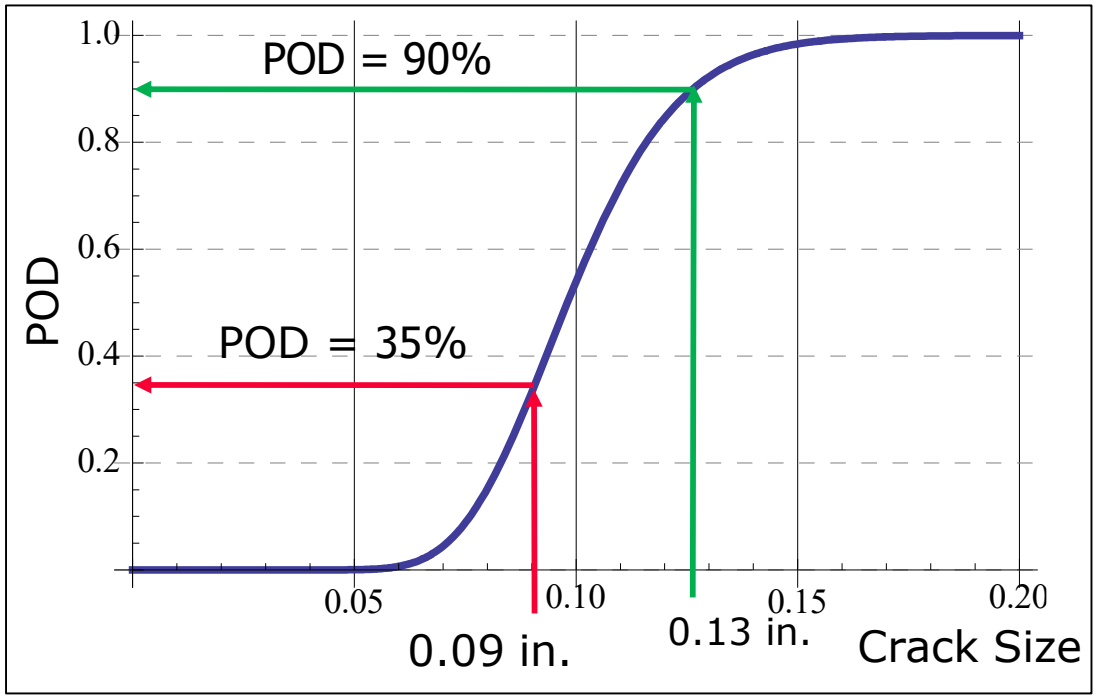


How the POD Works

Crack Growth Curve



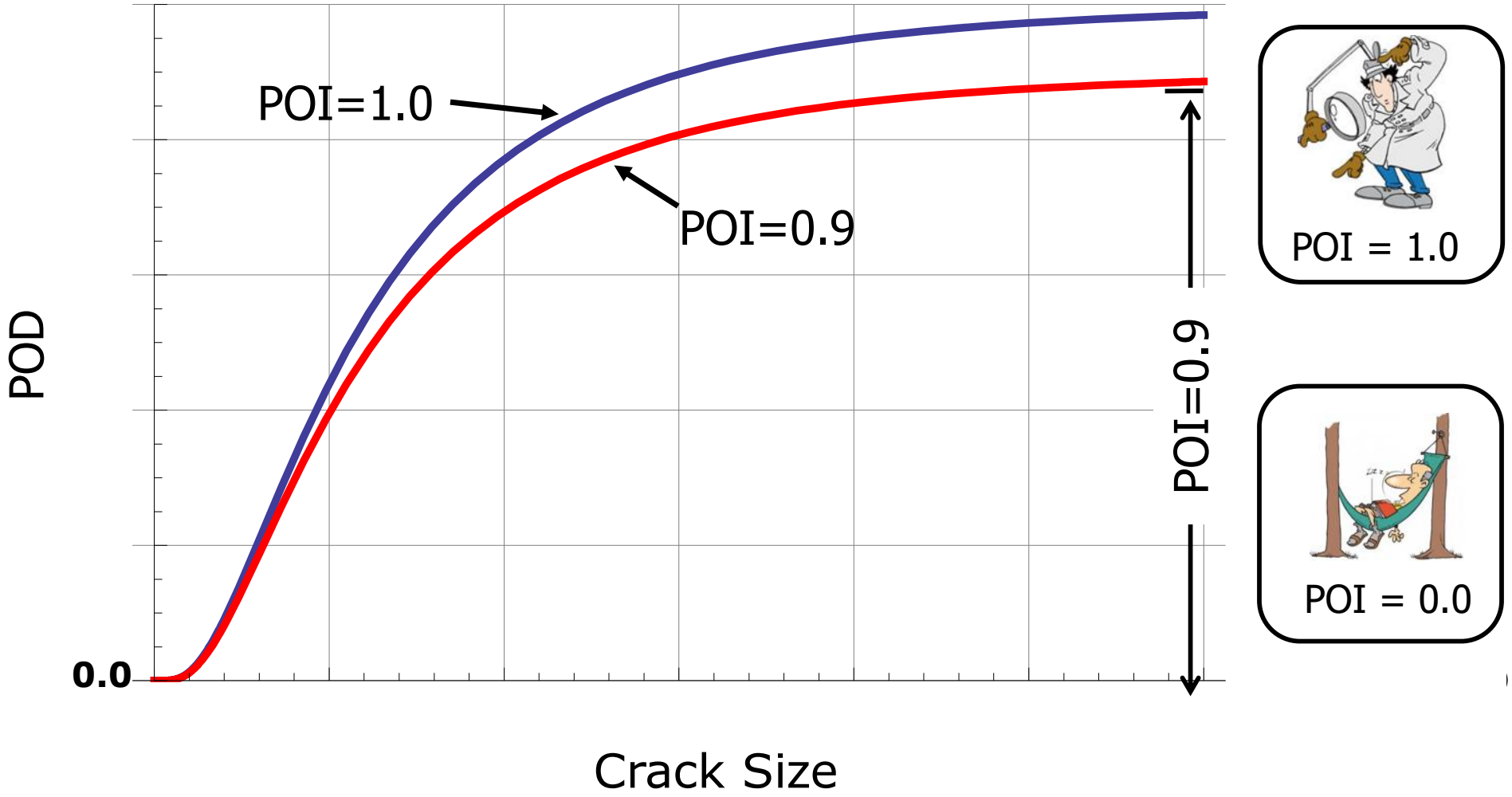
POD Curve



Typical industry standard for deterministic DTA is to use 90% value of POD

The crack will be detected and repaired in 35% of simulations

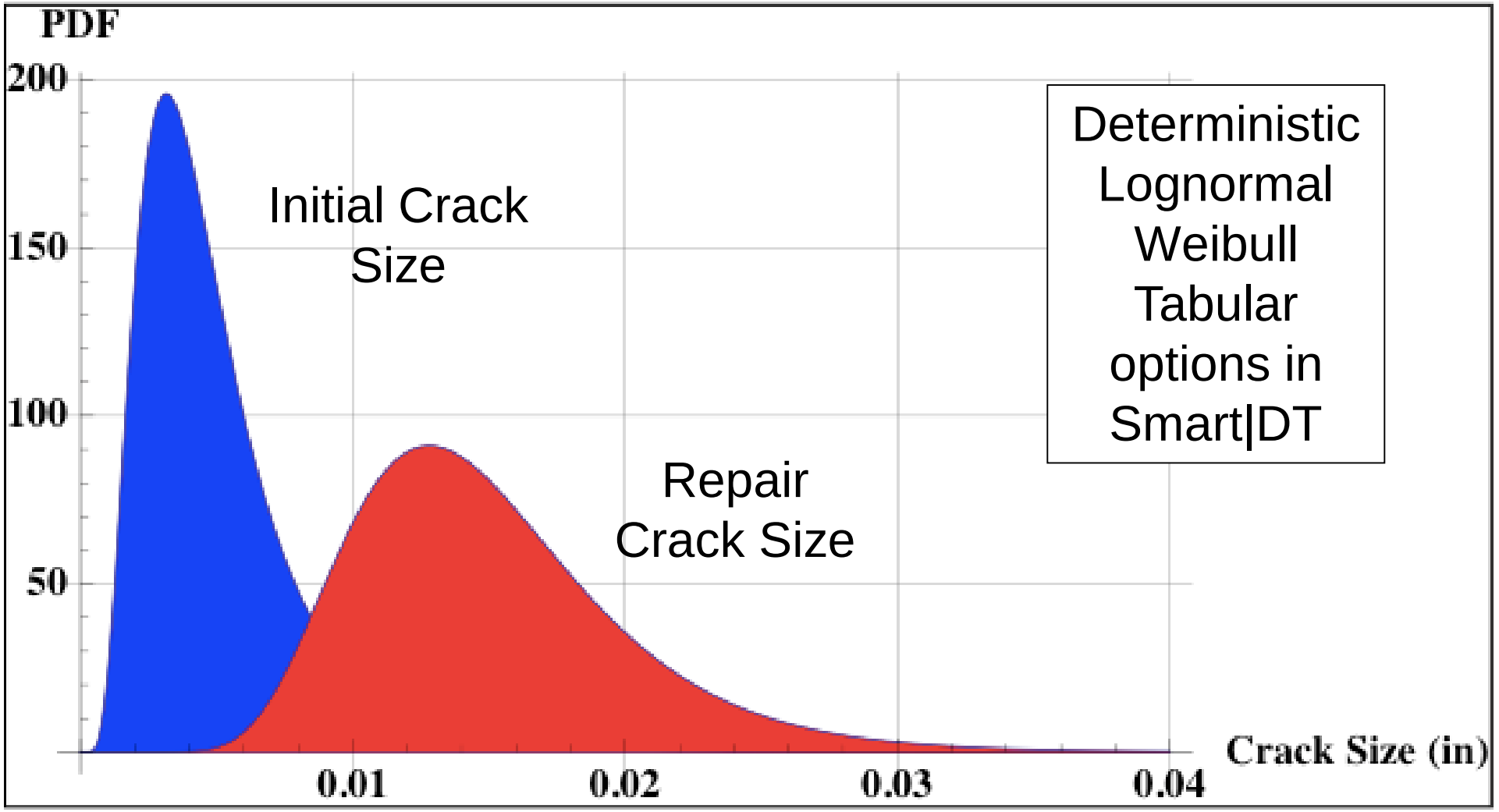
Probability of Inspection



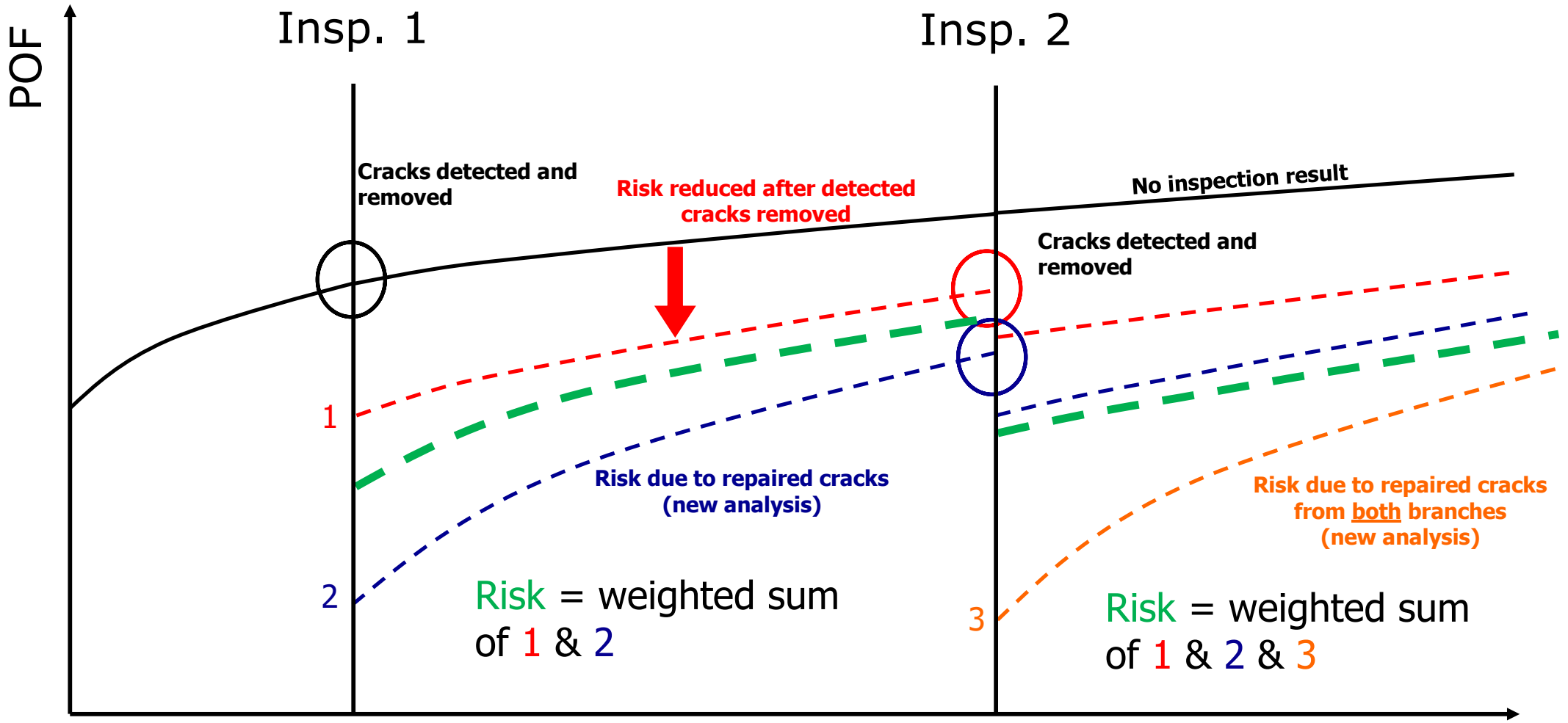
POI = 1.0

POI = 0.0

Repair Crack Size



Post Repair POF



- Treat inspections as multiple "branches" where each branch represents a repair scenario.

SMART|DT 1insp.smdt

SMART|DT

Information | Analysis | Material | Geometry | Loading | Inspections | Run | Results

0% complete. Start Analysis

DAT File

```
ANALYSIS_TIME_UNITS = Flights
! ----------------------------------------------------------------------
!       FRACTURE MECHANICS
! ----------------------------------------------------------------------
CRACK_GROWTH_CODE = MASTERC_USER mastercurve.avsn
INITIAL_CRACK_SIZE = LOGNORMAL 0.004292387 0.002922037
FRACTURE_TOUGHNESS = NORMAL 35.0 3.7
YIELD_STRENGTH = NORMAL 65.0 1.9
ULTIMATE_STRENGTH = NORMAL 76.0 1.6
! ----------------------------------------------------------------------
!       INSPECTIONS
! ----------------------------------------------------------------------
INSPECTIONS = 16000
INSPECTION_TYPE = 1

INSPECTION_ID = 1
PROB_OF_INSPECTION = DETERMINISTIC 1.0
POD = DETERMINISTIC 0.05 0.05
REPAIR_CRACK_SIZE = LOGNORMAL 0.004292387 0.002922037
! ----------------------------------------------------------------------
!       LOADING AND EVD PARAMETERS
! ----------------------------------------------------------------------
EVD_TYPE = USER 15.3 1.3 0.0
! ----------------------------------------------------------------------
!       DESCRIPTION
! ----------------------------------------------------------------------
! Training AA&S 2020
```

`Job.dat` file - Inspection information

Analysis Details

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

  Branch Number =   1 (Samples =        1000000)      8 Threads
  Sample no.         100000     10 % complete.
  Sample no.         200000     20 % complete.
  Sample no.         300000     30 % complete.
  Sample no.         400000     40 % complete.
  Sample no.         500000     50 % complete.
  Sample no.         600000     60 % complete.
  Sample no.         700000     70 % complete.
  Sample no.         800000     80 % complete.
  Sample no.         900000     90 % complete.
  Sample no.        1000000    100 % complete.
  Branch Number =   2 (Samples =         400000)
  Sample no.          40000     10 % complete.
  Sample no.          80000     20 % complete.
  Sample no.         120000     30 % complete.
  Sample no.         160000     40 % complete.
  Sample no.         200000     50 % complete.
  Sample no.         240000     60 % complete.
  Sample no.         280000     70 % complete.
  Sample no.         320000     80 % complete.
```

Main branch – no insp

Repair 1

Show/Export

Version 1.0.250 - Build 953

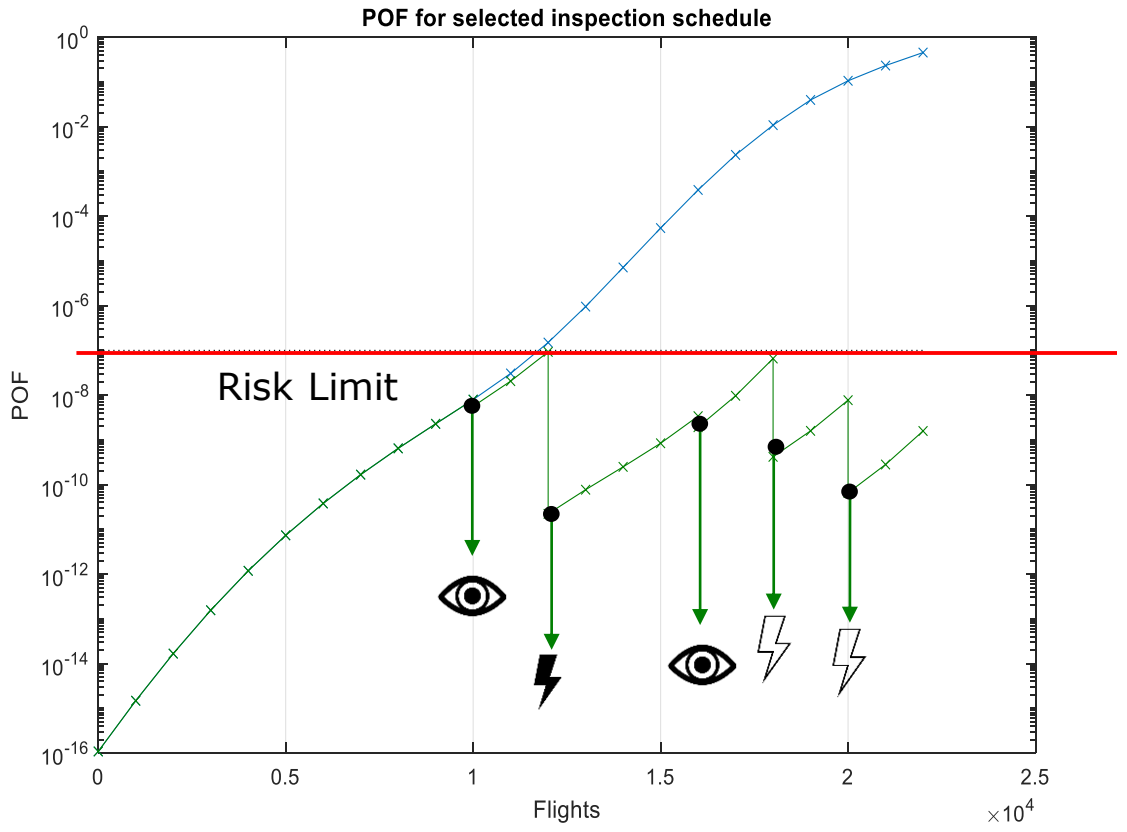
Flights

Optimized Risk Inspections (upcoming Fall 2022)

	Inspection Type	Sensitivity	Cost
↯	Automated bolt hole eddy current	↑	50x
↯	Eddy current sliding probe		10x
👁	Visual		1x

Results: Lowest inspection cost w risk < 1E-7

Visual 👁	10000
Automated bolt hole eddy current ↯	12000
Visual 👁	16000
Eddy current sliding probe ↯	17000
Eddy current sliding probe ↯	20000



Wednesday

3:30 PM - 4:00 PM

Fleet Management considering Inspection Schedule Optimization

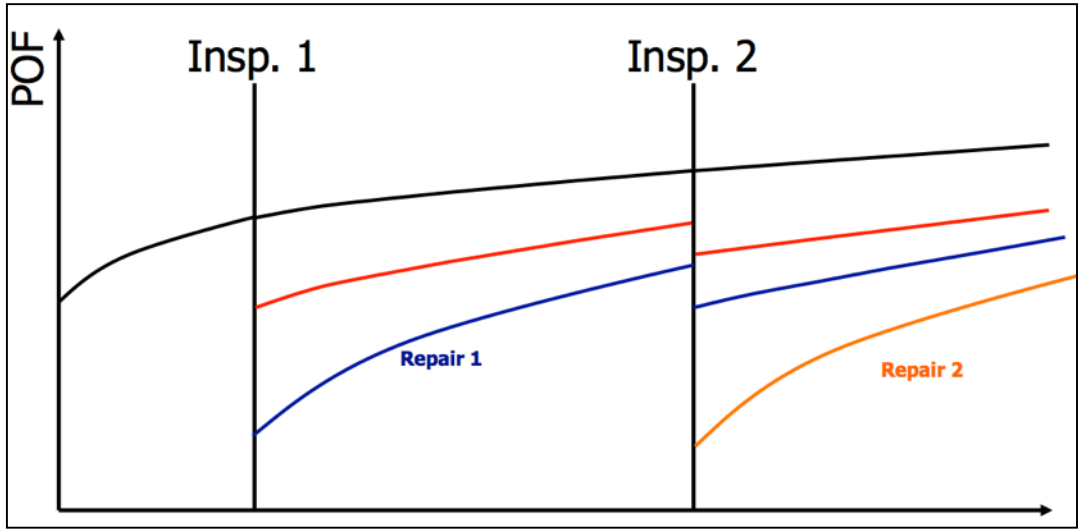
Abstract/Description

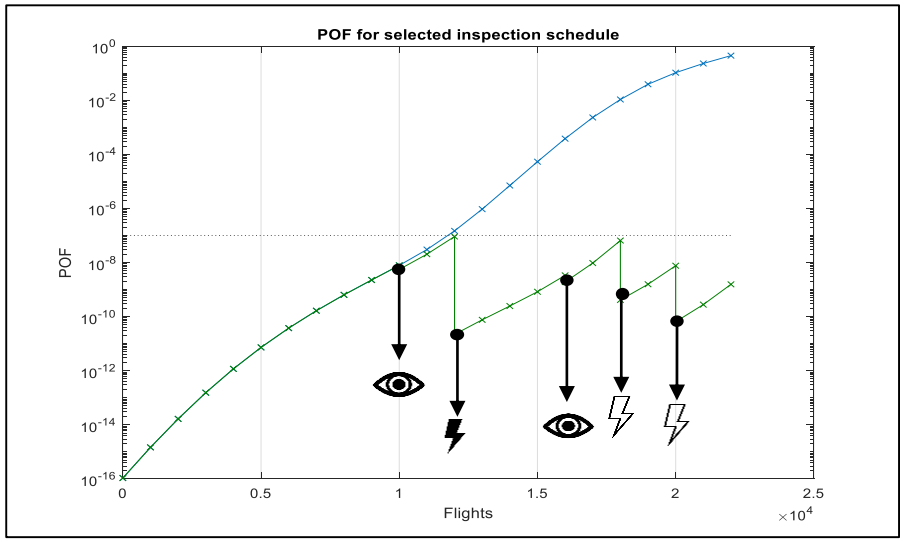
Presenter: Dr Juan Ocampo - AeroMatter

Authors: Dr Nathan Crosby - AeroMatter, Ms Beth Gamble - Textron Aviation, Mr Christopher Hurst - Textron Aviation, Dr Harry Millwater - University of Texas at San Antonio, Mr Marvin Nuss - Nuss Sustainment Solutions

Summary

- Inspection and repair can be simulated at any number of flights.
- The POD can be deterministic, lognormal, or tabular.
  - Library of PODs: eddy current, FPI, MOI, ultrasonic, visual, x-ray available in GUI.
- Arbitrary repair crack size (deterministic, lognormal, Weibull, & tabular options).
- The probability is computed as a series of independent "branches".
- Optimized inspection schedule capabilities upcoming





Questions

Supplemental Material

Example Problems:
see **`Inspection_Examples_Files`** folder
- **`(noinsp, 1insp, 2insp).smdt`**

The master curve file is also available if you want to build your own analysis (it is already embedded within the smdt files).
- **`mastercurve.avsn`**

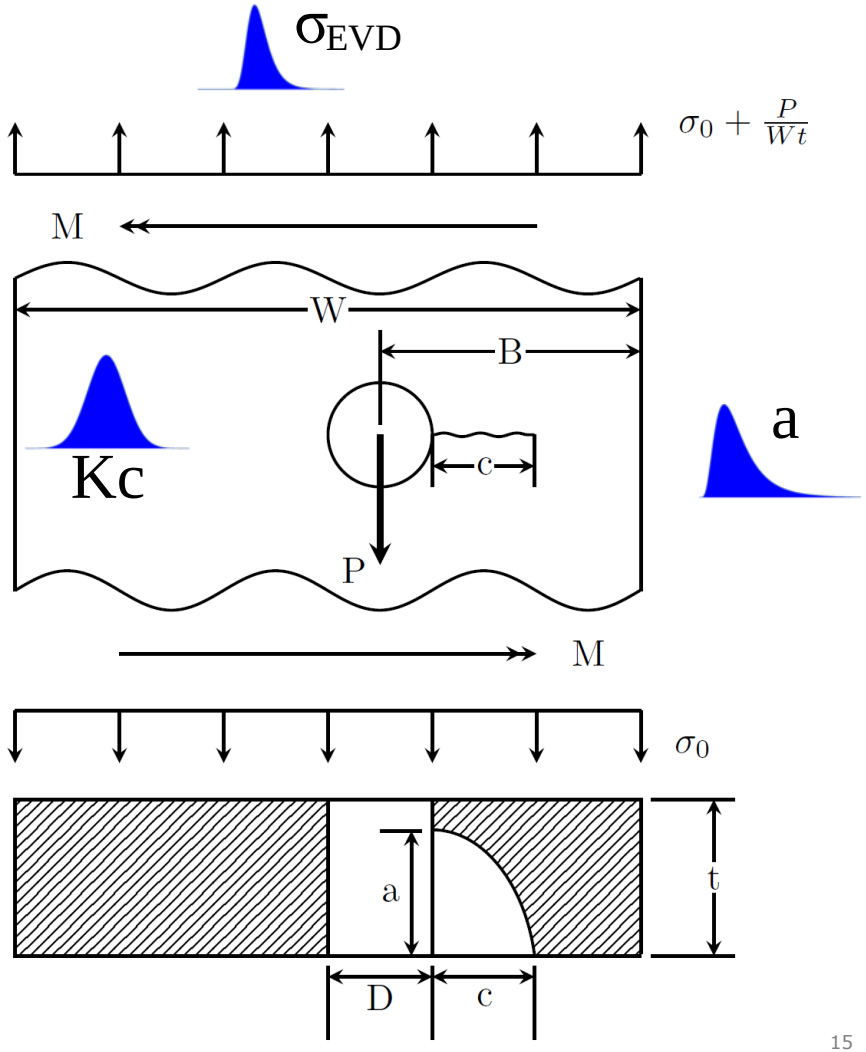
SMART|DT Inspection Material

Example	Initial Crack Size	Fracture Toughness	Extreme Value Distribution	Inspection
noinsp.smdt	Lognormal	Normal	Gumbel	None
1insp.smdt	Lognormal	Normal	Gumbel	Det. = 0.05
2insp.smdt	Lognormal	Normal	Gumbel	Prob.

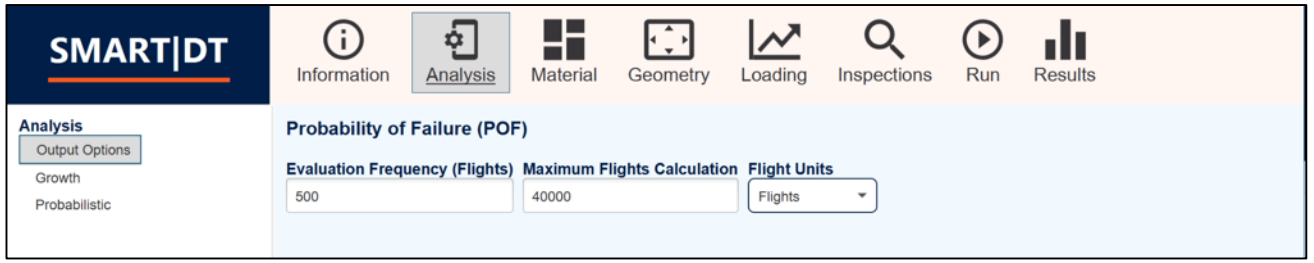
Baseline Problem

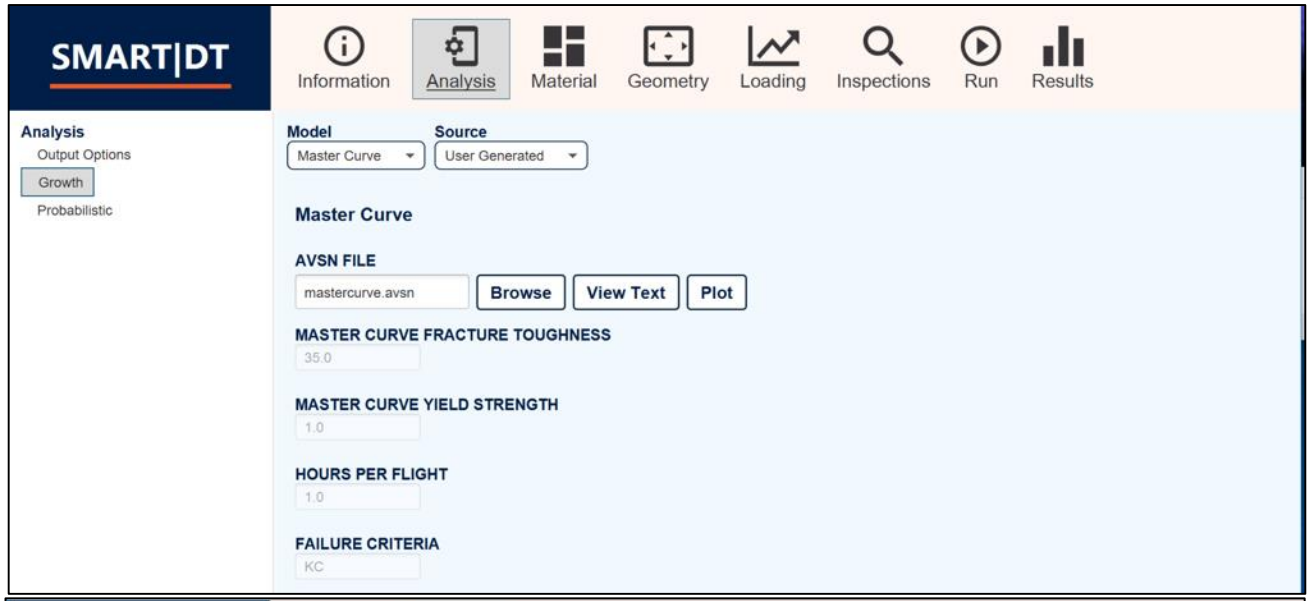
✓User-defined Master Curve

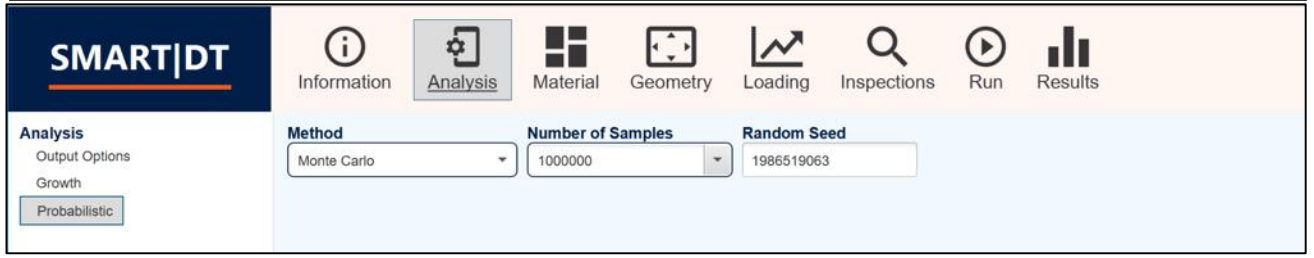
Variable	Statistics
Initial Crack size	Probabilistic Database
Fracture toughness	Probabilistic Database
EVD	Gumbel (μ=15.3,σ=1.30)



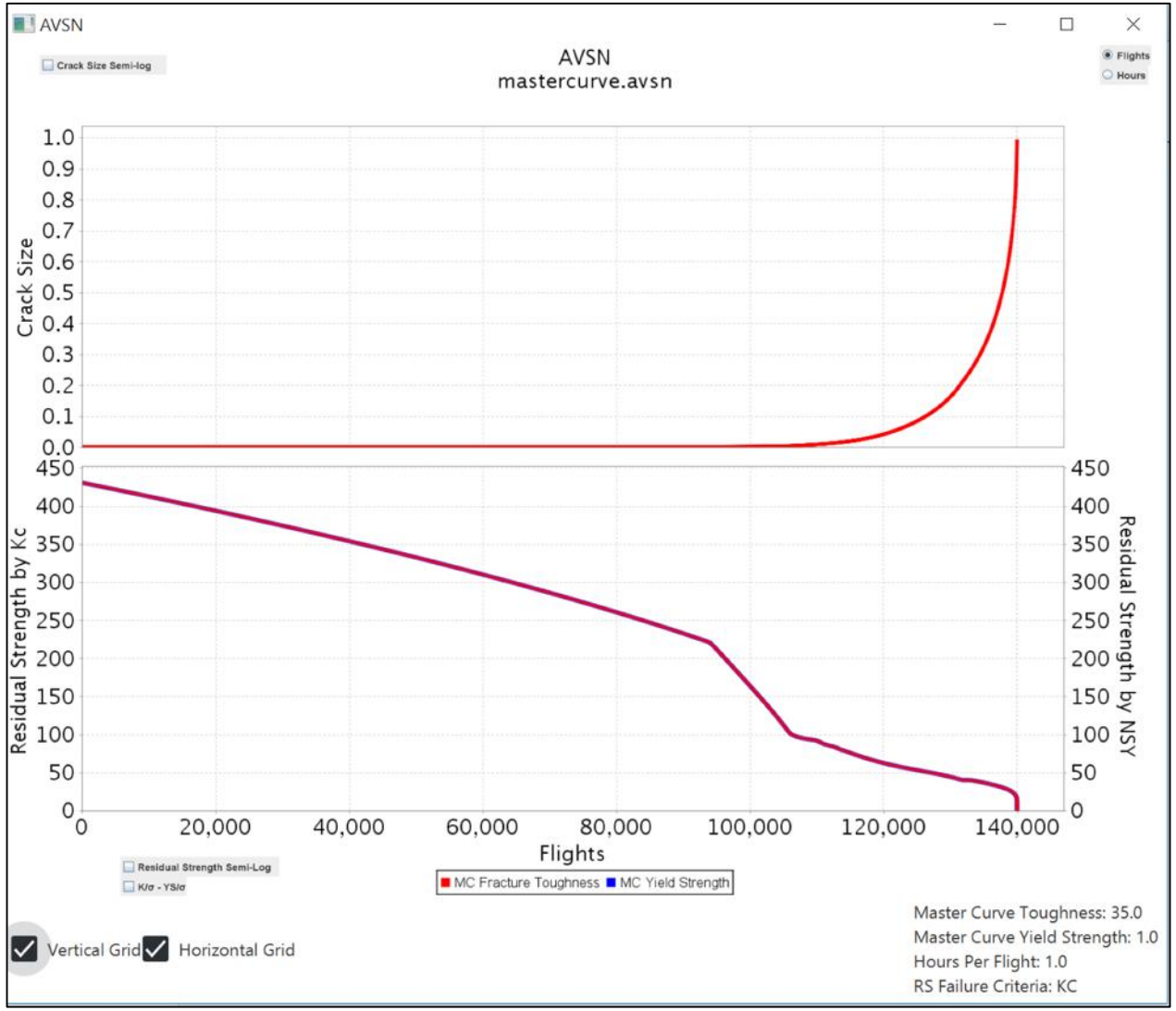
Analysis Tab





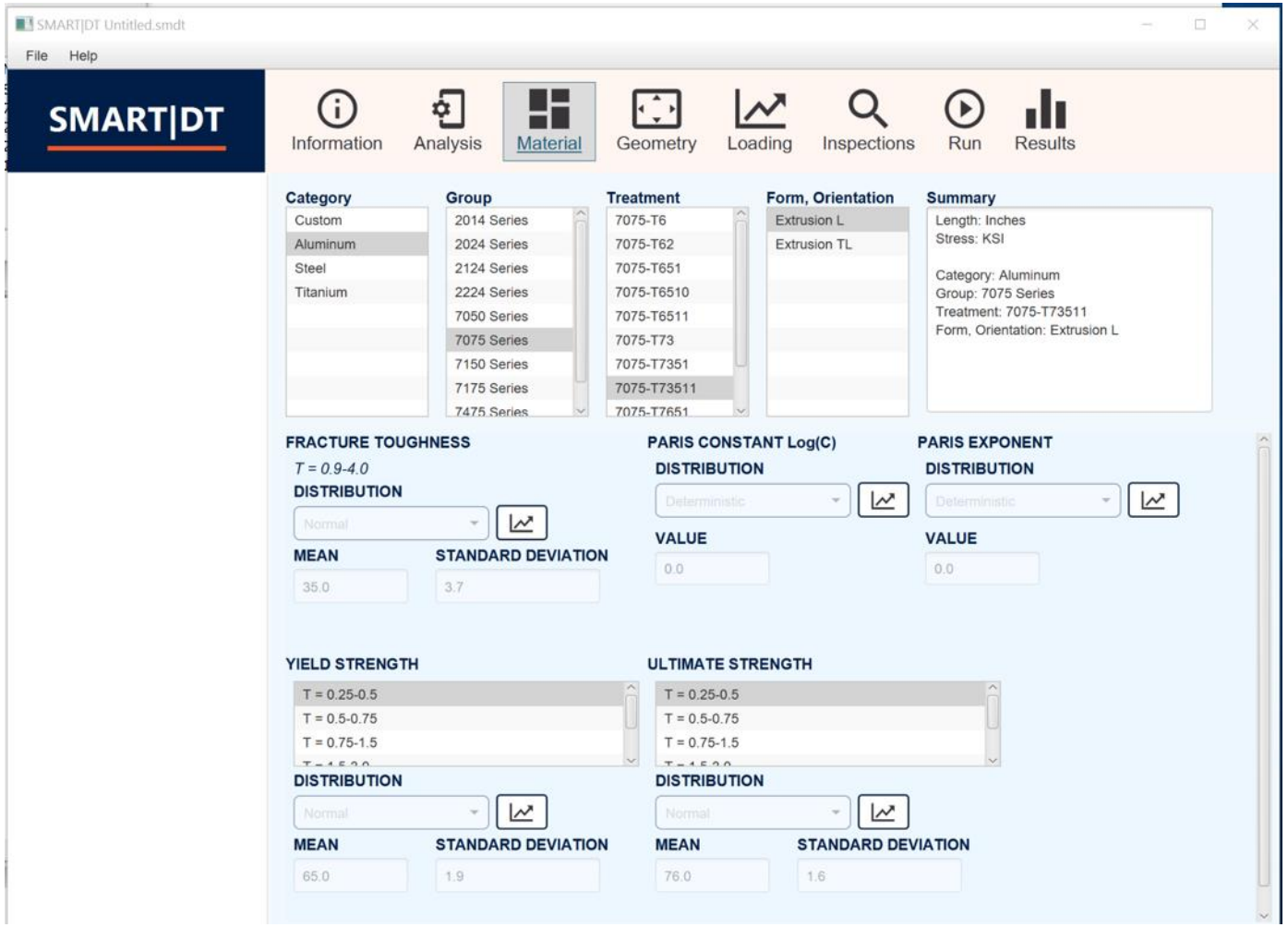


Crack Size & Residual Strength



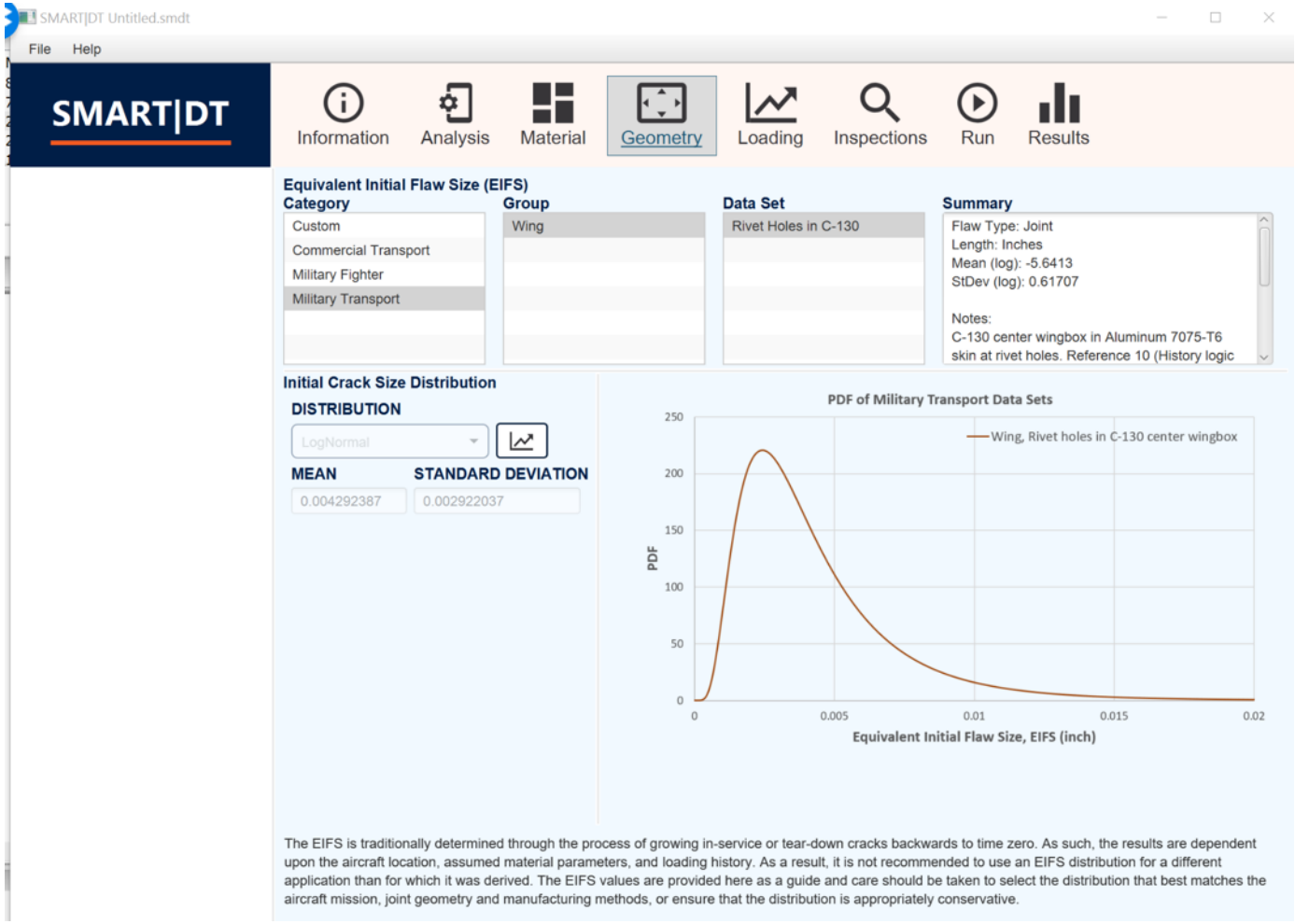
Material Selection

Aluminum -> 7075 Series -> 7075-T73511 -> Extrusion L

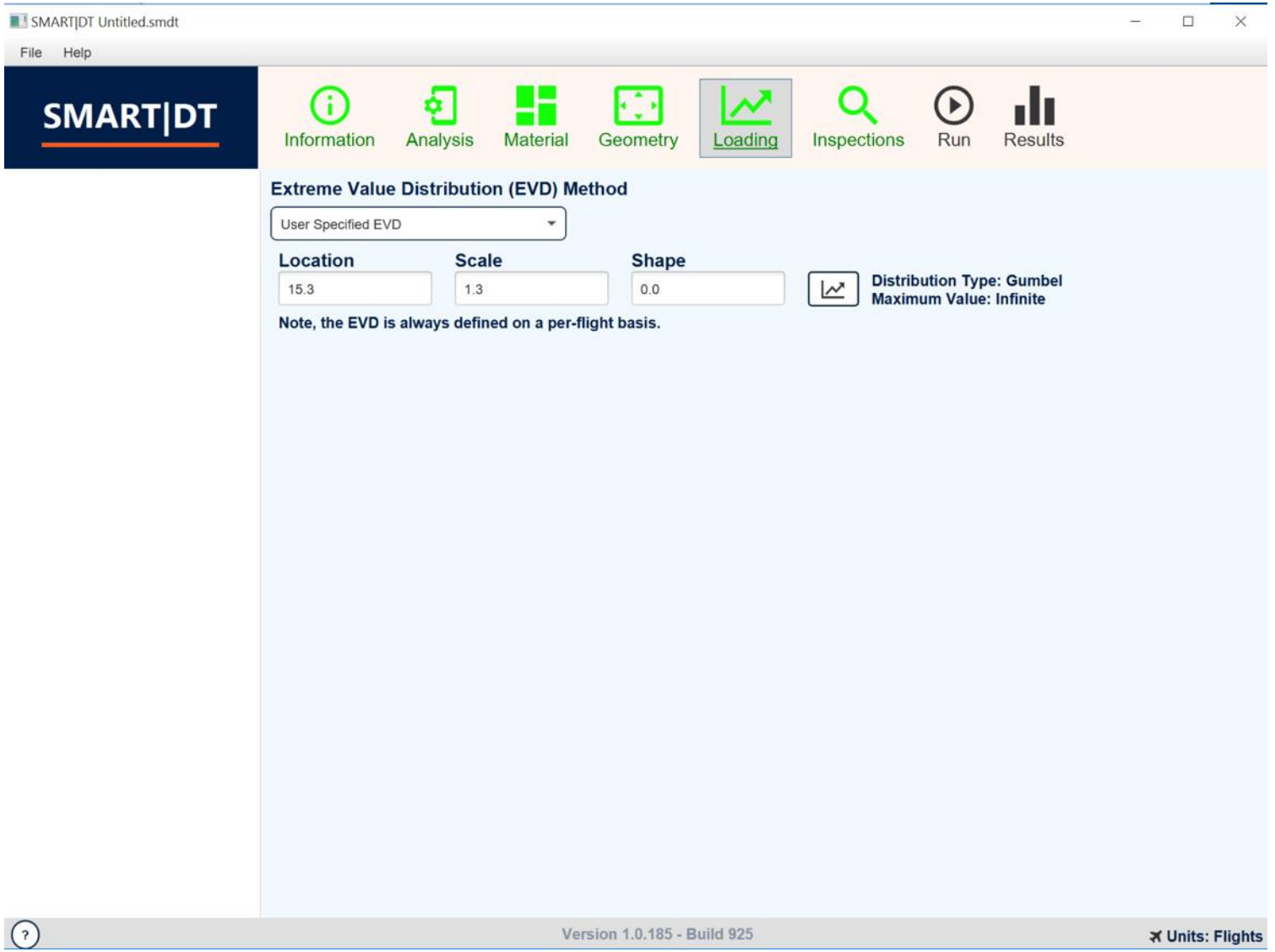


Geometry Selection

Military Transport -> Wing -> Rivet Holes in C130



Loading


SMART|DT Untitled.smdt
File
Help
SMART|DT
Information
Analysis
Material
Geometry
Loading
Inspections
Run
Results
Extreme Value Distribution (EVD) Method
User Specified EVD
Location
15.3
Scale
1.3
Shape
0.0
Distribution Type: Gumbel
Maximum Value: Infinite
Note, the EVD is always defined on a per-flight basis.
Version 1.0.185 - Build 925
Units: Flights

No Insp. for Baseline

SMART|DT Untitled.smdt

File Help

SMART|DT

Information Analysis Material Geometry Loading Inspections Run Results

Inspection Presets

Name	Type	Inspection Prob.	Detection Prob.	Repaired Crack
No Presets				

Delete Edit Add

Inspections

Flights	Preset	Type	Inspection Prob.	Detection Prob.	Repaired Crack
No Inspections					

Delete Edit Add

Version 1.0.185 - Build 925

Units: Flights

noinsp Results

SMART|DT noinsp.smdt

File Help

SMART|DT

Information Analysis Material Geometry Loading Inspections Run Results

Results

Probabiliy of Failure

Load External POF

POF Cumulative

Probability of Failure (POF) vs. Flights

Flights Hours

Probability of Failure (POF)

10^{0} 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16}

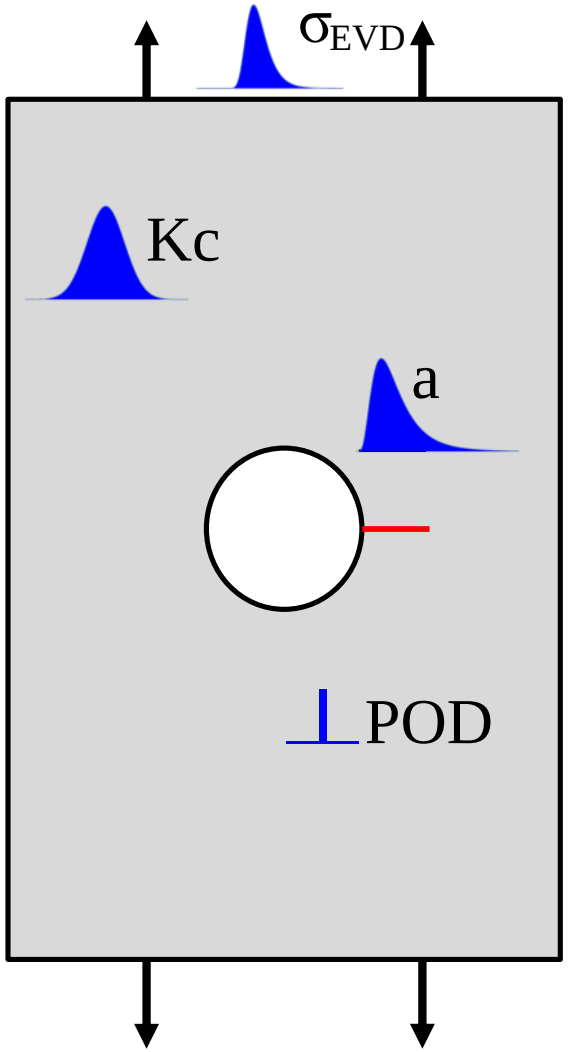
0 5,000 10,000 15,000 20,000 25,000 30,000 35,000 40,000

Flights

POF (w/o Insp.) noinsp_pof.csv

Vertical Grid Horizontal Grid

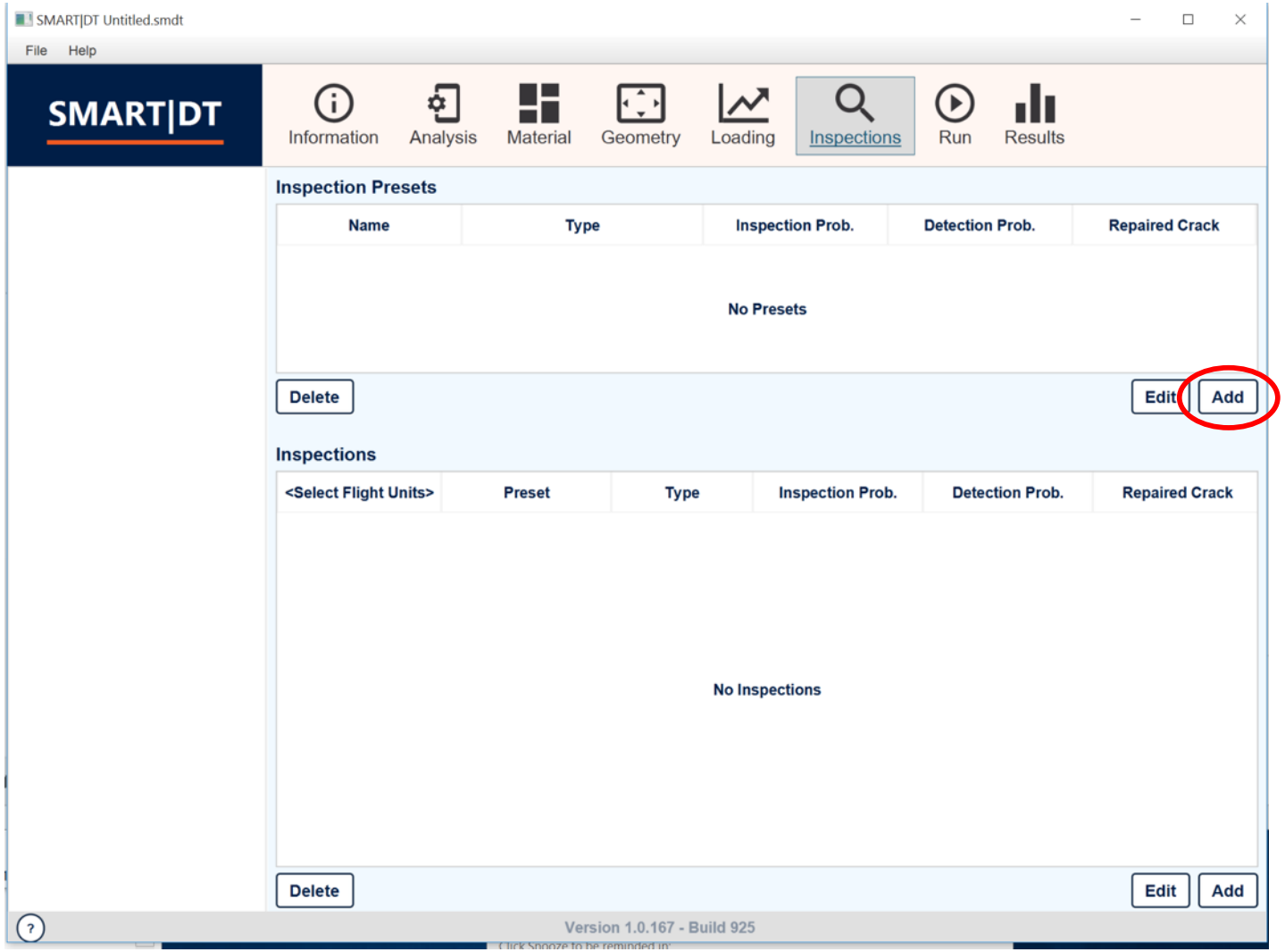
Problem Definition
One Deterministic Inspection



Variable	Statistics
Initial Crack size	Probabilistic Database
Fracture toughness	Probabilistic Database
EVD	Gumbel (μ=15.3,σ=1.30)
Inspection	16000 flights
POD	Deterministic = 0.05
Repair crack size	Same as initial
POI	1.0

All cracks ≥ 0.05 will be detected.

Adding an Inspection Preset



Adding an Inspection Preset

Add Inspection Preset

Add Inspection Preset

Name

Deterministic

Material	Inspection Type	Geometry	Equipment	Summary
Custom				
Aluminum				

Probability of Detection

DISTRIBUTION: Deterministic_

LENGTH (c): 0.05

DEPTH (a): 0.05

Probability of Inspection

VALUE: 1.0

Repaired Crack Size

- Same as Original
- Custom
- Perfect

DISTRIBUTION: LogNormal

MEAN: 0.004292387

STANDARD DEVIATION: 0.002922037

Cancel | Add

Adding an Inspection Time/Schedule

SMART|DT noinsp.smdt

File Help

SMART|DT

Information Analysis Material Geometry Loading Inspections Run Results

Inspection Presets

Name	Type	Inspection Prob.	Detection Prob.	Repaired Crack
Deterministic		1.0	2c: 0.05 a: 0.05	* μ0.004292387 σ0.00292...

Delete Edit Add

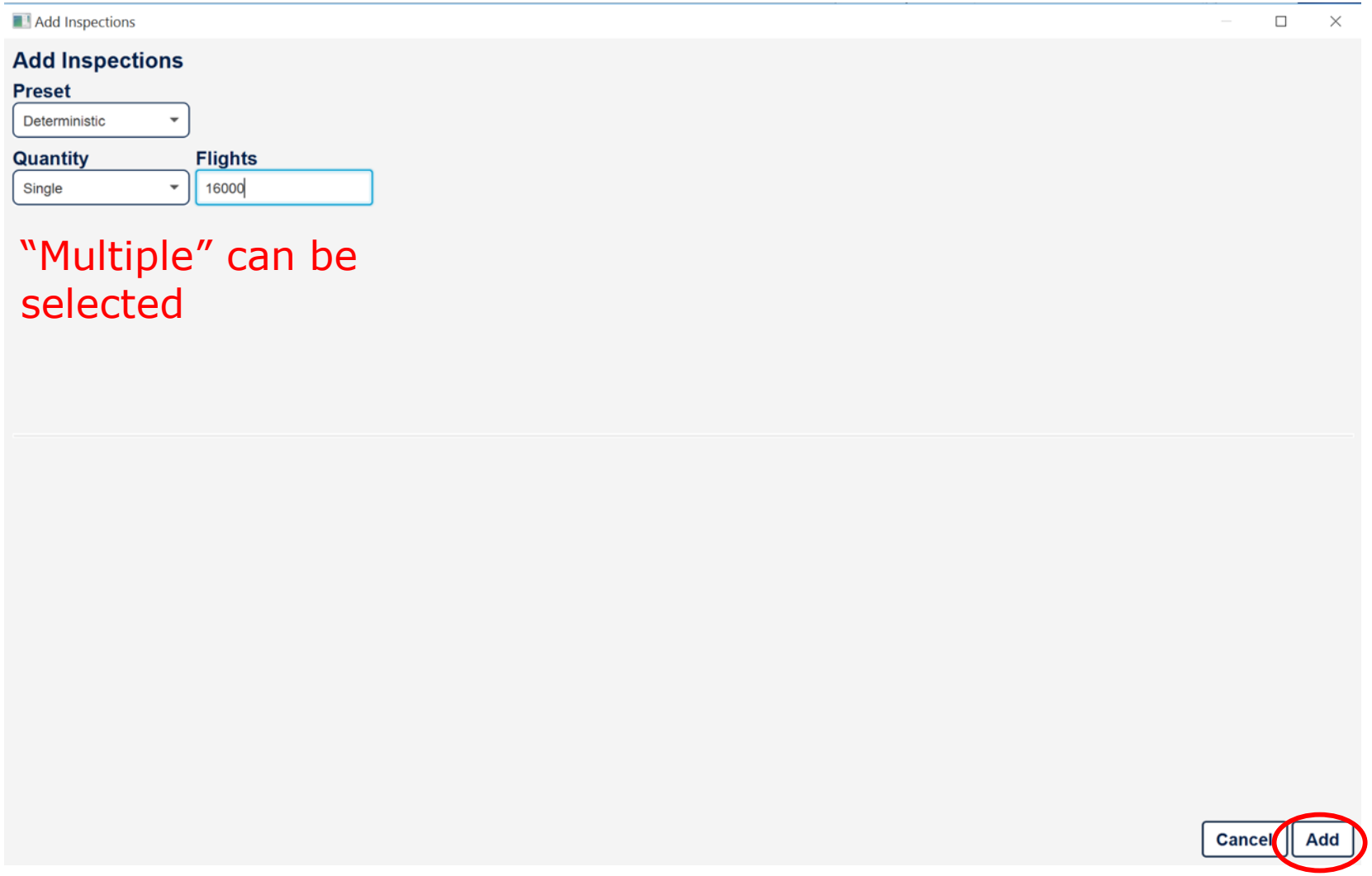
Inspections

Flights	Preset	Type	Inspection Prob.	Detection Prob.	Repaired Crack

No Inspections

Delete Edit Add

Adding an Inspection Time/Schedule



Inspection Tab

SMART|DT noinsp.smdt

File Help

SMART|DT

Information Analysis Material Geometry Loading Inspections Run Results

Inspection Presets

Name	Type	Inspection Prob.	Detection Prob.	Repaired Crack
Deterministic		1.0	2c: 0.05 a: 0.05	* μ0.004292387 σ0.00292...

Delete Edit Add

Inspections

Flights	Preset	Type	Inspection Prob.	Detection Prob.	Repaired Crack
16000	Deterministic		1.0	2c: 0.05 a: 0.05	* μ0.004292387 σ0.002...

Delete Edit Add

Run Tab

SMART|DT noinsp.smdt

File Help

SMART|DT

Information Analysis Material Geometry Loading Inspections Run Results

0% complete. Start Analysis

DAT File

```
! ------------------------------------------------------------------------
!       INSPECTIONS
! ------------------------------------------------------------------------
INSPECTIONS = 16000
INSPECTION_TYPE = 1

INSPECTION_ID = 1
PROB_OF_INSPECTION = DETERMINISTIC 1.0
POD = DETERMINISTIC 0.05 0.05
REPAIR_CRACK_SIZE = LOGNORMAL 0.004292387 0.002922037
! ------------------------------------------------------------------------
!       LOADING AND EVD PARAMETERS
! ------------------------------------------------------------------------
EVD_TYPE = USER 15.3 1.3 0.0
NUMBER_OF_USAGES = 0
! ------------------------------------------------------------------------
!       DESCRIPTION
```

Analysis Details

```
   Sample no.          240000      60 % complete.
   Sample no.          280000      70 % complete.
   Sample no.          320000      80 % complete.
   Sample no.          360000      90 % complete.
   Sample no.          400000     100 % complete.

 ********************************************
 ********* PDTA analysis complete ************
 ********************************************

 Total CPU  time =      22.406 secs
 Total wall time =       3.046 secs
```

Show/Export

1insp Results

SMART|DT noinsp.smdt

File Help

SMART|DT

Information Analysis Material Geometry Loading Inspections Run Results

Results

Probabiliy of Failure

Load External POF

POF Cumulative

Probability of Failure (POF) vs. Flights

Flights Hours

Probability of Failure (POF)

10^{0} 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16}

0 5,000 10,000 15,000 20,000 25,000 30,000 35,000 40,000

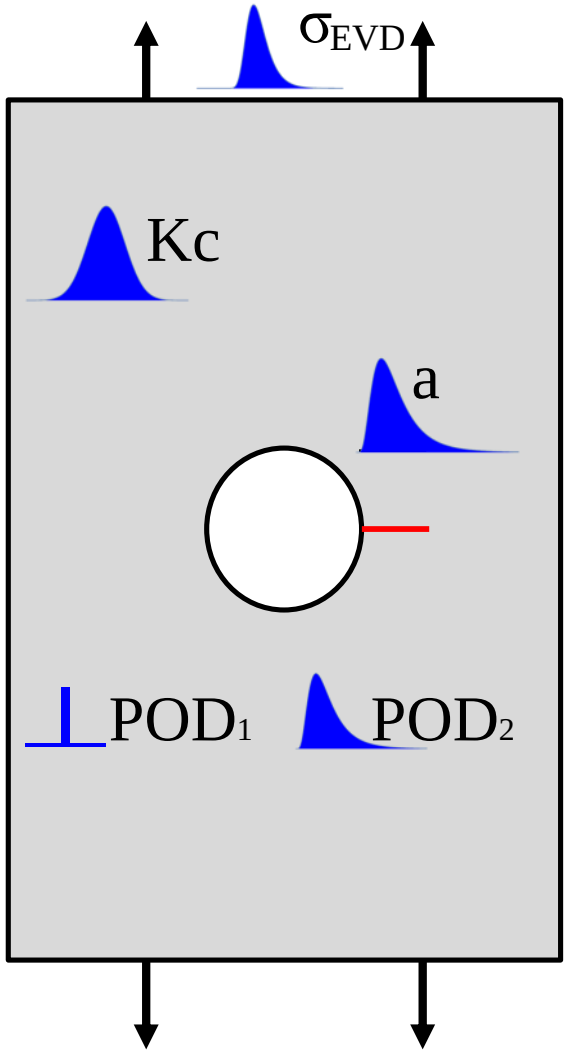
Flights

39.05% cracks detected

POF (w/o Insp.) noinsp_pof.csv POF (w/ Insp.) noinsp_pof.csv

Vertical Grid Horizontal Grid

Problem Definition
Two Inspections



Variable	Statistics
Initial Crack size	Probabilistic Database
Fracture toughness	Probabilistic Database
EVD	Gumbel (μ=15.3,σ=1.30)
Inspection 1	16,000 flights
POD 1	Deterministic = 0.05
Repair crack size 1	Same as initial
POI 1	1.0
Inspection 2	26,000 flights
POD 2	Probabilistic Database
POI 2	1.0
Repair crack size 2	Same as initial

Adding Another Inspection Preset

SMART|DT 1insp.smdt

File Help

SMART|DT

Information | Analysis | Material | Geometry | Loading | Inspections | Run | Results

Inspection Presets

Name	Type	Inspection Prob.	Detection Prob.	Repaired Crack
Deterministic		1.0	2c: 0.05 a: 0.05	* μ0.004292387 σ0.00292...

Delete | Edit | Add

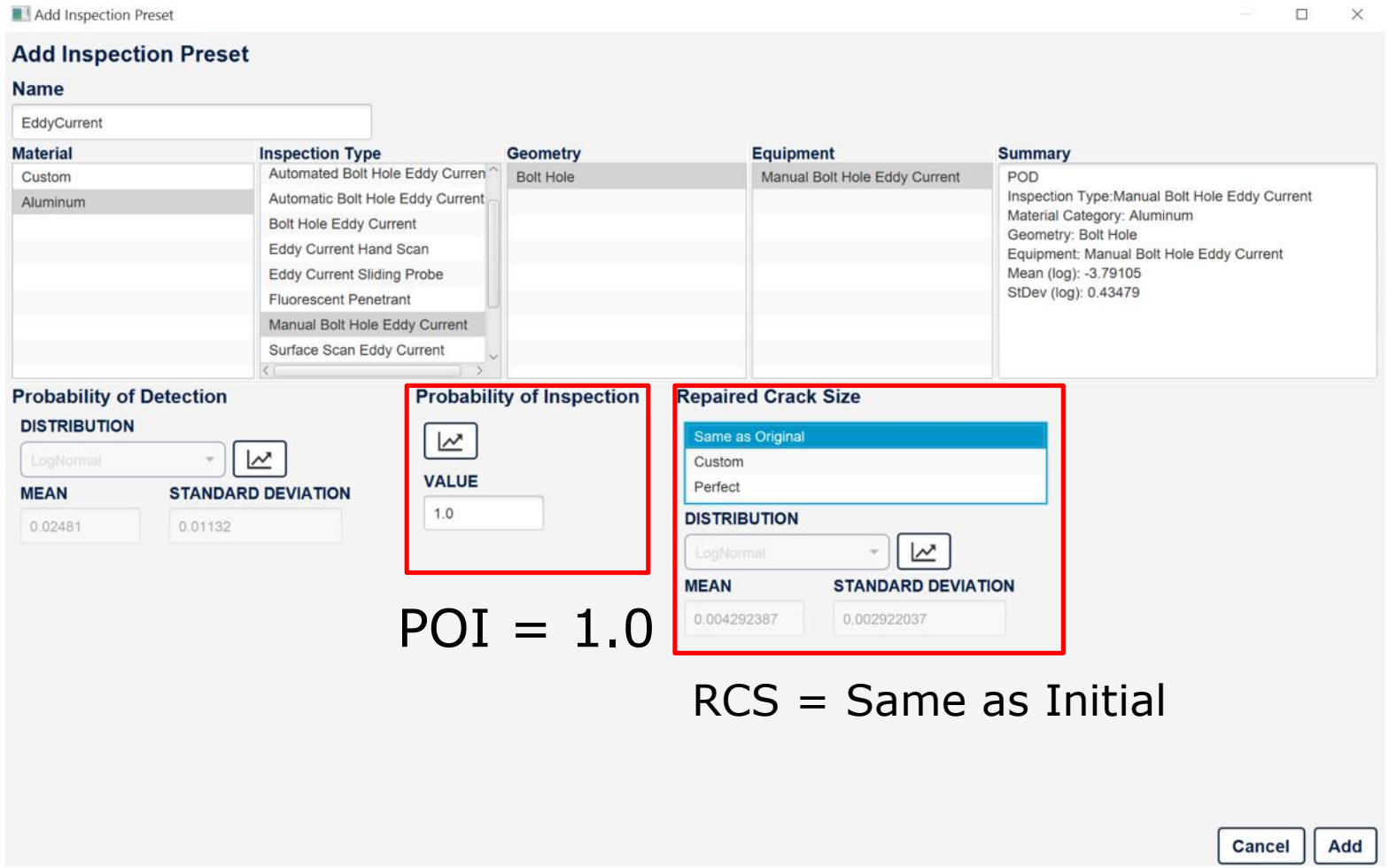
Inspections

Flights	Preset	Type	Inspection Prob.	Detection Prob.	Repaired Crack
16000	Deterministic		1.0	2c: 0.05 a: 0.05	* μ0.004292387 σ0.002...

Delete | Edit | Add

Eddy Current Preset

Aluminum -> Manual Bolt Hole Eddy Current -> Bolt Hole -> Manual Bolt Hole Eddy Current



POI = 1.0

RCS = Same as Initial

Inspection Schedule

Add Inspections

Add Inspections

Preset

EddyCurrent

Quantity Single

Flights 26000

Inspection Presets

Name	Type	Inspection Prob.	Detection Prob.	Repaired Crack
Deterministic		1.0	2c: 0.05 a: 0.05	* μ0.004292387 σ0.00292...
EddyCurrent	Manual Bolt Hole Eddy Current	1.0	μ0.02481 σ0.01132 LN	* μ0.004292387 σ0.00292...

Delete Edit Add

Inspections

Flights	Preset	Type	Inspection Prob.	Detection Prob.	Repaired Crack
16000	Deterministic		1.0	2c: 0.05 a: 0.05	* μ0.004292387 σ0.002...
26000	EddyCurrent	Manual Bolt Hole E...	1.0	μ0.02481 σ0.01132 LN	* μ0.004292387 σ0.002...

Delete Edit Add

Run

SMART|DT 1insp.smdt

File Help

SMART|DT

Information | Analysis | Material | Geometry | Loading | Inspections | Run | Results

0% complete. Start Analysis

DAT File

```
!       INSPECTIONS
! ------------------------------------------------------------------------
INSPECTIONS = 16000 26000
INSPECTION_TYPE = 1 2

INSPECTION_ID = 1
PROB_OF_INSPECTION = DETERMINISTIC 1.0
POD = DETERMINISTIC 0.05 0.05
REPAIR_CRACK_SIZE = LOGNORMAL 0.004292387 0.002922037

INSPECTION_ID = 2
PROB_OF_INSPECTION = DETERMINISTIC 1.0
POD = LOGNORMAL 0.02481 0.01132
REPAIR_CRACK_SIZE = LOGNORMAL 0.004292387 0.002922037
! ------------------------------------------------------------------------
!       LOADING AND EVD PARAMETERS
```

Analysis Details

```
   Sample no.         378000     60 % complete.
   Sample no.         441000     70 % complete.
   Sample no.         504000     80 % complete.
   Sample no.         567000     90 % complete.
   Sample no.         630000    100 % complete.

*****************************************
********* PDTA analysis complete ********
*****************************************

Total CPU  time =     28.203 secs
Total wall time =      4.130 secs
```

Show/Export

2insp Results

SMART|DT 1insp.smdt

File Help

SMART|DT

Information Analysis Material Geometry Loading Inspections Run Results

Results

Probabiliy of Failure

Load External POF

POF Cumulative

Probability of Failure (POF) vs. Flights

Flights Hours

Probability of Failure (POF)

10^{0} 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16}

0 5,000 10,000 15,000 20,000 25,000 30,000 35,000 40,000

Flights

39.05% cracks detected

62.55% cracks detected

POF (w/o insp.) 1insp_pof.csv POF (w/ insp.) 1insp_pof.csv

Vertical Grid Horizontal Grid