



TEXTRON AVIATION



# Introduction to Probabilistic Methods with Applications to Probabilistic Damage Tolerance Analysis



## Inspection Overview

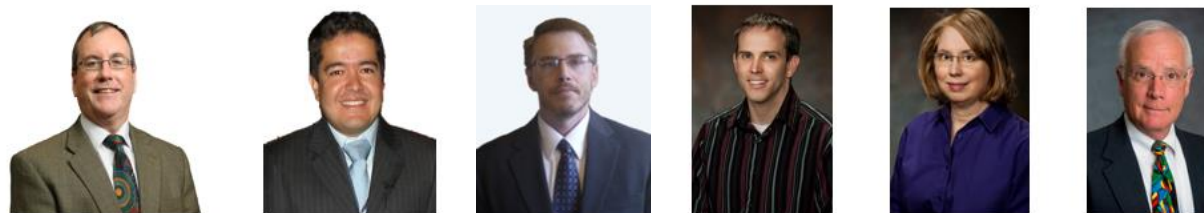
Harry Millwater - University of Texas at San Antonio,

Juan Ocampo, St. Mary's University,

Nathan Crosby, AeroMatter Inc.

Beth Gamble, Chris Hurst, Textron Aviation (Cessna)

Marv Nuss, Nuss Sustainment Solutions


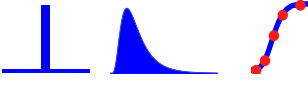


August 29, 2022



# Inspection Capabilities



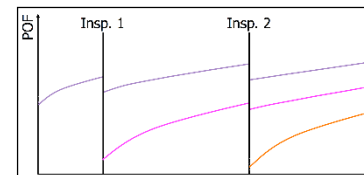
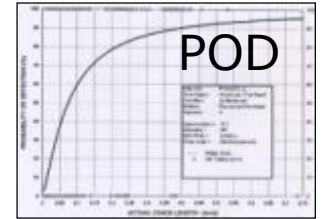
Feature	Possible Values	Notes
Inspection times	User-defined list of flight times & inspection types	Each inspection becomes a separate "branch" in the analysis
For each inspection type:		
Probability of Inspection (POI)	Range [0-1]	Weighted sum of POF w and w/o inspection
 POD	Deterministic Lognormal 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

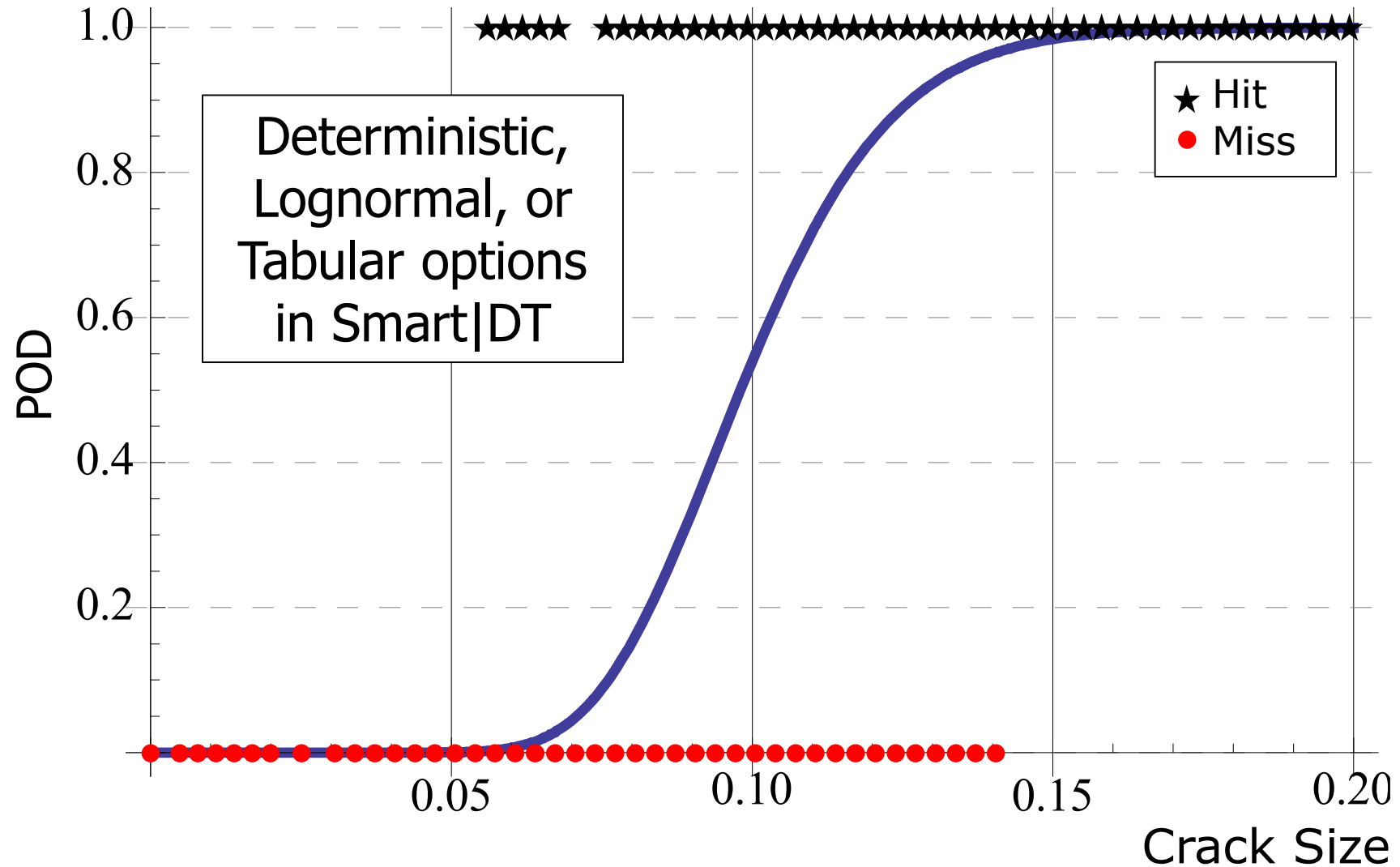
# Inspection Process



- 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.



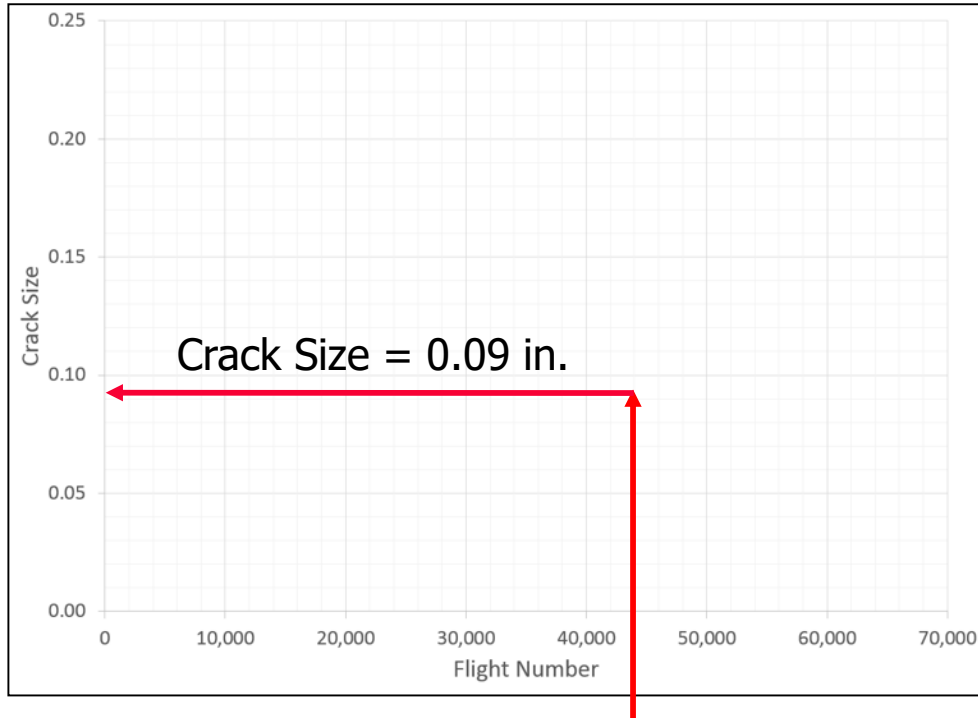
# POD (Probability of Detection)



# How the POD Works

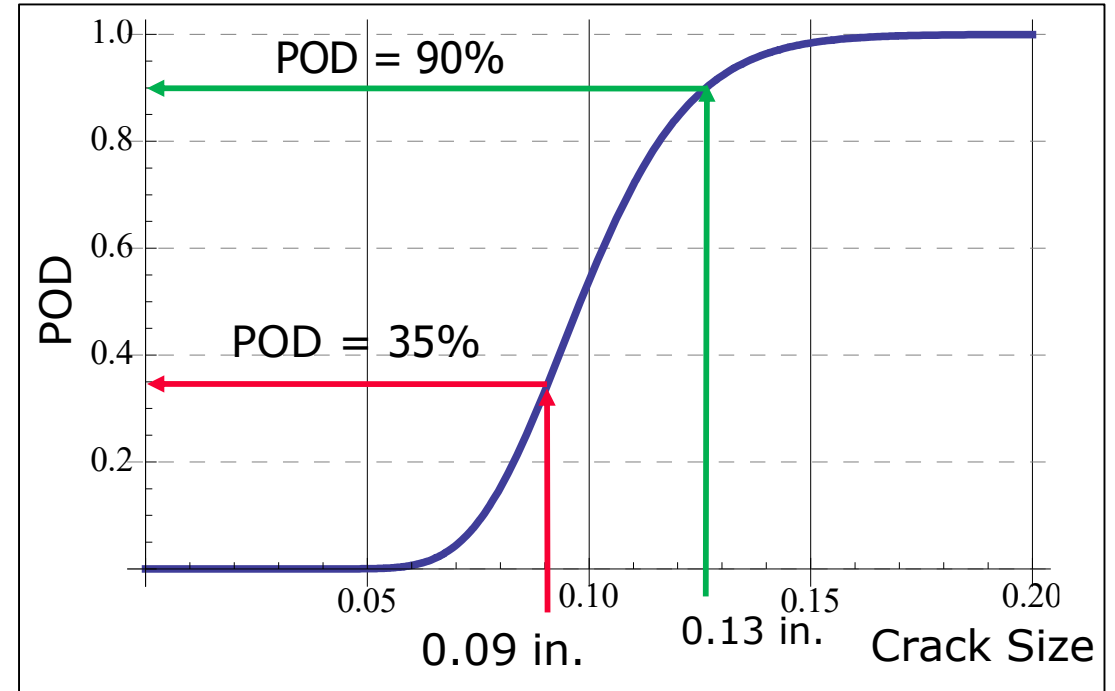


### Crack Growth Curve



Inspection at  
42,000 Flights

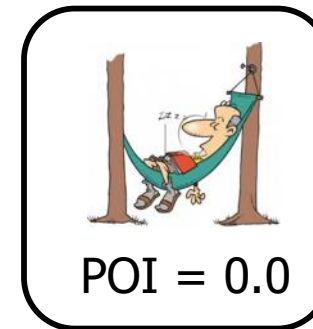
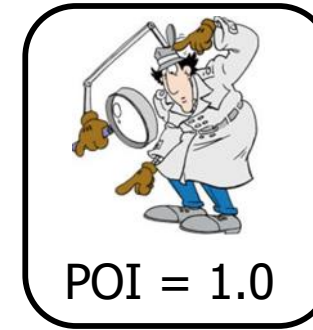
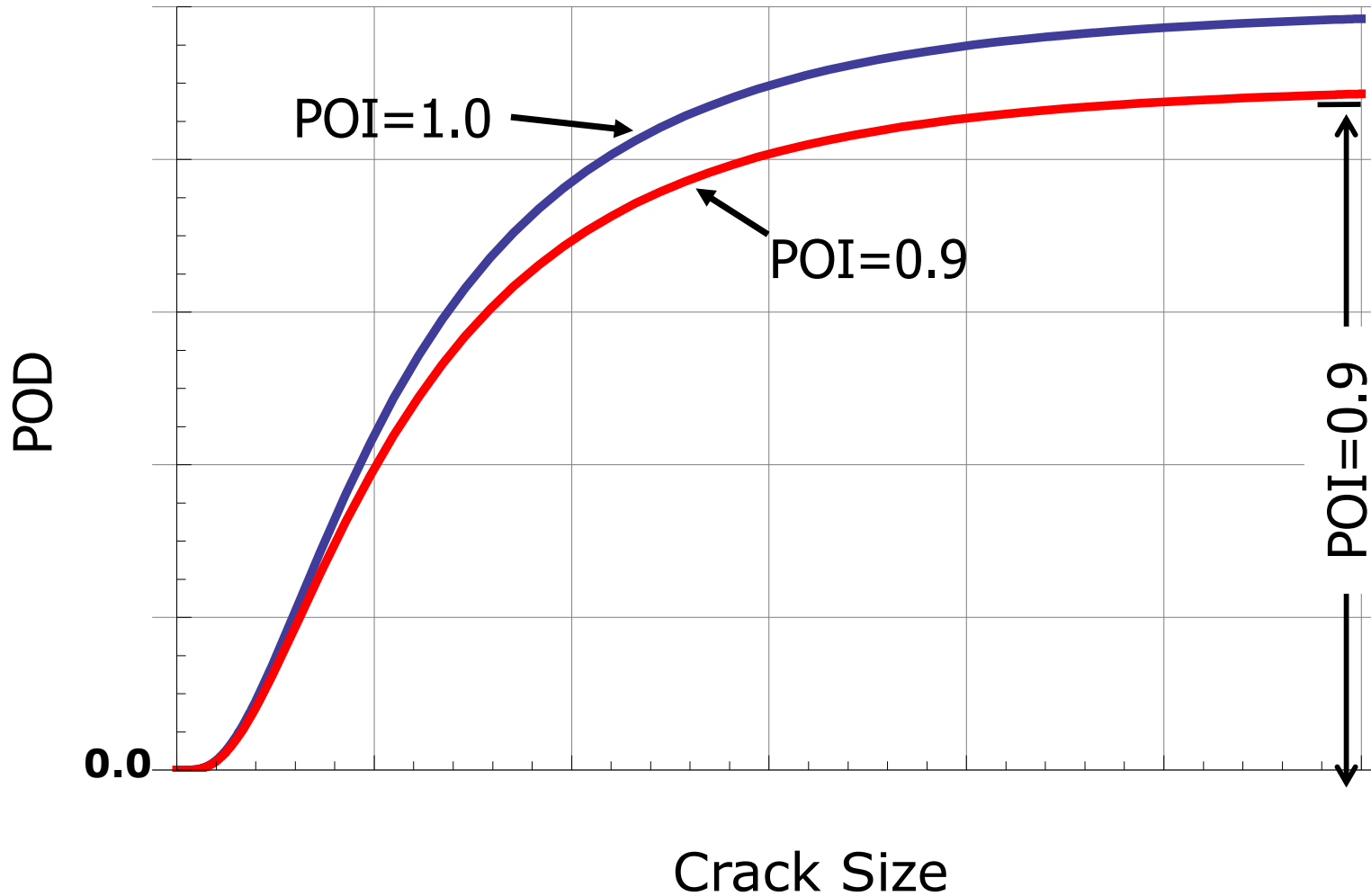
### POD Curve



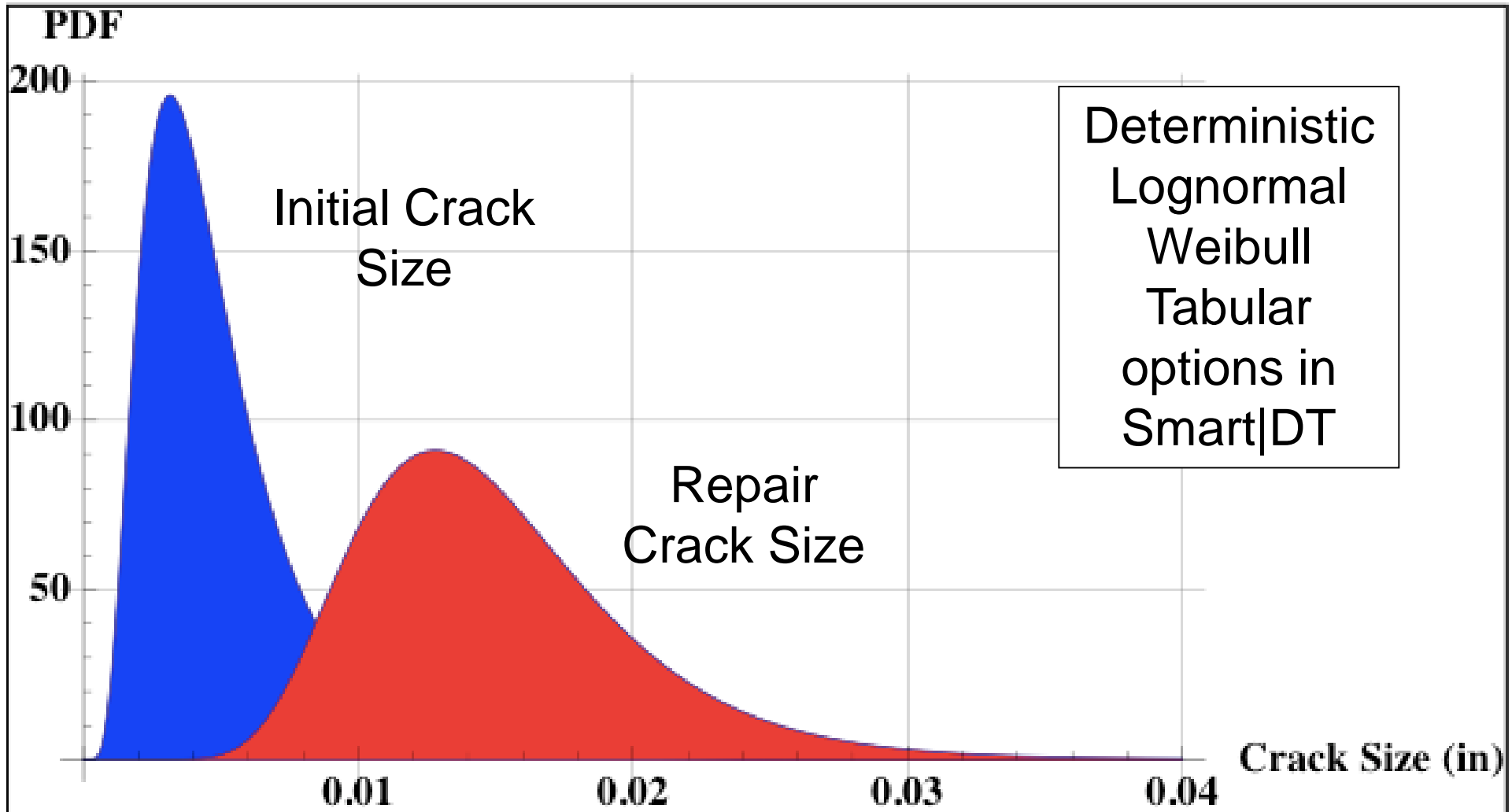
Typical industry standard for deterministic  
DTA is to use 90% value of POD

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

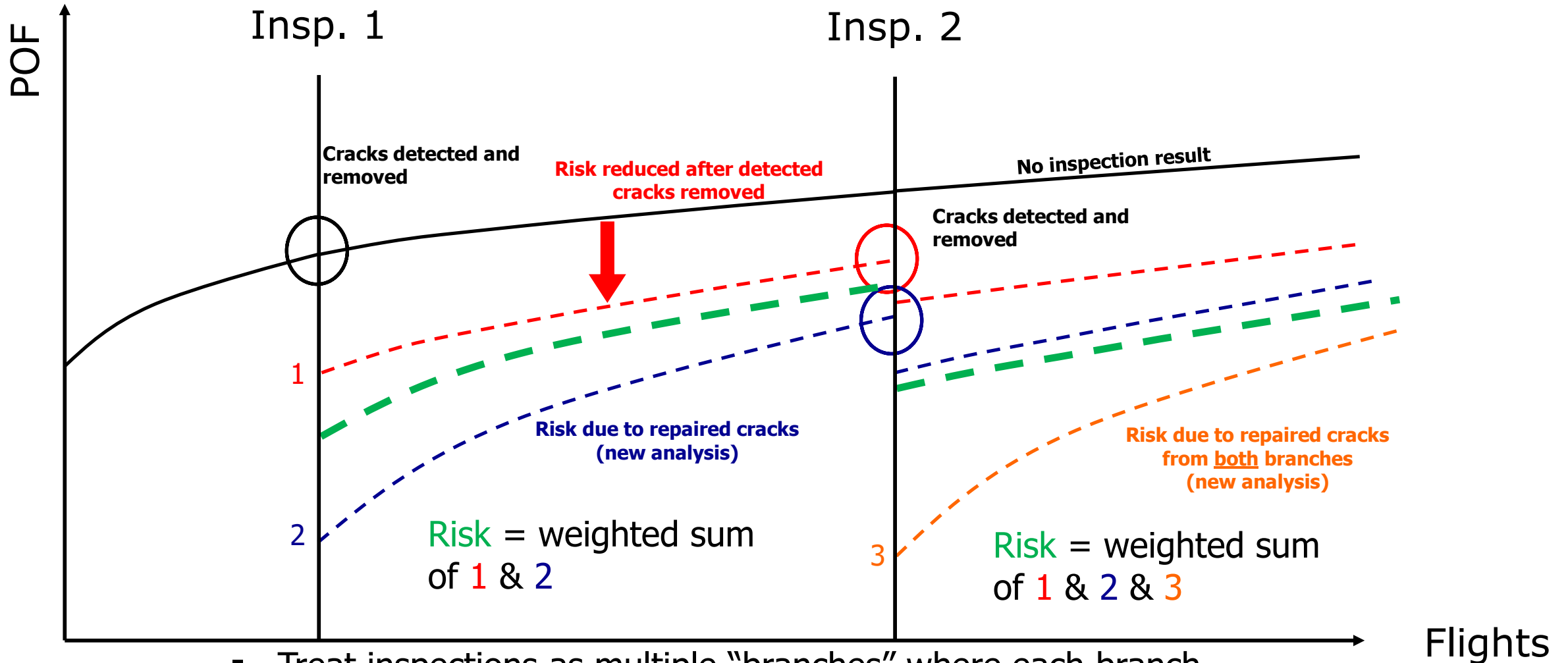
# Probability of Inspection



# Repair Crack Size



# Post Repair POF



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





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

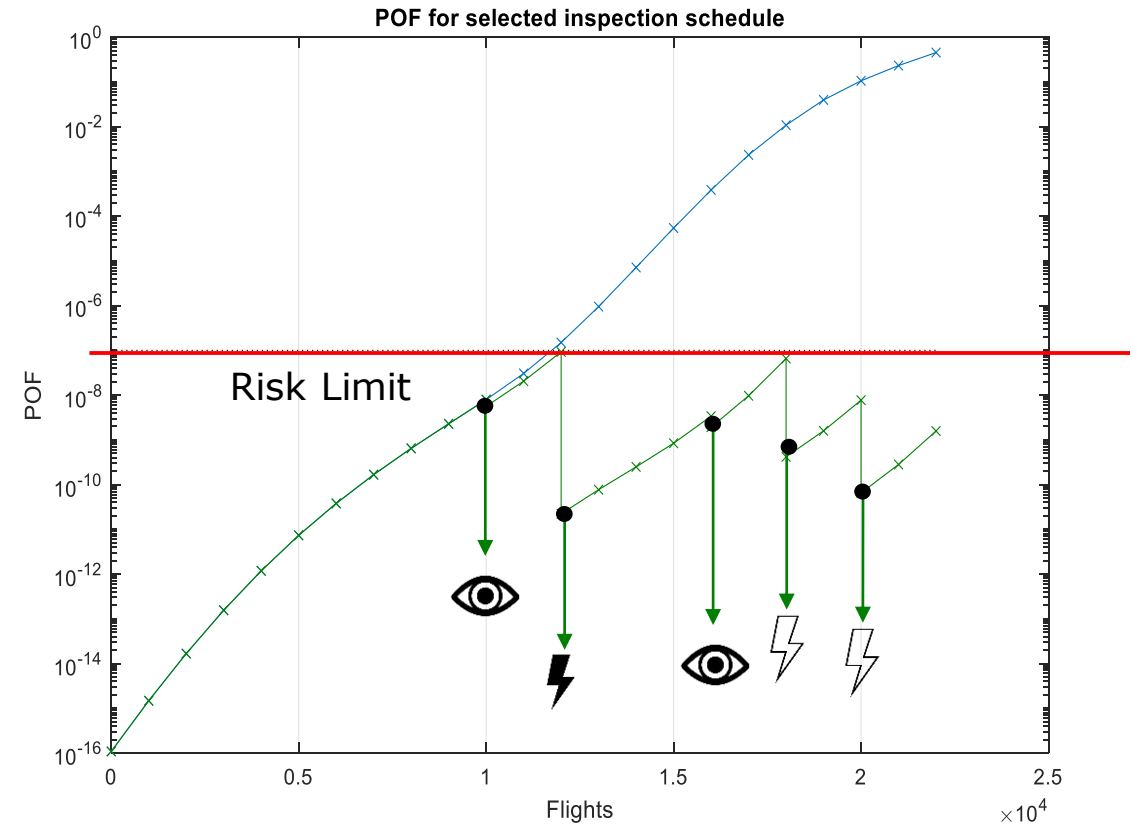
# Optimized Risk Inspections (upcoming Fall 2022)



	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

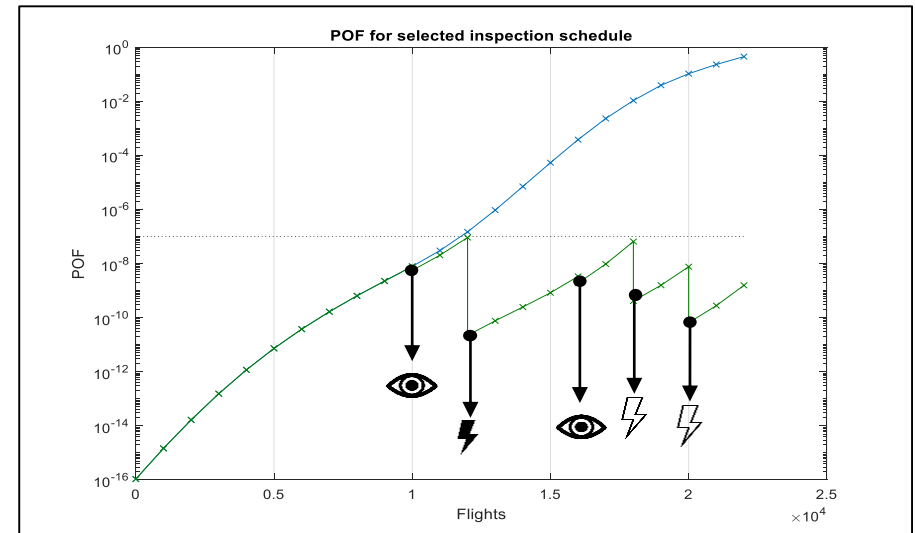
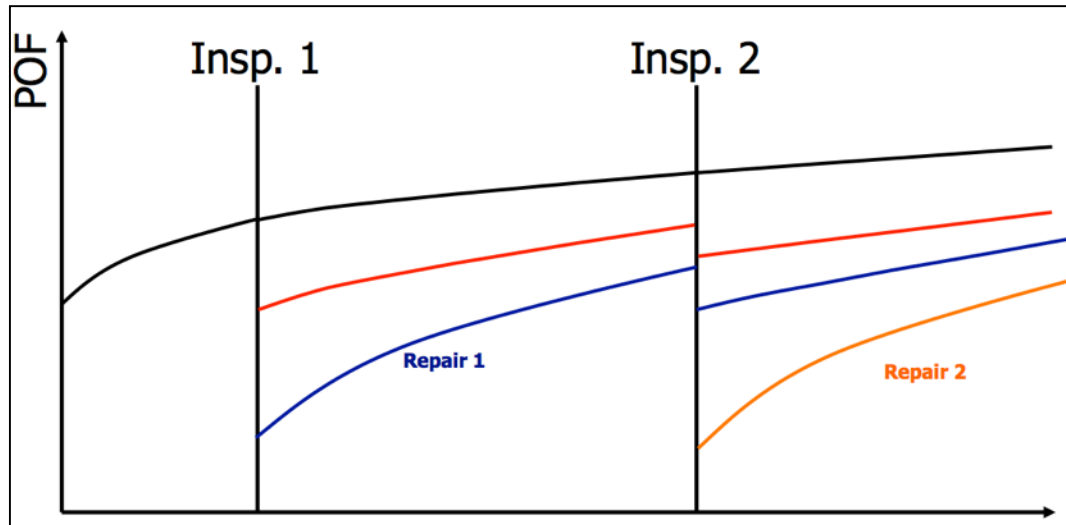
Presenter: Dr Juan Ocampo - AeroMatter

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



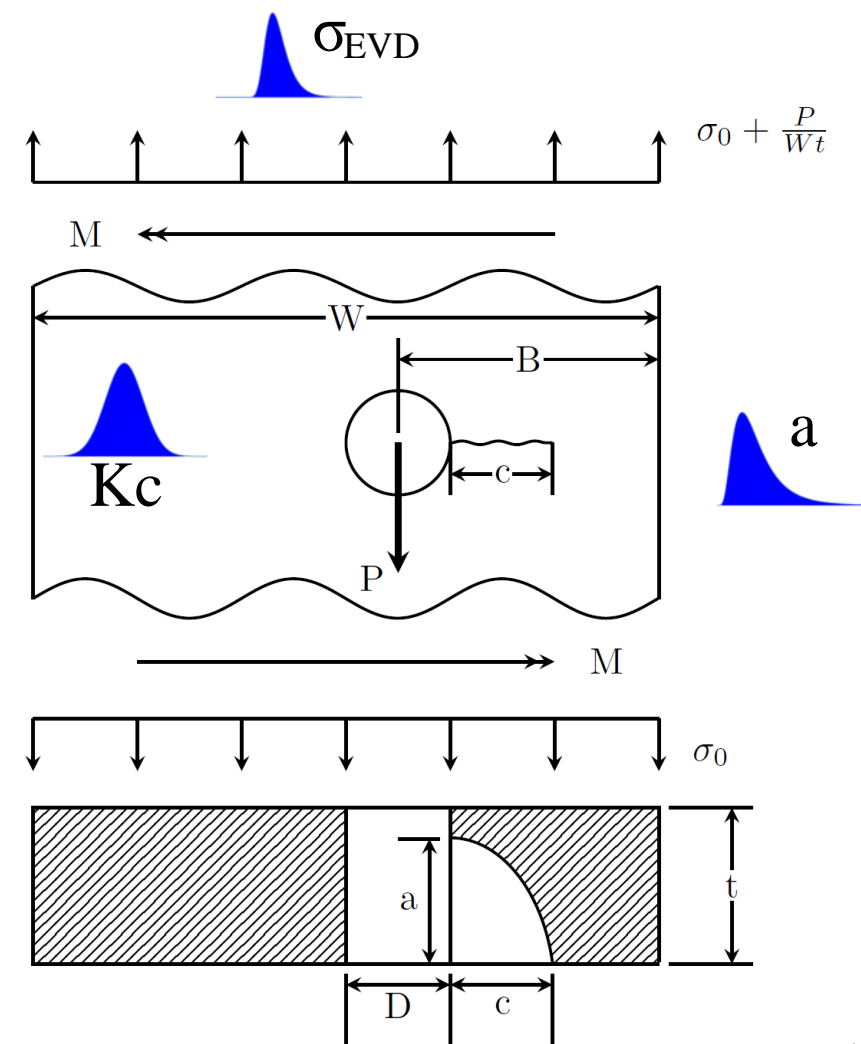
<u>Example</u>	<u>Initial Crack Size</u>	<u>Fracture Toughness</u>	<u>Extreme Value Distribution</u>	<u>Inspection</u>
<b>noinsp.smdt</b>	 Lognormal	 Normal	 Gumbel	None
<b>1insp.smdt</b>	 Lognormal	 Normal	 Gumbel	 Det. = 0.05
<b>2insp.smdt</b>	 Lognormal	 Normal	 Gumbel	 Prob.

# Baseline Problem



## ✓ User-defined Master Curve

Variable	Statistics
Initial Crack size	Probabilistic Database
Fracture toughness	Probabilistic Database
EVD	Gumbel ( $\mu=15.3, \sigma=1.30$ )



# Analysis Tab



**SMART|DT**

Information
Analysis
Material
Geometry
Loading
Inspections
Run
Results

**Analysis**

Output Options

Growth

Probabilistic

**Probability of Failure (POF)**

Evaluation Frequency (Flights)  Maximum Flights Calculation  Flight Units

**SMART|DT**

Information
Analysis
Material
Geometry
Loading
Inspections
Run
Results

**Analysis**

Output Options

Growth

Probabilistic

**Model**  **Source**

**Master Curve**

**AVSN FILE**

**MASTER CURVE FRACTURE TOUGHNESS**

**MASTER CURVE YIELD STRENGTH**

**HOURS PER FLIGHT**

**FAILURE CRITERIA**

**SMART|DT**

Information
Analysis
Material
Geometry
Loading
Inspections
Run
Results

**Analysis**

Output Options

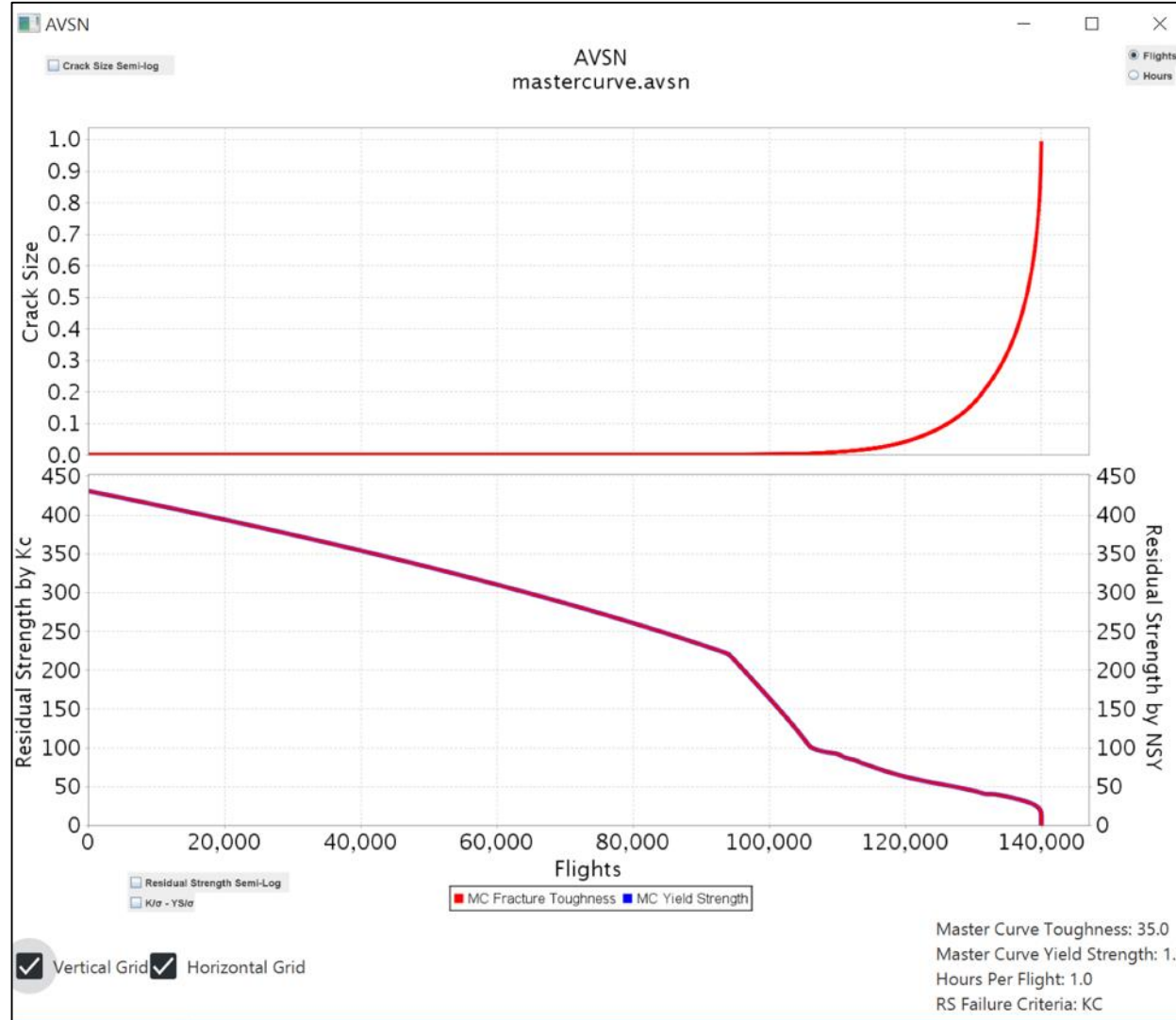
Growth

Probabilistic

**Method**  **Number of Samples**  **Random Seed**



# Crack Size & Residual Strength



# Material Selection



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

The screenshot shows the SMART|DT software interface with the following configuration:

- Category:** Aluminum
- Group:** 7075 Series
- Treatment:** 7075-T73511
- Form, Orientation:** Extrusion L
- Summary:** Length: Inches, Stress: KSI, Category: Aluminum, Group: 7075 Series, Treatment: 7075-T73511, Form, Orientation: Extrusion L

**FRACTURE TOUGHNESS**  
 $T = 0.9-4.0$   
 DISTRIBUTION: Normal  
 MEAN: 35.0, STANDARD DEVIATION: 3.7

**PARIS CONSTANT Log(C)**  
 DISTRIBUTION: Deterministic  
 VALUE: 0.0

**PARIS EXPONENT**  
 DISTRIBUTION: Deterministic  
 VALUE: 0.0

**YIELD STRENGTH**  
 T = 0.25-0.5, T = 0.5-0.75, T = 0.75-1.5, T = 1.5-2.0  
 DISTRIBUTION: Normal  
 MEAN: 65.0, STANDARD DEVIATION: 1.9

**ULTIMATE STRENGTH**  
 T = 0.25-0.5, T = 0.5-0.75, T = 0.75-1.5, T = 1.5-2.0  
 DISTRIBUTION: Normal  
 MEAN: 76.0, STANDARD DEVIATION: 1.6

# Geometry Selection



Military Transport -> Wing -> Rivet Holes in C130

The screenshot shows the SMART|DT software interface with the following components:

- Navigation Bar:** Information, Analysis, Material, **Geometry** (selected), Loading, Inspections, Run, Results.
- Equivalent Initial Flaw Size (EIFS) Configuration:**
  - Category:** Custom, Commercial Transport, Military Fighter, **Military Transport** (selected).
  - Group:** **Wing** (selected).
  - Data Set:** Rivet Holes in C-130 (selected).
  - Summary:**
    - Flaw Type: Joint
    - Length: Inches
    - Mean (log): -5.6413
    - StDev (log): 0.61707
    - Notes: C-130 center wingbox in Aluminum 7075-T6 skin at rivet holes. Reference 10 (History logic)
- Initial Crack Size Distribution:**
  - DISTRIBUTION:** LogNormal (selected).
  - MEAN:** 0.004292387
  - STANDARD DEVIATION:** 0.002922037
- PDF of Military Transport Data Sets:**
  - Graph showing PDF vs. Equivalent Initial Flaw Size, EIFS (inch).
  - Y-axis (PDF): 0 to 250.
  - X-axis (EIFS): 0 to 0.02.
  - Curve: Wing, Rivet holes in C-130 center wingbox.
- Disclaimer:**

The EIFS is traditionally determined through the process of growing in-service or tear-down cracks backwards to time zero. As such, the results are dependent upon the aircraft location, assumed material parameters, and loading history. As a result, it is not recommended to use an EIFS distribution for a different application than for which it was derived. The EIFS values are provided here as a guide and care should be taken to select the distribution that best matches the aircraft mission, joint geometry and manufacturing methods, or ensure that the distribution is appropriately conservative.

# 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	Scale	Shape
15.3	1.3	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

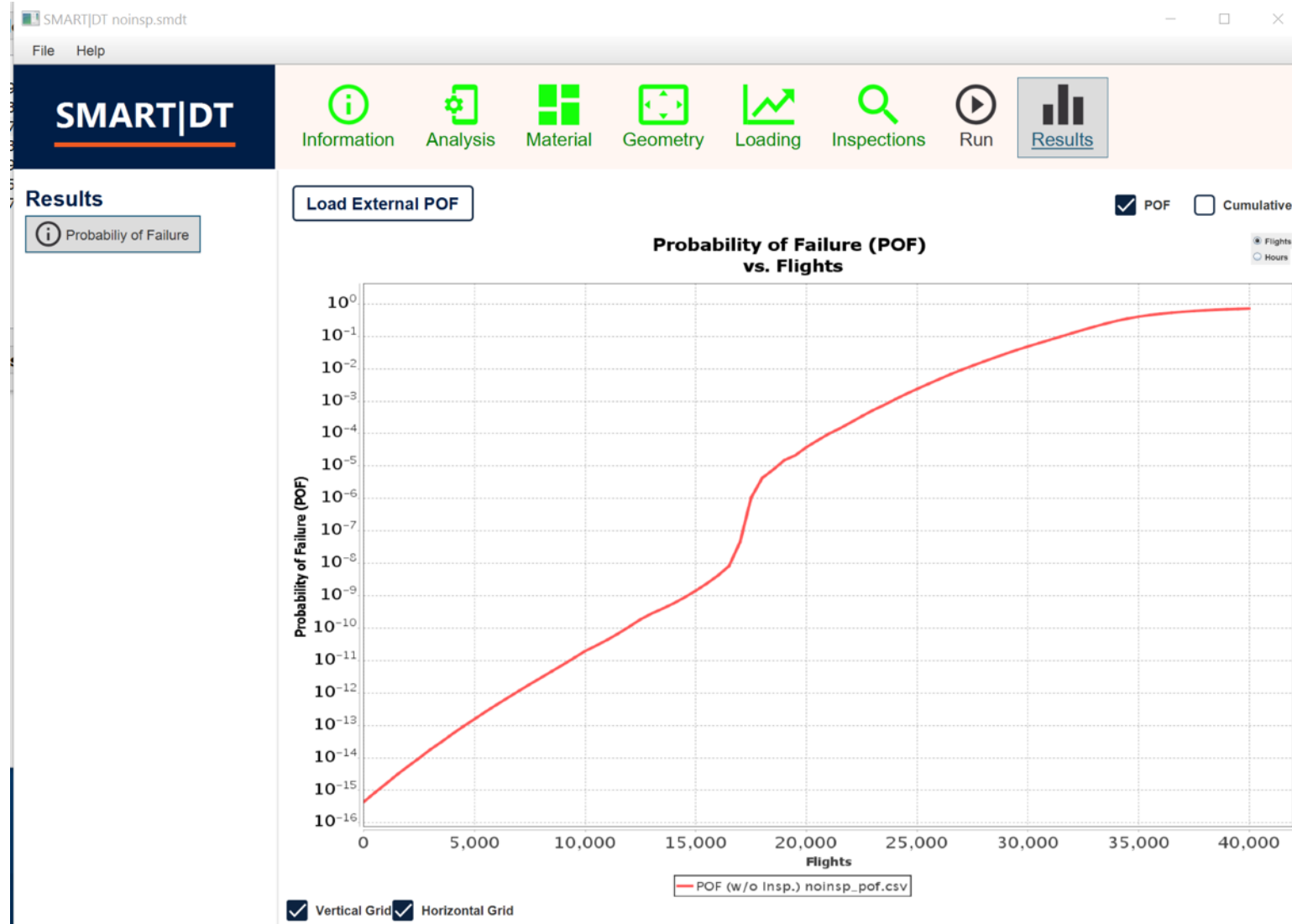
### Inspections

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

Delete Edit Add

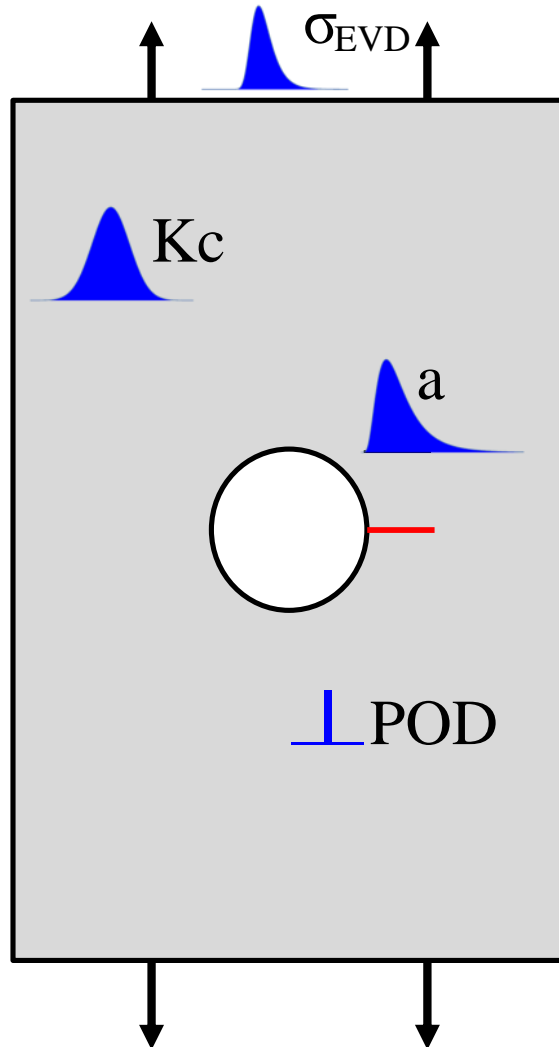
Version 1.0.185 - Build 925 Units: Flights

# noinsp Results



# Problem Definition

## One Deterministic Inspection



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

All cracks  $\geq 0.05$   
will be detected.

# Adding an Inspection Preset



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

<Select Flight Units>	Preset	Type	Inspection Prob.	Detection Prob.	Repaired Crack
No Inspections					

Delete Edit Add

Version 1.0.167 - Build 925



# Adding an 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	* $\mu$ 0.004292387 $\sigma$ 0.00292...

Delete Edit Add

### Inspections

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

Delete Edit **Add**

# Adding an Inspection Time/Schedule



Add Inspections

**Add Inspections**

Preset  
Deterministic

Quantity: Single      Flights: 16000

Cancel Add

“Multiple” can be selected

# 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	* $\mu$ 0.004292387 $\sigma$ 0.00292...

Delete Edit Add

### Inspections

Flights	Preset	Type	Inspection Prob.	Detection Prob.	Repaired Crack
16000	Deterministic		1.0	2c: 0.05 a: 0.05	* $\mu$ 0.004292387 $\sigma$ 0.002...

Delete Edit Add

# Run Tab



SMARTJDT noinsp.smdt

File Help

**SMARTJDT**

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.

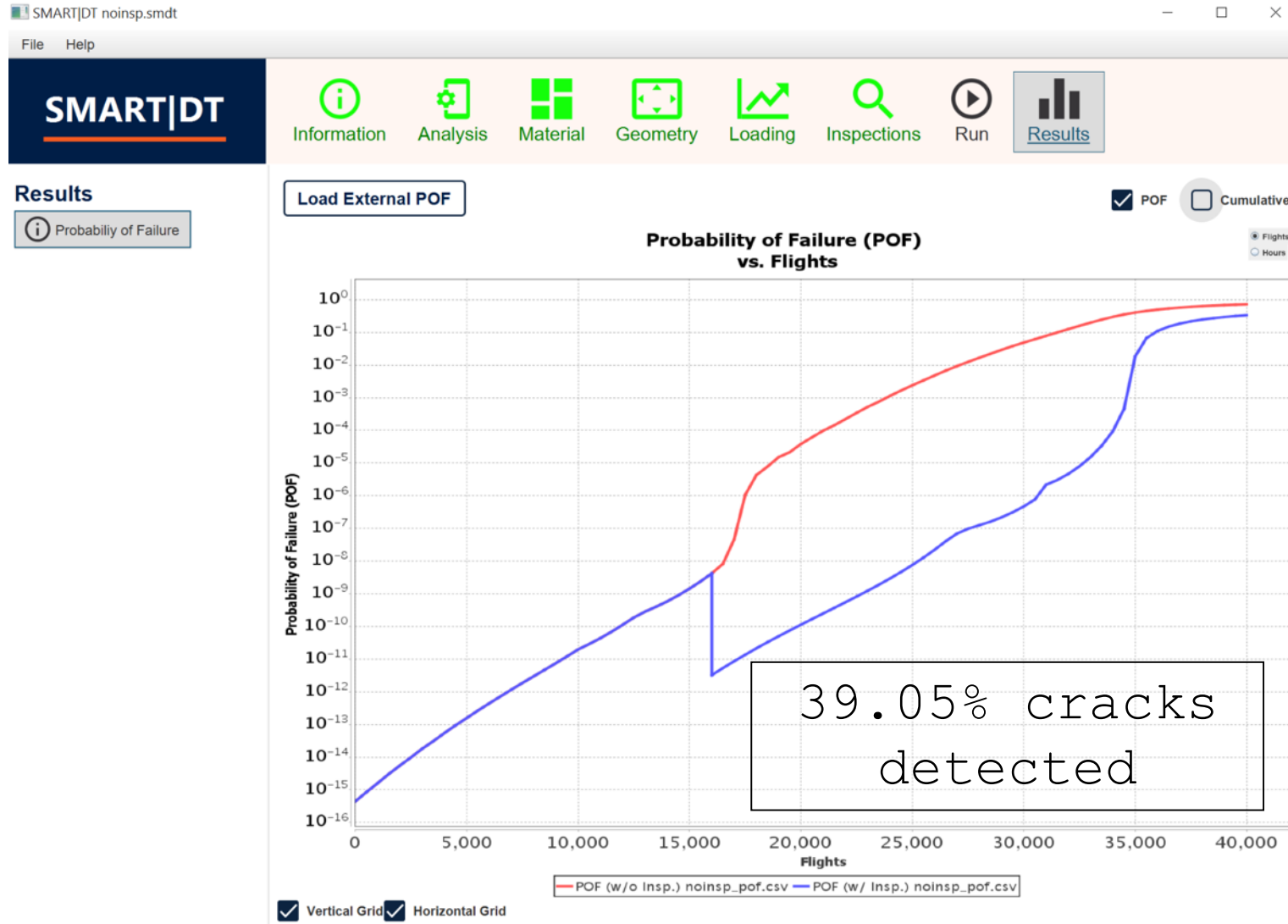
*****
***** PDTA analysis complete *****
*****

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

```

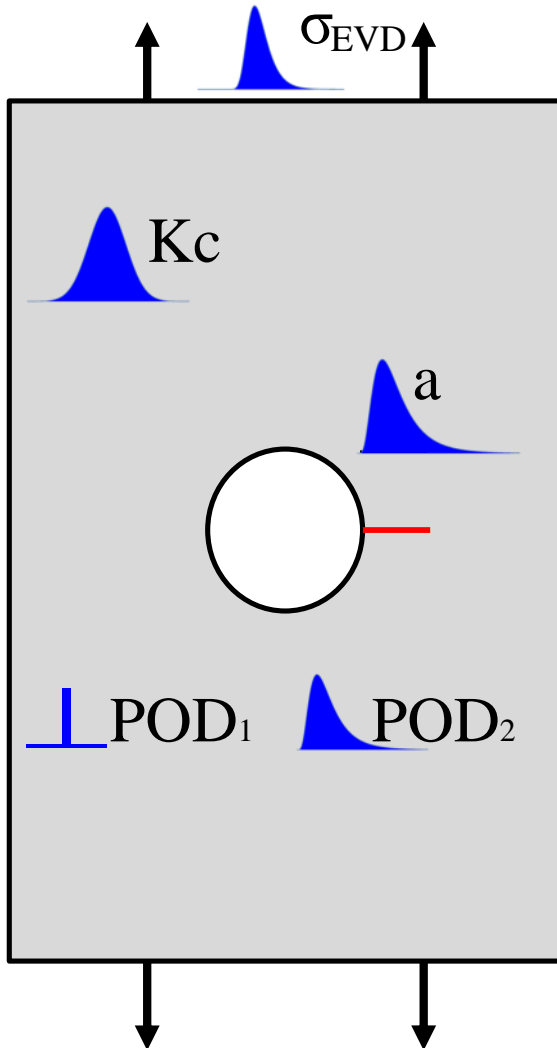
**Show/Export**

# 1insp Results



# Problem Definition

## Two Inspections



Variable	Statistics
Initial Crack size	Probabilistic Database
Fracture toughness	Probabilistic Database
EVD	Gumbel ( $\mu=15.3, \sigma=1.30$ )
Inspection 1	16,000 flights
POD 1	Deterministic = 0.05
Repair crack size 1	Same as initial
POI 1	1.0
Inspection 2	<b>26,000 flights</b>
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	* $\mu$ 0.004292387 $\sigma$ 0.00292...

Delete Edit **Add**

### Inspections

Flights	Preset	Type	Inspection Prob.	Detection Prob.	Repaired Crack
16000	Deterministic		1.0	2c: 0.05 a: 0.05	* $\mu$ 0.004292387 $\sigma$ 0.002...

Delete Edit Add



# Eddy Current Preset



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

Add Inspection Preset

**Add Inspection Preset**

Name: EddyCurrent

Material	Inspection Type	Geometry	Equipment	Summary
Custom	Automated Bolt Hole Eddy Current	Bolt Hole	Manual Bolt Hole Eddy Current	POD
Aluminum	Automatic Bolt Hole Eddy Current			Inspection Type: Manual Bolt Hole Eddy Current
	Bolt Hole Eddy Current			Material Category: Aluminum
	Eddy Current Hand Scan			Geometry: Bolt Hole
	Eddy Current Sliding Probe			Equipment: Manual Bolt Hole Eddy Current
	Fluorescent Penetrant			Mean (log): -3.79105
	Manual Bolt Hole Eddy Current			StDev (log): 0.43479
	Surface Scan Eddy Current			

**Probability of Detection**

DISTRIBUTION: LogNormal

MEAN: 0.02481      STANDARD DEVIATION: 0.01132

**Probability of Inspection**

VALUE: 1.0

**Repaired Crack Size**

Same as Original

DISTRIBUTION: LogNormal

MEAN: 0.004292387      STANDARD DEVIATION: 0.002922037

POI = 1.0

RCS = Same as Initial

Cancel Add

# 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

