The Single Flight Probability of Failure: Past, Present, and Future: An Open Discussion

Juan Ocampo, Nathan Crosby,
Harry Millwater, Marv Nuss, and Beth Gamble

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Outline

- ✓ The SFPOF
  - ✓ Original Definition
  - ✓ PROF V3.#
  - ✓ SMART|DT
  - ✓ Example Problems
- ✓Risk Assessment Survey
- ✓SMART|DT Overview
  - ✓ Current Developments
    - ✓ Adaptive Multiple Important Sampling
    - ✓ Bayesian Updating
    - ✓ Optimized Inspections
    - ✓ Fleet Management
- ✓ Discussion and Where to Go Next

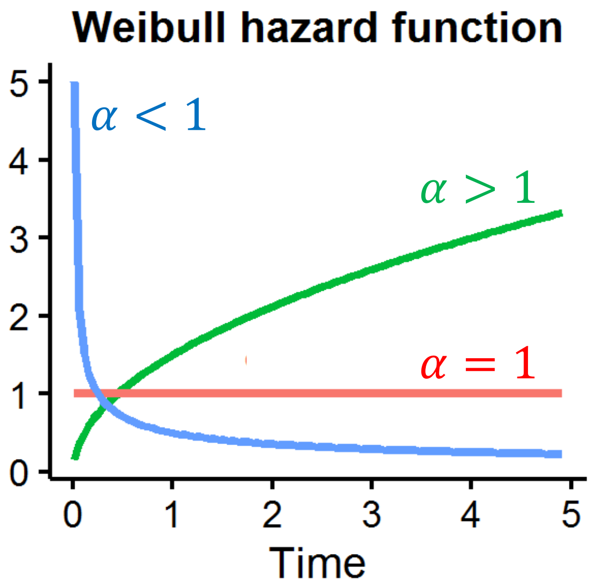
Traditional Hz. Fn.

- For a Weibull distribution

$$F(t) = 1 - exp\left(-\left(\frac{t}{\alpha}\right)^{\beta}\right)$$

$$f(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} exp\left(-\left(\frac{t}{\alpha}\right)^{\beta}\right)$$

$$HR(t) = \frac{f(t)}{1 - F(t)}$$



https://www.erikdrysdale.com/survival/

The hazard function (or hazard rate (HR), failure rate, risk of failure) specifies the instantaneous failure rate of death or failure at time *t*, given that the individual survives up to *t*

SFPOF By Lincoln

- The SFPOF introduced by Lincoln in 1985 can be defined as:

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

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

Without accounting for the fact that failure has not previously occurred

SFPOF By Barrens (V2.0)

- The SFPOF (Lincoln) was updated in PROF V2.0

$$POF(t) = \underbrace{\int_0^{a_c} f(a) \int_0^{\infty} g(K_c)[1 - F_{EVD}(\sigma_{RS}(t))]dK_c da}_{\text{Crack is smaller than critical but max. stress exceeds residual strength}} + \underbrace{[1 - F(a_c)]}_{\text{Crack is bigger than critical}}$$

PROF V3.# - Lincoln

Failure is assumed to occur during a flight when a crack exceeds a critical size during the flight or when the largest stress in the flight exceeds the residual stress for the existing flaw size at the location

$$h_1(t) = \frac{f_{haz}(t)}{1 - F_{haz}(t)}$$

$$h_2(t) = POF(t) = \frac{1}{t_f} \int_{-\infty}^{\infty} \int_0^{a_{haz}} \left[1 - F_{EVD}\left(\sigma_{RS}(t)\right)\right] \cdot f(a)da \cdot f(K_c)dK_c$$

$$SFPOF(t) = h_1(t) + h_2(t)$$ (Lincoln)

a_{haz} = crack size that produces the mean fracture toughness when encountering the average (the value at 63.2 percentile in Gumbel distribution) max stress in a flight

t_f = hours per flight

Freudenthal Method in PROF in PROF V3.#

- The conditional probability, given *Kc* and the initial flaw size a_0, of failing on flight *n* is the probability of surviving the first *n-1* flights and failing in flight *n*, and since peak loads are independent from flight to flight this is given by:

$$f_L(n|K_c,a_0) \cong \bar{H}\left(\frac{K_c}{\alpha(a(a_0,n))}\right)\prod_{i=1}^{n-1} H\left(\frac{K_c}{\alpha(a(a_0,i))}\right),$$

$$hz(n|K_c,a_0) = \frac{f_L(t)}{\bar{F}_L(t)} :$$

$$hz_{stress}(t) = \int_{-\infty}^{\infty} f_k(K_C) \int_0^{\infty} f_{a_0}(a_0)[1 - H\left(\frac{K_C}{\alpha(a(a_0,t))}\right) da_0 dK_C$$

SMART SFPOF 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)

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

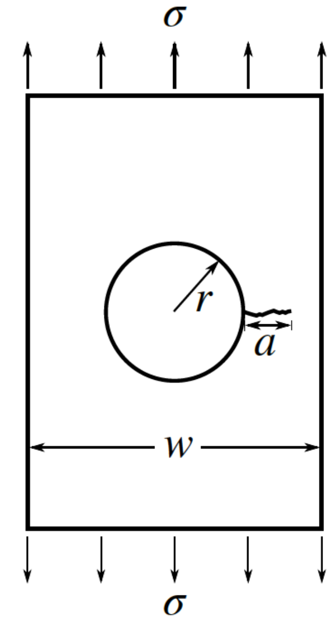
$$CTPOF(t) = \int \left[1 - \prod_{i=1}^{t} F_{EVD}\left(\sigma_{RS}(t_i)\right)\right] f_{\mathbf{x}}(\mathbf{x})\,d\mathbf{x}$$

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

Freudenthal formulation
(Available in in Smart|DT)

F_{EVD} – CDF of the maximum stress per flight (extreme value distribution)
$\sigma_{RS}(t)$ – residual strength

Handbook Example



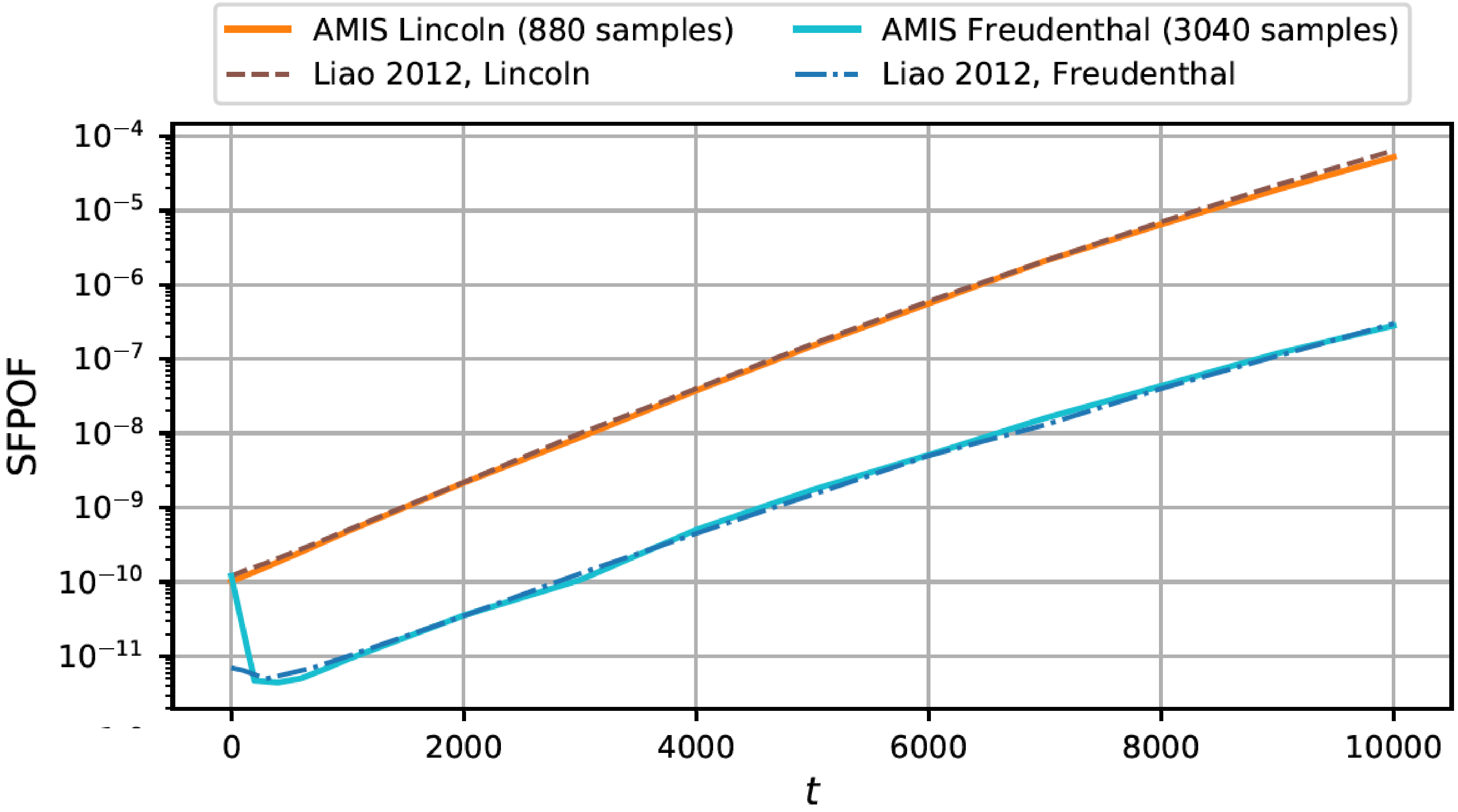
$$a\left(t\right) = a_0 \exp\left(t \cdot 2.93 \times 10^{-4}\right)$$

$$\beta\left(a\left(t\right)\right) = \underbrace{\left(0.6762 + \frac{0.8734}{0.3246 + a\left(t\right)/r}\right)}_{\beta_{\text{hole}}} \times \underbrace{\left(\sqrt{\sec\left(\frac{\pi\left(r + a\left(t\right)\right)}{w}\right)}\right)}_{\beta_{\text{width}}}$$

$$\sigma_{\text{rs}}\left(a\left(t\right)\right) = \frac{K_c}{\beta\left(a\left(t\right)\right)\sqrt{\pi\, a\left(t\right)}}$$

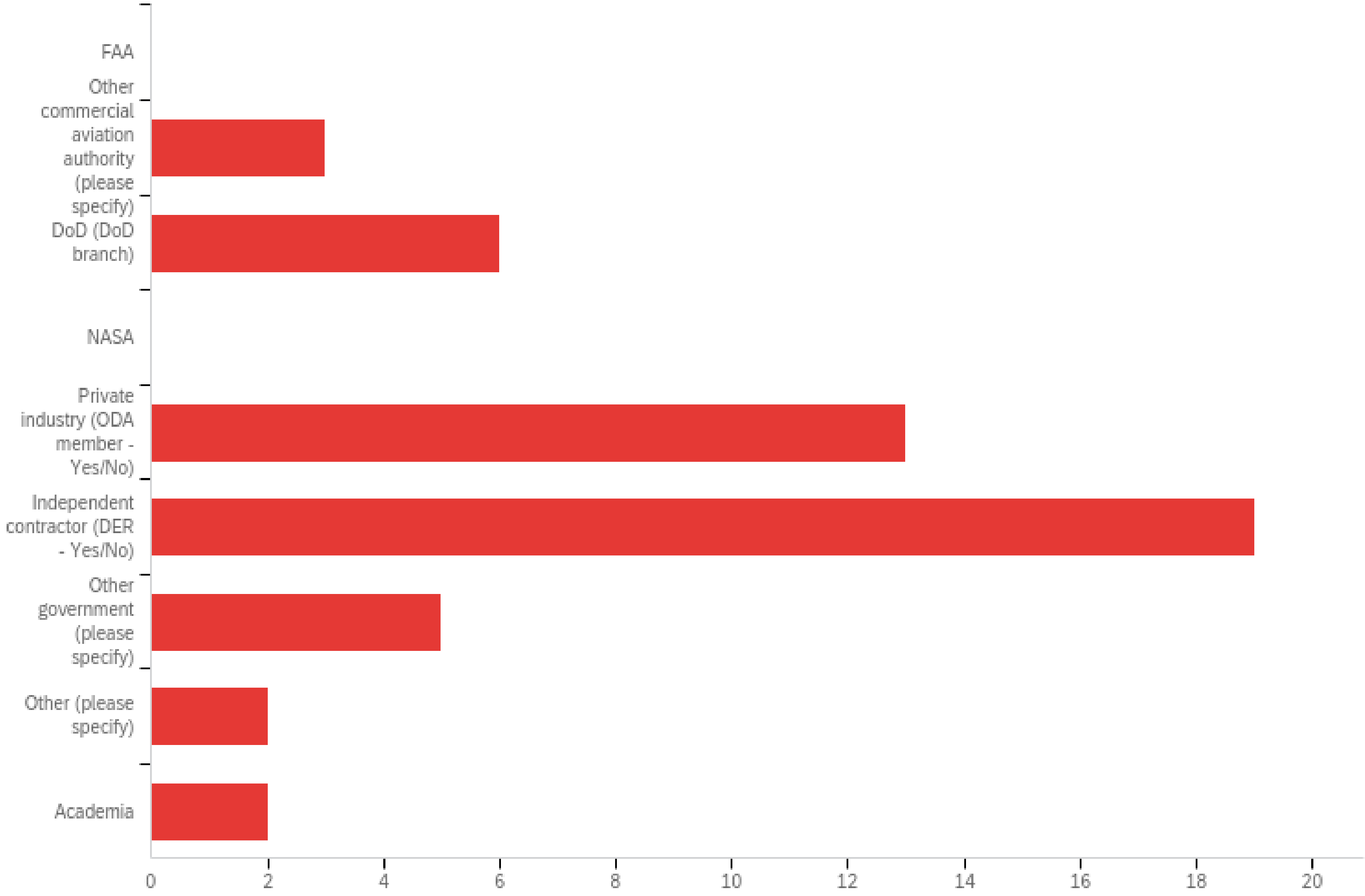
Random Variable	Distribution	Parameters
Initial crack size a_0	Lognormal	mean $= 0.0030$ in standard deviation $= 0.0047$ in
Fracture toughness K_c	Normal	mean $= 34.8\ \text{ksi} \cdot \text{in}^{1/2}$ standard deviation $= 3.9\ \text{ksi} \cdot \text{in}^{1/2}$
Maximum stress σ_{EVD}	Weibull	location $= 5.0$ ksi scale $= 10.0$ ksi shape $= 5.0$
Width, w		10.0 in
Hole Radius, r		0.125 in

Handbook Example Results

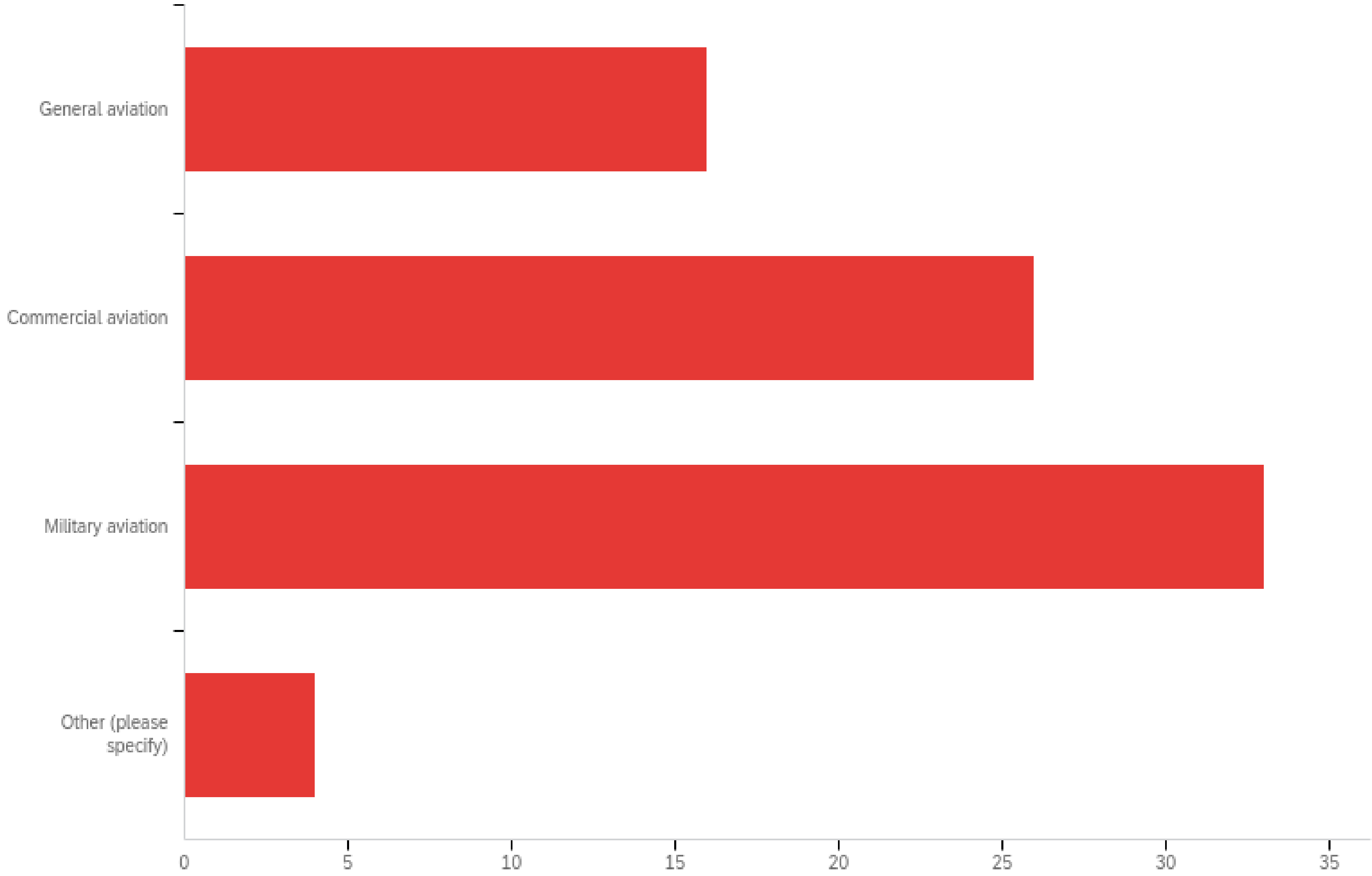


Risk Assessment Survey
Dec. 7th 2022

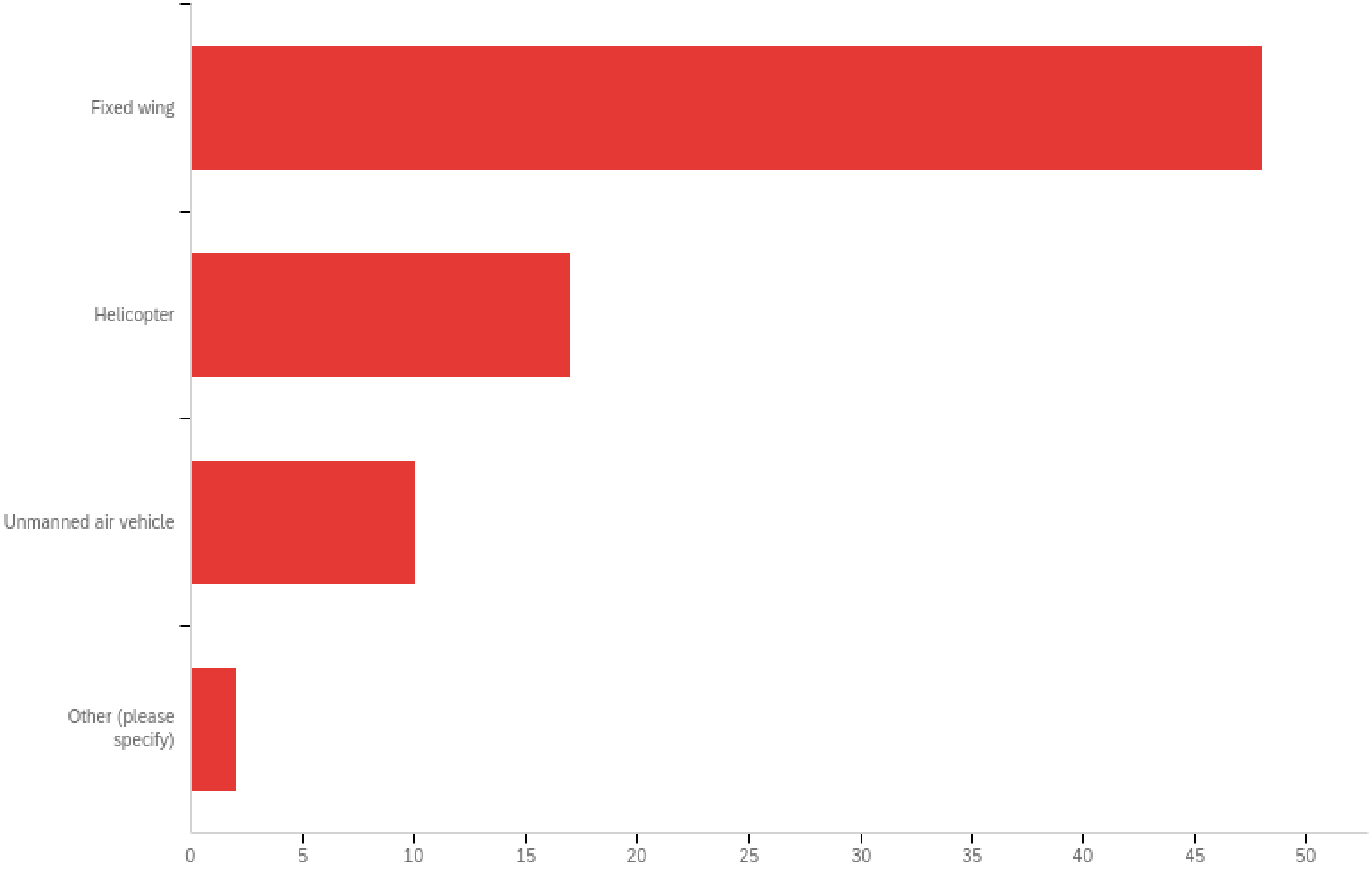
Indicate your employment agency



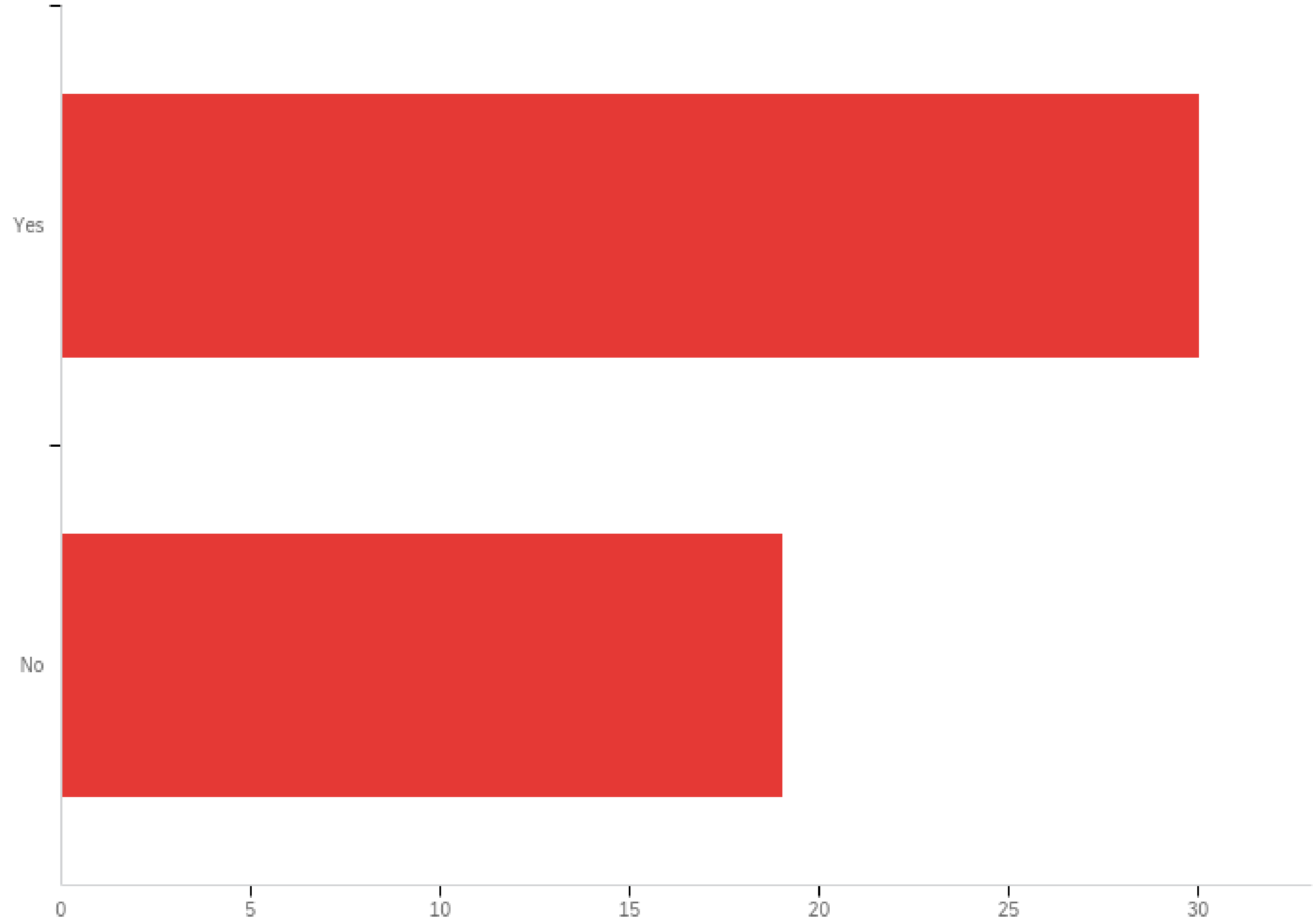
What type of aircraft industry do you typically support?



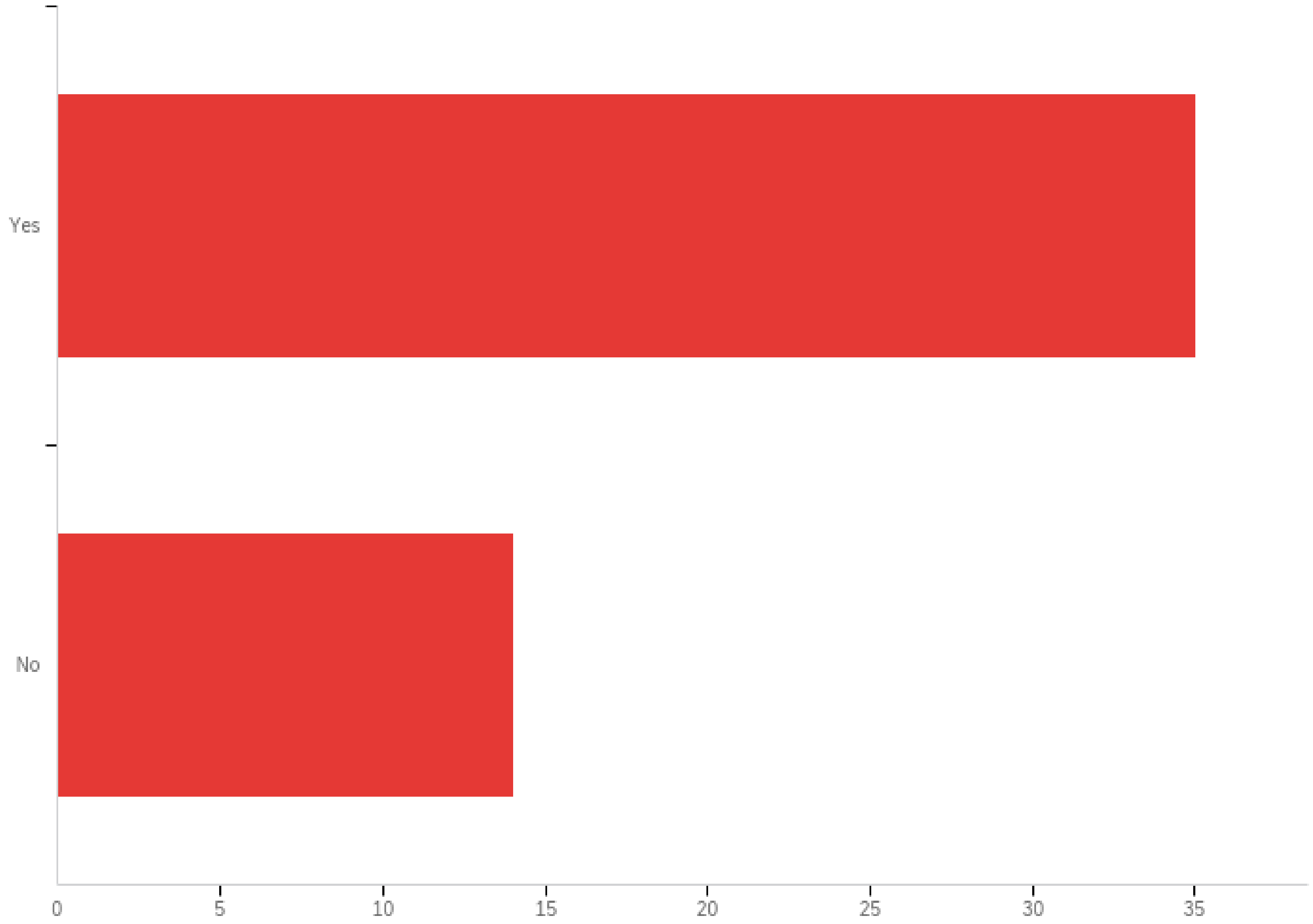
What type of aircraft do you typically support?



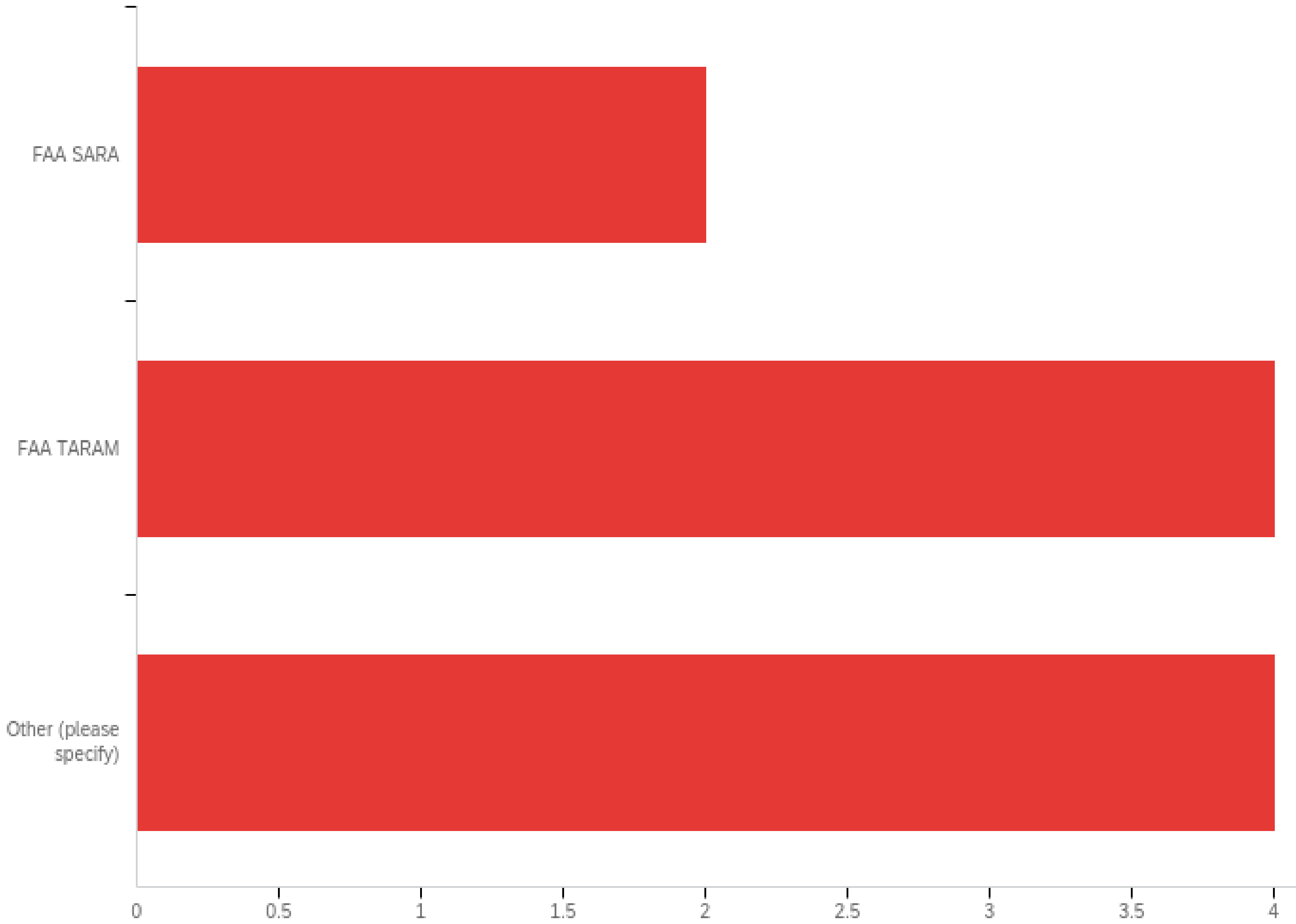
Have you used probabilistic risk assessment methods to calculate fatigue life (crack initiation)?

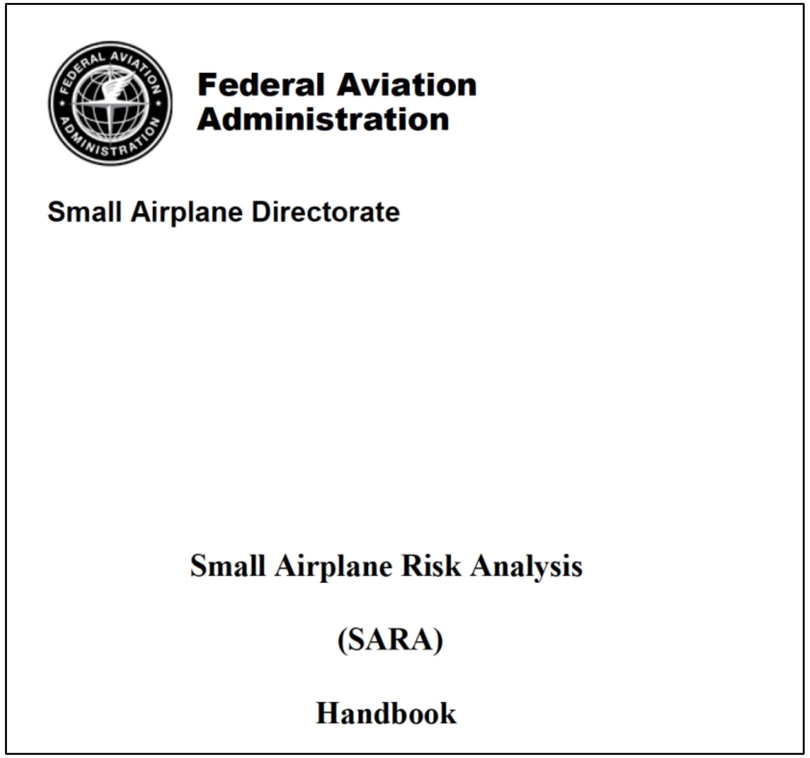


Have you used probabilistic risk assessment methods for damage tolerance assessments (crack growth)?



Have you used the FAA SARA or TARAM documents for risk assessment for Part 23 or 25 aircraft or other guidance documents?





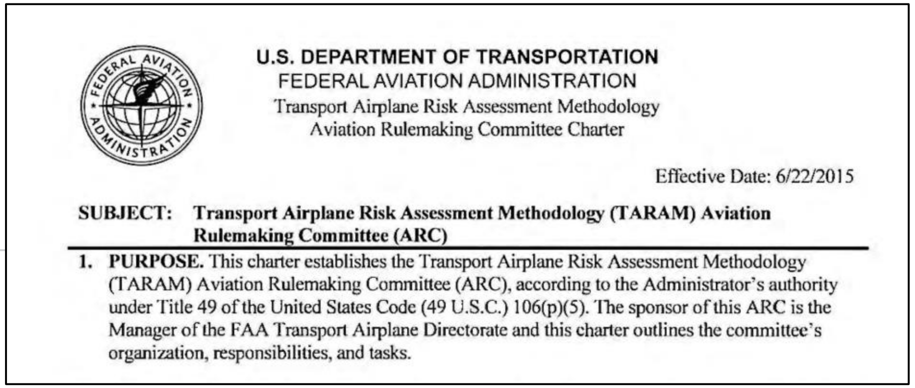
Federal Aviation Administration

Small Airplane Directorate

Small Airplane Risk Analysis

(SARA)

Handbook



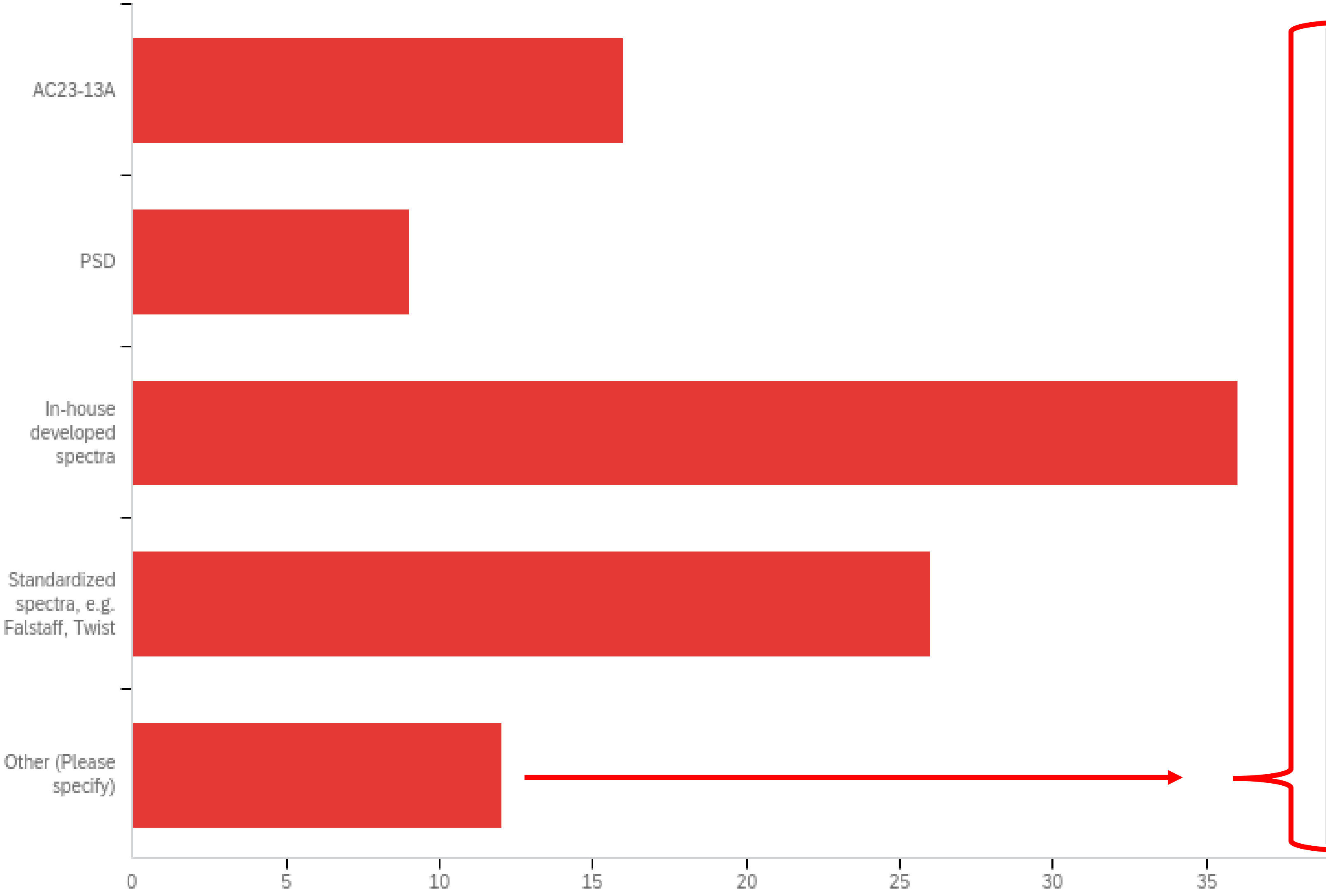
U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Transport Airplane Risk Assessment Methodology
Aviation Rulemaking Committee Charter

Effective Date: 6/22/2015

SUBJECT: Transport Airplane Risk Assessment Methodology (TARAM) Aviation Rulemaking Committee (ARC)

1. **PURPOSE.** This charter establishes the Transport Airplane Risk Assessment Methodology (TARAM) Aviation Rulemaking Committee (ARC), according to the Administrator's authority under Title 49 of the United States Code (49 U.S.C.) 106(p)(5). The sponsor of this ARC is the Manager of the FAA Transport Airplane Directorate and this charter outlines the committee's organization, responsibilities, and tasks.

What source(s) do you use for generating load spectra for fatigue/damage tolerance analyses?



UDRI / Tom Swift
L/ESS
from government
OLM
Patrick Safarian Method
Loads & Environment Strain Survey
Provided by MRO
Spectra developed from in-service loads measurement program
Measured spectra published by DOT/FAA, MIL-A-8860
Usually combination of measured spectra form L/ESS
supplied by client

What source do you use for your equivalent initial defect/flaw size distribution? (I)

Fleet history records
FAA Guidance - Patrick Safarian
Fractograpghy data from FSFT
AF DT Handbook
DOT/FAA/CT-93/69
In house EIFS using damage-findings back-extrapolated using Master-Curve
internal, customer, other literature
Maintenance records, or testing
inspection data
Dod , AFGROW
Defects measure by micro CT, or microstructure variables, and occasionally classic LEFM determined EIFS from coupon tests

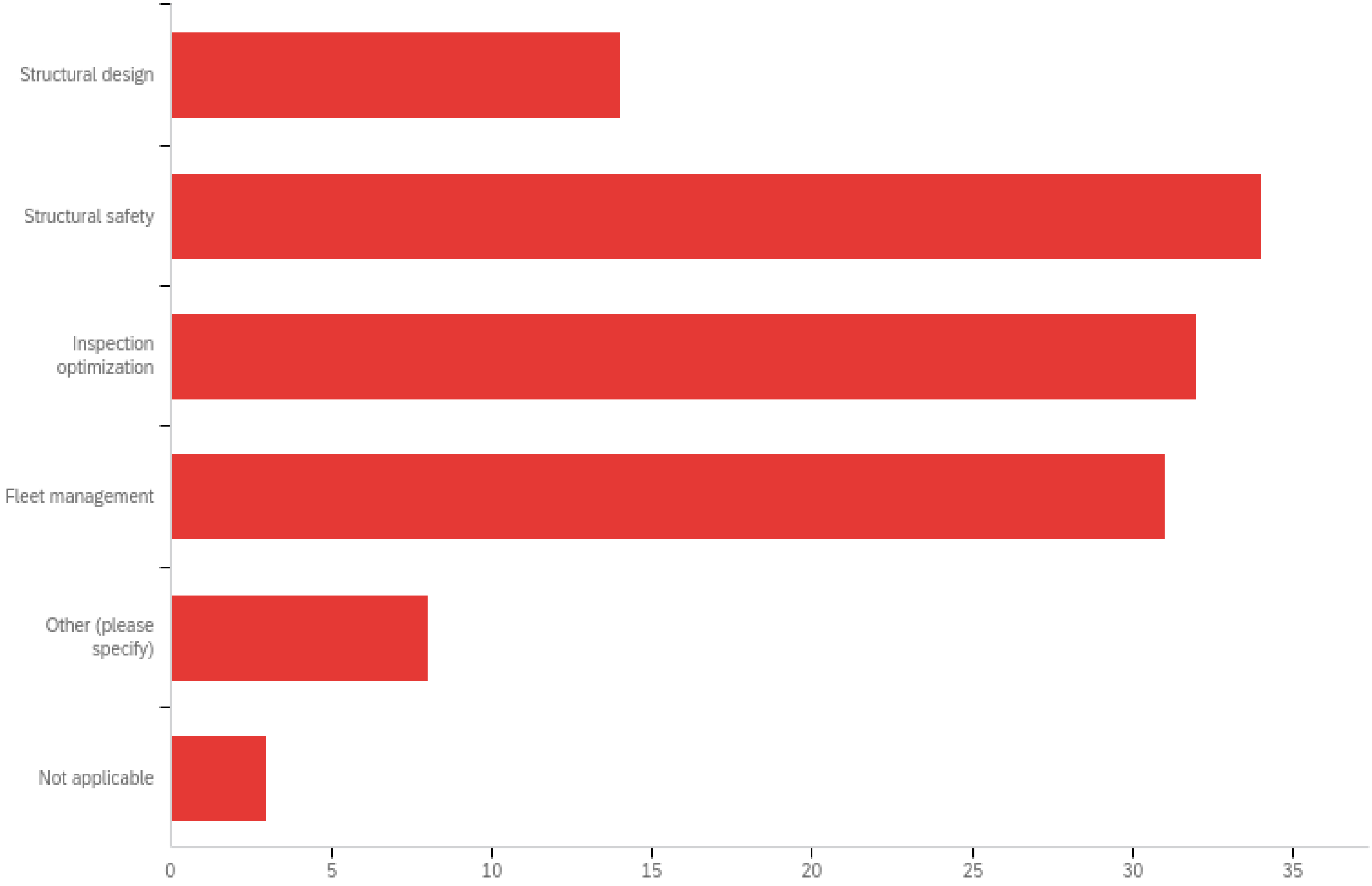
data
FAA sourced data
In-service damage data, material database, published in references
JSSG-2006
Patrick Safarian
Teardown data when available.
In-house developed (some measured some computed)
.030
USAF
JSSG-2006; MIL-A-83444; NASA-STD-2009; AFFDL-TR-79-3021; EN-SB-08-002; EZ-SB-13-003; AC 25-24; Tom Swift
EIFS from in-service data, coupon data investigation

What source do you use for your equivalent initial defect/flaw size distribution? (II)

Industry standards, e.g. JSSG-2006
Seattle ACO unpublished guidance
experimental data
Aircraft tear down
Crack inspection data
inspection crack data
FSFT data
Military type flaw sizes
DOT/FAA/CT-93/69 II
Developed from fleet data

Field and/or FSDT data
Seattle ACO Guidance Published 10/99 (Dr. Safarian)
Wild ass guess (WAG)
non-destructive inspection
Historical Data

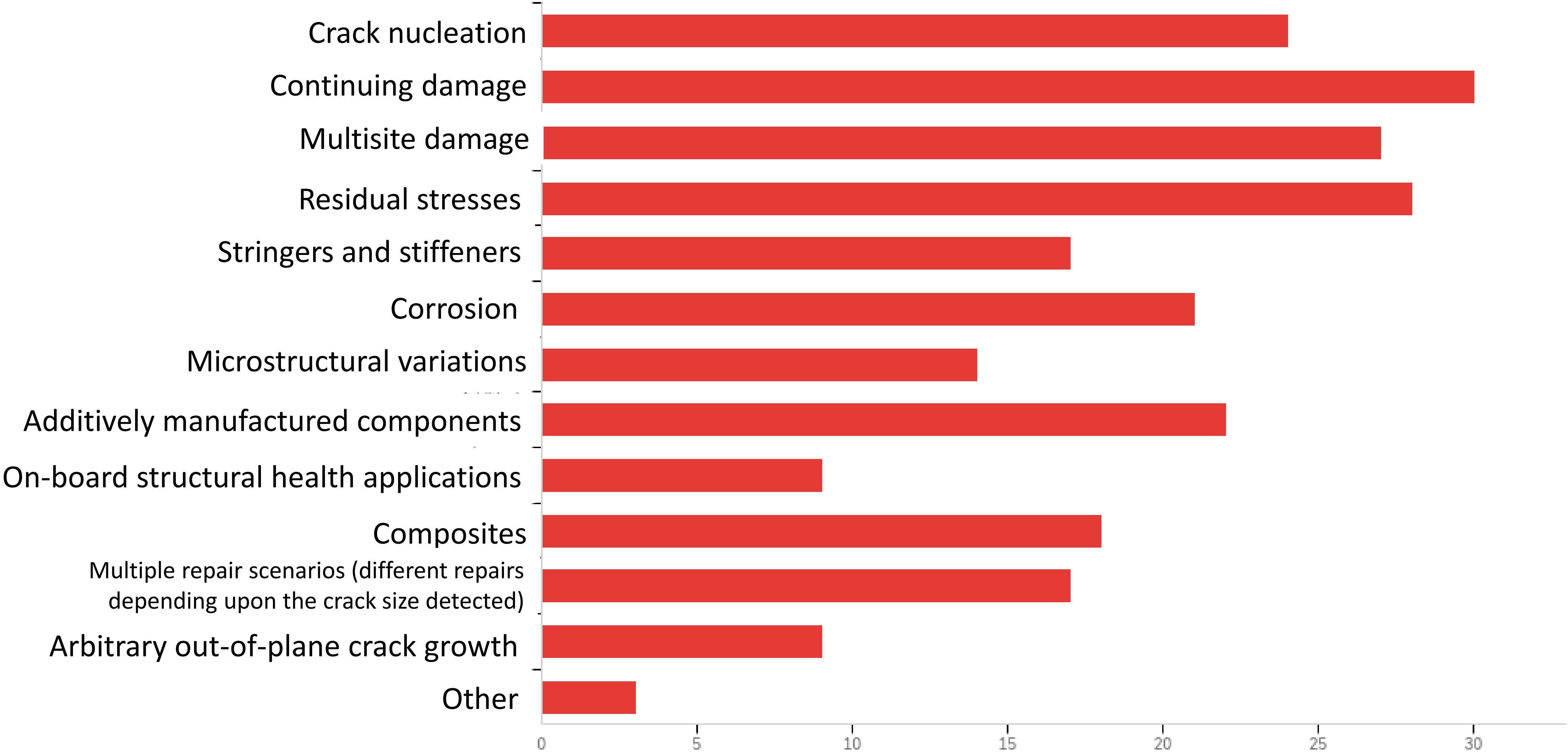
For what purpose do you use risk assessment results?



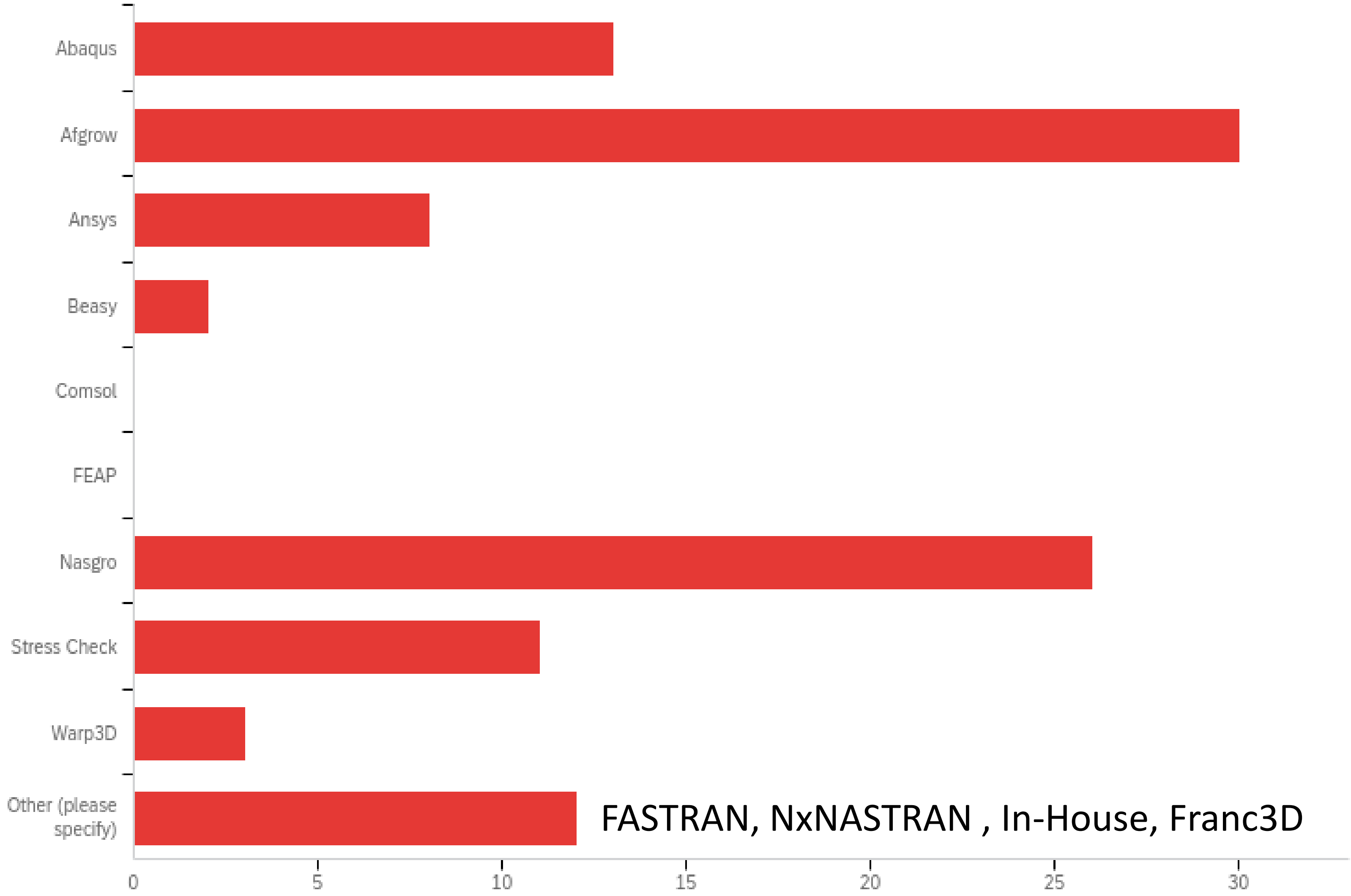
For what purpose do you use risk assessment results?

Other:
We are currently working on using PRA as a relative assessment tool to justify short delays in inspections when they fall outside convenient maintenance opportunities
Research/Demo approaches for design, safety, management
Justification for Airworthiness Directives
WFD Assessment
probabilistic methods have to be approved by the FAA for civil aviation. I have not heard of an FAA approval for probabilistic methods to certify airplanes (approve data).
Life of type (aircraft retirement prediction)
Defining structrral Life limit as per MIL-A-1530D, also fleet risk when unexpected damage is found
Research

Are there structural/fracture mechanics capabilities that you would like to use with risk assessment methods?

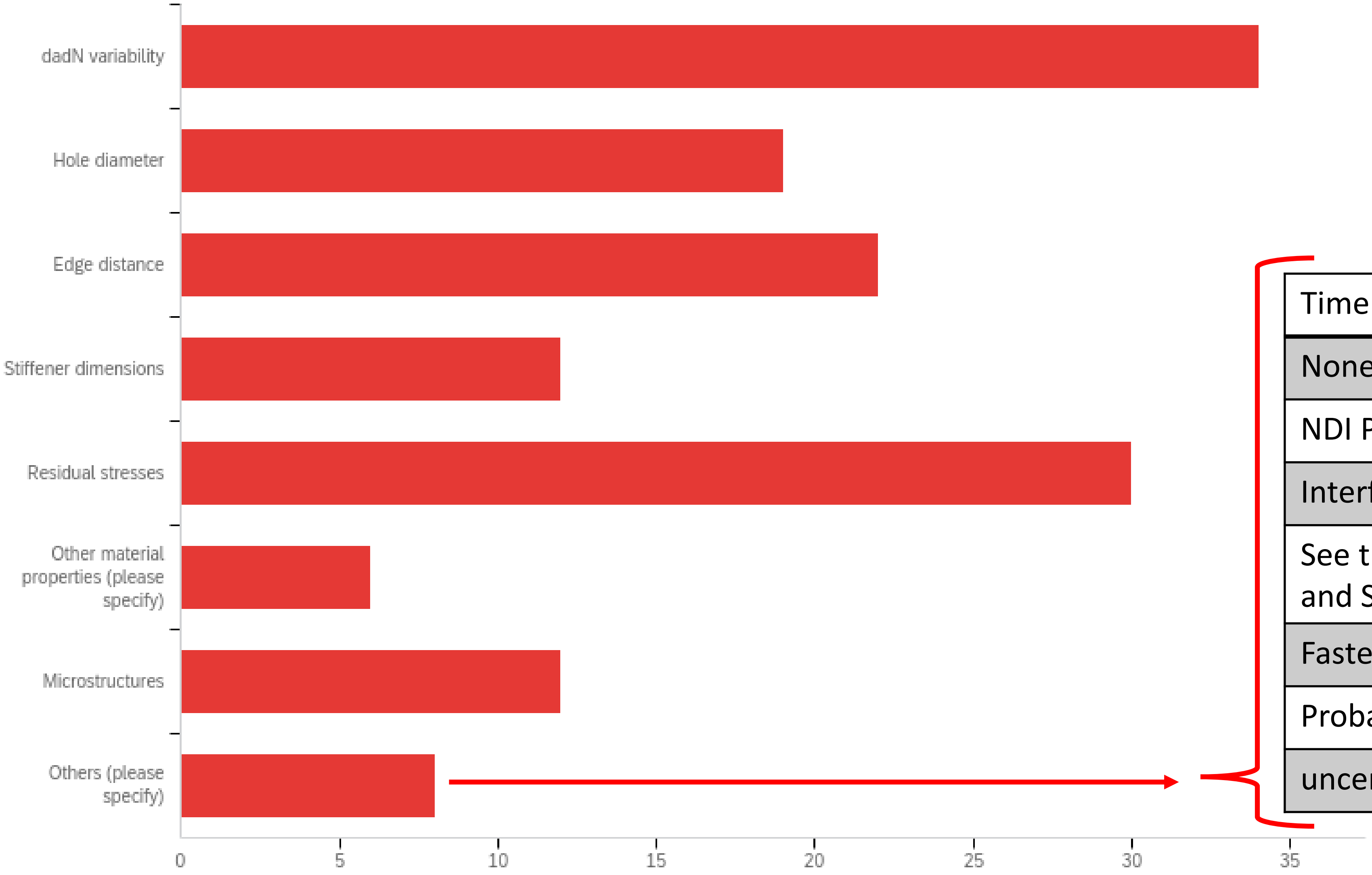


Are there software (commercial or open source) that you would like to use with a risk assessment analysis? (select all that apply)



FASTRAN, NxNASTRAN , In-House, Franc3D

In addition to the equivalent initial flaw size (EIFS), fracture toughness and loading, are there additional random variables you would like to consider during a risk analysis and if so, what variables?



Time from last inspection to failure

None of the above

NDI POD

Interference

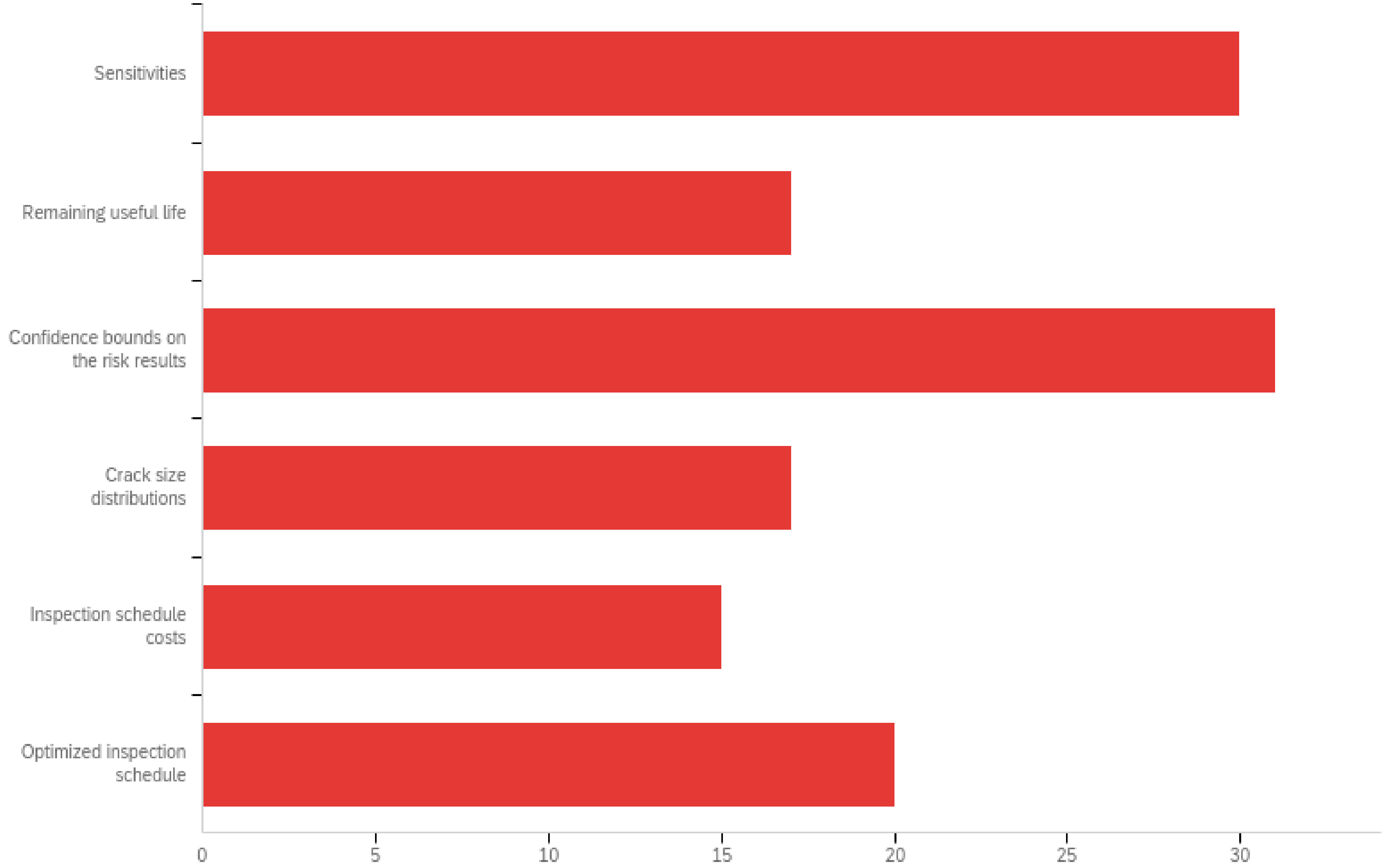
See those parameters by Fawaz in 2001 and SwRI separately several years later.

Fastener fit and fill

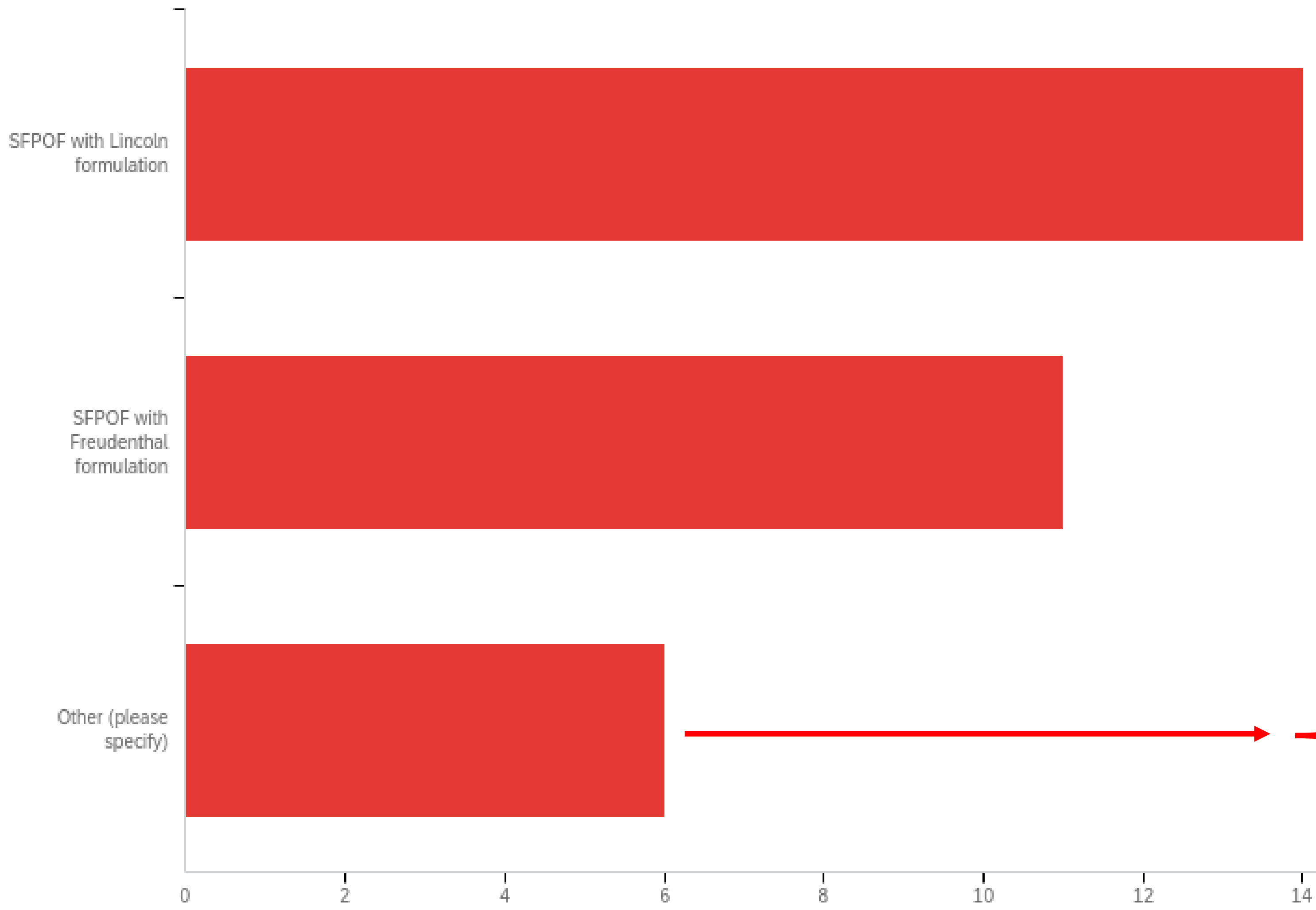
Probability of detection (POD)

uncertainties in SIF calc

Are there probabilistic outputs that would be useful that you don't currently obtain?



Do you use the Single Flight Probability of Failure (SFPOF) as your risk assessment measure?

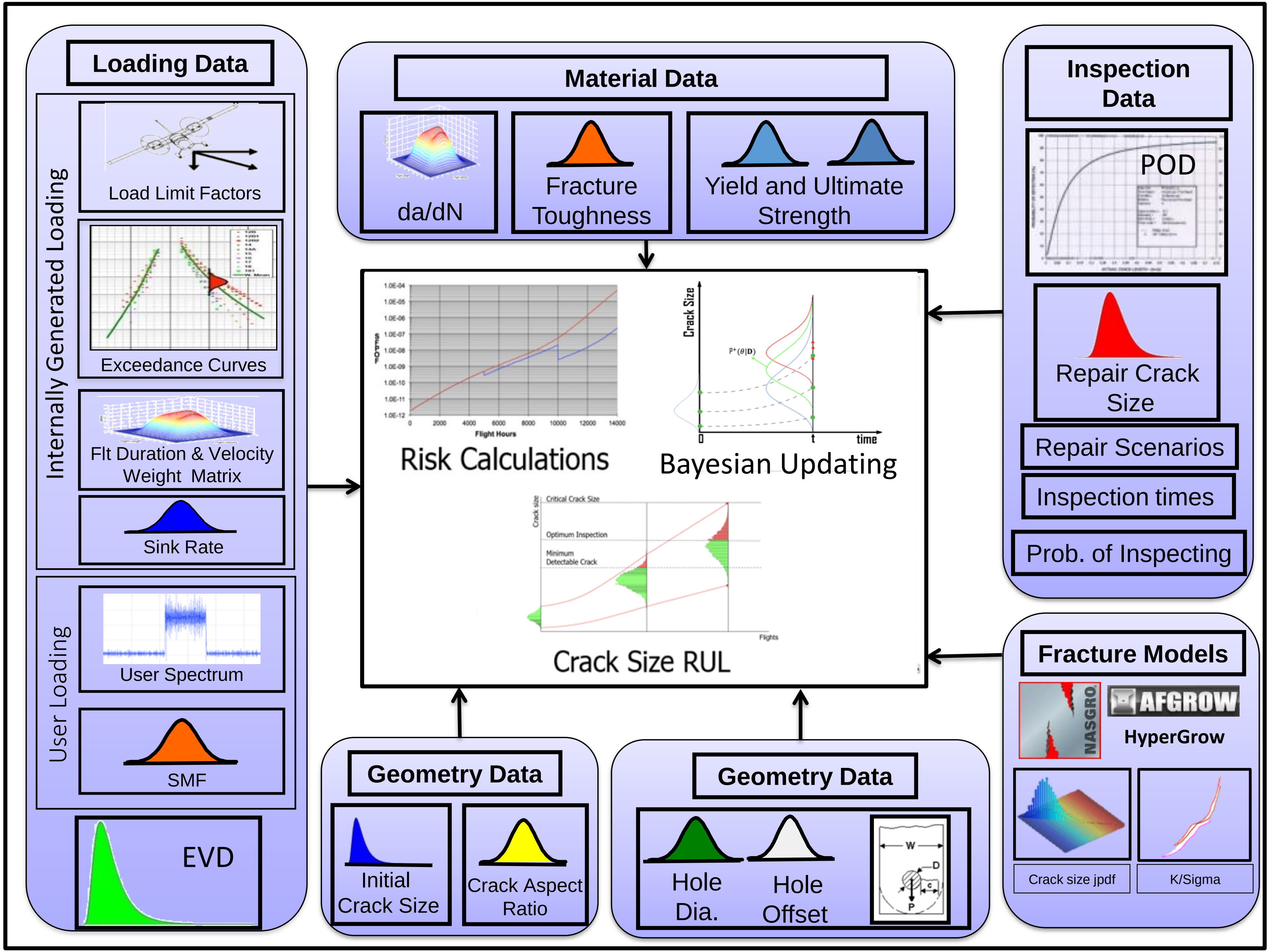


- To be honest I am not entirely sure - I think it is the top-most one as the software we used attempts to mimic PROF
- Fleet level Weibull analysis
- HR calculated from CPOF
- the supporting data bases do not have a adequate pedigree for computational accuracy.
- Survival analysis
- This was discussed at some stage for Fracrisk, but not sure of the outcome

Are there other desirable capabilities or features not previously mentioned?

Failsafe structure
Need to establish the means to define the parameter variation data bases.
In using PRA I get somewhat frustrated at the extreme sensitivities to particulkar inputs. Understanding these sensitivities and why they occur is not always straight-forward. For instance POI can cause hugh changes in results in some cases but not others. And of course how do we know what a good POI number is? 0.95? 0.90?
crack shape effects
NDI updating using Bayesian, damage sensor results updating; load sensor data updating
assessment based on positive and negative findings of an operating fleet
Risk of rogue flaw from manufacturing process or accidental damage from inspection/maintenance
Updating of risk predictions using Bayesian Inference
Risk assessment methods only work with sufficient data for the random variables and there is not enough data to satisfy FAA or military certification officials to make absolute risk assessments. Risk assessments are always relative which is not much use for my customers.

The SMART Software



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

Risk Calculations

Bayesian Updating

Crack Size RUL

Fracture Models

HyperGrow

Crack size jpdf

K/Sigma

Geometry Data

Initial Crack Size

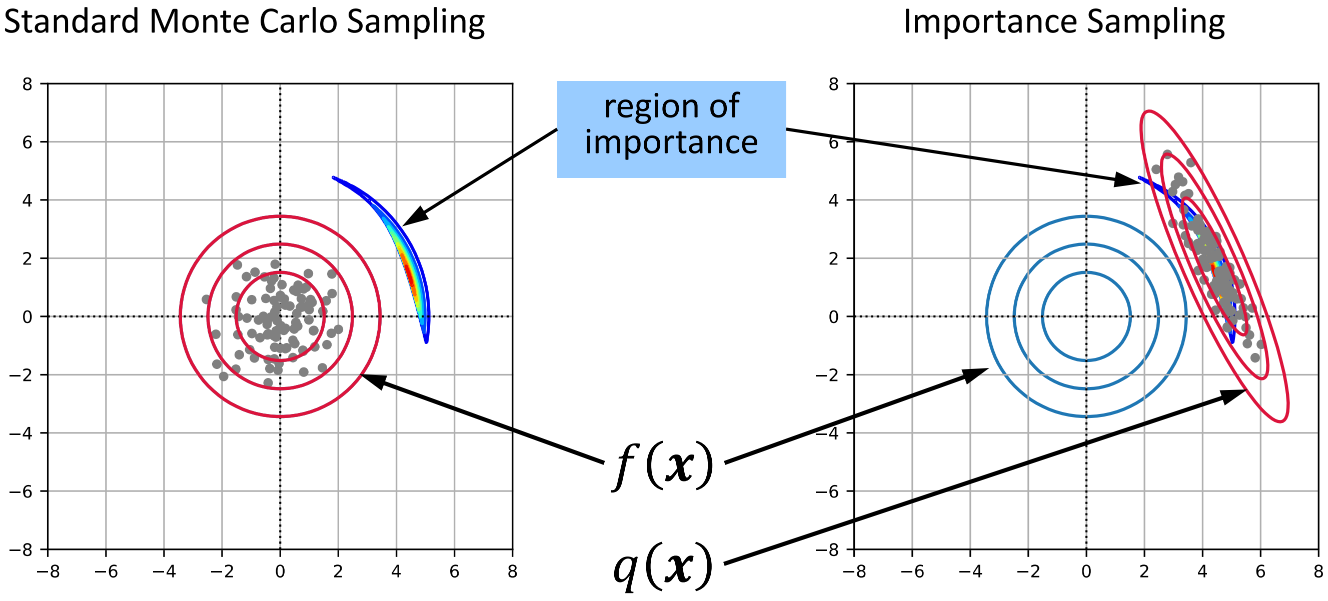
Crack Aspect Ratio

Geometry Data

Hole Dia.

Hole Offset

Importance Sampling



$$\mathbb{E}[H(\boldsymbol{x},t)] = \int H(\boldsymbol{x},t)\, f(\boldsymbol{x})\,\mathrm{d}\boldsymbol{x}$$

$$\widehat{\mathbb{E}}[H(\boldsymbol{x},t)] = \frac{1}{N}\sum_i H(\boldsymbol{x}_i,t)$$

$$\mathbb{E}[H(\boldsymbol{x},t)] = \int H(\boldsymbol{x},t)\,\frac{f(\boldsymbol{x})}{q(\boldsymbol{x})}\, q(\boldsymbol{x})\,\mathrm{d}\boldsymbol{x}$$

$$\widehat{\mathbb{E}}[H(\boldsymbol{x},t)] = \frac{1}{N}\sum_i H(\boldsymbol{x}_i,t)\boxed{w(\boldsymbol{x}_i)}$$

Importance weight
$w(\boldsymbol{x}_i) = f(\boldsymbol{x}_i)\;/\;q(\boldsymbol{x}_i)$

- Define $\quad H(\boldsymbol{x};t) = 1 - F_{\mathrm{EVD}}\big(\sigma_{\mathrm{RS}}(\boldsymbol{x};t)\big)$
- From

$$\mathrm{var}\big(\widehat{\mathbb{E}}\big) = \frac{1}{N^2}\sum_i \left(\boxed{H(\boldsymbol{x}_i,t)\frac{f(\boldsymbol{x}_i)}{q(\boldsymbol{x}_i)} - \widehat{\mathbb{E}}}\right)^2$$

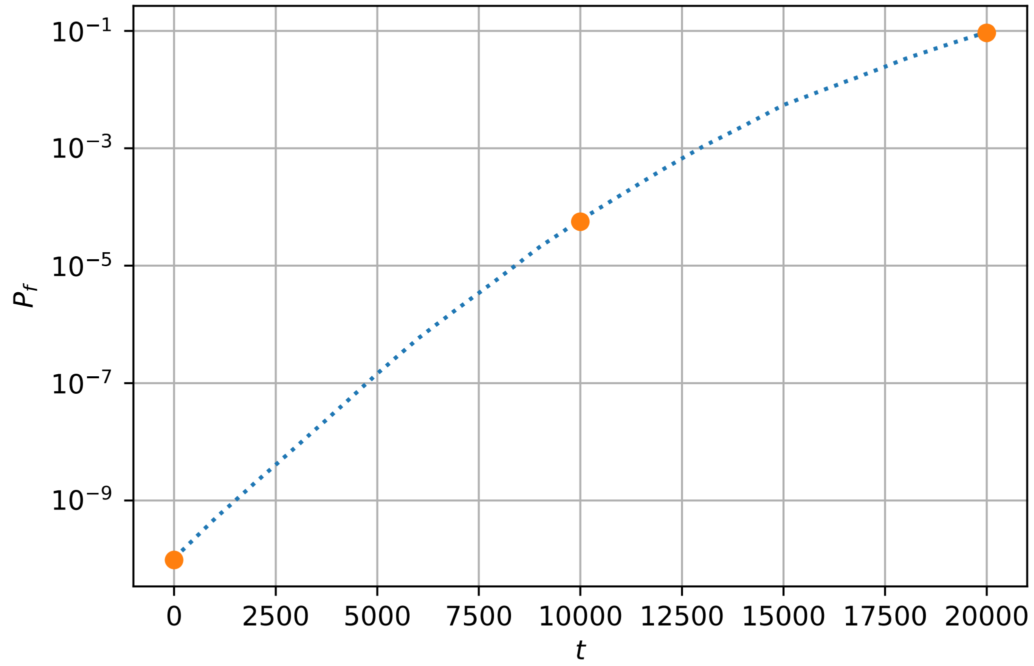
the estimator variance is 0 when

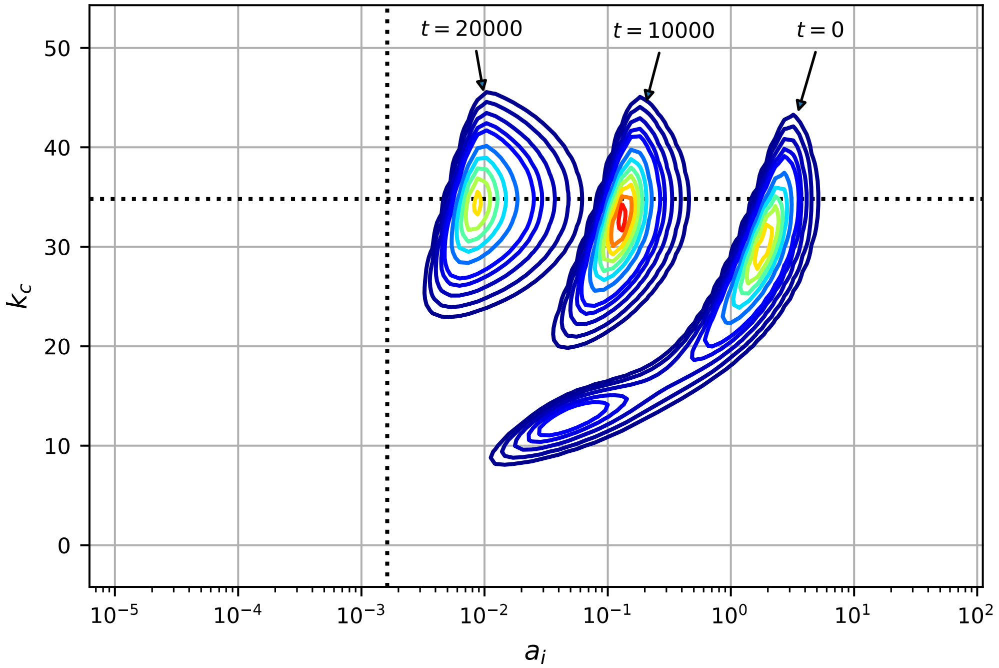
$$H(\boldsymbol{x}_i,t)\frac{f(\boldsymbol{x}_i)}{q(\boldsymbol{x}_i)} - \widehat{\mathbb{E}} = 0$$

so the optimal estimated density is

$$\hat{g}(\boldsymbol{x}_i) = \frac{H(\boldsymbol{x}_i,t)f(\boldsymbol{x}_i)}{\widehat{\mathbb{E}}}$$

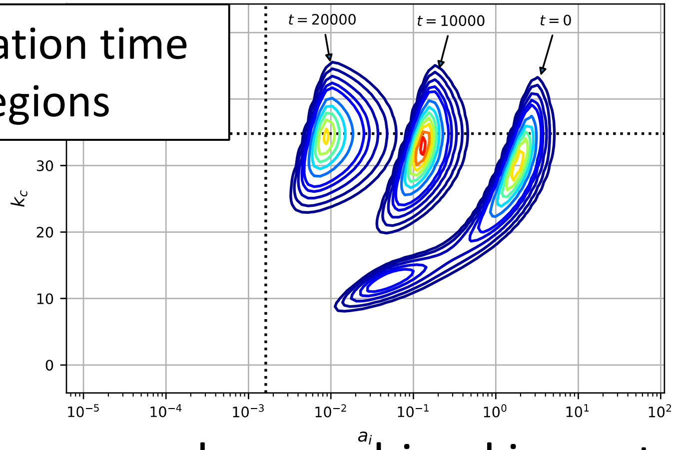
Standard Adaptive Importance Sampling Approach



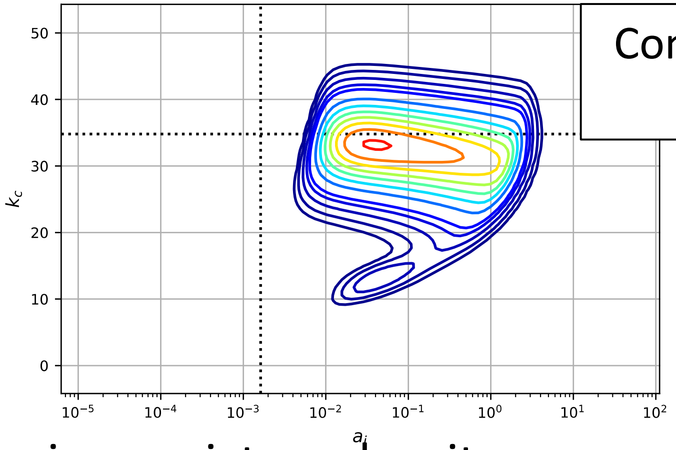


- Adapt a sampling density to the important region for each evaluation time, t
  - Regions move as t changes
  - Regions can be multimodal
- Adaptation process require several iterations to converge for each t using small sample sizes

Adaptive Multiple Importance Sampling Approach

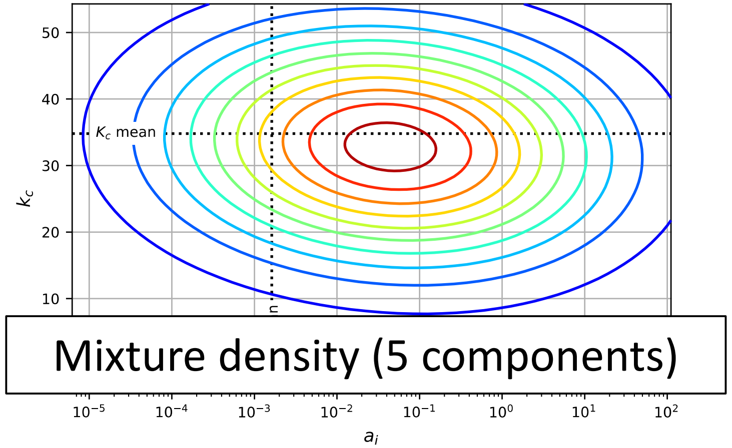


Individual evaluation time important regions

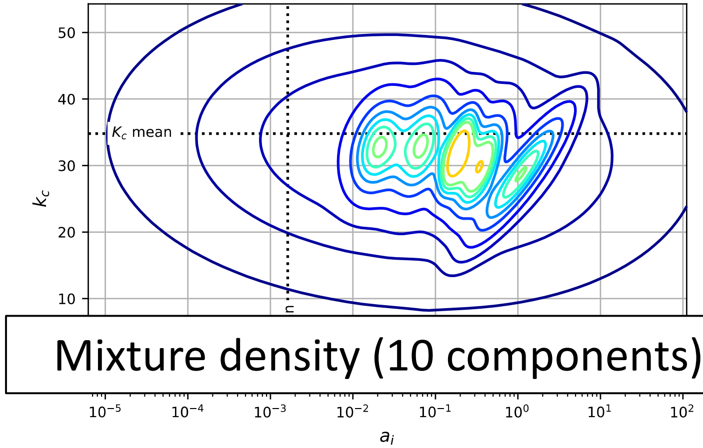


Combined important region

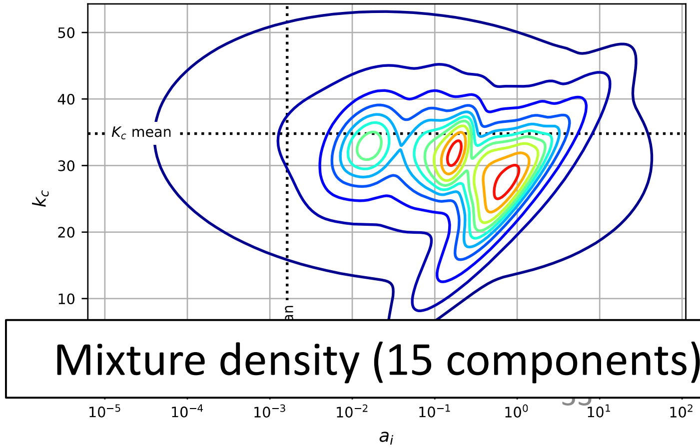
- Approximate the averaged or combined important region using a mixture density composed of multivariate normal sampling densities optimized for individual evaluation times
- Key advantage is that samples can be used for more than one important region where regions overlap



Mixture density (5 components)

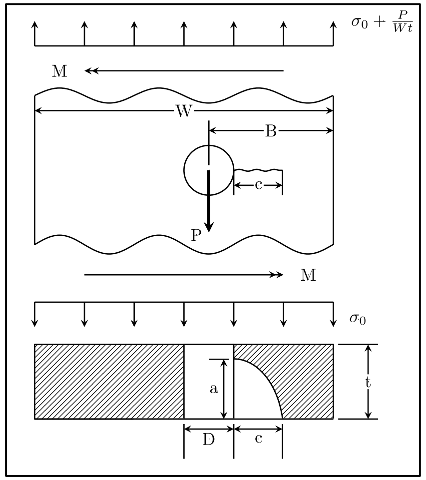


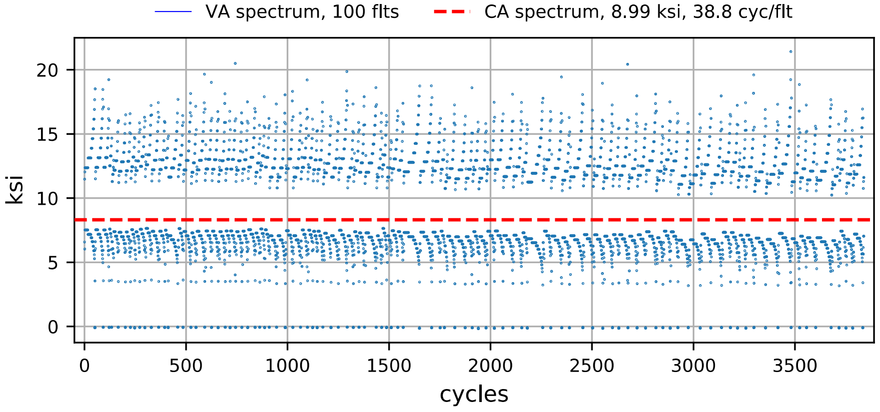
Mixture density (10 components)



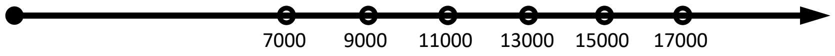
Mixture density (15 components)

NASGRO Example with Inspections and Repairs





Inspection Schedule



Parameter	Value
Width	Deterministic 2.5 in
Thickness	Deterministic 0.25 in
Initial Crack Size	$LN(0.005, 0.002)$ in
Aspect Ratio (A/C) [1]	$N(1.5, 0.14)$
Fracture Toughness	$N(34.8, 3.90)$ ksi $\sqrt{\text{in}}$
Log Paris Constant	$N(-8.777, 0.08)$
Paris Exponent	Deterministic 3.273
Hole Diameter	Deterministic 0.1562 in
Hole Offset [2]	$N(0.5, 0.05)$ in
Maximum Stress per Flight	$EVD(16.74, 2.08, 0.0)$ ksi
Probability of Detection	$LN(0.021, 0.028)$ in

New NASGRO API interface

[1] Random A/C values were clipped to Nasgro CC16 stress intensity factor limits

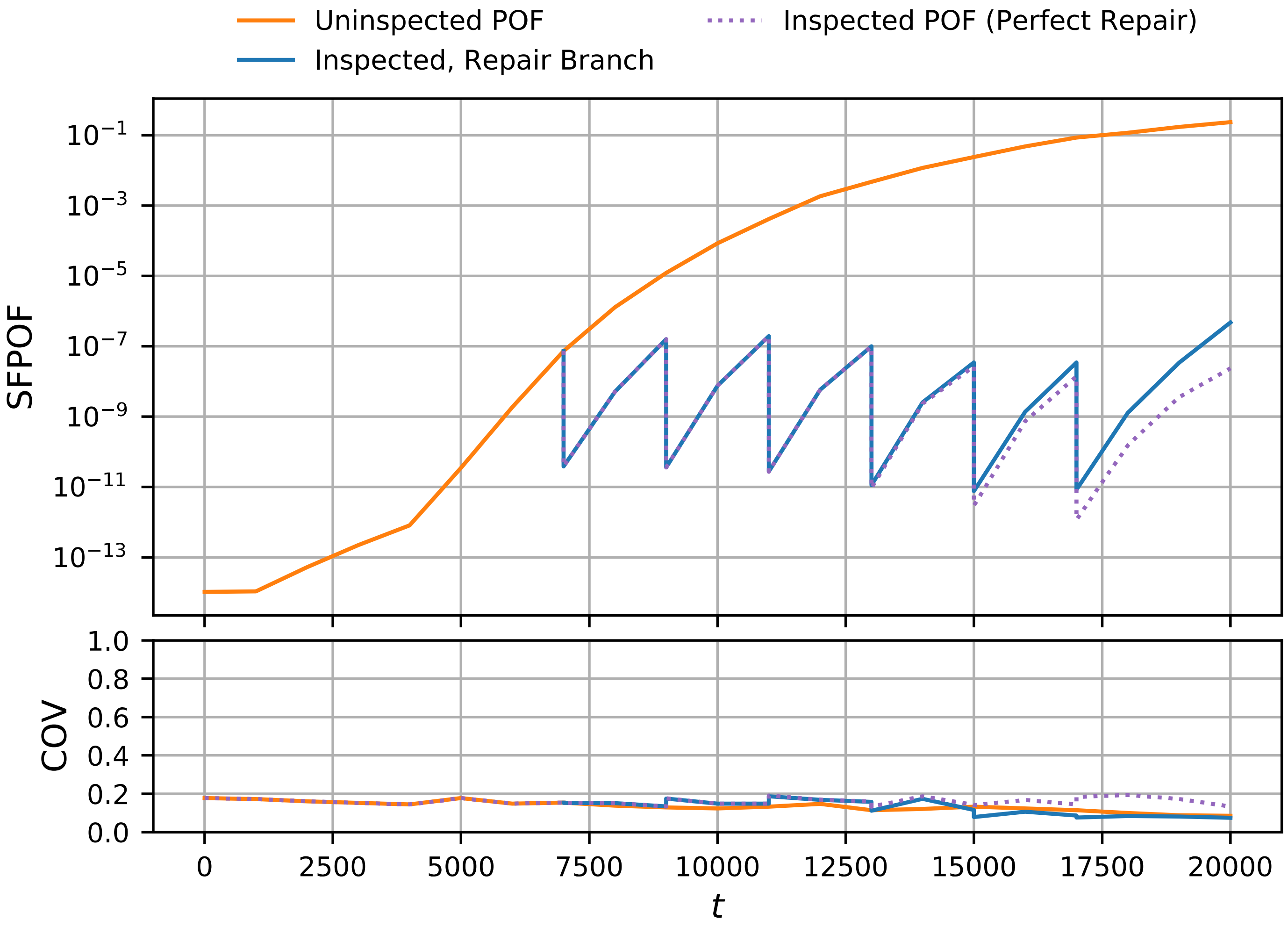
$$0.1 \le A / C \le 10$$

[2] Random Hole Offset values outside Nasgro CC16 stress intensity factor limit

$$\frac{D + C}{2\,B + C} \le 0.7$$

were treated as immediate fracture

POF Results with Repairs



- PDTA AMIS
  - Inspected POF: 4060 samples
  - Uninspected POF: +0 samples
  - Percent Cracks Det: +140 samples
  - Repairs Branch POFs: 4060 samples
- 8260 total samples
- COV for the total POF including repairs decreases because the combined POF is increasing by an order of magnitude
- Total run time: ~28min

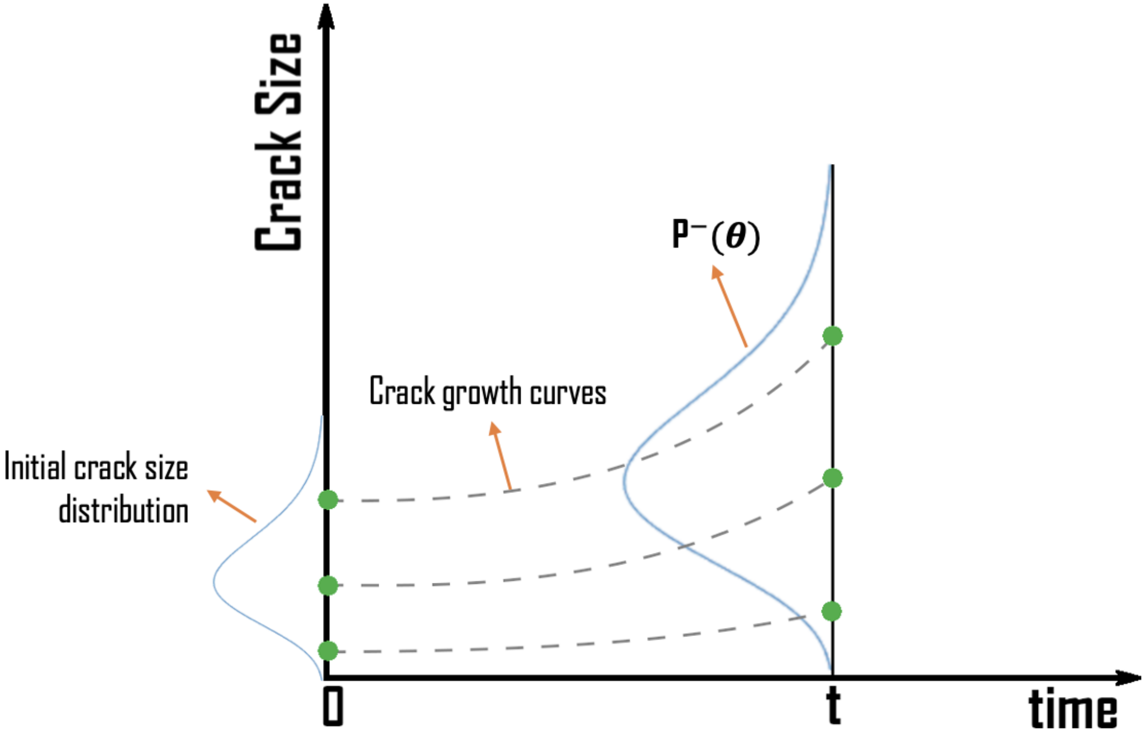
Bayes theorem

$$\underbrace{P^{+}(\theta|\boldsymbol{D})}_{\text{Posterior distribution}} = \frac{\overbrace{L(\boldsymbol{D}|\theta)}^{\text{Likelihood}} \cdot \overbrace{P^{-}(\theta)}^{\text{Prior distribution}}}{\underset{\text{Normalization factor}}{\underset{\downarrow}{NF}}}$$

- $\boldsymbol{\theta}$ represents the parameters mean(μ) →independent variable
  and standard deviation(σ)→assumed, it will be fixed,
- $\mathbf{D}$ represents the vector of the measurements (or inspections),
- **P⁻** represents the prior distribution → Distribution of crack size at the time,
- $\mathbf{L}(\mathbf{D}|\boldsymbol{\theta})$ represents the likelihood function of the parameters.
- **NF** Normalization Factor, used to get a probability density function.
- **P⁺** represents the posterior distribution given the detected crack sizes.

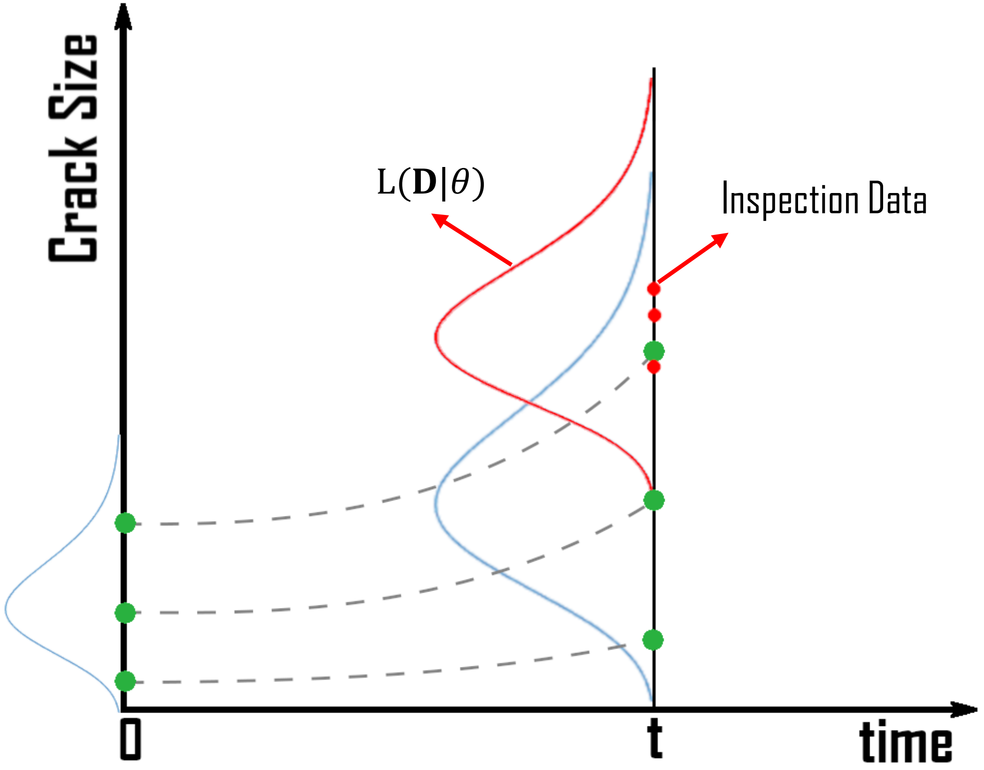
Bayesian Updating

$$\underbrace{P^{+}(\theta|\mathbf{D})}_{\text{Posterior distribution}} = \frac{\overbrace{L(\mathbf{D}|\theta)}^{\text{Likelihood}} \cdot \overbrace{P^{-}(\theta)}^{\text{Prior distribution}}}{\underset{\text{Normalization factor}}{\underset{\downarrow}{NF}}}$$



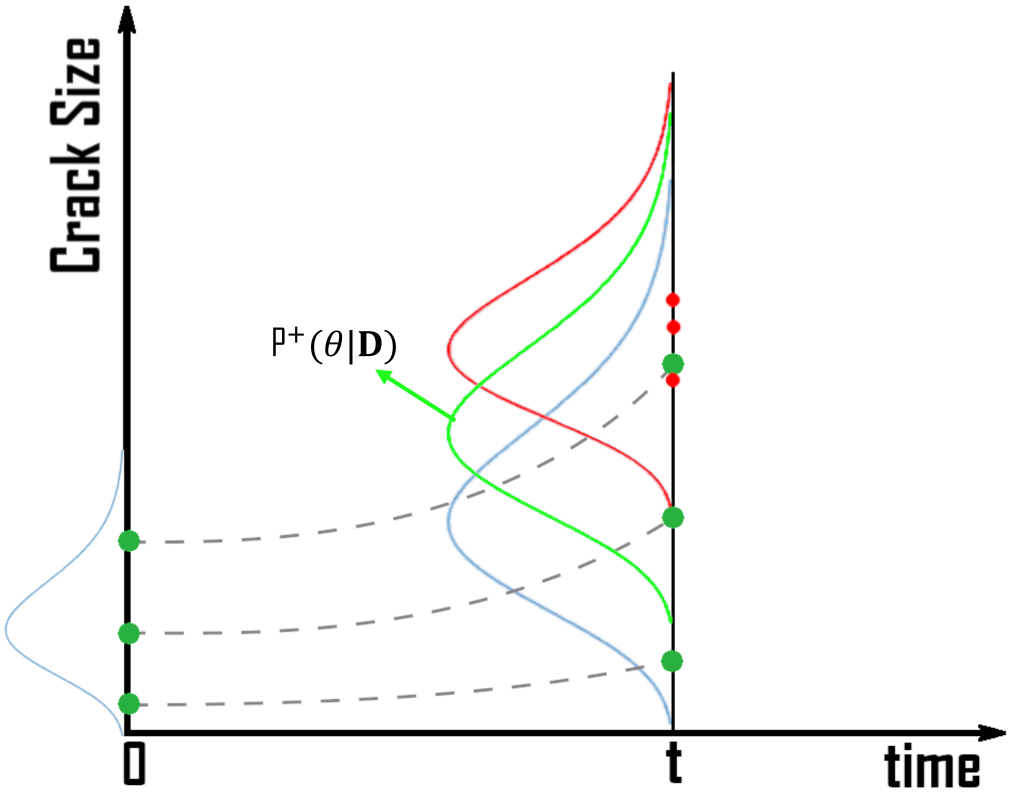
Bayesian Updating

$$\underbrace{P^{+}(\theta|\mathbf{D})}_{\text{Posterior distribution}} = \frac{\overbrace{L(\mathbf{D}|\theta)}^{\text{Likelihood}} \cdot \overbrace{P^{-}(\theta)}^{\text{Prior distribution}}}{\underset{\text{Normalization factor}}{\underset{\downarrow}{NF}}}$$

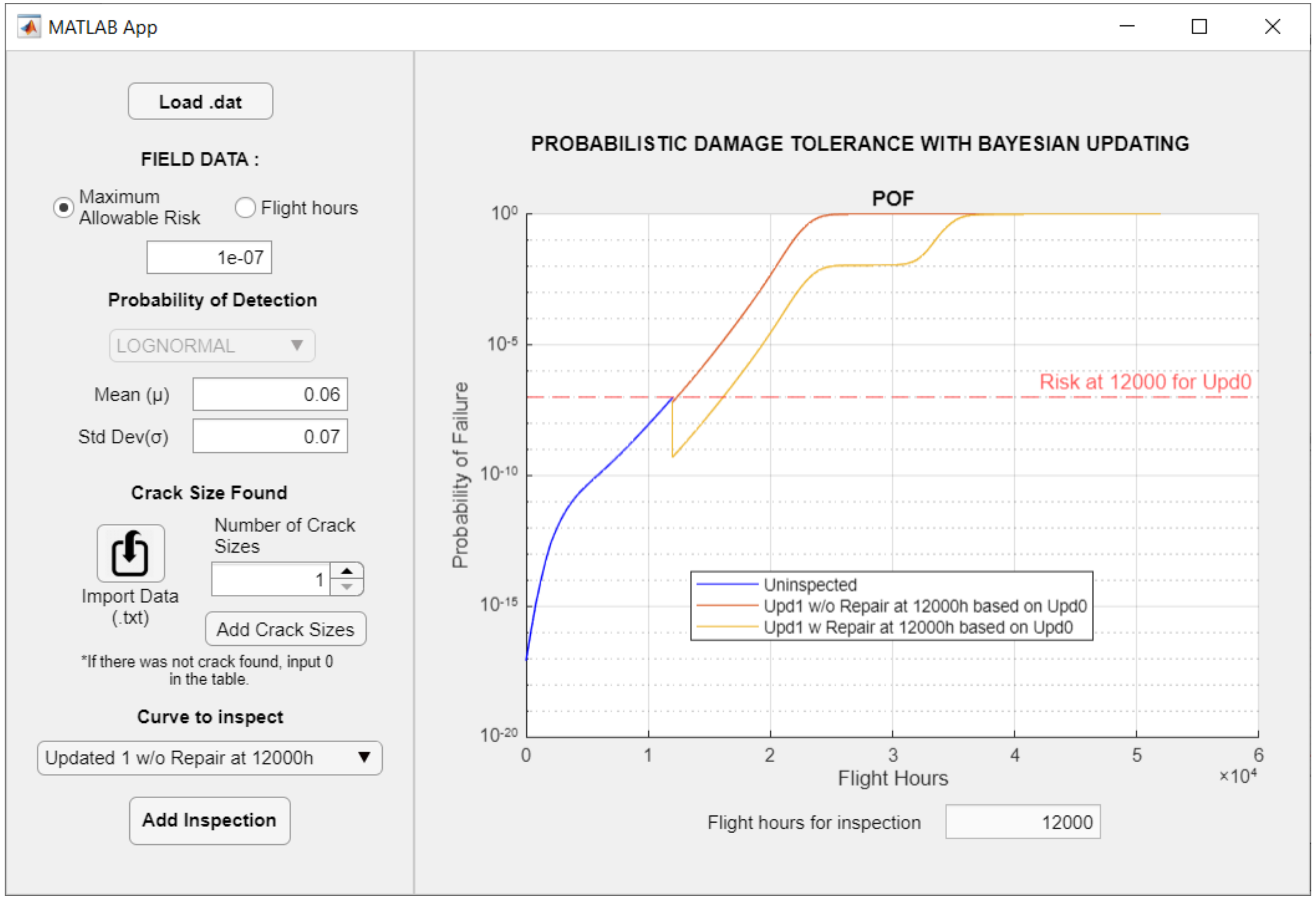


Bayesian Updating

$$\underbrace{P^{+}(\theta|\mathbf{D})}_{\text{Posterior distribution}} = \frac{\overbrace{L(\mathbf{D}|\theta)}^{\text{Likelihood}} \cdot \overbrace{P^{-}(\theta)}^{\text{Prior distribution}}}{\underset{\substack{\downarrow \\ \text{Normalization factor}}}{NF}}$$



Results Crack size No detection



FIELD DATA :

● Maximum Allowable Risk ○ Flight hours

1e-07

Probability of Detection

LOGNORMAL

Mean (μ) 0.06

Std Dev(σ) 0.07

Crack Size Found

Import Data (.txt)

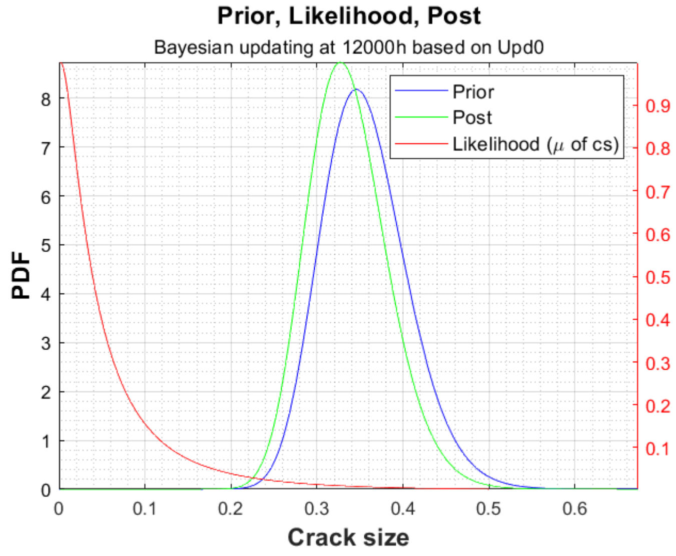
Number of Crack Sizes 1

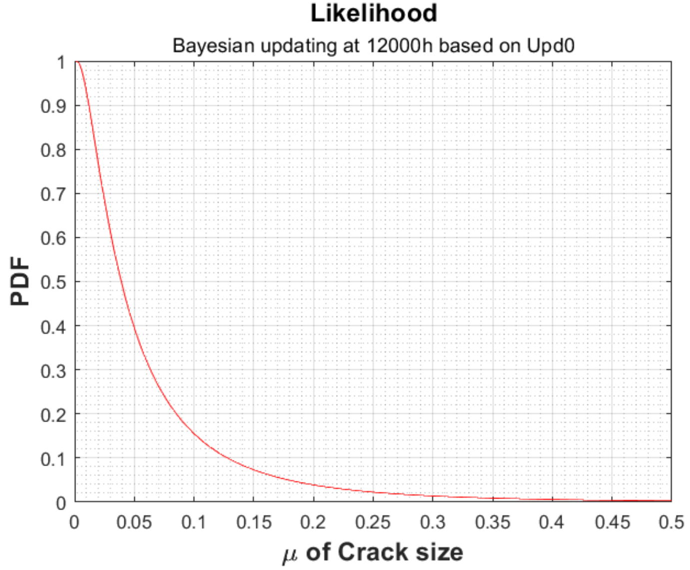
*If there was not crack found, input 0 in the table.

Curve to inspect

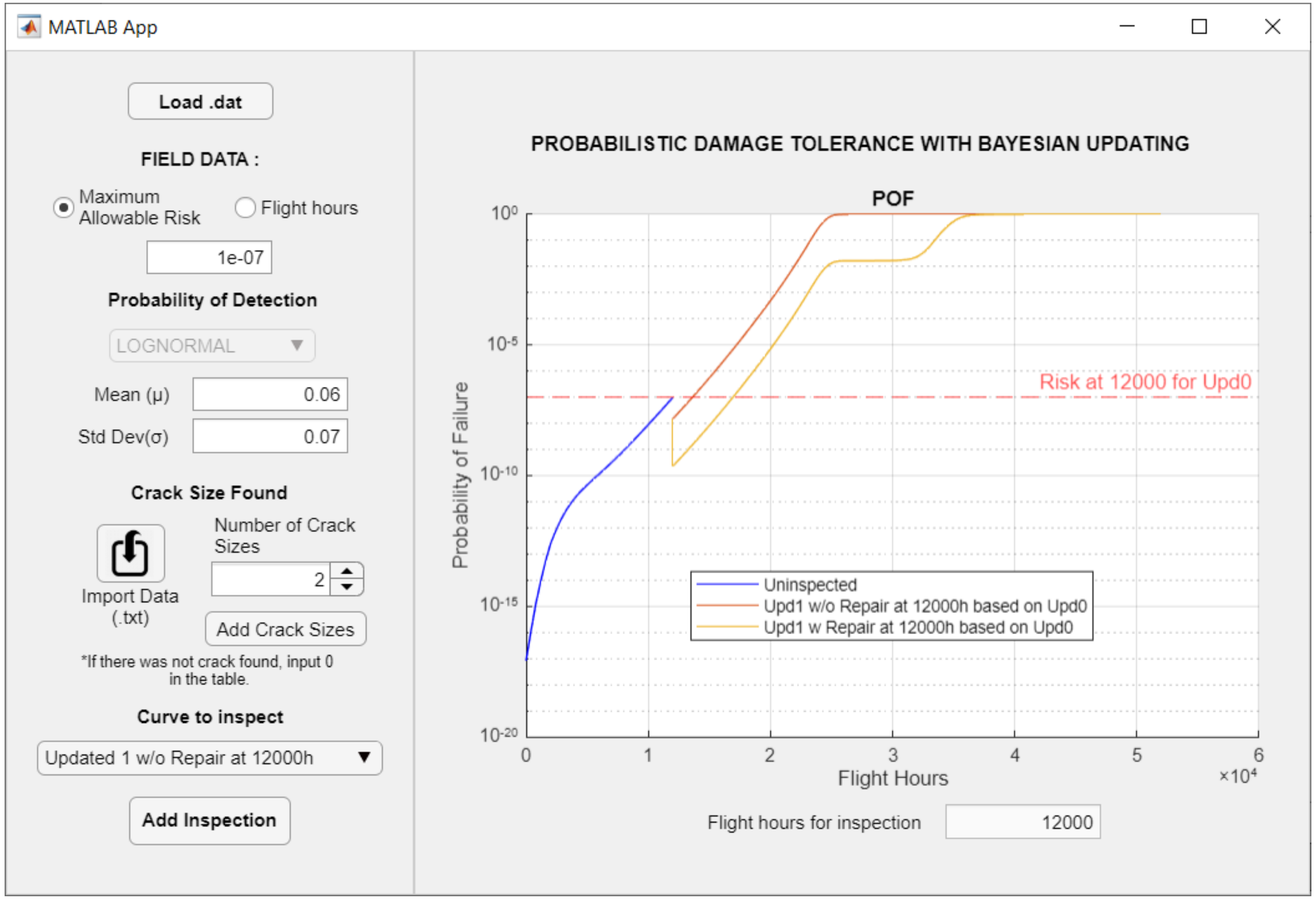
Updated 1 w/o Repair at 12000h

Flight hours for inspection 12000





Results Crack size det.= 0.3 and 0.2 in



FIELD DATA :

● Maximum Allowable Risk ○ Flight hours

1e-07

Probability of Detection

LOGNORMAL

Mean (μ) 0.06

Std Dev(σ) 0.07

Crack Size Found

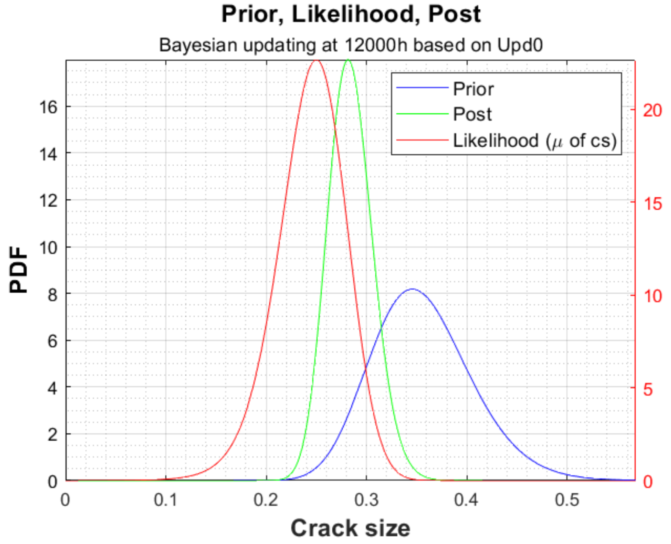
Number of Crack Sizes 2

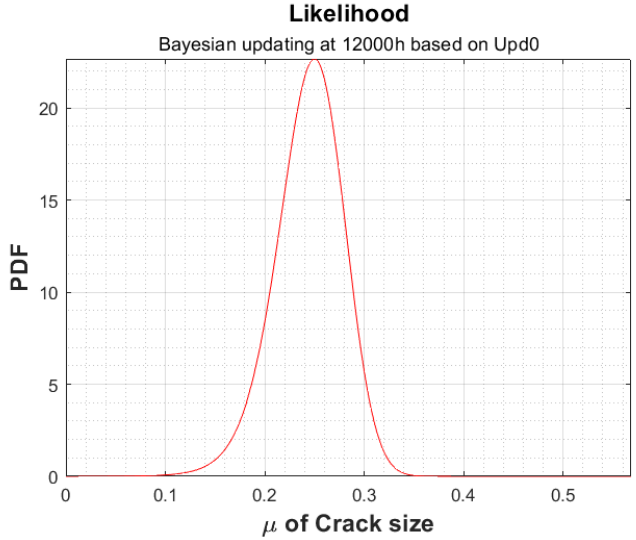
*If there was not crack found, input 0 in the table.

Curve to inspect

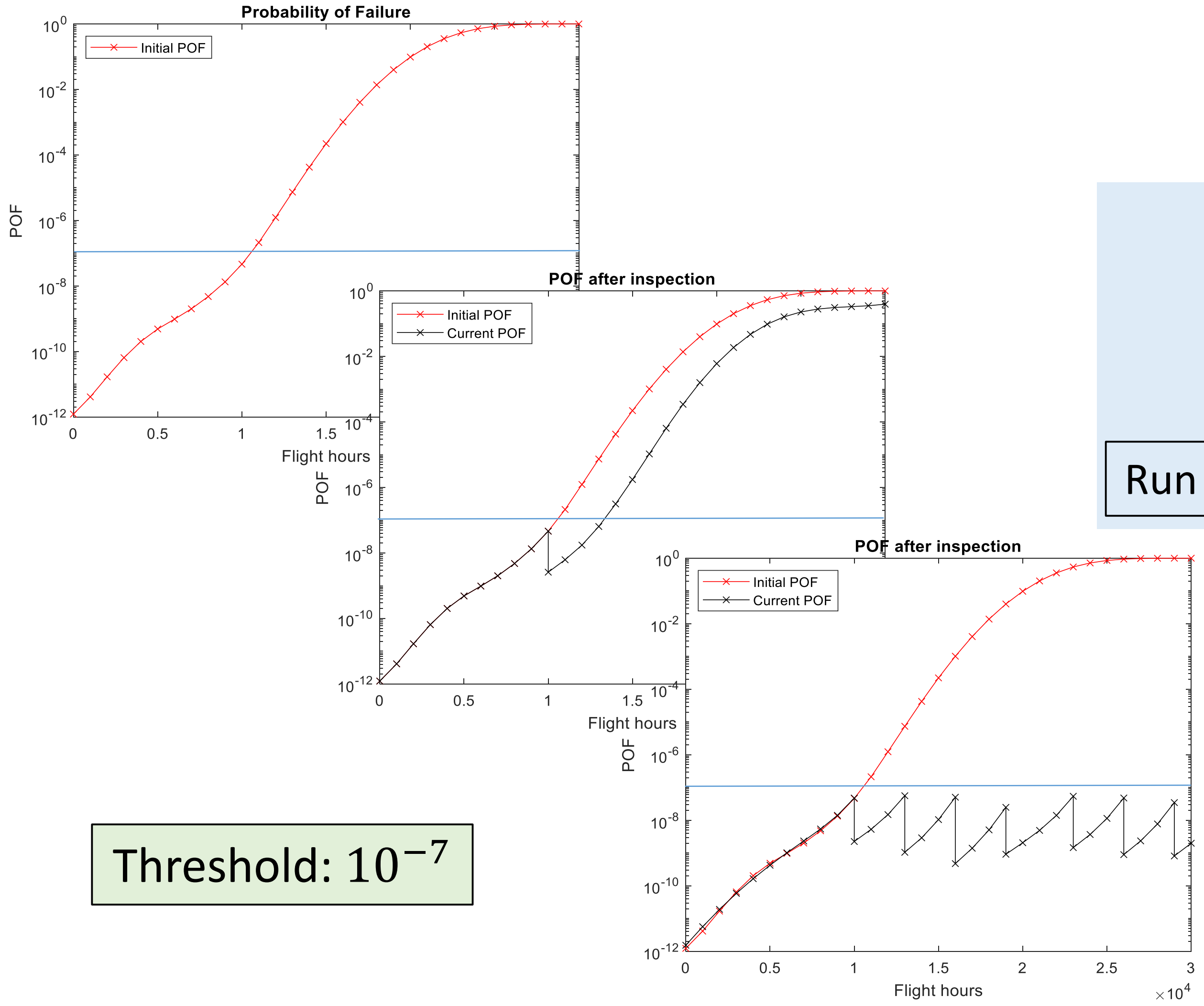
Updated 1 w/o Repair at 12000h

Flight hours for inspection 12000

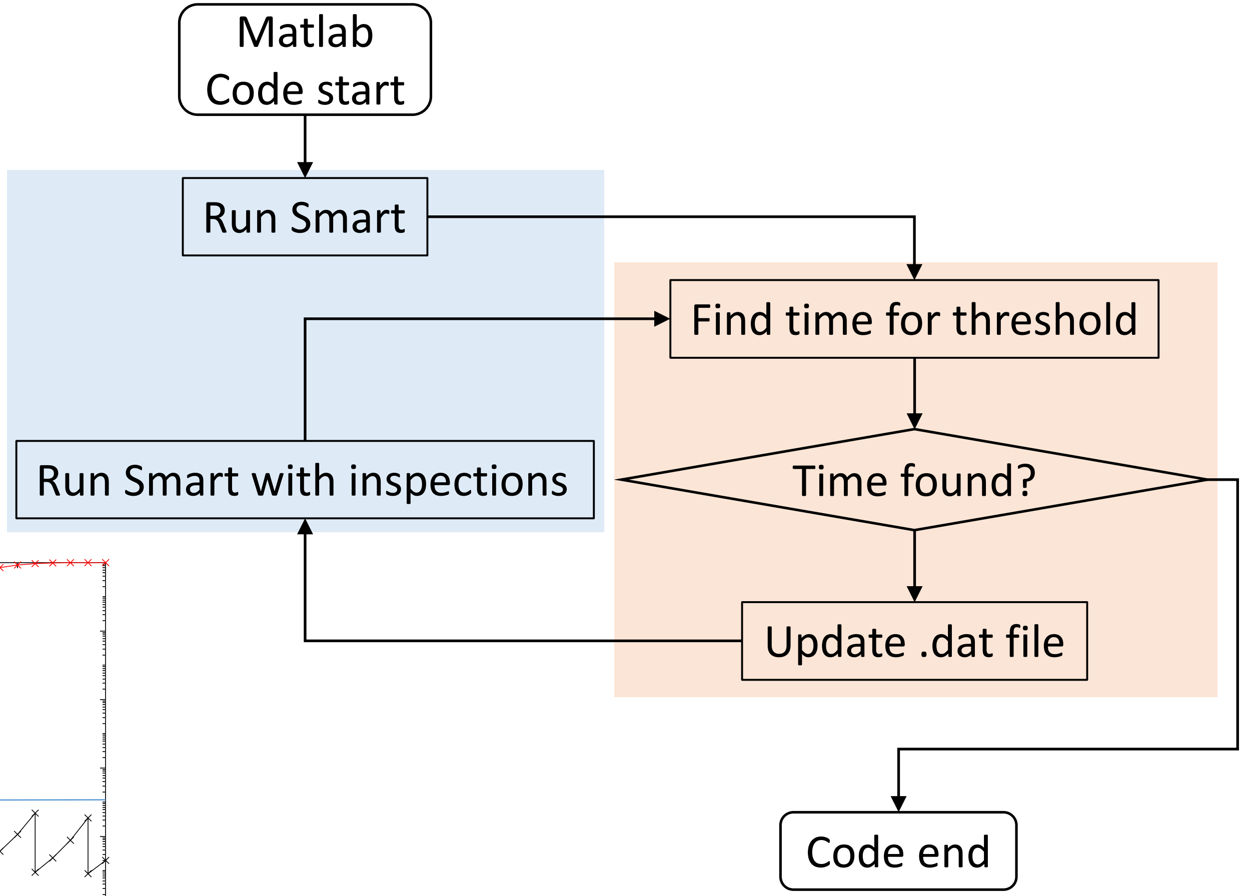




Optimized Inspections - Constant risk threshold



Threshold: 10^{-7}



Matlab Code start

Run Smart

Find time for threshold

Time found?

Update .dat file

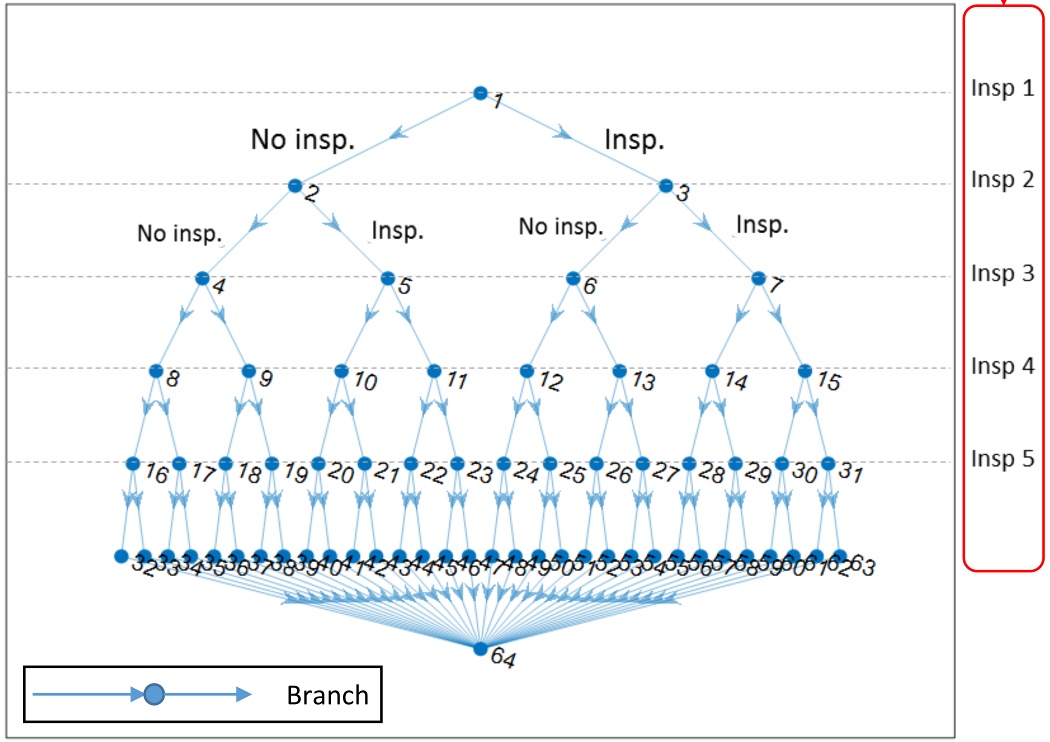
Run Smart with inspections

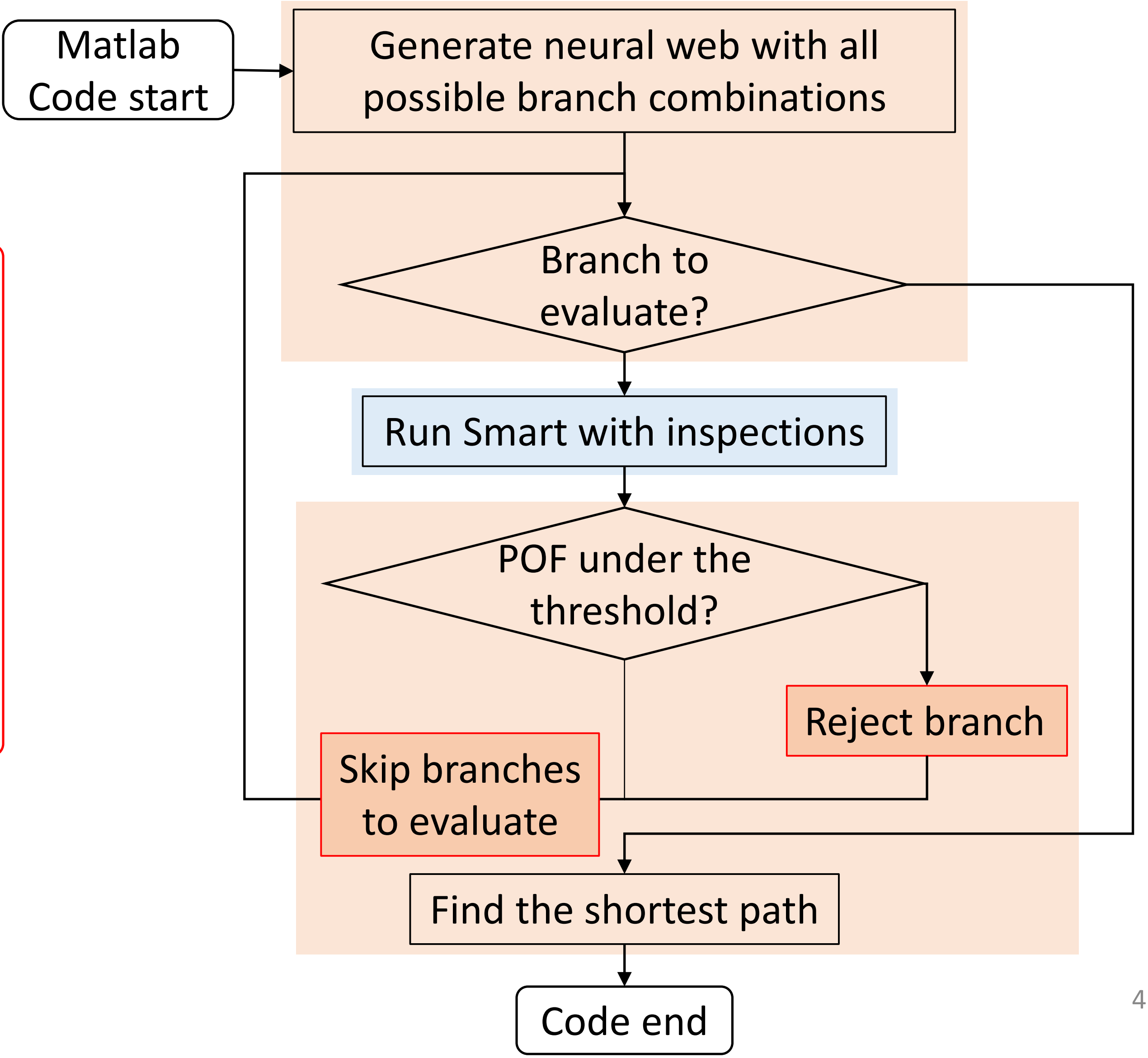
Code end

Optimized Inspections - Shortest Path Method

User defined candidate inspection times

Neuronal Web





Matlab Code start

Generate neural web with all possible branch combinations

Branch to evaluate?

Run Smart with inspections

POF under the threshold?

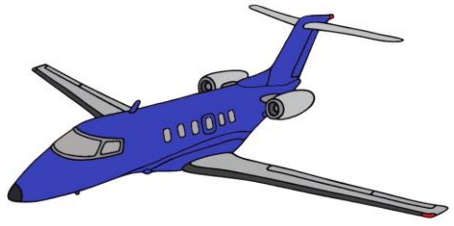
Reject branch

Skip branches to evaluate

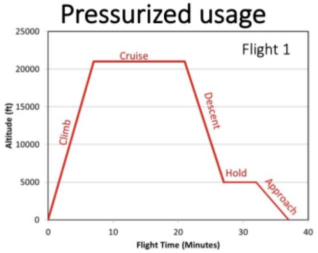
Find the shortest path

Code end

Optimized Inspections - Input Data



Random Variable	Distribution	Parameters
Paris m	Binormal	Mean = 2.586 Standard Deviation = 0.0
Paris c (log)	Binormal	Mean = -7.888 Standard Deviation = 0.04
Correlation	-	0
Walker Exponent	-	0.82
Ultimate Stress	Normal	Mean = 69.0 ksi Standard Deviation = 0.0 ksi
Yield Stress	Normal	Mean = 58.0 ksi Standard Deviation = 0.0 ksi
Hole Offset	Normal	Mean = 0.9000 in Standard Deviation = 0.0 in



Parameter	Value
Design Load Limit Factors	Man (-1.50 3.60) Gust (-3.00 5.00)
Ground Stress	-100 psi
One-g Stress	3800 psi
Average Velocity	300 knots

Segment	Weight	KEAS	% Duration
CLIMB	14511	246	0.19
CRUISE	13709	221	0.55
DESCENT	13100	300	0.14
HOLD	12932	250	0.06
APPROACH	12803	150	0.06

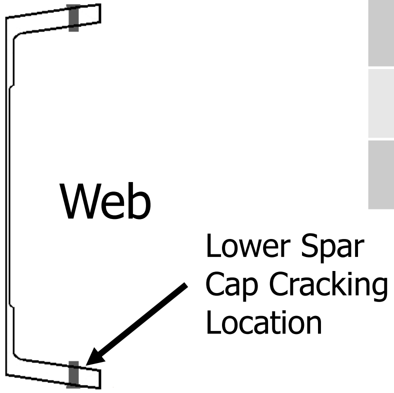
V_C = 300 KEAS

MTOW = 17200 lb

Sort matrix in ascending order for speed & weight

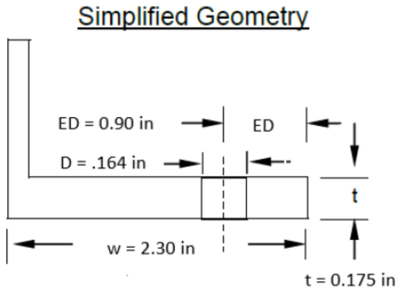
Flight Time (hrs)	% of Flights	Average Speed During Flight, % Max Takeoff Weight				
		0.500	0.826	0.833	0.957	1.00
0.62	1.0	0.14	0.19	0.13	0.38	0.16

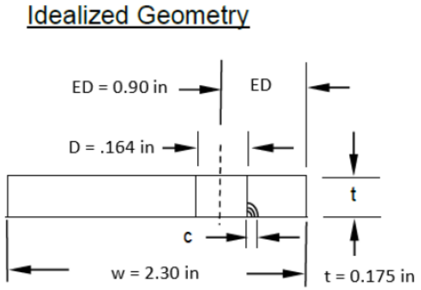
Flight Time (hrs)	% of Flights	Average Speed During Flight, % Design Velocity				
		0.803	0.810	0.816	0.834	0.855
0.62	1.0	0.14	0.13	0.16	0.38	0.19



Wing Forward Spar

Variable	Dist. Type	Mean	St. Dev.	Notes
Initial Crack Size	Lognormal	0.00248 in	0.00129	Reamed Fastener Hole
Repair Crack Size	Lognormal	0.00248 in	0.00129	Assuming Repair is Replacement of Part
Fracture Toughness	Normal	26.0 ksi	2.0	7050-T651 Plate
EVD	Gumbel	14.5 ksi	0.8	

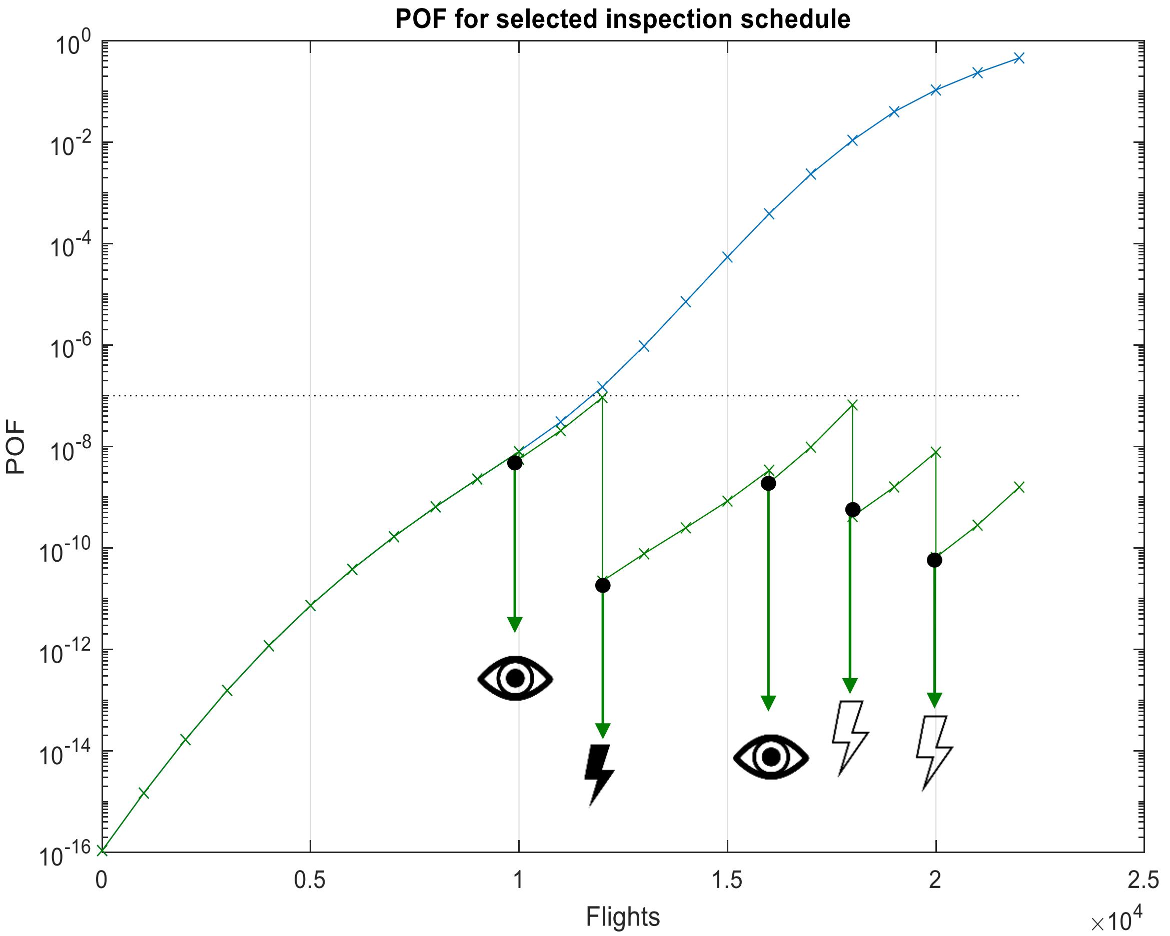

Simplified Geometry

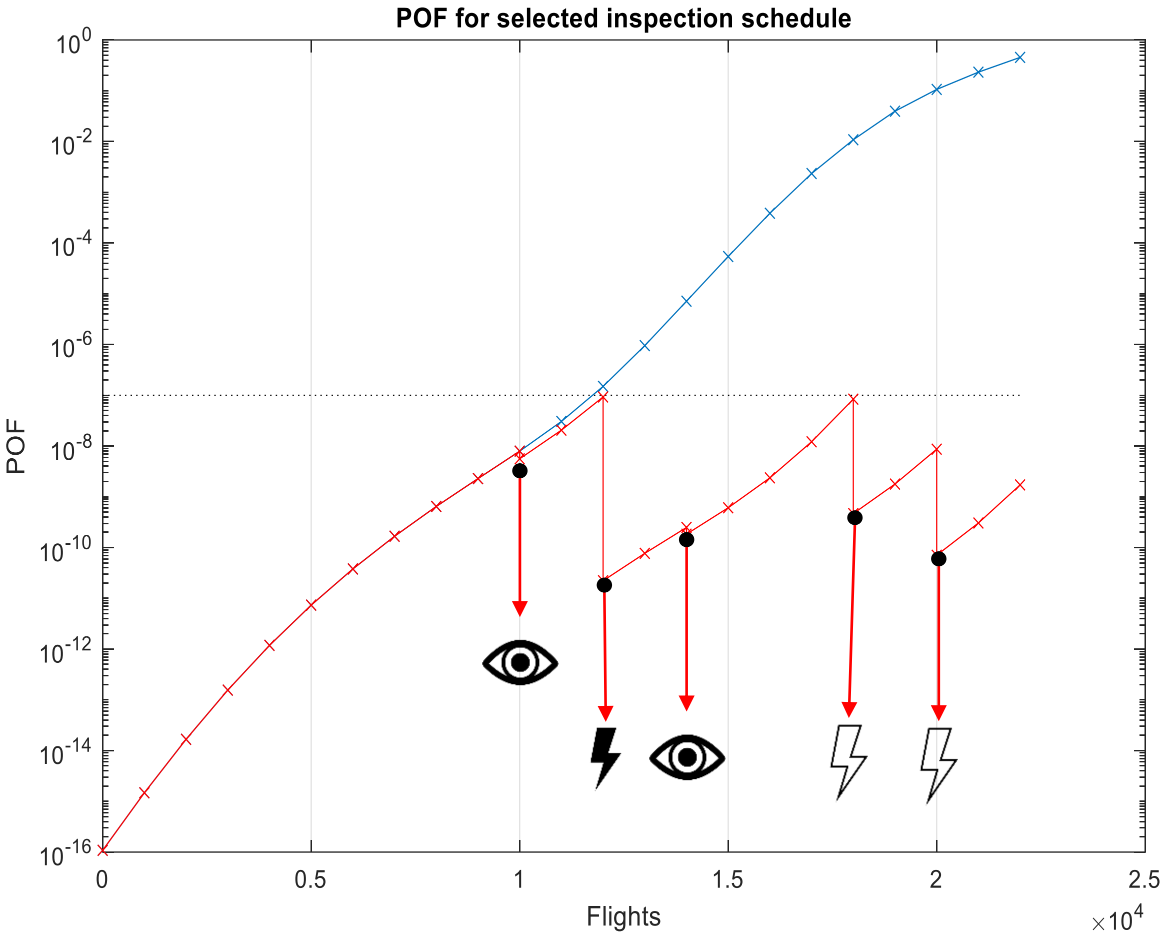

Idealized Geometry

Inspections	Inspection Type	Material	Crack Type	Dist. Type	Mean [in]	St. Dev. [in]	Source	Cost
POD 1	Automated bolt hole eddy current	Aluminum	T	Lognormal	0.0180	0.0109	Aeronautical Applications of Non-destructive	50x
POD 2	Eddy current sliding probe	Aluminum	Overall	Lognormal	0.0788 +0.0625	0.0302	NDE Capabilities Book	10x
POD 3	Visual	Aluminum		Lognormal	0.99714 +0.0625	3.66907	NDE Capabilities Book	1x

Optimized Inspections - Results

Possible inspection times = [2000, 4000, 6000, 8000, 10000, 12000, 14000, 16000, 18000, 20000]

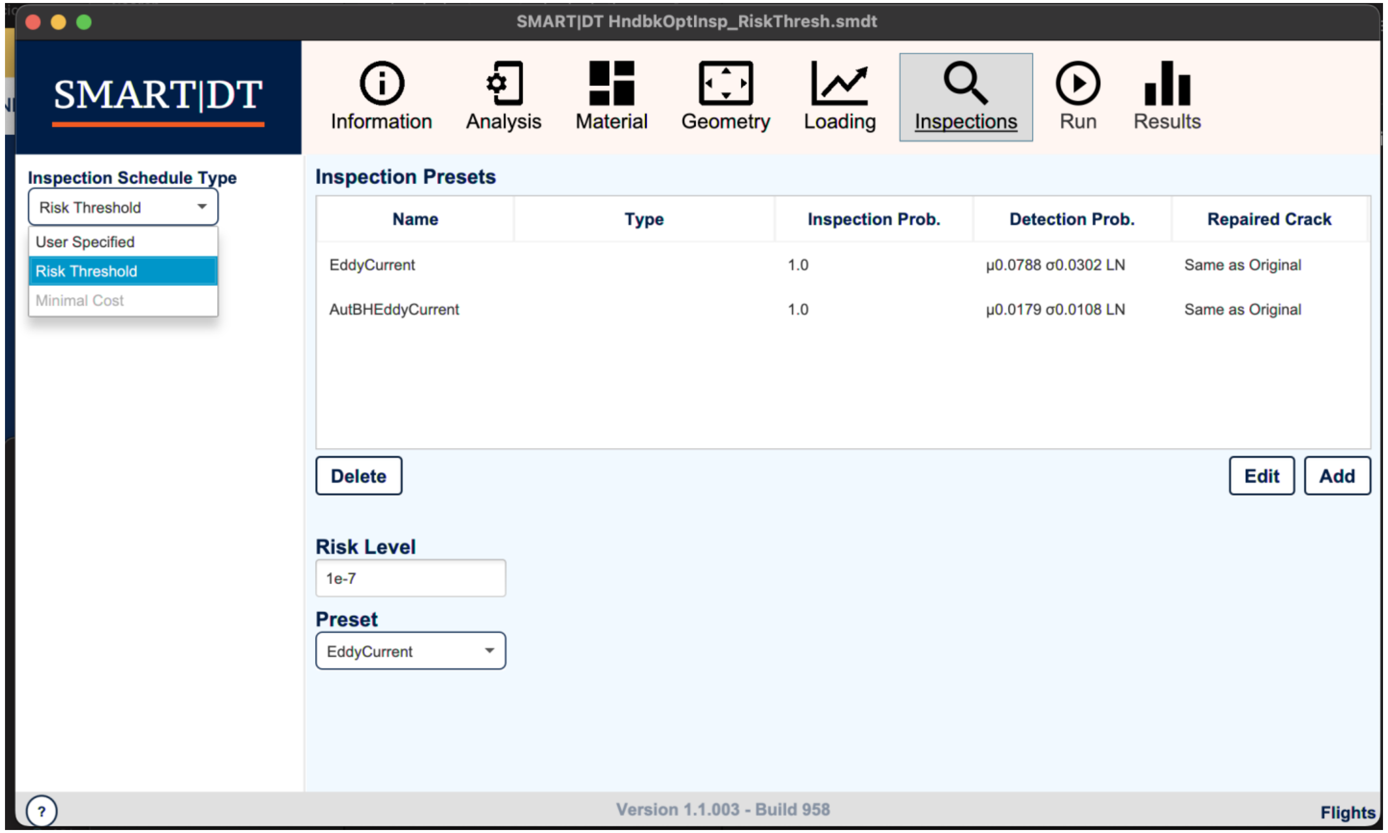




Operations = 1,048,576

SMART-DT runs= 1,287

How it looks in SMART



Inspection Schedule Type

Risk Threshold

- User Specified
- Risk Threshold
- Minimal Cost

Inspection Presets

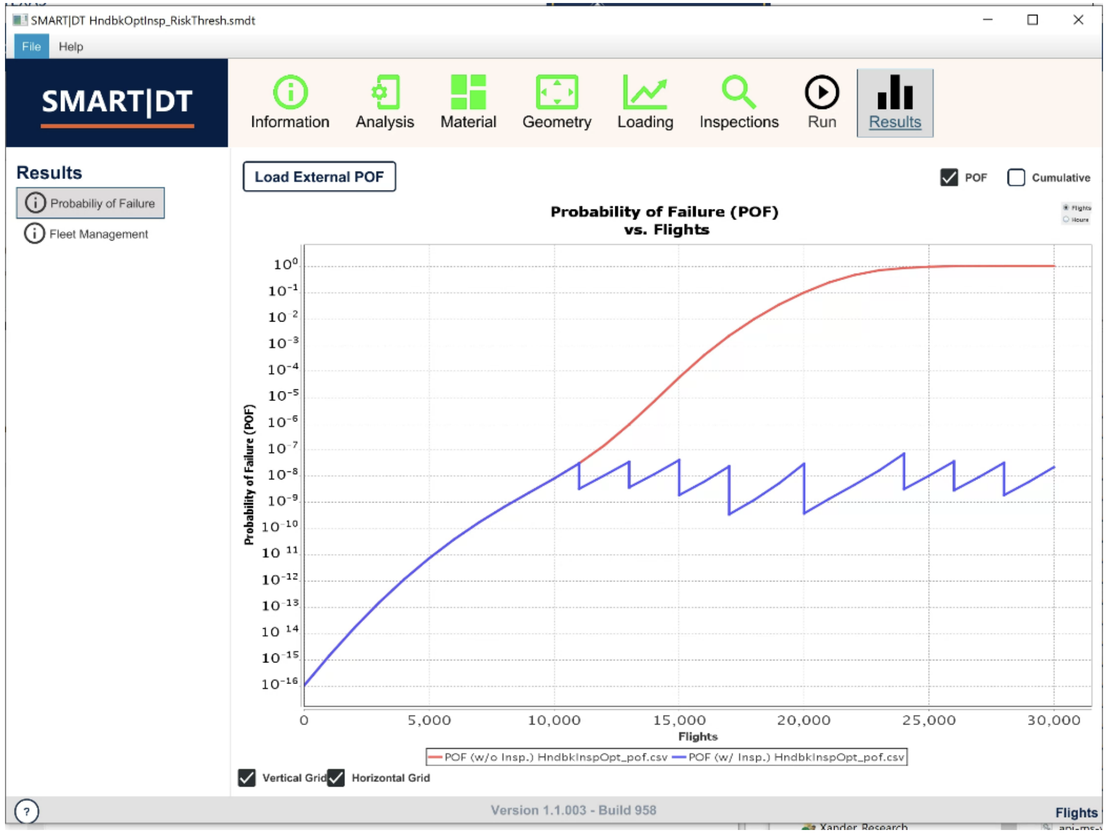
Name	Type	Inspection Prob.	Detection Prob.	Repaired Crack
EddyCurrent		1.0	μ0.0788 σ0.0302 LN	Same as Original
AutBHEddyCurrent		1.0	μ0.0179 σ0.0108 LN	Same as Original

Risk Level

1e-7

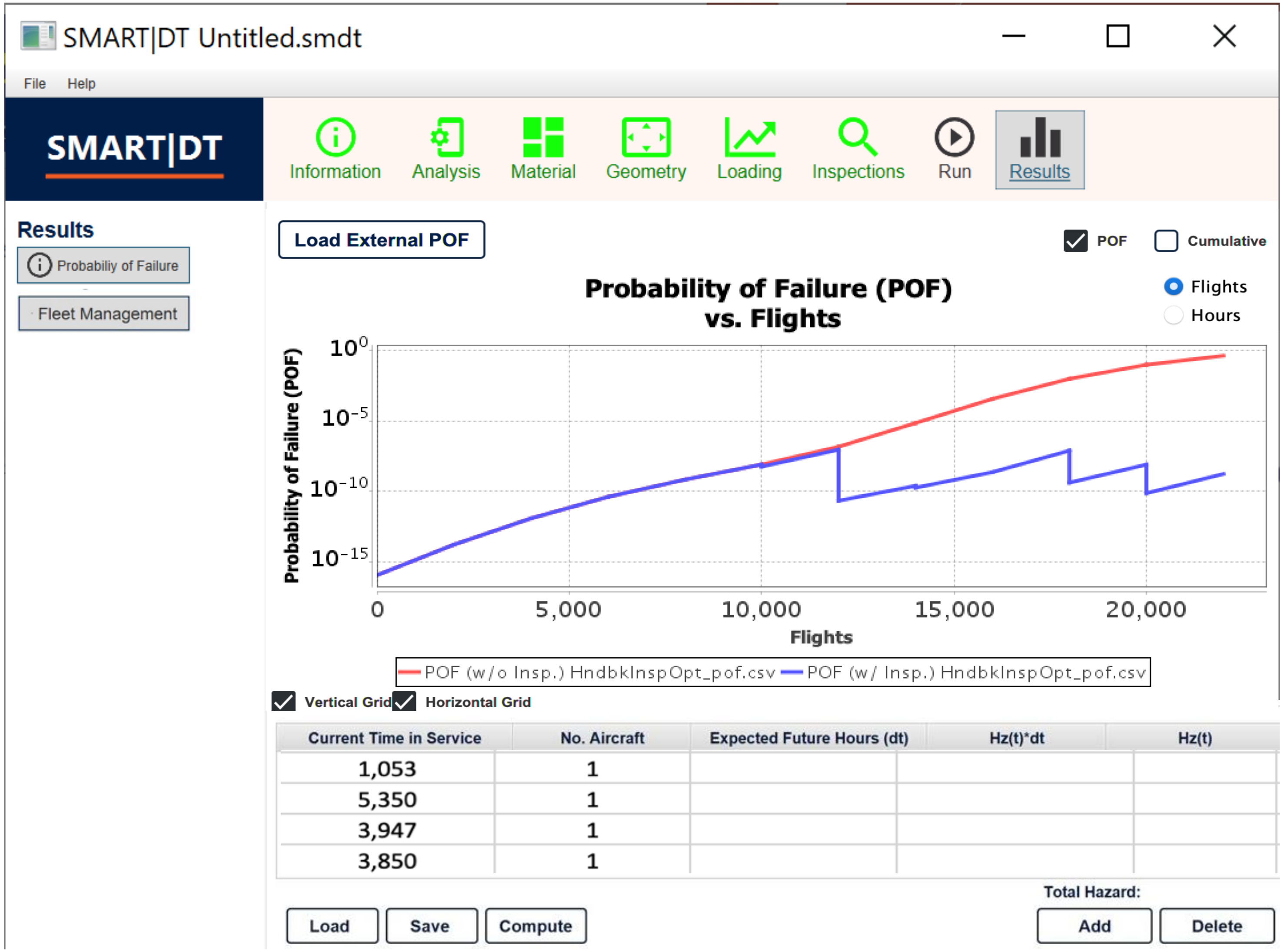
Preset

EddyCurrent



Fleet Management

Airplane number	Time in service
1	1,053
2	5,350
3	3,947
4	3,850
5	7,500
6	12,300
7	17,683
8	6,356
9	8,540
10	7,640

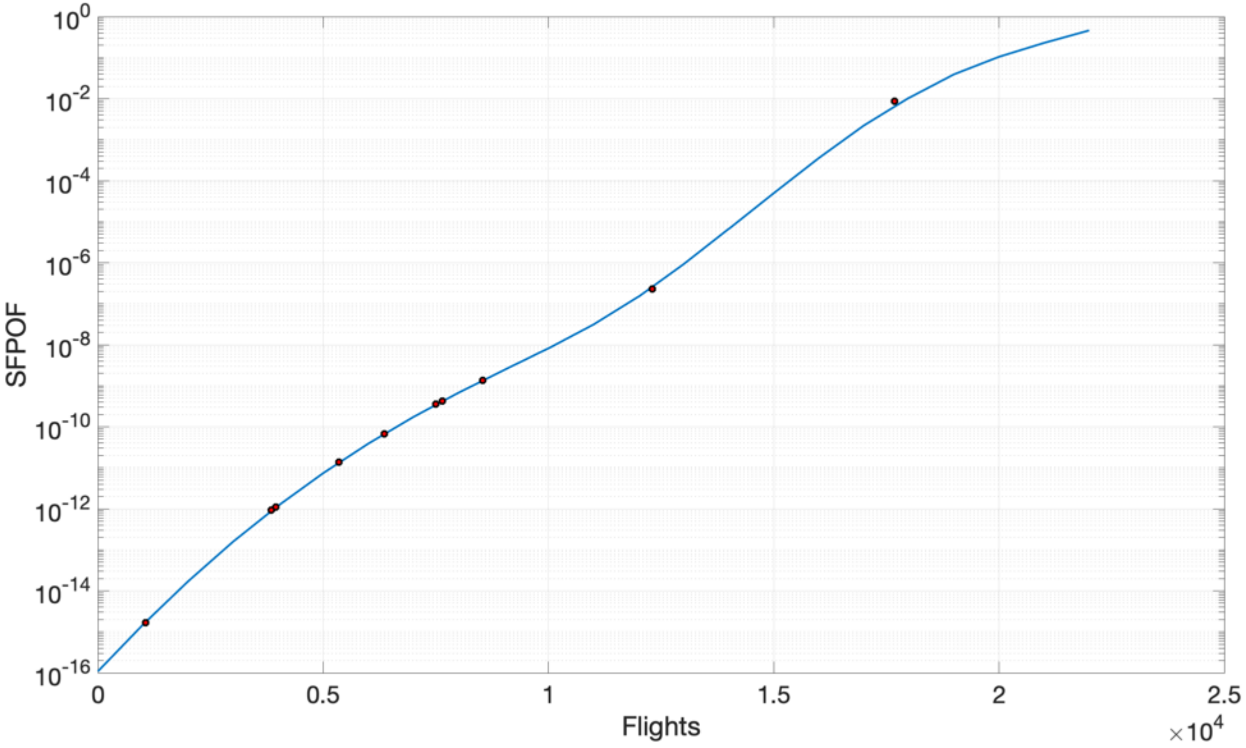


Current Time in Service	No. Aircraft	Expected Future Hours (dt)	Hz(t)*dt	Hz(t)
1,053	1			
5,350	1			
3,947	1			
3,850	1			

Fleet Management

- Scenario 1 – without inspections

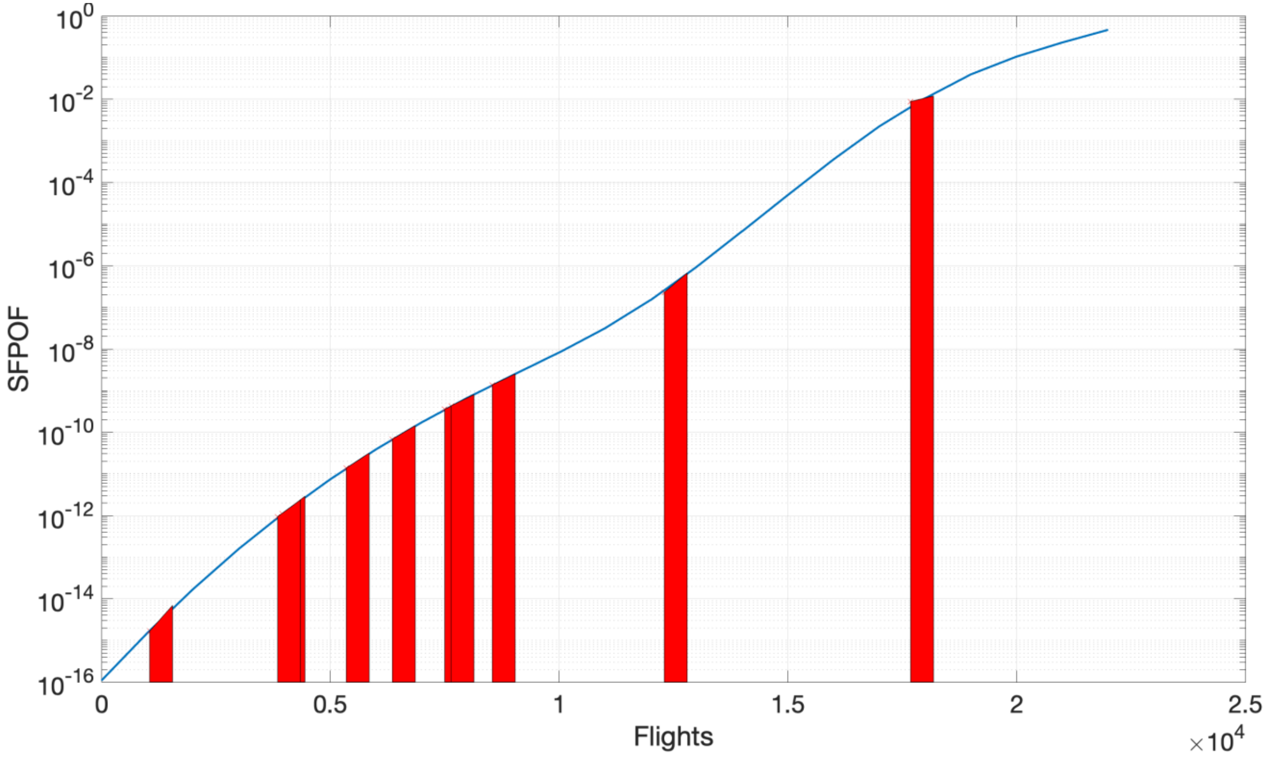
Airplane number	Time in service	Hazard Rate	Probability of Failure For Expected Future Hours		
			100	500	1,000
1	1,053	2.32E-15	3.10E-13	3.10E-12	1.02E-11
2	5,350	1.84E-11	2.00E-09	1.31E-08	4.04E-08
3	3,947	1.14E-12	1.24E-10	1.21E-09	3.98E-09
4	3,850	1.04E-12	1.09E-10	9.64E-10	3.43E-09
5	7,500	4.24E-10	4.49E-08	2.74E-07	8.25E-07
6	12,300	3.79E-07	4.18E-05	2.87E-04	9.94E-04
7	17,683	7.88E-03	8.29E-01	5.29E+00	1.67E+01
8	6,356	8.66E-11	9.33E-09	6.01E-08	1.77E-07
9	8,540	1.60E-09	1.68E-07	1.01E-06	3.05E-06
10	7,640	4.94E-10	5.19E-08	3.21E-07	9.91E-07
Total Hazard			8.29E-01	5.29E+00	1.67E+01



Fleet Management

- Scenario 1 – without inspections

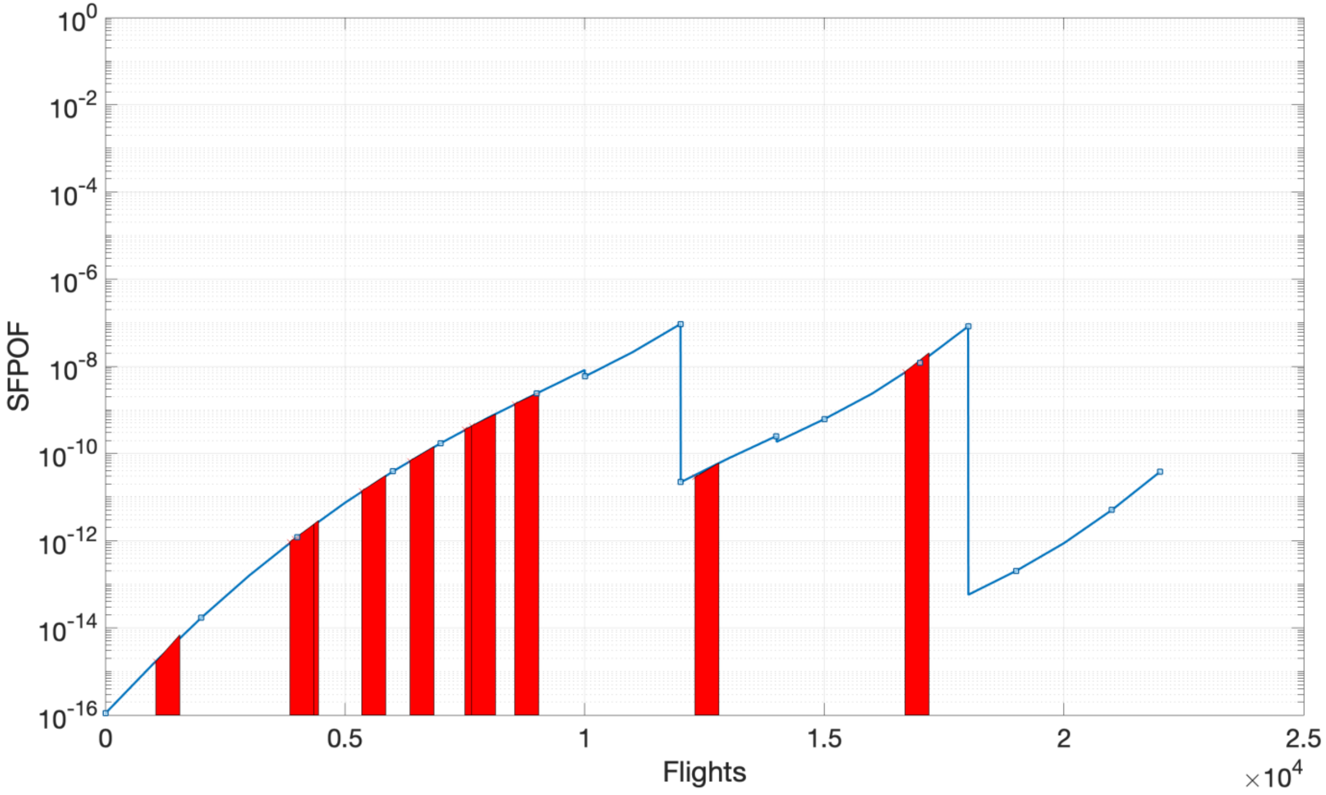
Airplane number	Time in service	Hazard Rate	Probability of Failure For Expected Future Hours		
			100	500	1,000
1	1,053	2.32E-15	3.10E-13	3.10E-12	1.02E-11
2	5,350	1.84E-11	2.00E-09	1.31E-08	4.04E-08
3	3,947	1.14E-12	1.24E-10	1.21E-09	3.98E-09
4	3,850	1.04E-12	1.09E-10	9.64E-10	3.43E-09
5	7,500	4.24E-10	4.49E-08	2.74E-07	8.25E-07
6	12,300	3.79E-07	4.18E-05	2.87E-04	9.94E-04
7	17,683	7.88E-03	8.29E-01	5.29E+00	1.67E+01
8	6,356	8.66E-11	9.33E-09	6.01E-08	1.77E-07
9	8,540	1.60E-09	1.68E-07	1.01E-06	3.05E-06
10	7,640	4.94E-10	5.19E-08	3.21E-07	9.91E-07
Total Hazard			8.29E-01	5.29E+00	1.67E+01



Fleet Management

- Scenario 2 - With inspections

Airplane number	Time in service	Hazard Rate	Probability of Failure For Expected Future Hours		
			100	500	1,000
1	1,053	1.67E-15	3.10E-13	3.10E-12	1.02E-11
2	5,350	1.37E-11	2.00E-09	1.31E-08	4.04E-08
3	3,947	1.10E-12	1.24E-10	1.21E-09	3.98E-09
4	3,850	9.40E-13	1.09E-10	9.64E-10	3.43E-09
5	7,500	3.53E-10	4.49E-08	2.74E-07	8.25E-07
6	12,300	2.85E-11	4.11E-09	2.61E-08	7.14E-08
7	17,683	7.46E-09	9.50E-07	6.73E-06	2.80E-05
8	6,356	6.79E-11	9.33E-09	6.01E-08	1.77E-07
9	8,540	1.36E-09	1.68E-07	1.01E-06	3.05E-06
10	7,640	4.29E-10	5.19E-08	3.21E-07	9.91E-07
Total Hazard			1.23E-06	8.45E-06	3.31E-05



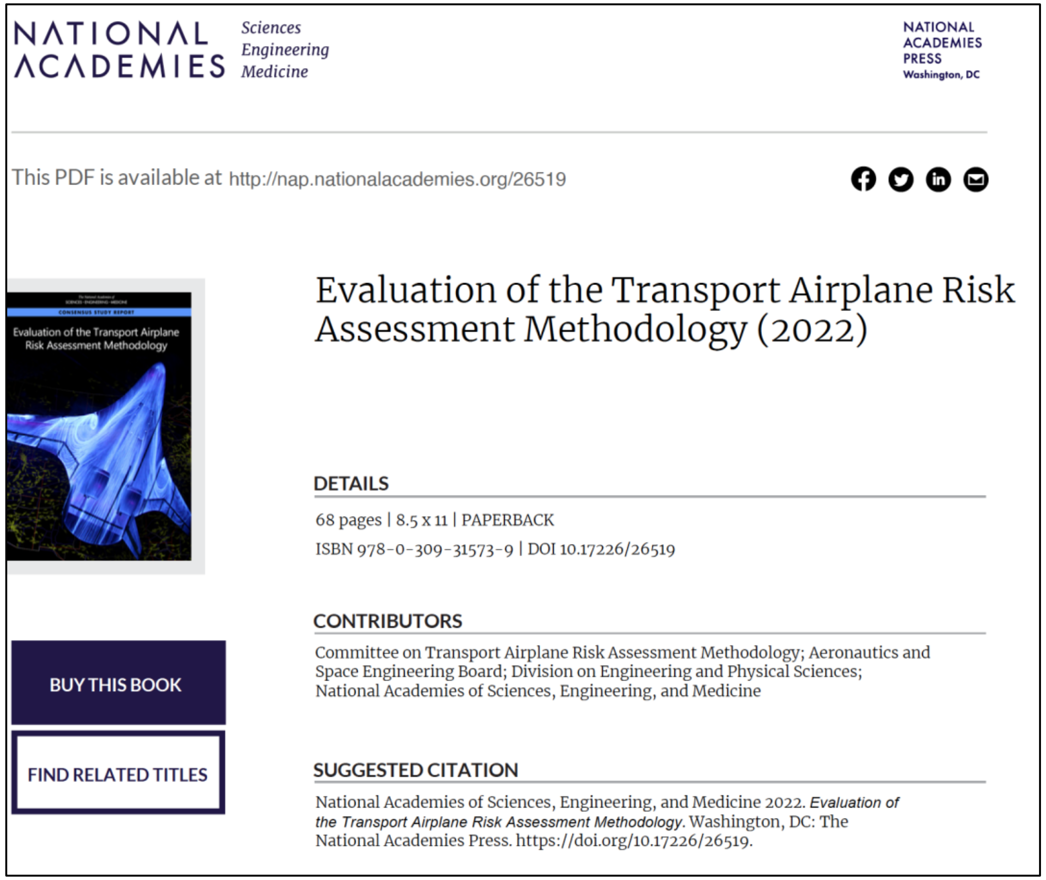
Discussion and Where to Go Next

- Lincoln Vs. Freudenthal?
- Benchmark problems for the community
- Additional Capabilities?
- Additional Random Variables?
- Risk Assessment for Composite Structures?
  - NDI
  - Damage Tolerance
- Additive Manufacturing
- We are looking for parallel analyses between SMART and PROF for problems of use (non-academic) to the community.
- Recommendations from a review of the FAA's TARAM risk assessment process. (Next Slide)

Discussion and Where to Go Next

- **Recommendation 12:** Within 18 months of receipt of this report, the Federal Aviation Administration should develop and maintain a technical training program for aviation safety engineers and their management who conduct and review Transport Airplane Risk Assessment Methodology analysis. The training should include the concepts of probabilistic risk analysis and the use of risk assessment results in the continued operational safety (COS) decision-making, similar in scope to those used in other federal agencies, to ensure the assumptions and limitations of the probabilistic risk analysis techniques are applied to the COS of commercial airplane operations.

- **Recommendation 13:** Within 6 months of receipt of this report, the Federal Aviation Administration should initiate research and continuous improvement programs in probabilistic risk analysis, including the use of risk assessment results in continued operational safety decision-making.



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