Probabilistic Continued Operational Safety Risk Assessment and the Use of Equivalent Initial Flaw Size

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Outline

- History of Equivalent Initial Flaw Size (EIFS)
- Effect of EIFS distributions on sample airplane cracking scenarios
- Limitations and cautions regarding use of EIFS
- Unresolved issues going forward

Background

- UTSA grant from FAA to study probabilistic risk assessment
  - Developing **SM**all **A**ircraft **R**isk **T**echnology (SMART) software
  - Dr. Harry Millwater is Primary Investigator
  - Dr. Juan Ocampo developed the bulk of the code
  - UTSA subcontract with NuSS to provide technical advice

    (I've learned much from Millwater and Ocampo regarding probabilistics)
- Key input/output:
  - EIFS is one key input
  - Single Flight Probability of Failure (SFPOF) is one key output
- Presentations earlier this week described SMART features

UTSA: University of Texas – San Antonio

Acknowledgements

I learned much about EIFS from:

- Laura Domyancic, Southwest Research Institute
- Bob Eastin, FAA (retired)
- Dr. Michael Gorelik, FAA
- Chris Hurst, Textron Aviation
- Dr. Harry Millwater, UTSA
- Dr. Michael Shiao, US Army (Aberdeen)
- Dr. Mark Thomsen, USAF (Hill)
- Dr. Eric Tuegel, USAF (Wright Patterson)

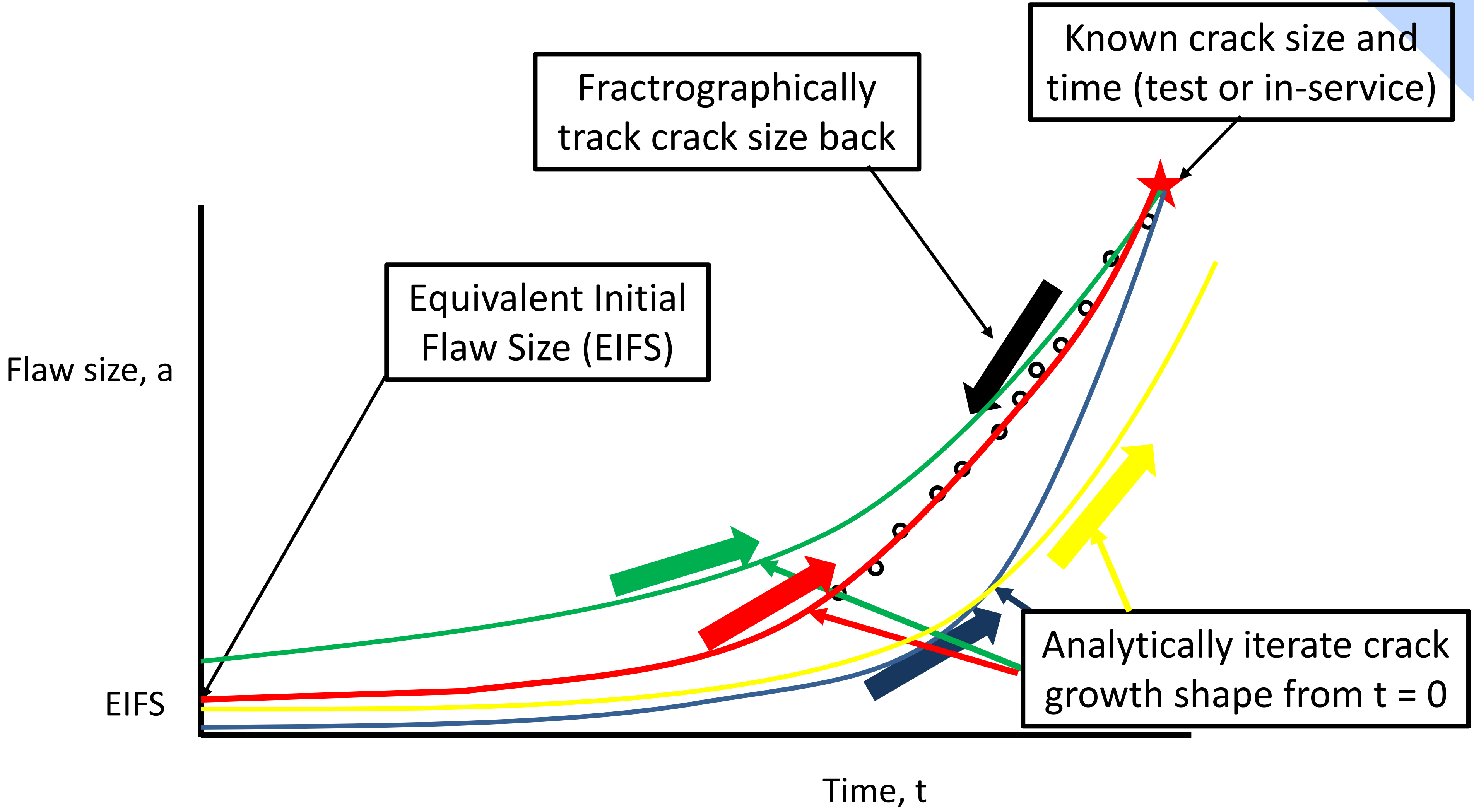
EIFS Background

- USAF established damage tolerance method based on assumption of initial quality flaws in structure
  - Damage tolerance: 0.05” rogue flaw
  - Durability: 0.005” quality flaw (now more often 0.01”)
  - Used F-4 and A-7 data to quantify flaw sizes
    - ♦ Fatigue test
    - ♦ In-service

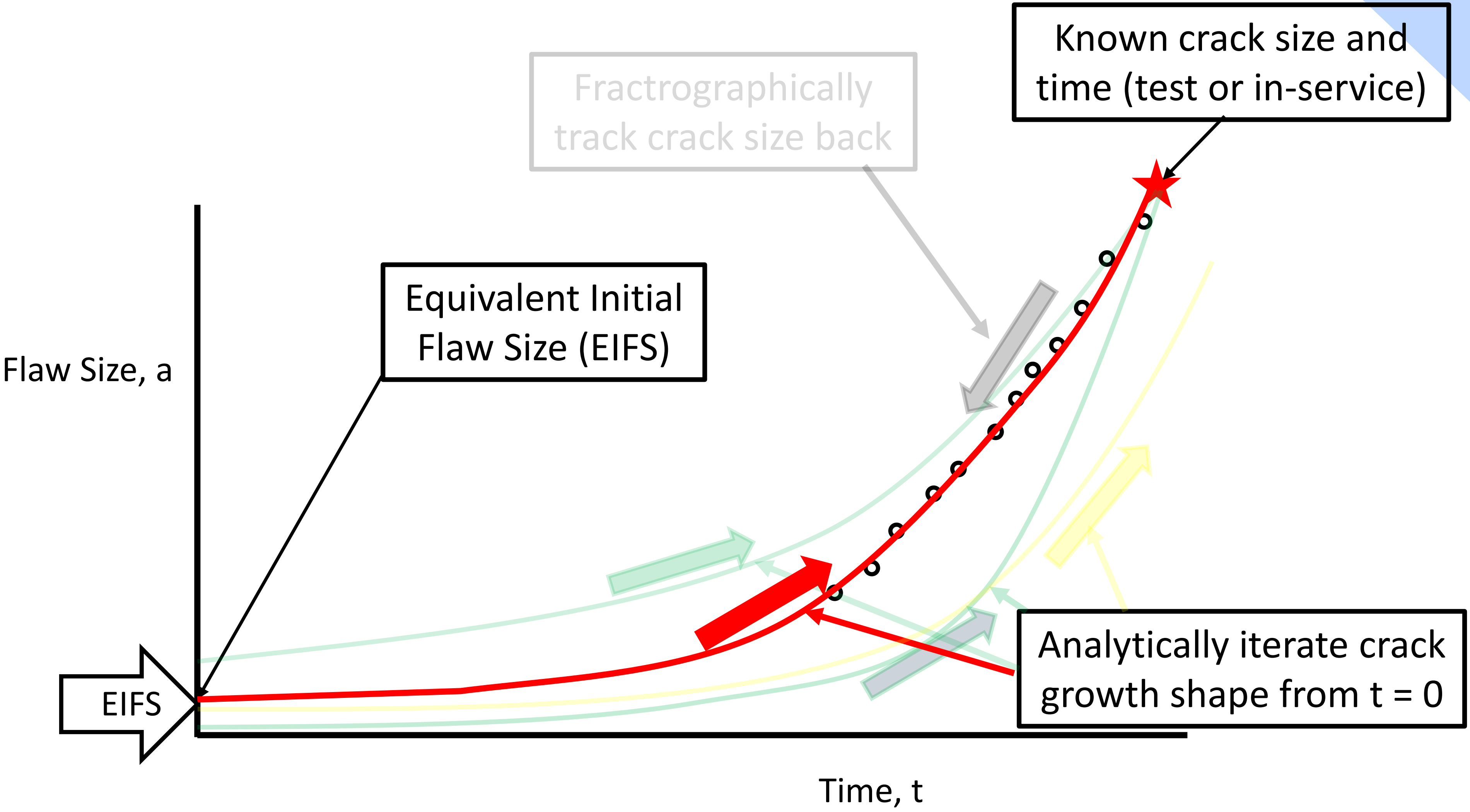
EIFS Background

- USAF method to determine EIFS based on:
  - Known manufacturing processes
  - Known aircraft usage
  - Known aircraft material, loads

EIFS Calculation Method



EIFS Calculation Method



EIFS Background

- USAF caveats/cautions regarding EIFS concept
  - AFFDL-TM-76-83-FBE, Equivalent Initial Quality Method, 1976:
    - ♦ "The objective of using the equivalent initial quality method is to quantify the quality of a fastener hole produced by *certain manufacturing and processing procedures*."
  - AFFDL-TR-78-206, Fastener Hole Quality, 1978:
    - ♦ "…the equivalent initial flaw size (EIFS), a *fictitious* size of a flaw existing at the time of manufacture within the fastener hole."
    - ♦ "The EIFS is that *pseudo* fatigue crack assumed to be present in a fastener hole at time zero…"

Italics added for emphasis

EIFS Background

- USAF caveats/cautions regarding EIFS concept
  - AFFDL-TM-76-58-FBE, Applications of the Equivalent Initial Quality Method (1977):
    - "…further research is required to reveal the limitations of the method. For example, studies are necessary to investigate the sensitivity of the method to *type of damage, damage size and shape, stress level, material, load transfer, type of fastener, etc.*"

Italics added for emphasis

Original USAF EIFS Data

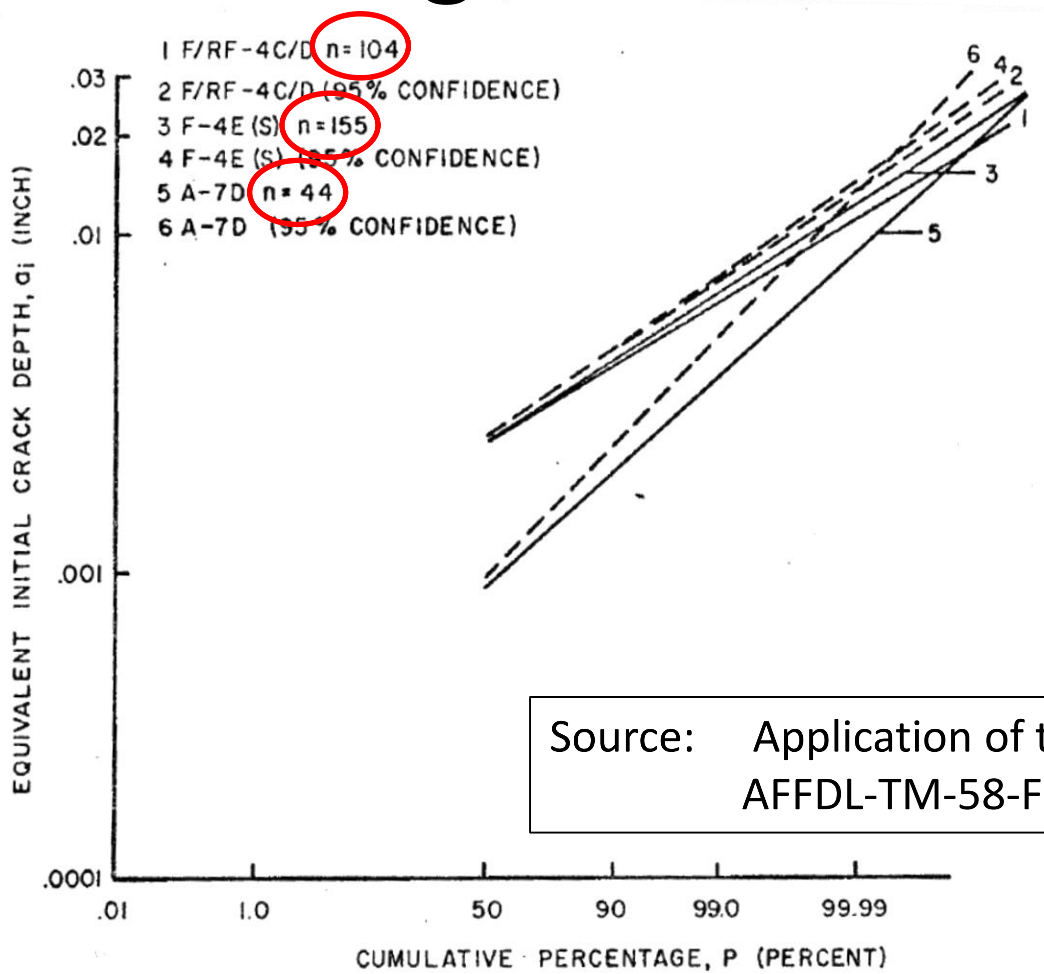
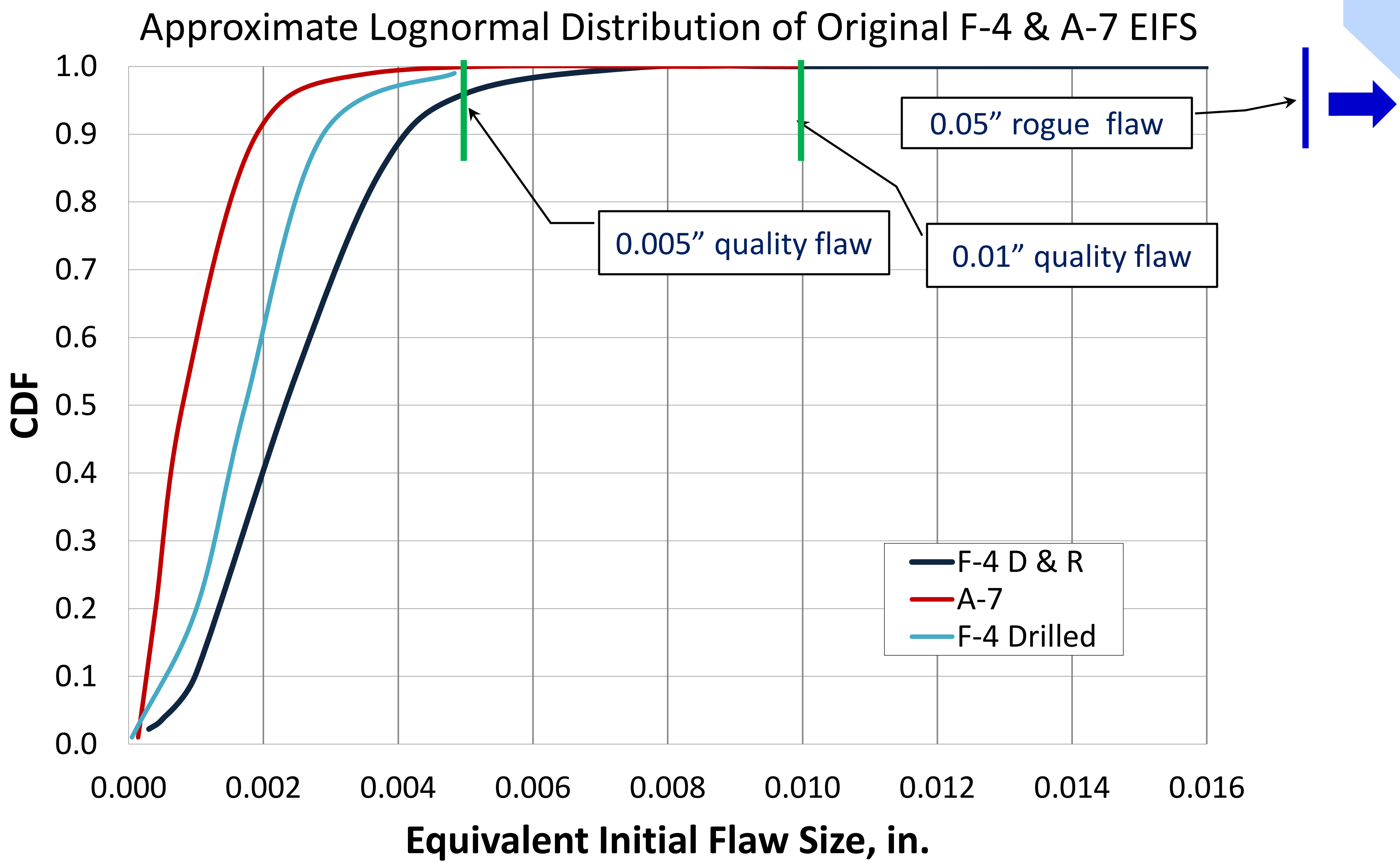


Figure 29. Equivalent Initial Crack Depth Distributions for F/RF-4C/D, F-4E(S) and A-7D Aircraft

Source: Application of the Equivalent Initial Quality Method AFFDL-TM-58-FBE, July 1977, James L. Rudd

Comparison of Original F-4 & A-7 EIFS



EIFS Comparison

Material	Mean (in)	STD (in)	Distribution	Source
Al 7075-T651	0.00248	0.00129	-	F-4 Drilled & Reamed
Al 7178-T6	0.00173	0.00091	-	F-4 Drilled
Al 7075-T6	0.0008	0.0009	-	A-7
Al 2024-T3	0.00030	0.000019	-	Fawaz, S. (Joint I)
Al 2024-T3	0.00088	0.000437	-	Fawaz, S. (Joint II)
Al 2024-T3	0.00030	0.000030	-	Fawaz, S. (Joint III)
Al 2024-T3	0.01187	0.00856	-	Fawaz, S. (Joint IV)
Al 2024-T3	0.1181	0.000394	Weibull	Makeev et al.
Al 2024-T351	0.00076	0.000831	Weibull	Maymon, G.
Al 7075-T6	0.00906	0.00197	Lognormal	Liu and Mahadevan
Al 7075-T735	0.000211	0.000180	Weibull	Weiand & Millwater
Ti-6Al-4V	0.000023	0.000013	Lognormal	Golden, Millwater, & Yang

All but first 3 rows courtesy of Dr. Michael Shiao, US Army

Probabilities Associated with Initial Flaws

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USAF guidelines

- 0.05” – once in a fleet $\cong 10^{-7}$
- 0.01” – once in an aircraft $\cong 10^{-4}$
  - 10,000 critical holes on an aircraft?
- Weibull distribution generally fits the EIFS data best

Application of EIFS for Civil Applications

- Virtually no public EIFS data based on civil applications
- Is use of USAF EIFS data appropriate?
  - Variation in:
    - ♦ Material
    - ♦ Usage
    - ♦ Geometry (load transfer)
- Of all the variables, how much influence is EIFS?
- Good input needed for good output

Input into SMART for Generic Problem

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“Control” input

- Geometry:
  - Generic hole 0.2” dia., 0.1” t
- Material:
  - AL 2024-T3, K_c = 34 ksi√in, log Paris C = -8.1, m = 3.2
- Usage:
  - Ordinary small airplane usage profile
  - 1g stress = 6,000 psi
- NASGRO generated crack growth curve based on above parameters
- Inspection POD:
  - Mean POD= 0.076”, Std. Dev = 0.033”, lognormal dist.

Input into SMART for Generic Problem

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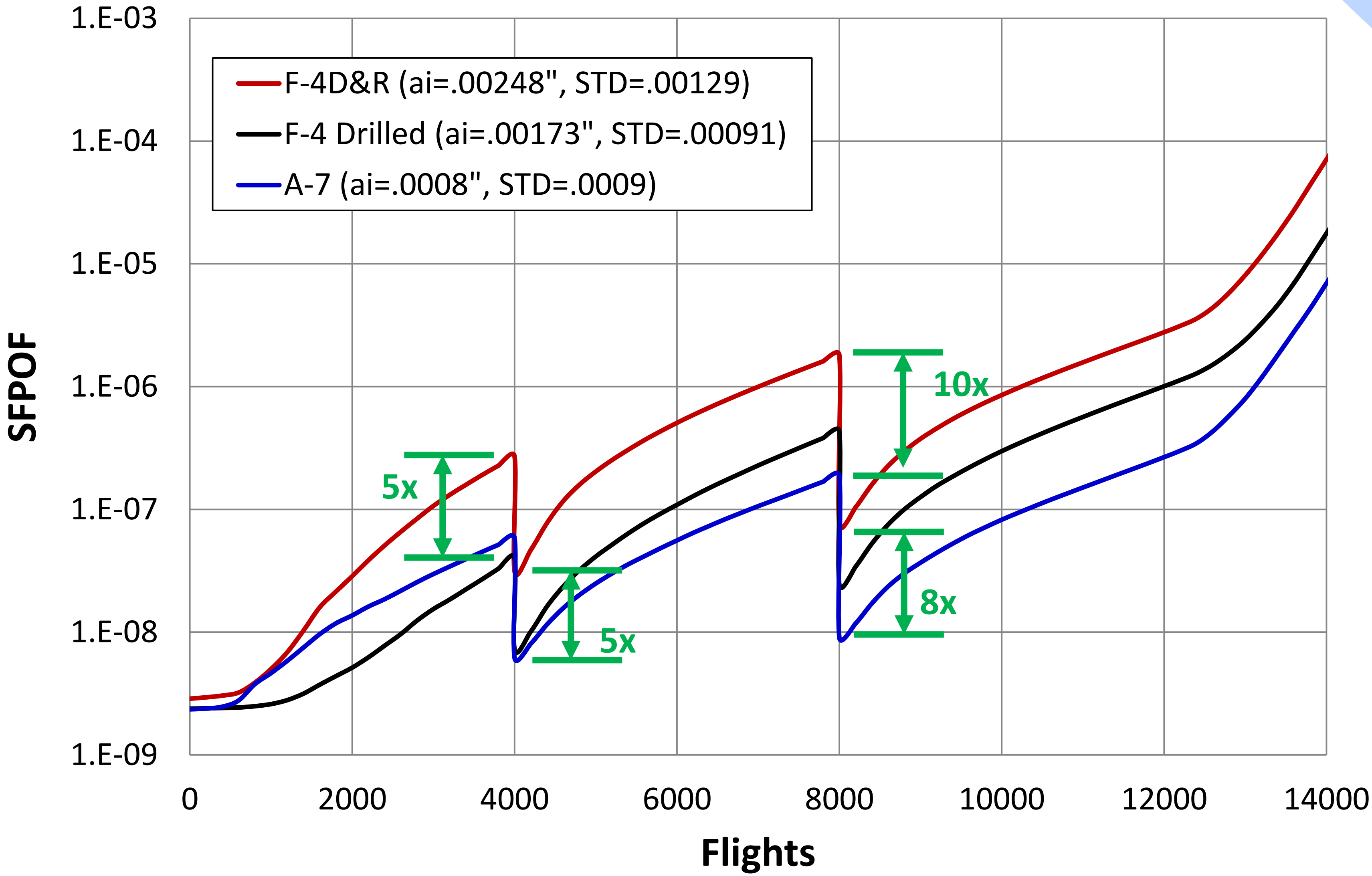
<u>"Variable" input</u>

- EIFS variation:
  - a_i from 0.0004" to 0.01"
  - a_i std. dev.
  - a_i distribution – lognormal vs. Weibull
- K_c std. dev.
- POD
  - Small a_{det} =0.03", large a_{det} =0.2"
- 1g stress $\pm$5%

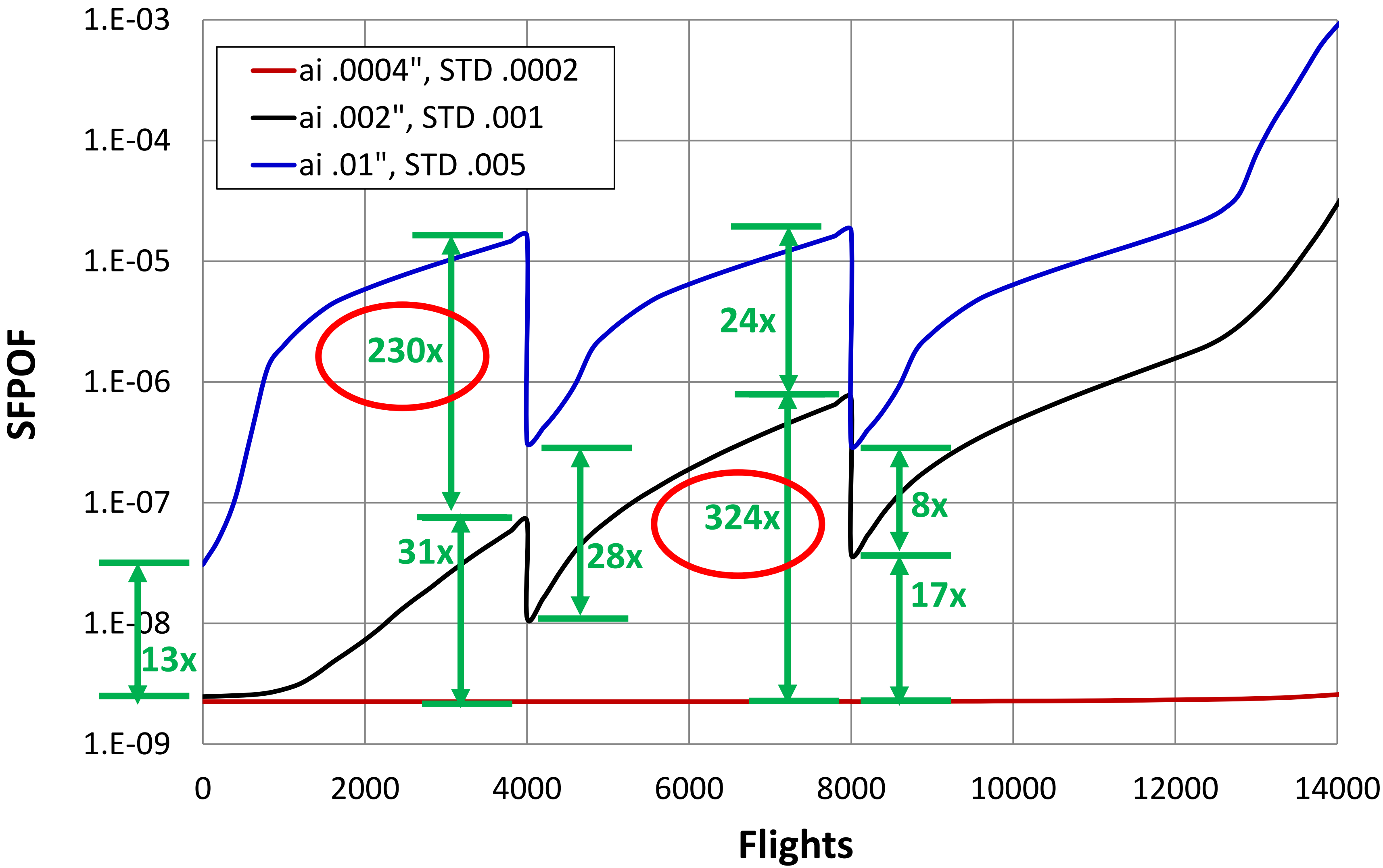
<u>**Key output**</u>

- Single Flight Probability of Failure (SFPOF)
  - Desired accuracy is factor of 2-5

SFPOF Variation between F-4, F-4, A-7 EIFS



SFPOF Variation with EIFS



SFPOF Variation for "Average" EIFS

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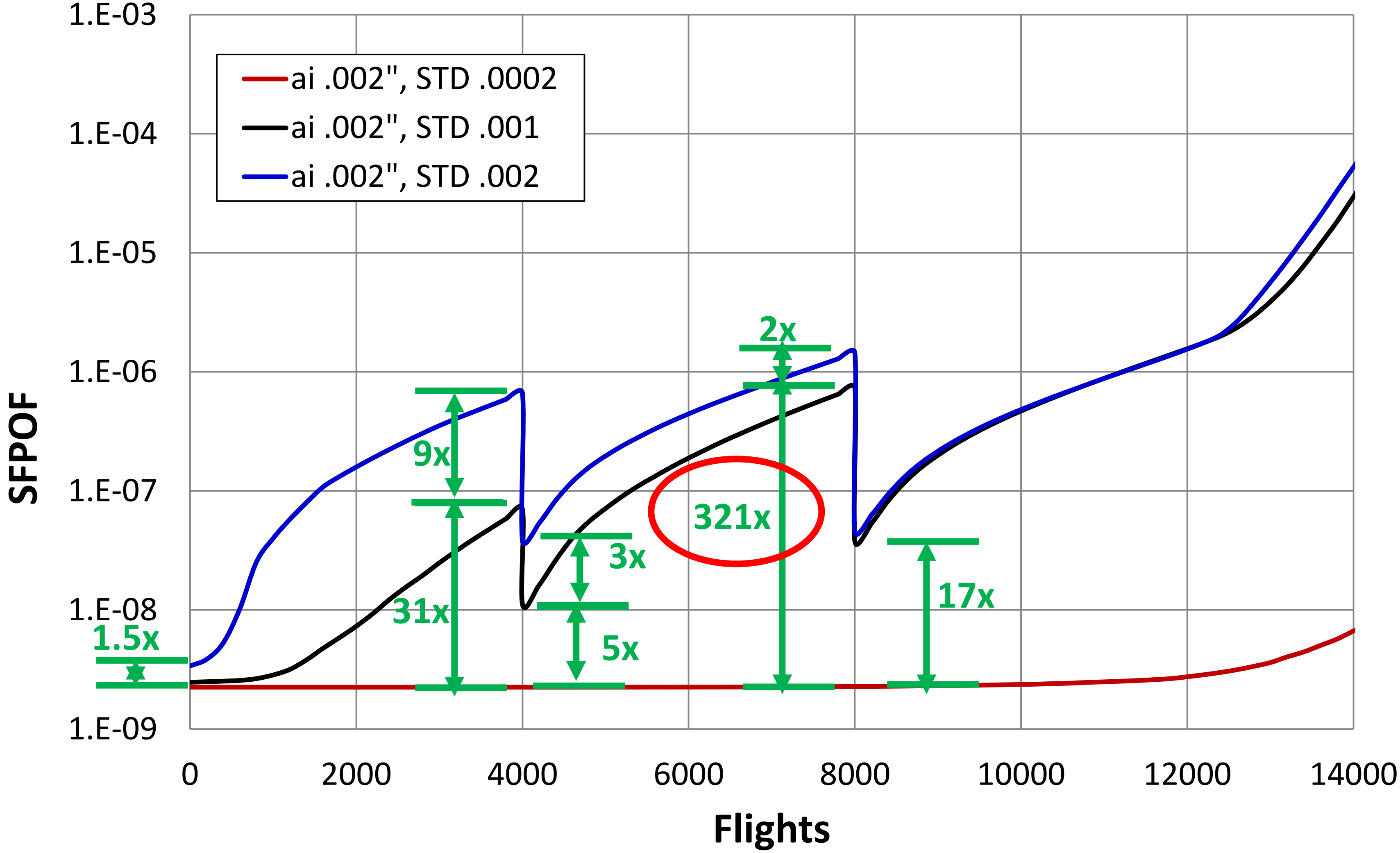
(Vary Lognormal Distribution Standard Deviation)



Compare Lognormal to Weibull EIFS Distribution

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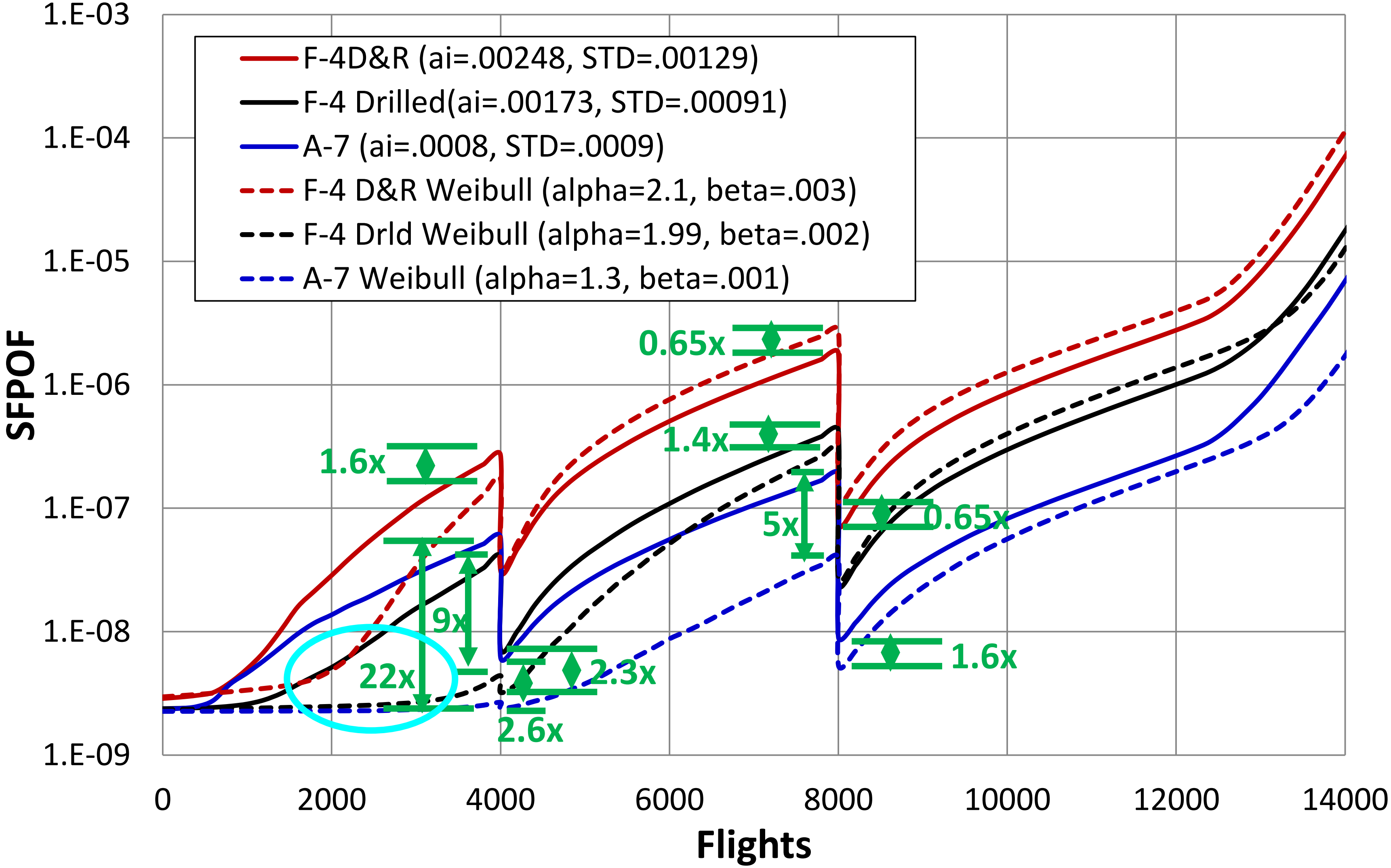
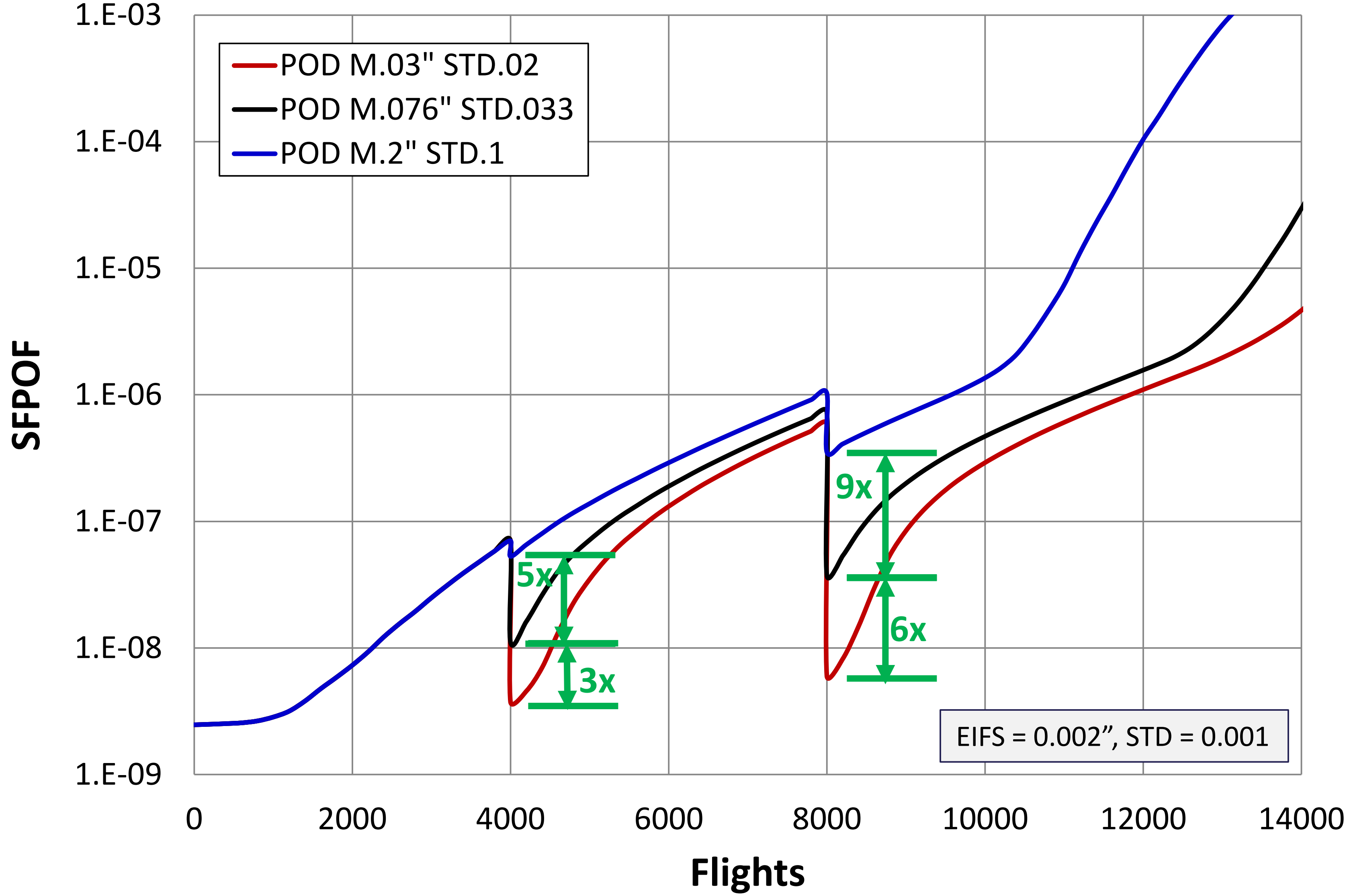
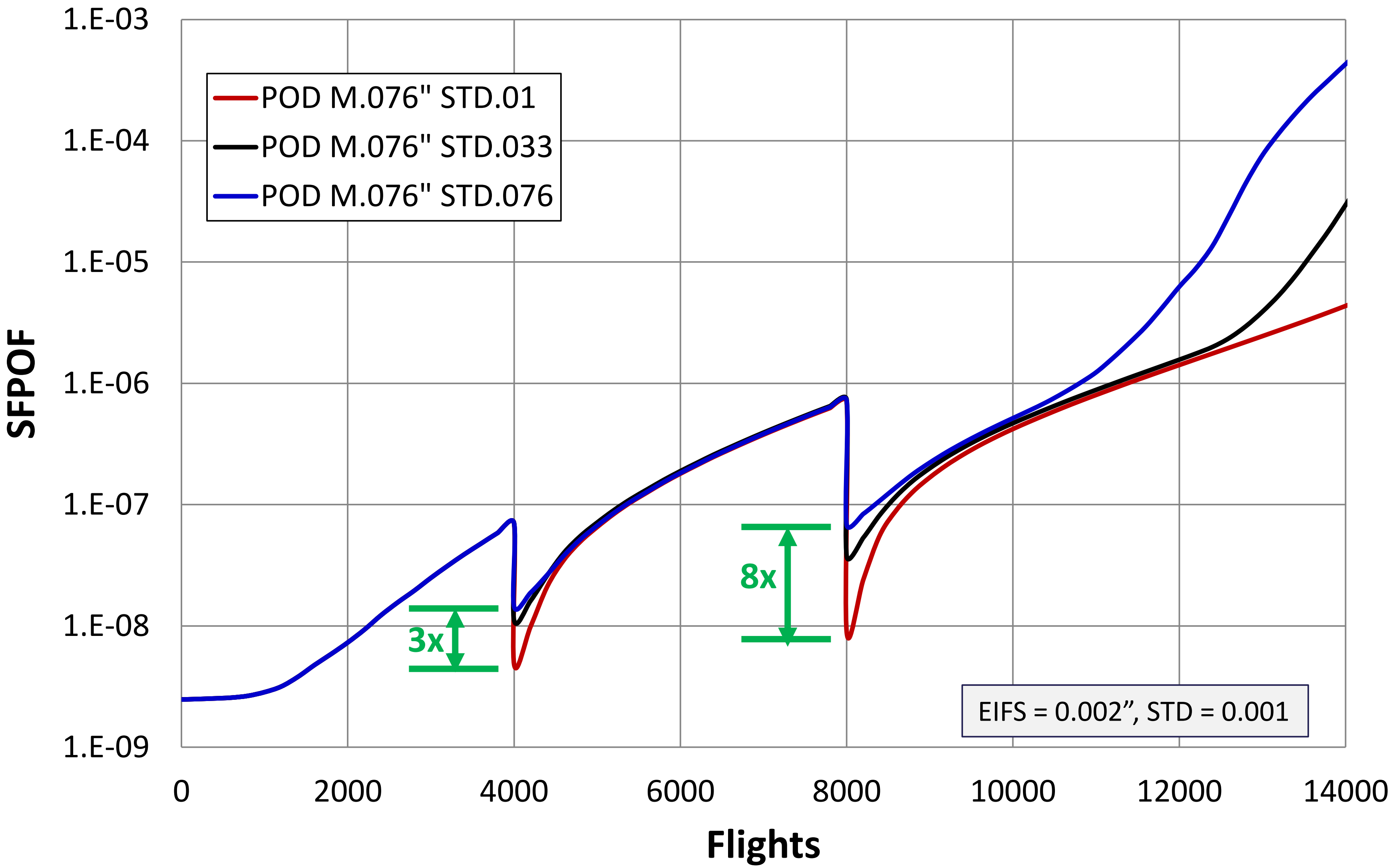


SFPOF Variation with POD



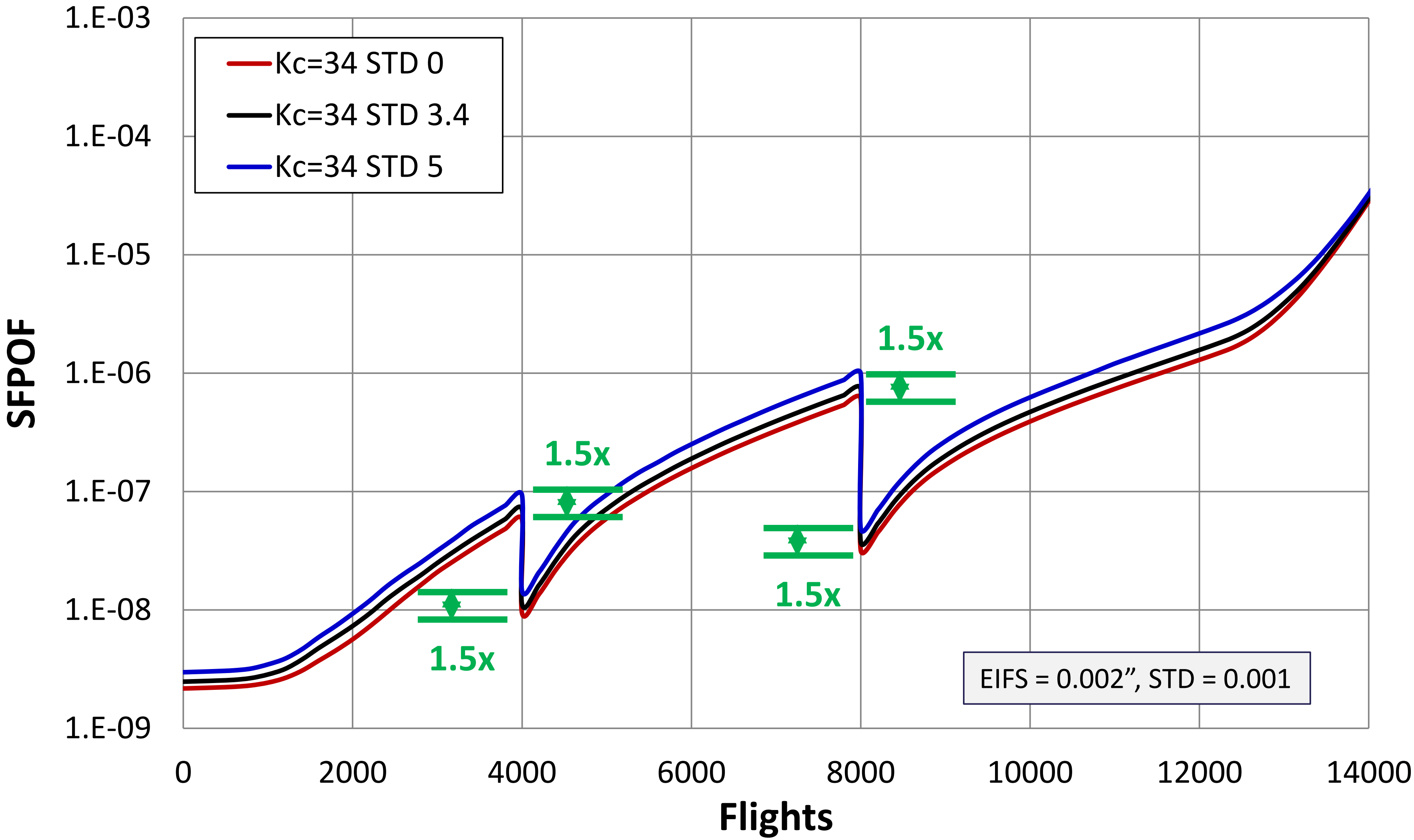
SFPOF Variation with POD

(Medium Detectable Size – Vary Std. Dev.)

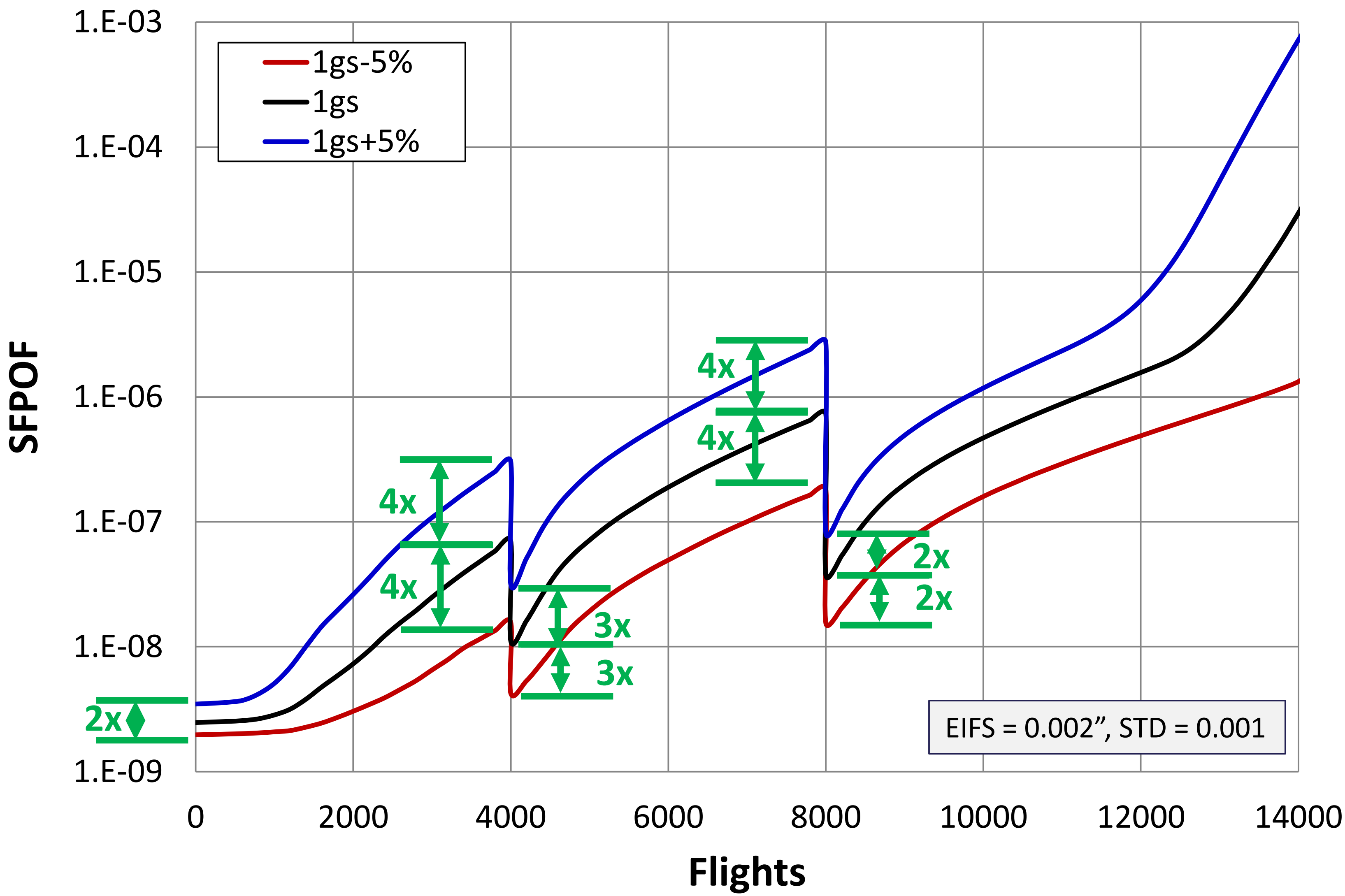


SFPOF Change with K_c Variability

(Vary Standard Deviation)



SFPOF Variation with 1g Stress



NuSS' Interpretation of Results

- A-7/F-4/F-4 EIFS range factor of **3** produced SFPOF range factor of **5-10**
  (0.0008" – 0.00173" – 0.00248")
- EIFS range factor of **25** produced SFPOF range factor as high as **7000**
  (0.0004" – 0.01")
- EIFS distribution variation range factor of **10** produced SFPOF range factor as high as **600**
  (for a_i = 0.002", std. dev. varied 0.0002 – 0.002)
- EIFS distribution shape produced SFPOF range factor of **1.5-20**
  (A-7/F-4/F-4 EIFS Lognormal vs. Weibull distribution)

Desired SFPOF accuracy is within a factor of 5

NuSS' Interpretation of Results

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- POD range factor of **7** produced SFPOF range factor of **15-50**

  (POD 0.03" – 0.2")
- POD distribution variation range factor of **8** produced SFPOF range factor of **3-8**

  (POD mean 0.076", lognormal std. dev varied 0.01 – 0.076)
- K_c std dev. variation produced little change in SFPOF (factor=**1.5**)
- 1g stress variation ±5% produced SFPOF range factor of **±4**

Desired SFPOF accuracy is within a factor of 5

Summary of Results

- EIFS variation had by far the most important effect on SFPOF in this study
  - a_i size
  - a_i size distribution
  - a_i distribution shape
- Yet, there are little data for EIFS and its effect on specific application

- SMART can account for variation in other important parameters that weren't included in this study:
  - da/dN
  - Usage exceedances

Questions Going Forward

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- How do we know if we are using the right EIFS for a particular application?
  - How does EIFS vary with usage?
    - (maneuver vs. gust)
  - How does EIFS vary with geometry?
    - (load transfer)
  - How does EIFS vary with material?
    - (Al-Al-Ti-Steel)
  - How does EIFS vary with manufacturing process?
    - Mfg – mfg
    - Automated vs. manual drilling
    - Old airplanes vs. new

- Reliable COS risk assessment requires good estimates of SFPOF
- Good estimates of SFPOF require good estimates of EIFS

COS: Continued Operational Safety

Turbine Engine Approach to EIFS

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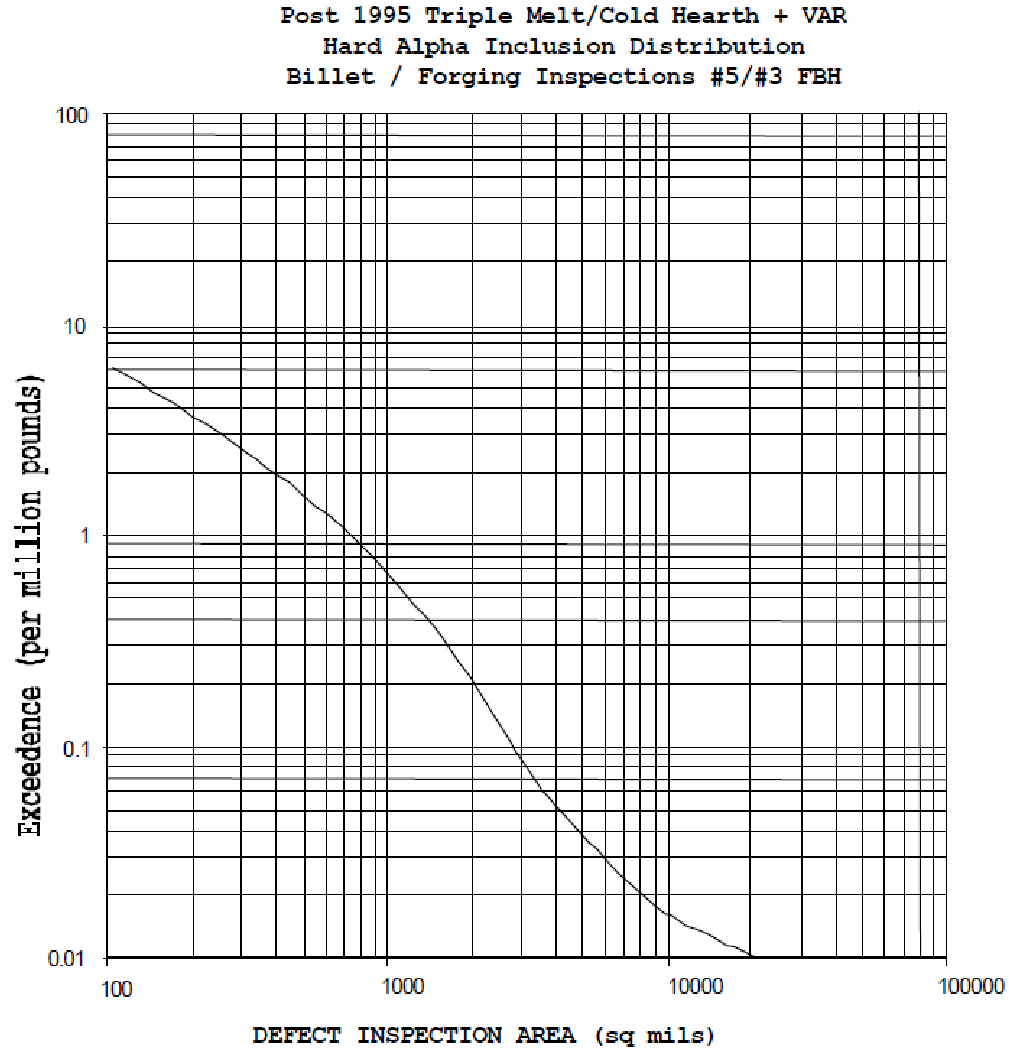
- From FAA AC33.14-1, Damage Tolerance for High Energy Turbine Engine Rotors, 1/8/01
  - Includes anomaly distributions for various titanium conditions
  - No. of defects/1M lbs. of metal vs. defect area

Anomaly Distribution Example

FIGURE A3-1



Recommendations

- FAA is committed to risk management approach to COS
  - FAA needs to facilitate study of EIFS for civil aircraft
    - Bring manufacturers together
    - Sponsor research
    - Develop generic data
  - Successful approach for turbine engines a good model
  - The effects of da/dN and usage variation should also be studied

Should industry explore alternatives to how EIFS is determined?

Notable References on EIFS

- Equivalent Initial Quality Method, USAF report AFFDL-TM-76-83-FBE, Sept. 1976, Rudd and Gray
- Damage Tolerance Assessment of F-4 Aircraft, AIAA-P-76-904, 1976, Pinckert (McAIR)
- Applications of the Equivalent Initial Quality Method, USAF report AFFDL-TM-77-58-FBE, July 1977, Rudd
- Fastener Hole Quality, USAF Report AFFDL-TR-78-206, Dec. 1978, Noronha, Henslee, Gordon, Wolanski, Yee (General Dynamics – Ft. Worth)
- Economic Life Determination for a Military Aircraft, AIAA Journal of Aircraft Vol. 36, No. 5, Sept-Oct 1999, Lincoln (USAF) and Melliere (Boeing-StL)
- The history, logic and uses of the Equivalent Initial Flaw Size approach to total fatigue life prediction, Procedia Engineering 2 (2010) 47-58, Johnson, GA Tech

What do you think?

Thanks for your attention!

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