DETERMINING REINSPECTION INTERVALS

USAF Aircraft Structural Integrity Program Conference
4 – 6 December, 2007

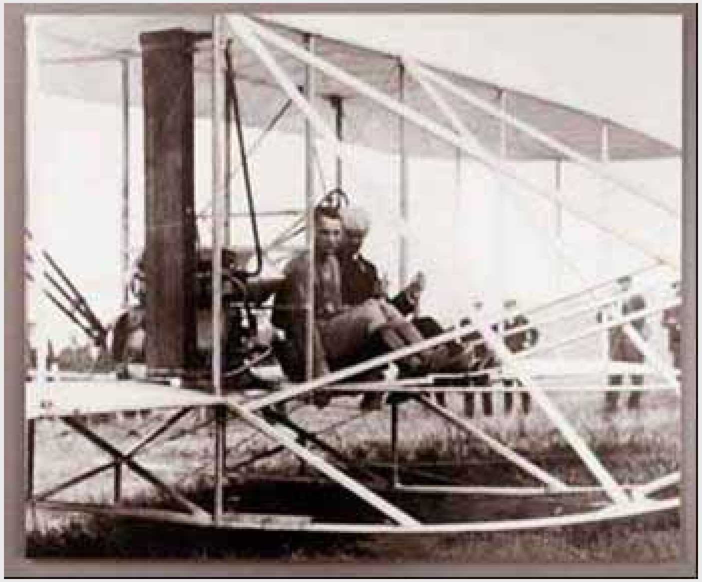
Alan P. Berens

Agenda

- How we got here
- Aging fleets need inspections
- Inspection Scheduling
- Concerning POD(a) and $a_{90/95}$
- Emphasize missed cracks
- Using inspection results

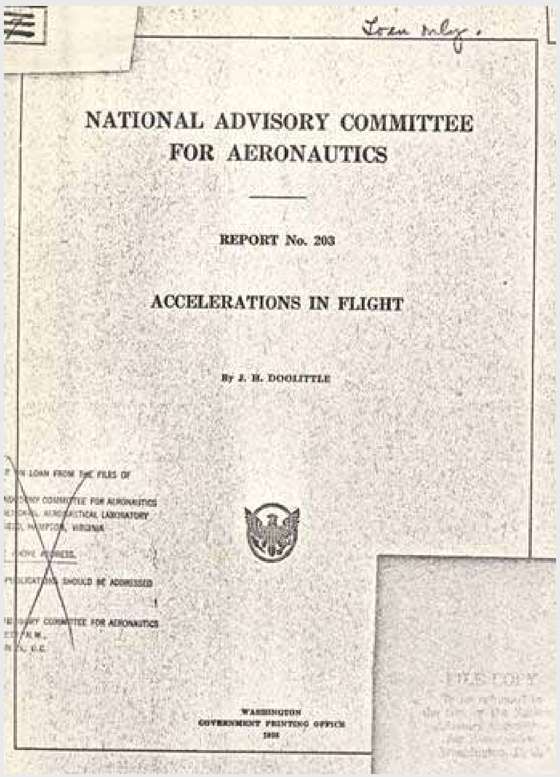
Structural Problems Started with the Wright Brothers

- Propeller broke on September 1908 while demonstrating flight to US Army at For Myers Virginia.
- Orville survived. Lt. Selfridge didn’t.



Static Strength Requirements

- Static strength requirements.
- Load magnitudes?
- Early flight loads data collected in Dayton, 1924. Reported by Doolittle in a Masters Degree thesis for MIT.

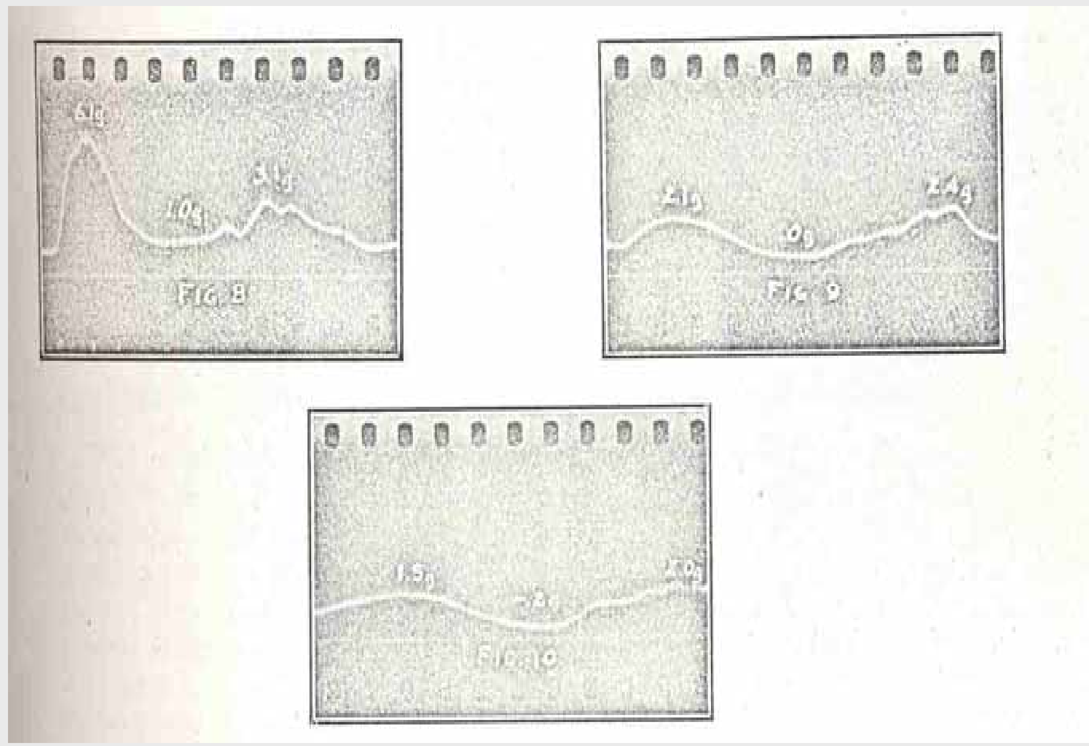

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 203

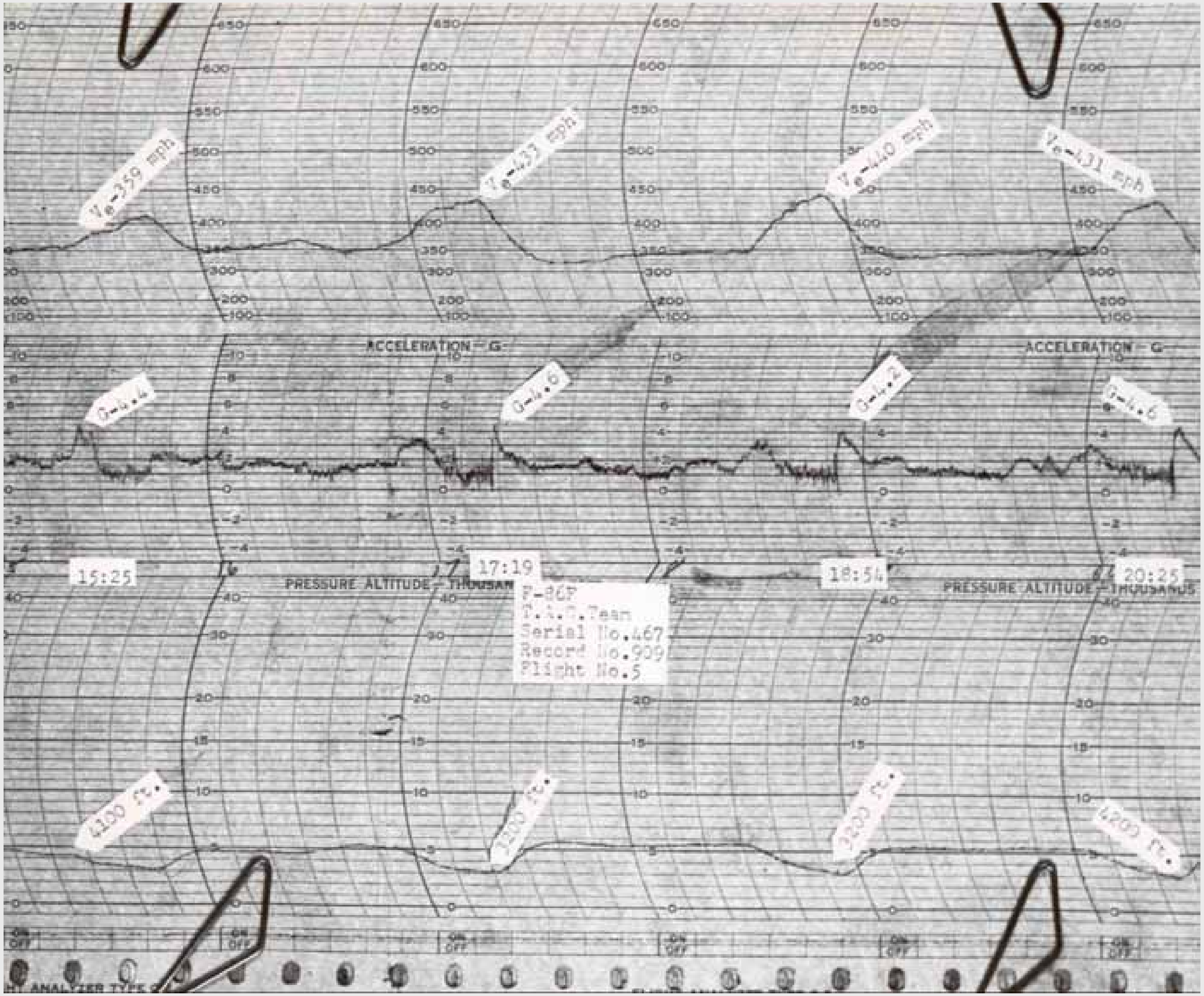
ACCELERATIONS IN FLIGHT

By J. H. DOOLITTLE

WASHINGTON
GOVERNMENT PRINTING OFFICE



Flight Loads Data in the early 1950's



Fatigue Was Not an Early Problem?

1950 Textbook– ***Aircraft Structures***, David Perry, Head, Department of Aeronautical Engineering, Penn State University

“The maximum loads occur only a few times during the service life of the airplane, and fatigue failures of the type which are considered in the engine design need not be considered in the airframe design.”

Fatigue Became a Problem

- Higher strength alloys allowed higher design stress levels and airframe fatigue did become a problem,

1954 de Havilland Comet

1957 B-47

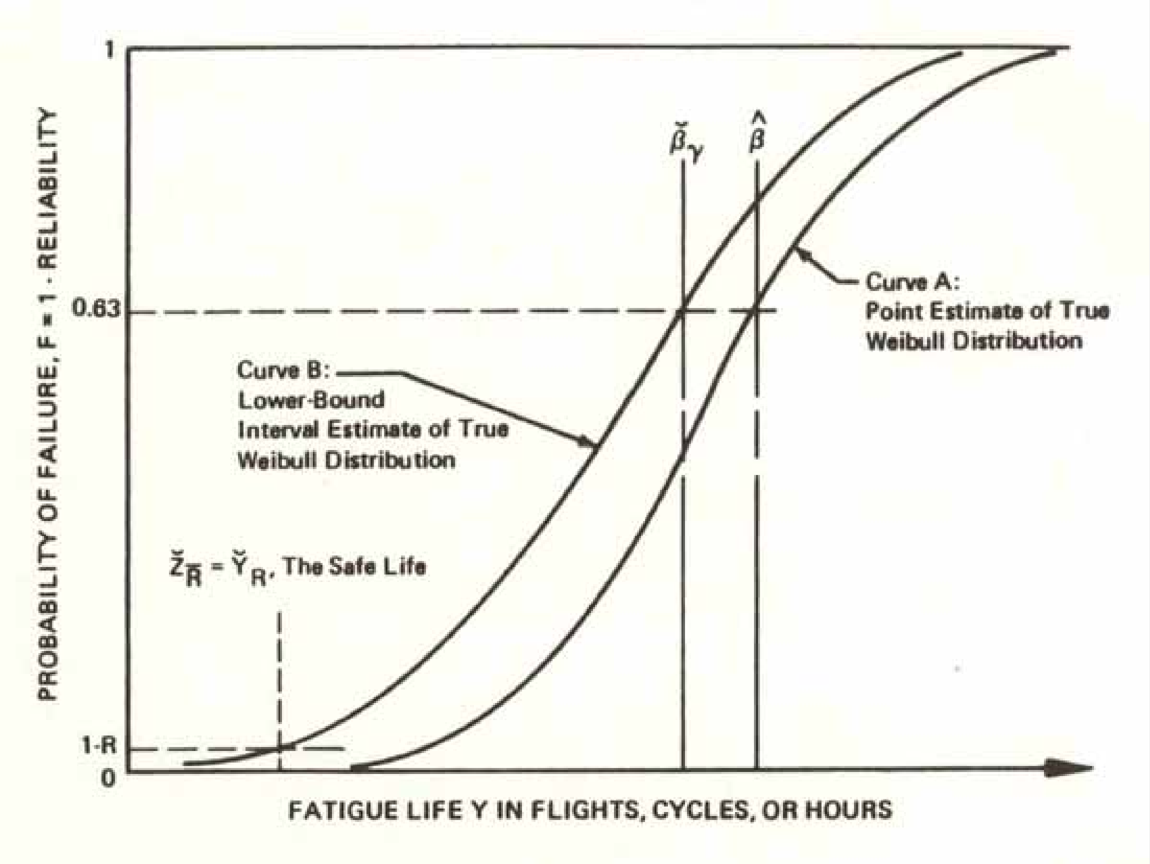
1958 - AF Formally established ASIP

- Cradle to grave concern with structural integrity.
- Grave defined in terms of "Safe Life“.
- What is safe life for a fleet?
  - Fraction of test life.
  - Palmgren-Miner damage accumulation.
  - Reliability based – i.e., probabilistic evaluation.
  - All of the above.

Reliability Based – 60's to mid 70's

- Time to failure/crack initiation

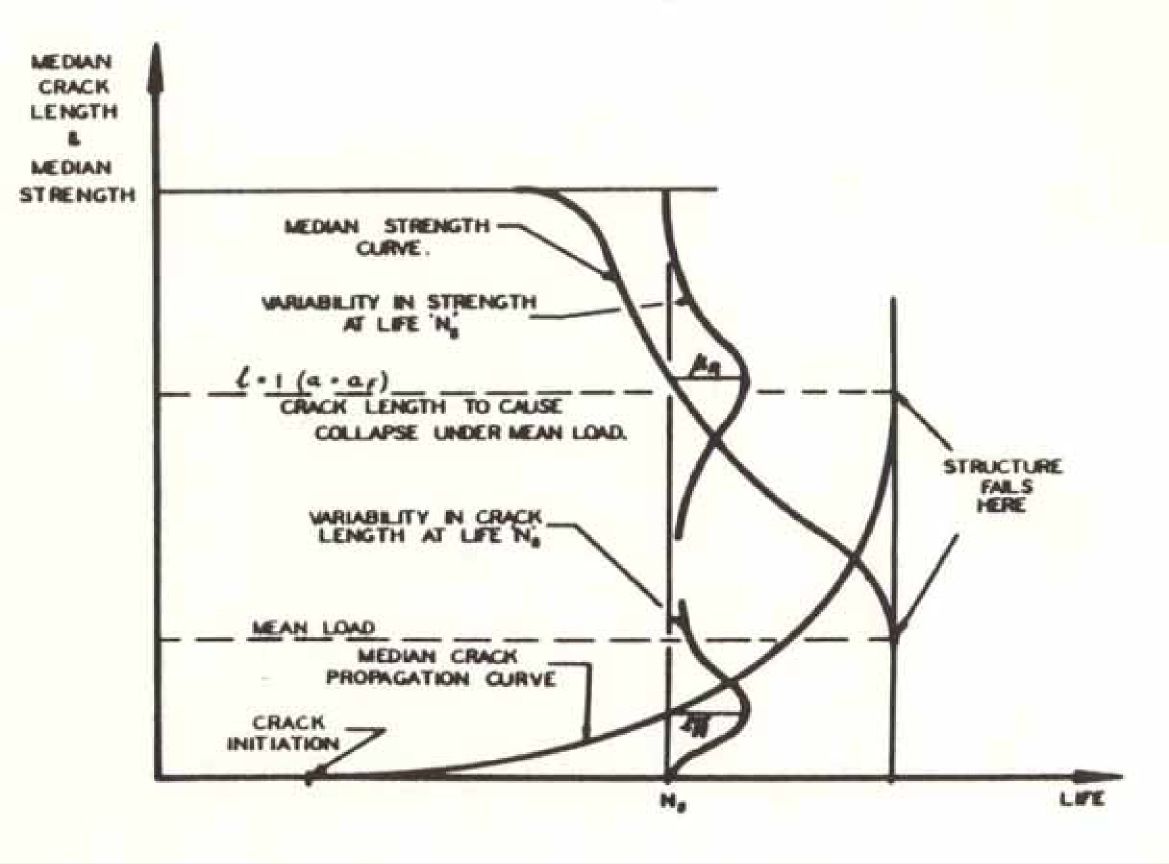
(Trapp, Freudenthal, Yang, Butler, Whittaker, Sarphie, and others)



(From Whittaker and Besuner, AFML-TR-69-65)

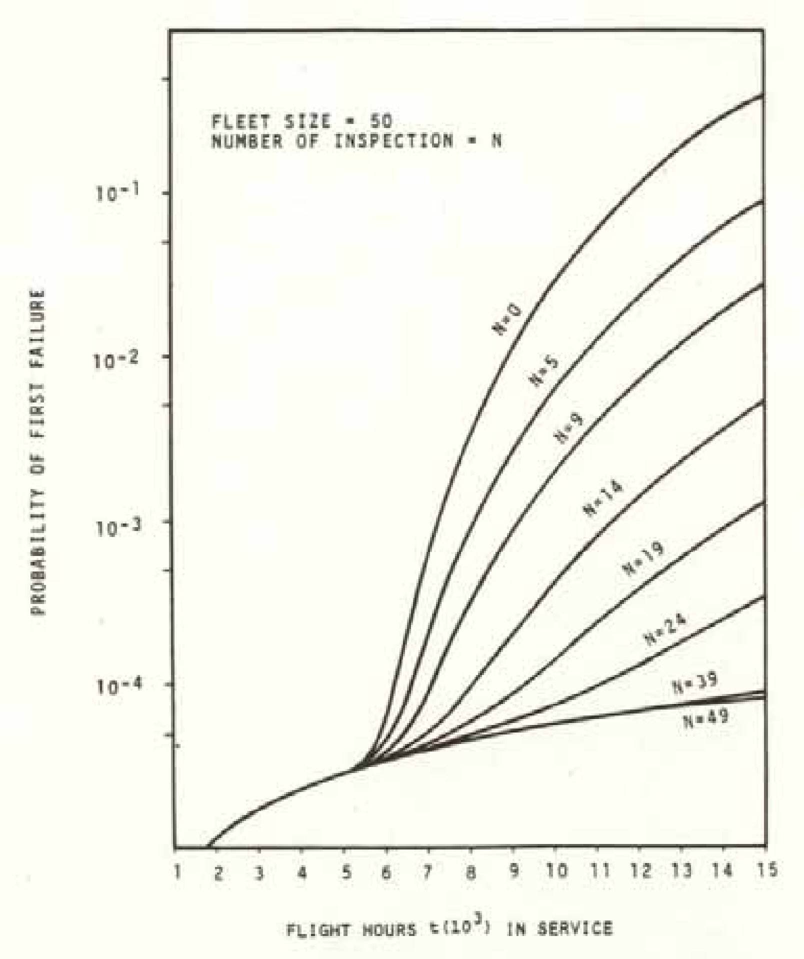
Strength Reduction Based

- Enter Fracture Mechanics

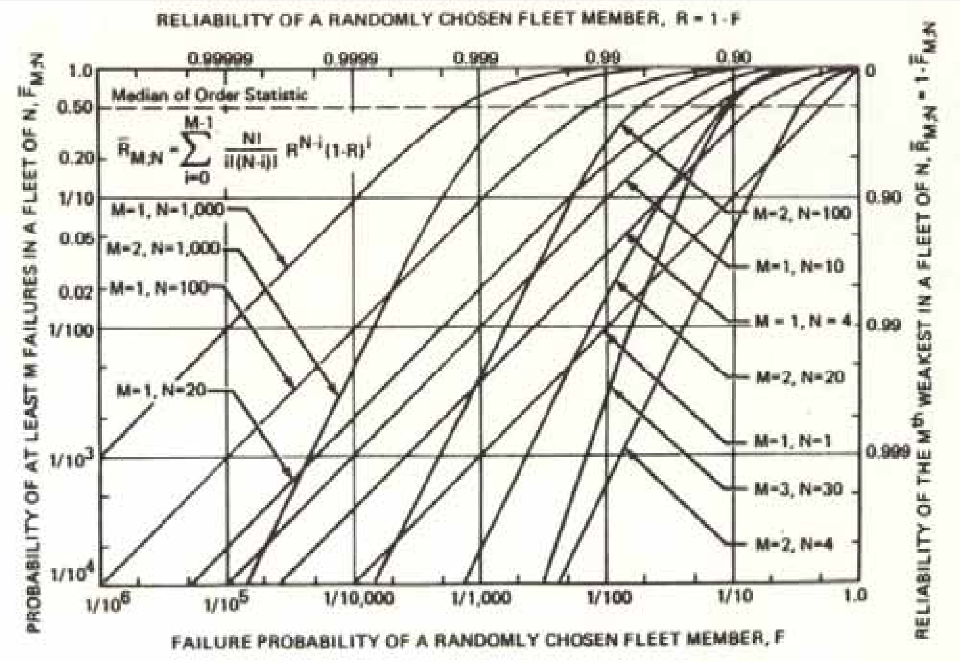


From Payne, ASTM STP 511

Management Statistical Goodies



From Yang and Trapp, AFML-TR-74-29

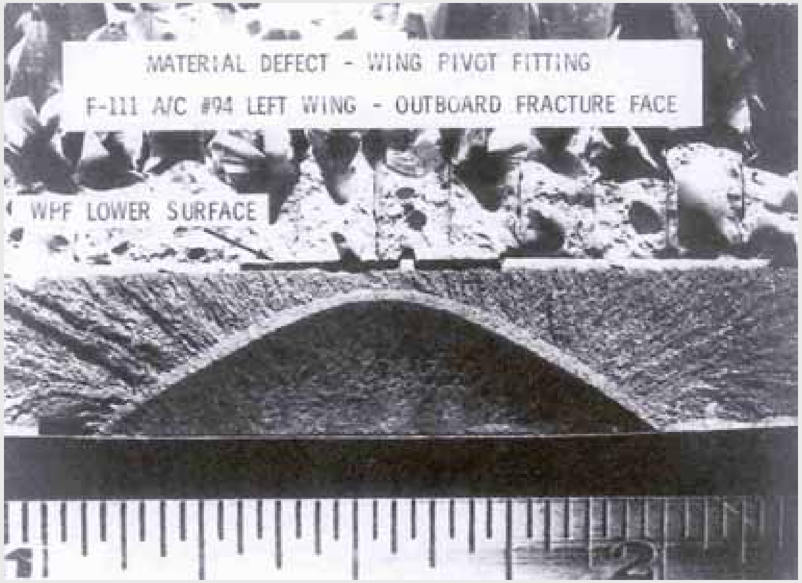


From Whittaker and Besuner, AFML-TR-69-65

The F-111 Problem

- December 22, 1969

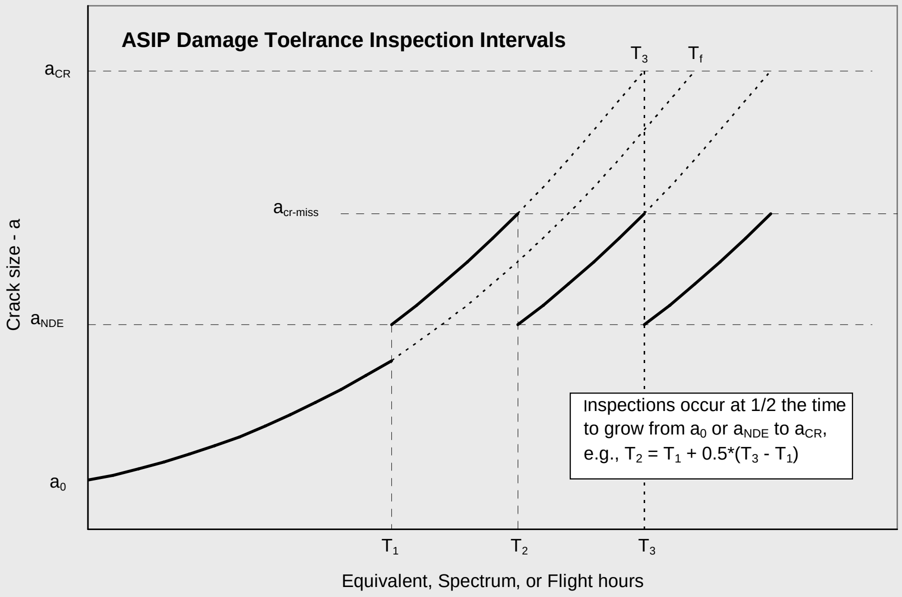
Safe life wing failed at about 100 hours during pull-up from a weapons pass.



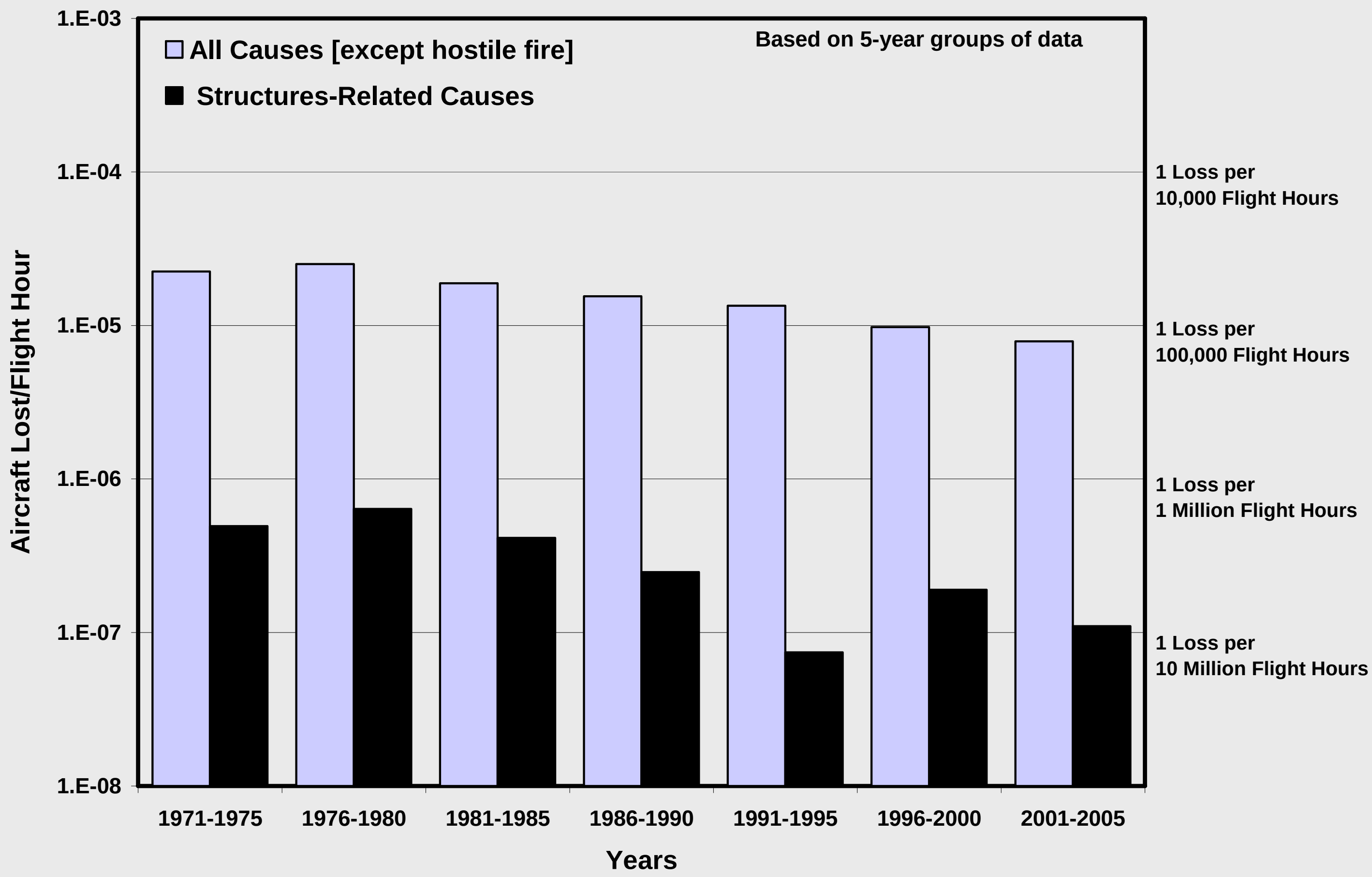
Crack initiated at manufacturing defect.

Damage Tolerance

- Mil-A-83444, Mil-Std-1530A
- Quantify and bound potential damage in the structure.
- a_0 - equivalent flaw size that bounds the rare rogue flaw damage.
- Do first inspection at $T_1 = T_f/2$.
- Ideally, T_1 > design life.
- When necessary, schedule future inspections based on the NDE detectable crack size, a_{NDE}. When available $a_{NDE} = a_{90/95}$.
- Essentially a deterministic analysis – except for a_{NDE}.



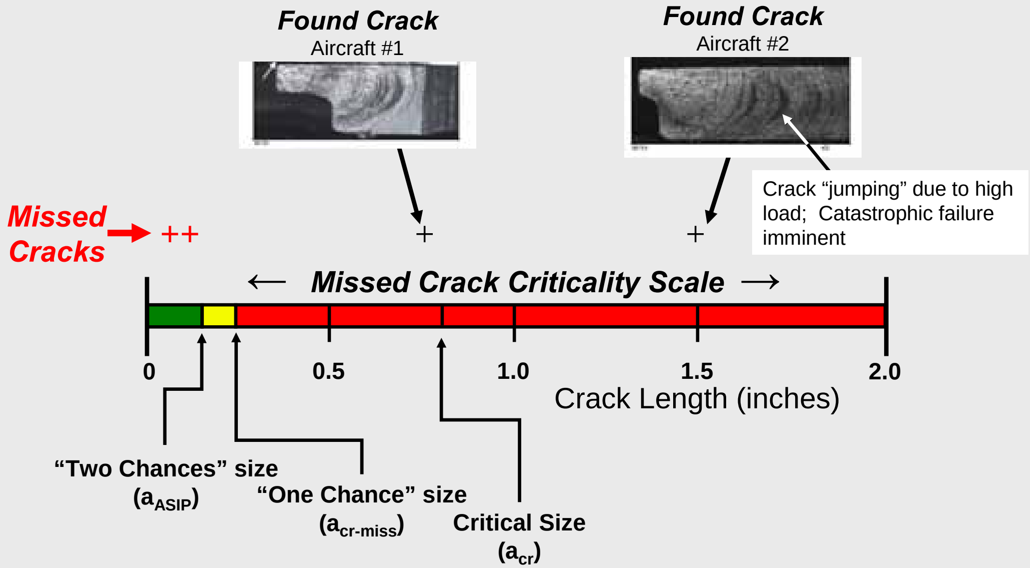
USAF Loss Rates



From Butkus, Gallagher, Babish, 9th Int'l Fatigue Conference, 2006

Aging Aircraft

- Unknown status of the sizes of cracks at critical locations.
- Cracks are being found.
  - Some of reasonably significant size.
- Cracks are being missed
  - Some of definitely significant size.



From Butkus, et al, ICAF 2007

Now What?

- Can safety in the aging fleets be ensured through inspections?
- How are inspection intervals to be determined?
  - Too seldom impacts safety.
  - Too often impacts availability and costs.
- Are there better approaches to scheduling inspections?
  - Metric other than a_{NDE} ($a_{90/95}$)?
  - Risk analyses?
  - Engineering judgment?

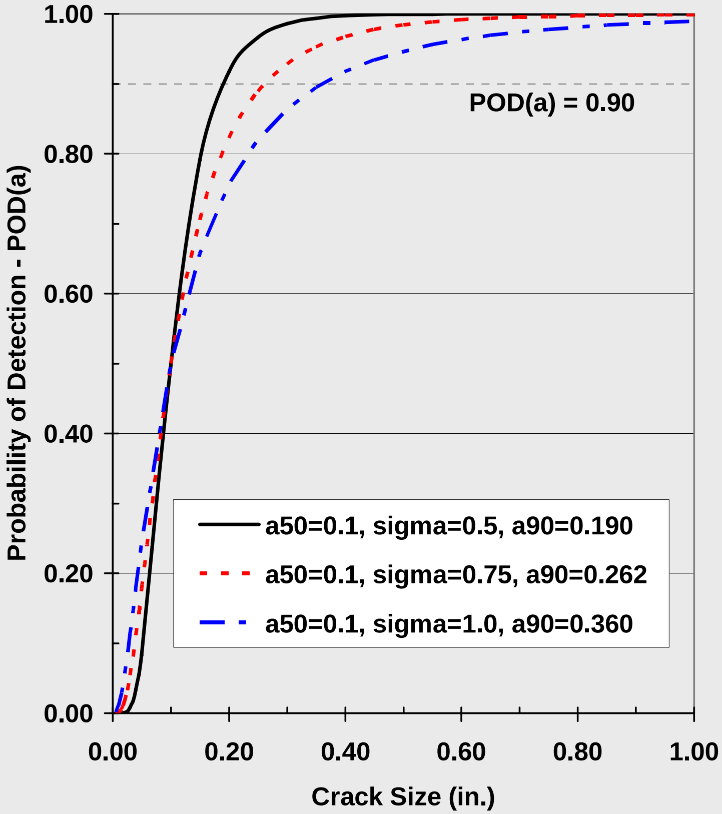
Need a Different Metric Than a_{NDE}

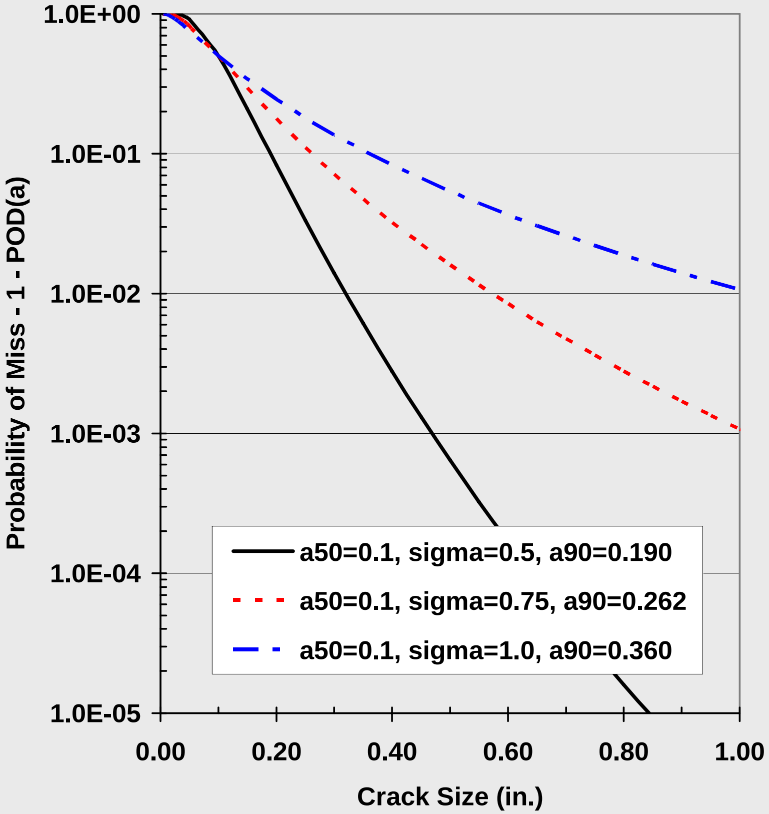
- There are problems with using $a_{90/95}$ from a laboratory evaluation of NDE capability for use in scheduling inspections.
- In particular, need better focus on size of cracks in the structure after the inspection and repair action – i.e. the misses.
- Consider the $a_{90/95}$ problems.

Note: Let a_{ASIP} (however defined) represent the different metric to distinguish from the NDE detectable crack size (a_{NDE} or a90/95) for scheduling inspections.

What is the NDE detectable crack size?

- POD(a) is proportion of cracks of size a that are expected to be found at the inspection.
- 1-POD(a) is proportion of size a that might be missed.





- One number capability summary? – POD(a_{90}) = 0.90?

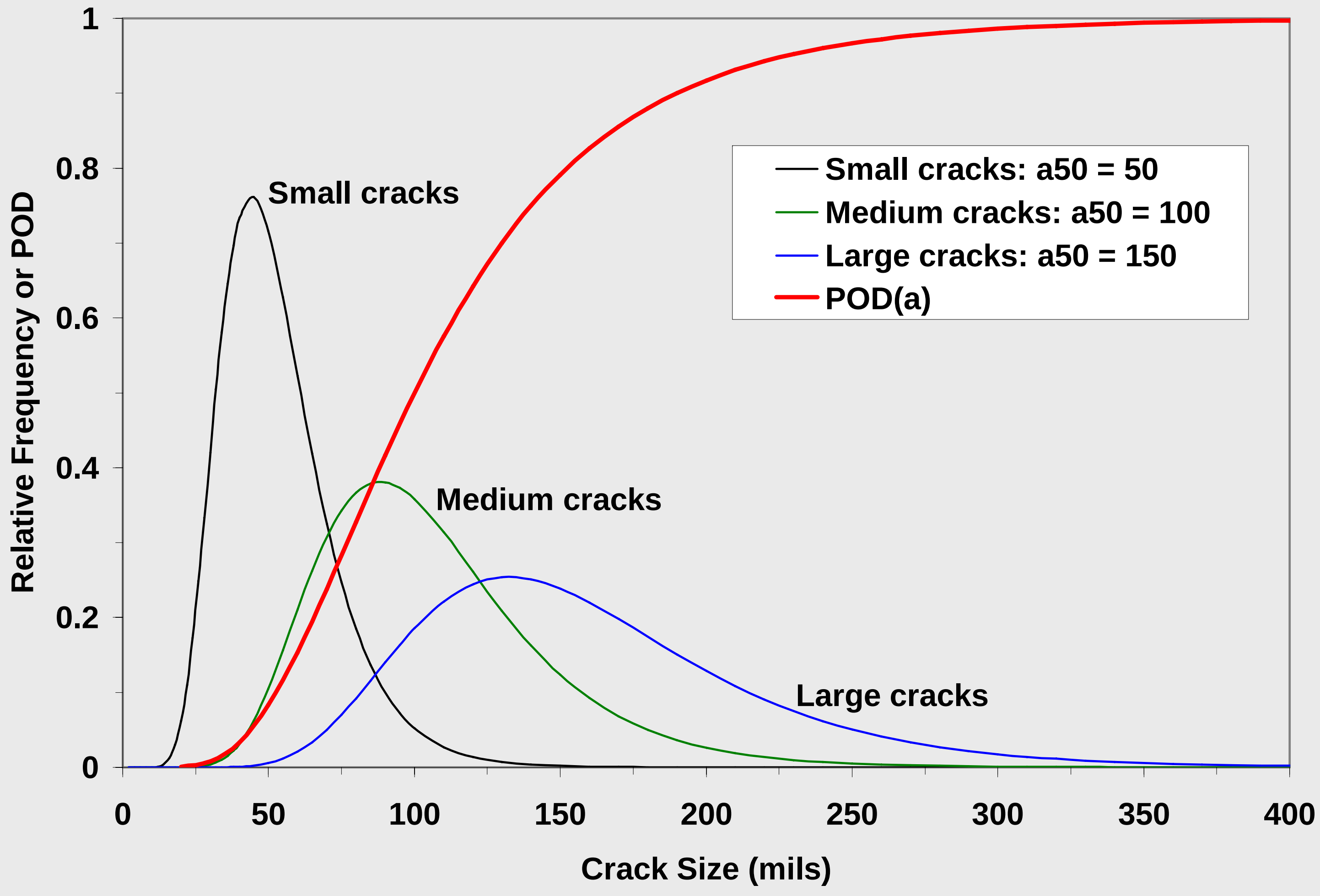
Why the 90/95 combination?

- By definition, $a_{90/95}$ is the lower 95 percent confidence bound on an estimate of a_{90}.
- Early POD(a) analyses were based on binomial distribution theory for detecting a crack of fixed size, a.
- Detecting all 29 cracks in a small range of sizes was demonstration of $a_{90/95}$ crack size for the largest crack in the range.
- More desirable combinations of miss probability and/or confidence level required many more cracks in the small range.
- Decision was made to use $a_{90/95}$ as the “NDE detectable” crack size for scheduling inspections.
  - Likely to be conservative.
  - According to Rummel, early arguments were over capabilities as evaluated, not by either the 90 or 95 choice.

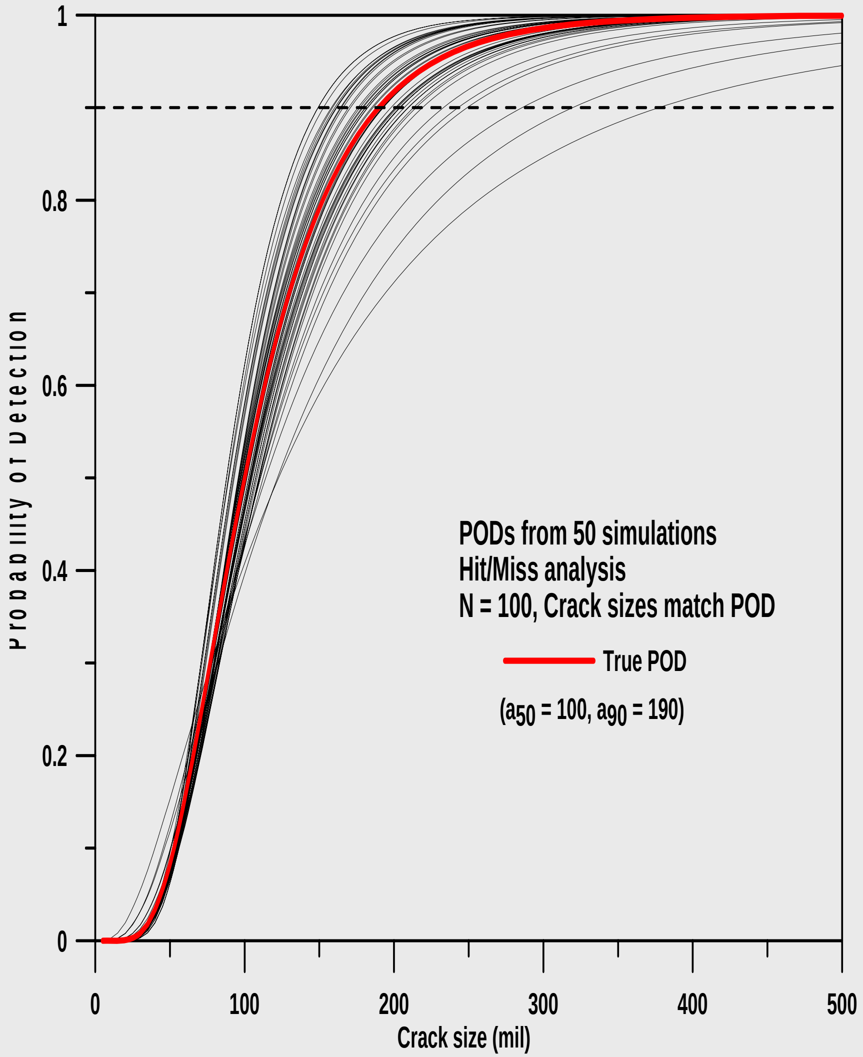
Why not $a_{90/95}$?

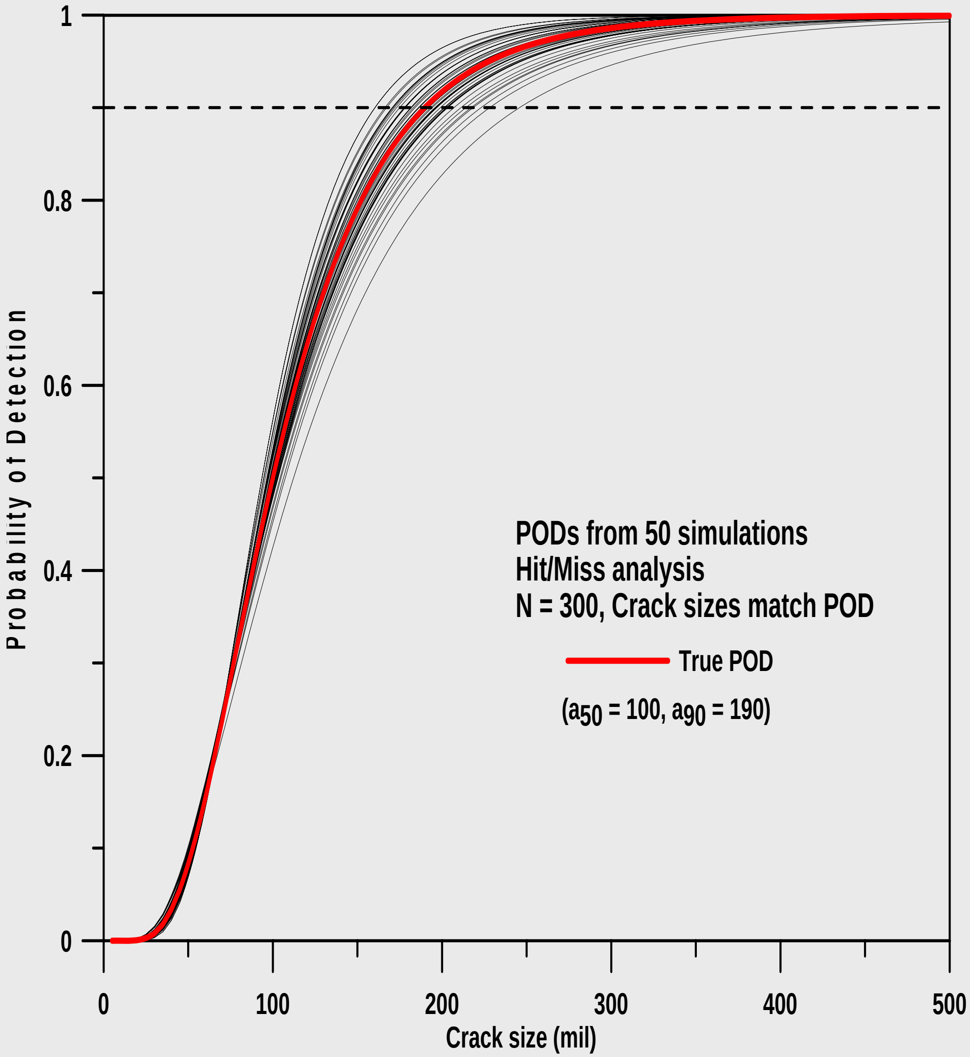
- 90% detectability is not so great when many cracks are getting bigger.
- $a_{90/95}$ is not a property of the NDI system.
- When all is right, $a_{90/95}$ will still be less than a_{90} in about 5% of demonstrations.
- Scatter in $a_{90/95}$ is large and greatly influenced by the design of the capability demonstration and slope of POD(a).
  - Number of cracks
  - Sizes of cracks

$a_{90/95}$ Scatter Demonstration

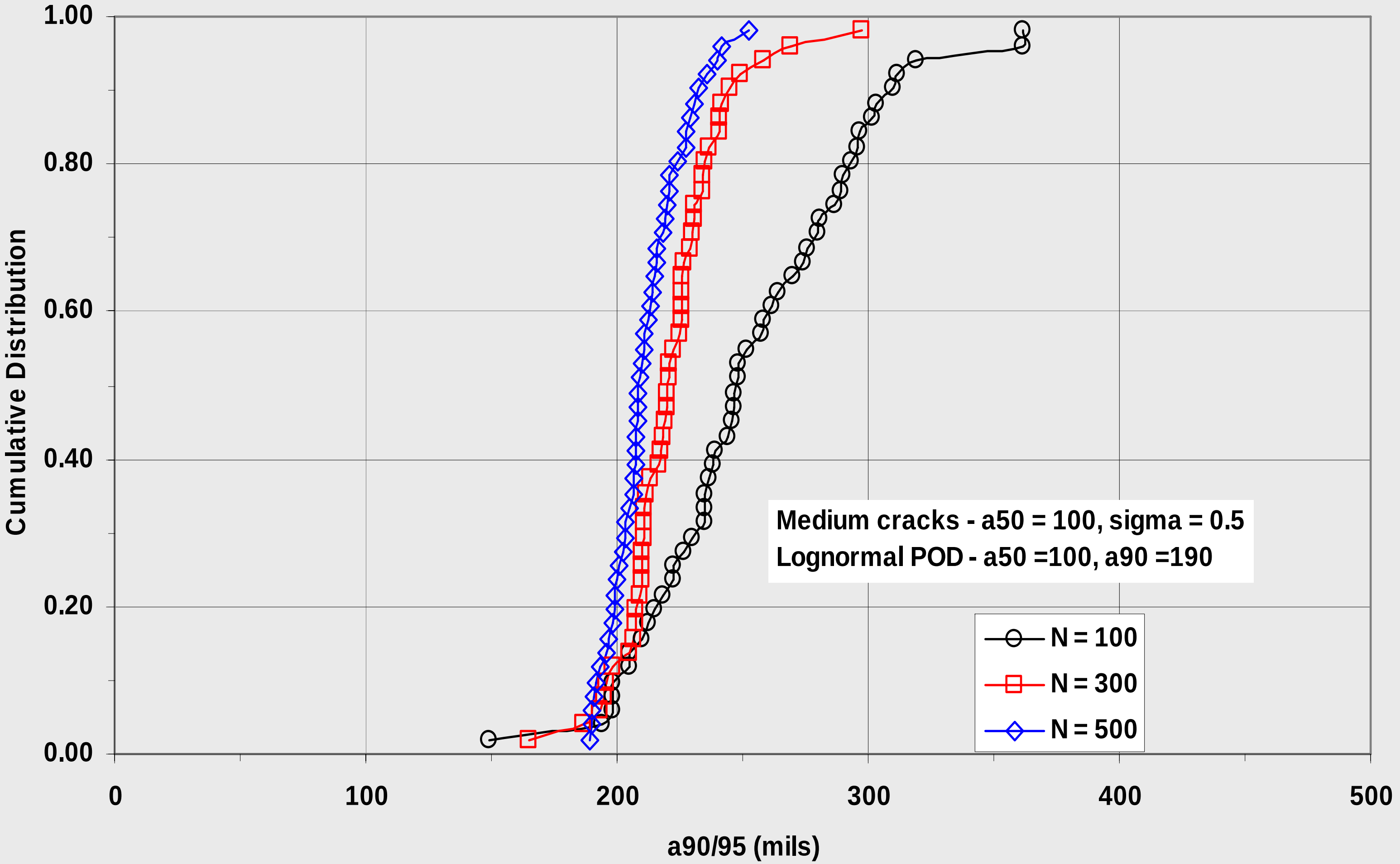


Example of POD(a) Scatter from Demos

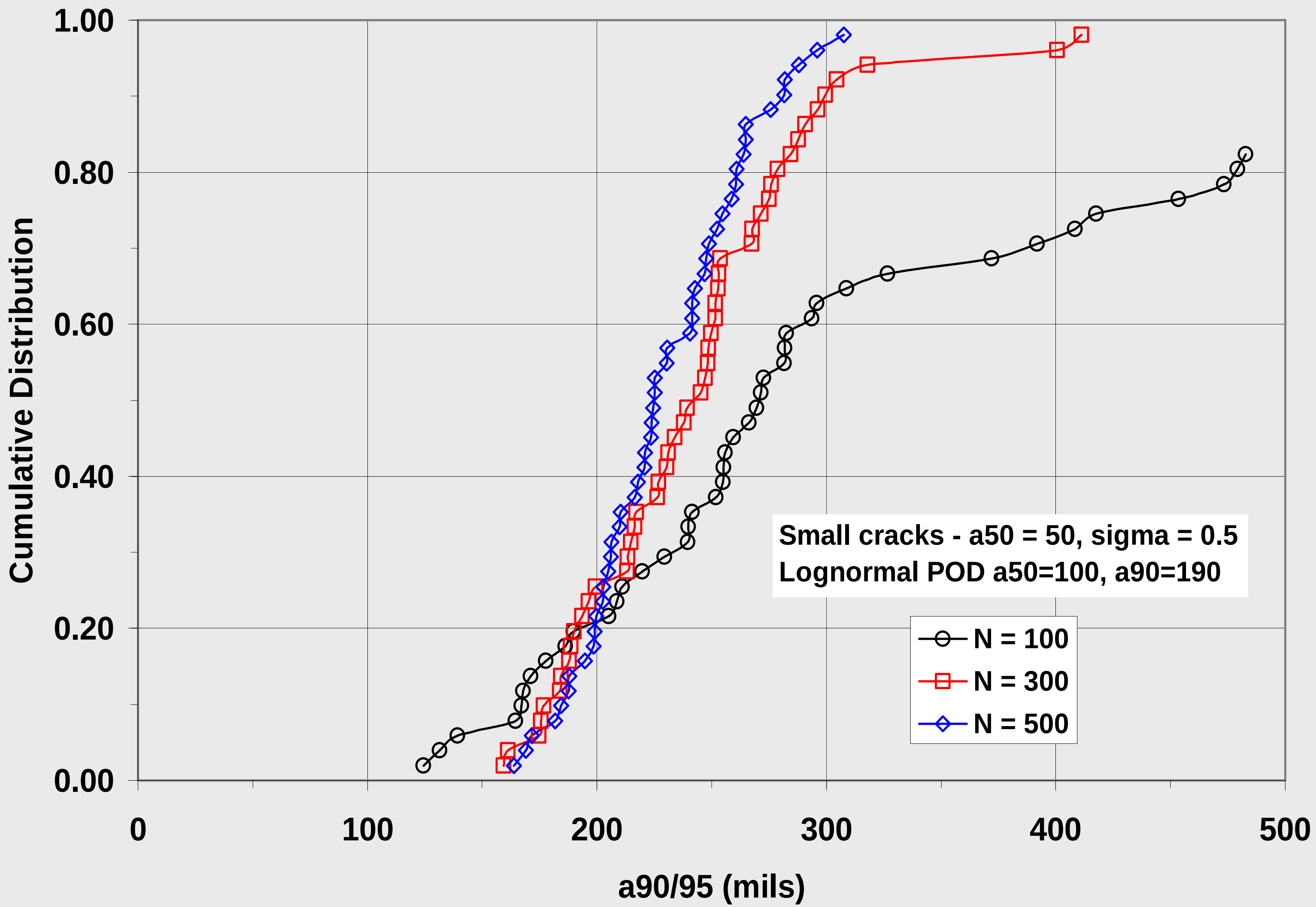




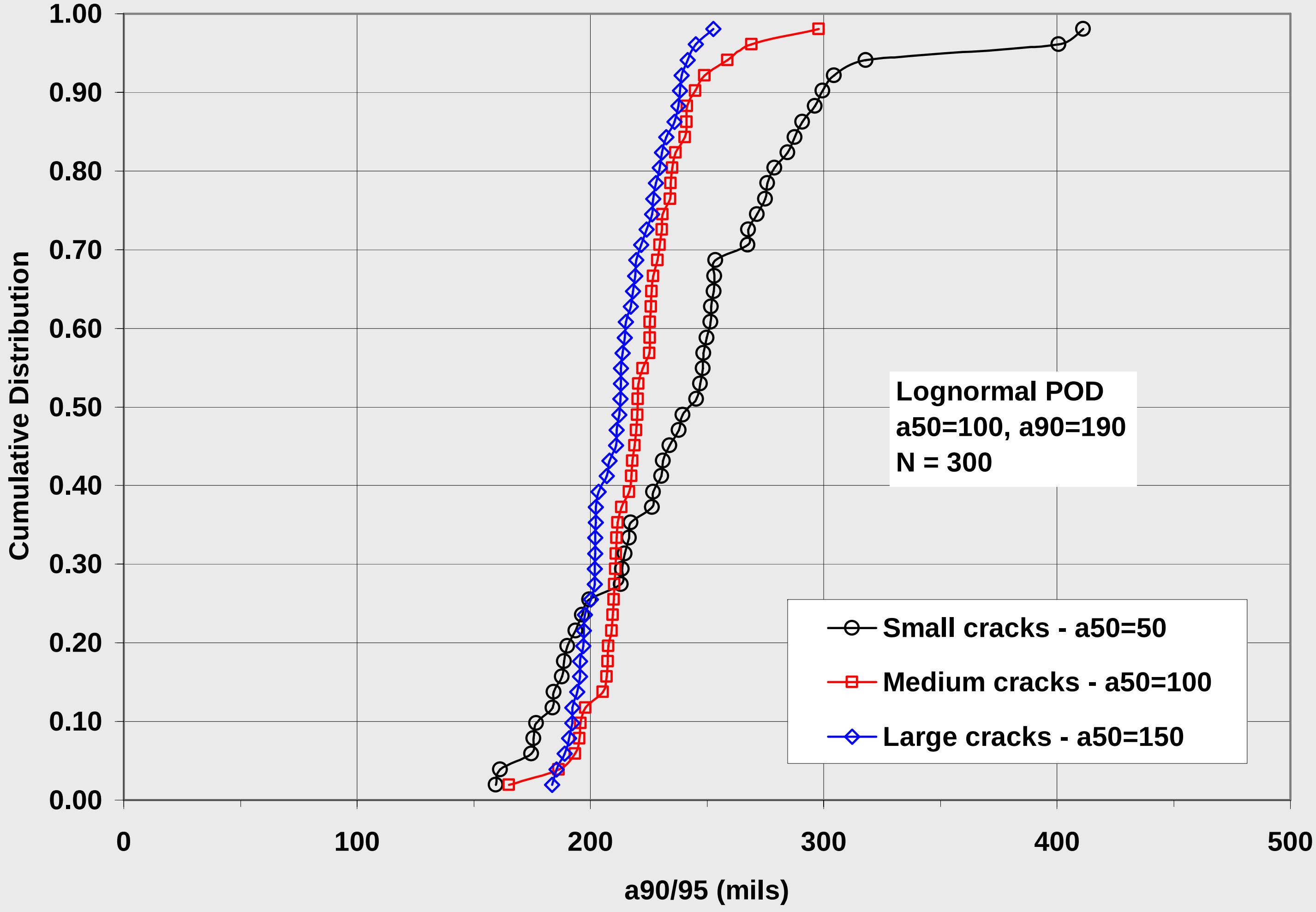
$a_{90/95}$ Sample Size Scatter – Medium Cracks



$a_{90/95}$ Sample Size Scatter – Small Cracks



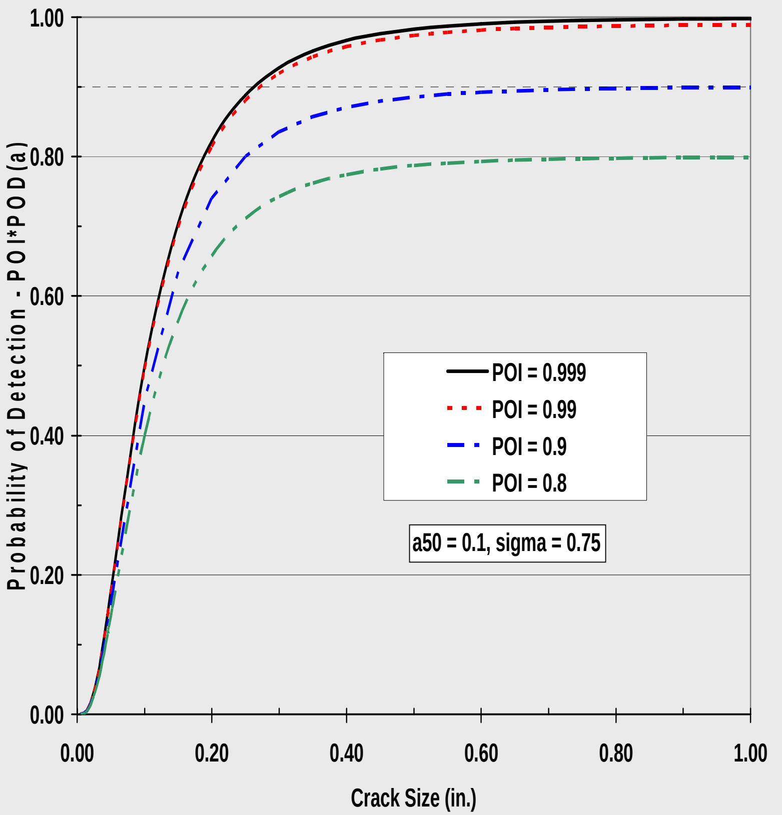
$a_{90/95}$ Scatter Due to Demo Crack Sizes

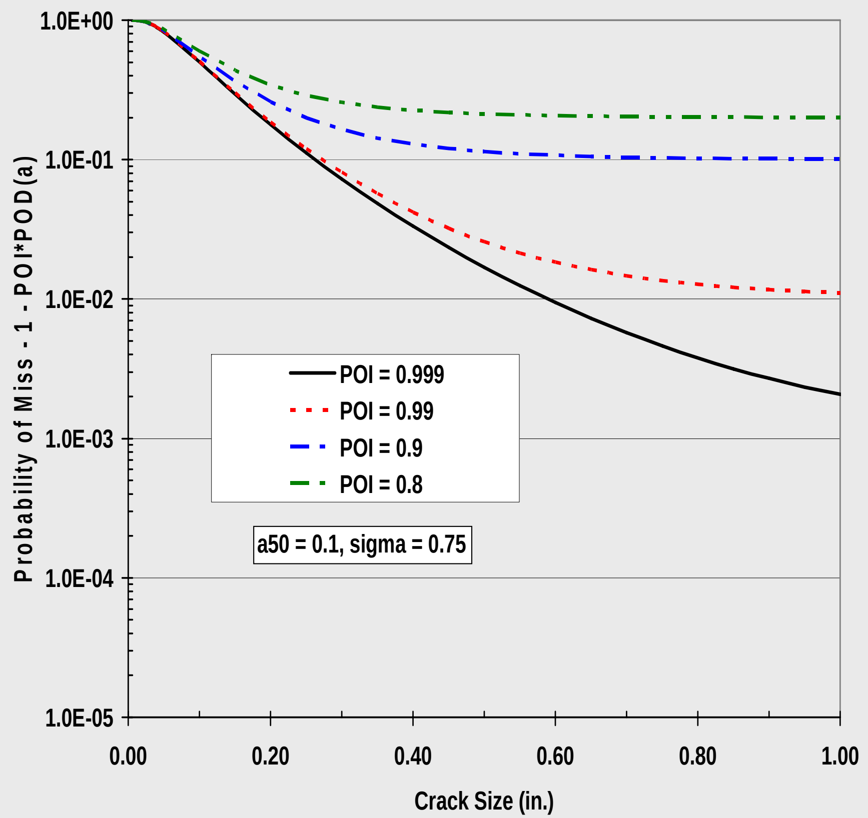


Another $a_{90/95}$ Problem

- POI term introduced to account for missing cracks that almost surely should have been found.

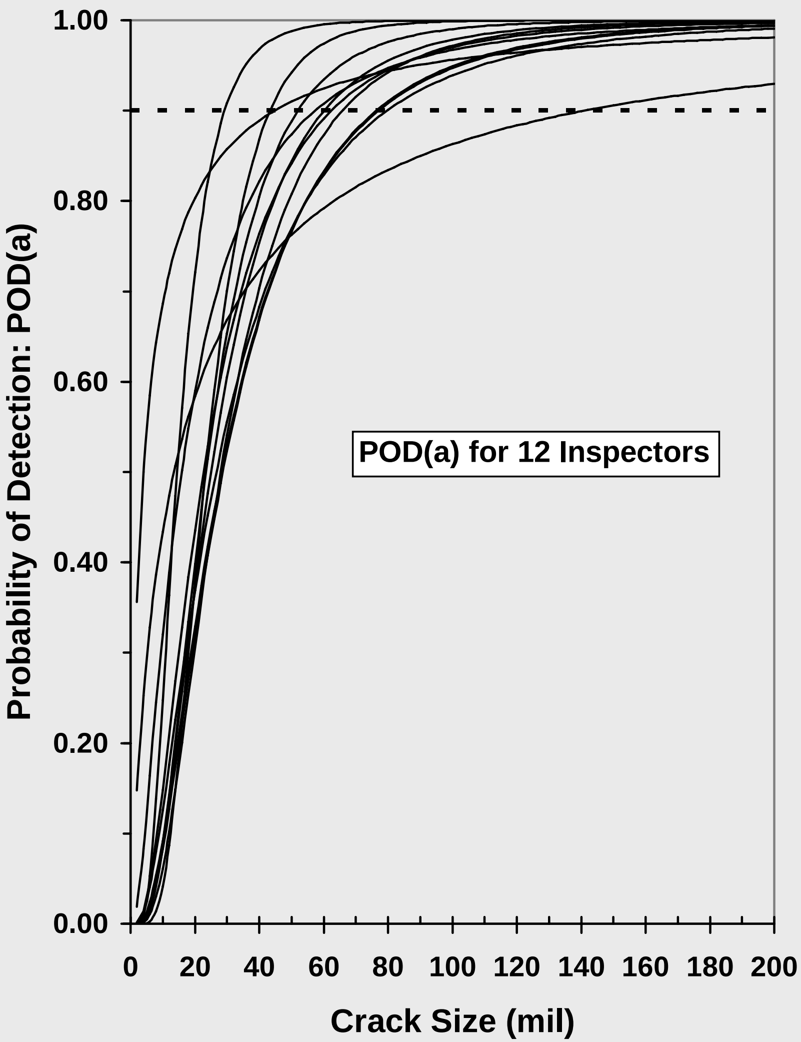
$$POD(a) = POI*POD_{lab}(a)$$

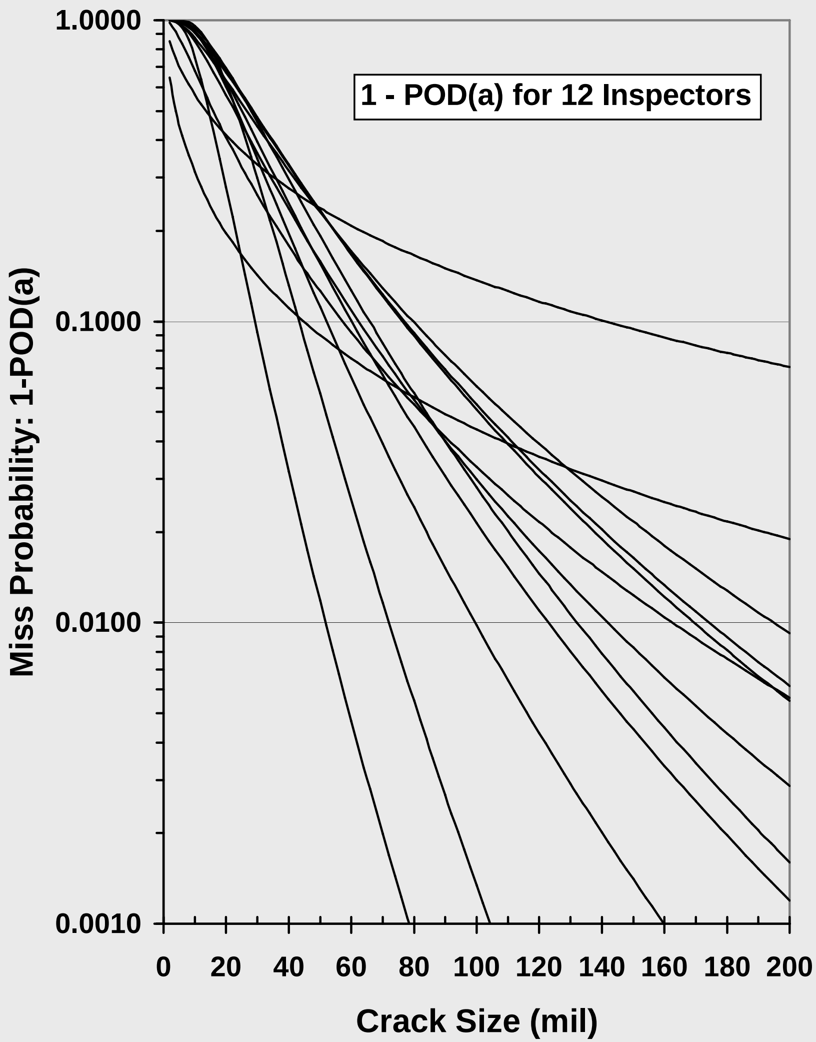




- What is $a_{90/95}$ when POD doesn't reach 0.90?

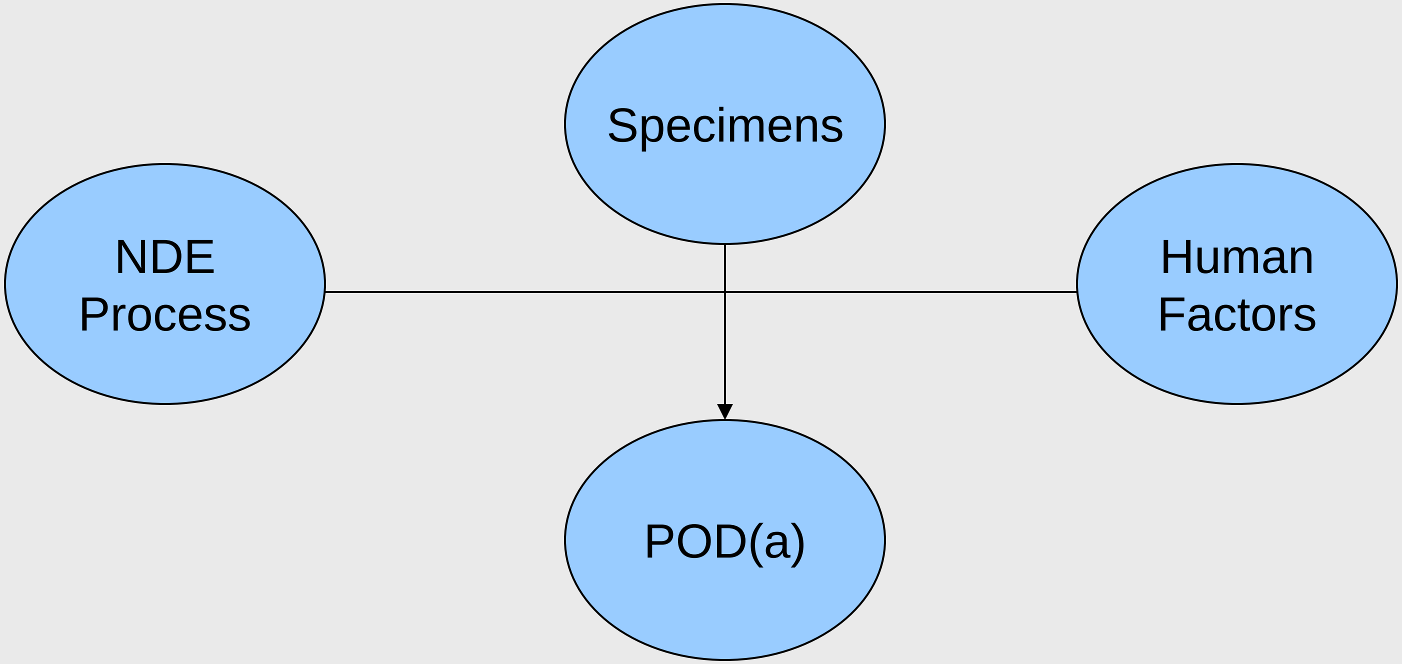
What is POD(a) for an Inspection?





POD(a) Evaluation Problems

- NDE evaluation specimens are not truly representative of structure.
  - Non representative cracks.
  - Non representative structure.
  - Repeated use of same specimens.

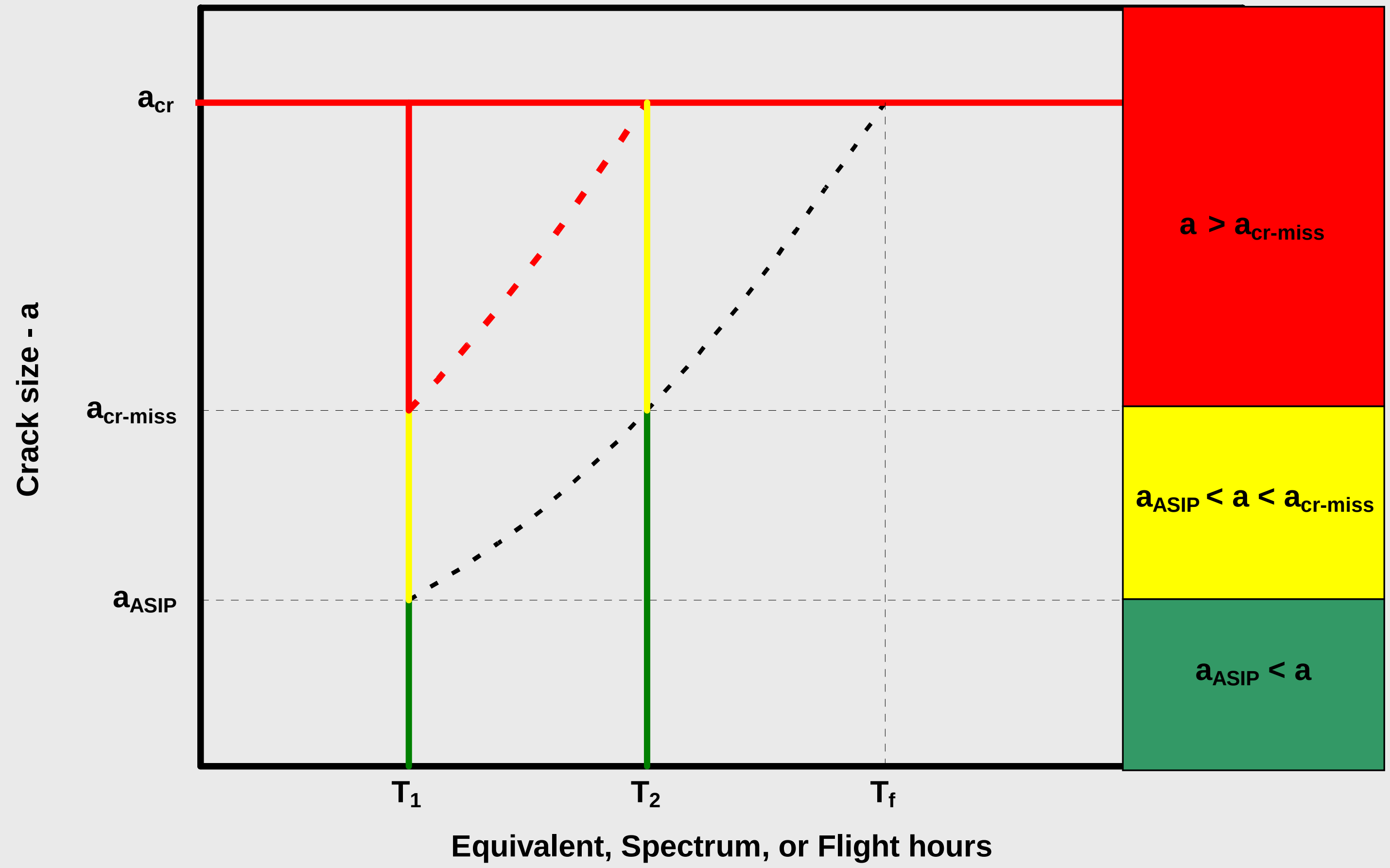


POD Evaluations Are Necessary

- There is a real need for POD evaluations other than the determination of a_{NDE}.
  - Compare/evaluate inspection systems.
    - Identify improved systems
    - Identify areas for improvement
  - Evaluate inspectors.
    - Human factors
- Easily compared capability summaries?
  - POD(a) functions hard to compare.
  - For properly designed evaluation, a_{90} crack size may be an adequate one number summary for above objectives.
  - Confidence intervals/hypothesis tests on a_{90}. Let the statisticians worry about the details.

What Then?

- For inspection scheduling, shift emphasis to size of cracks that might be missed at an inspection.



Post Inspection Crack Sizes

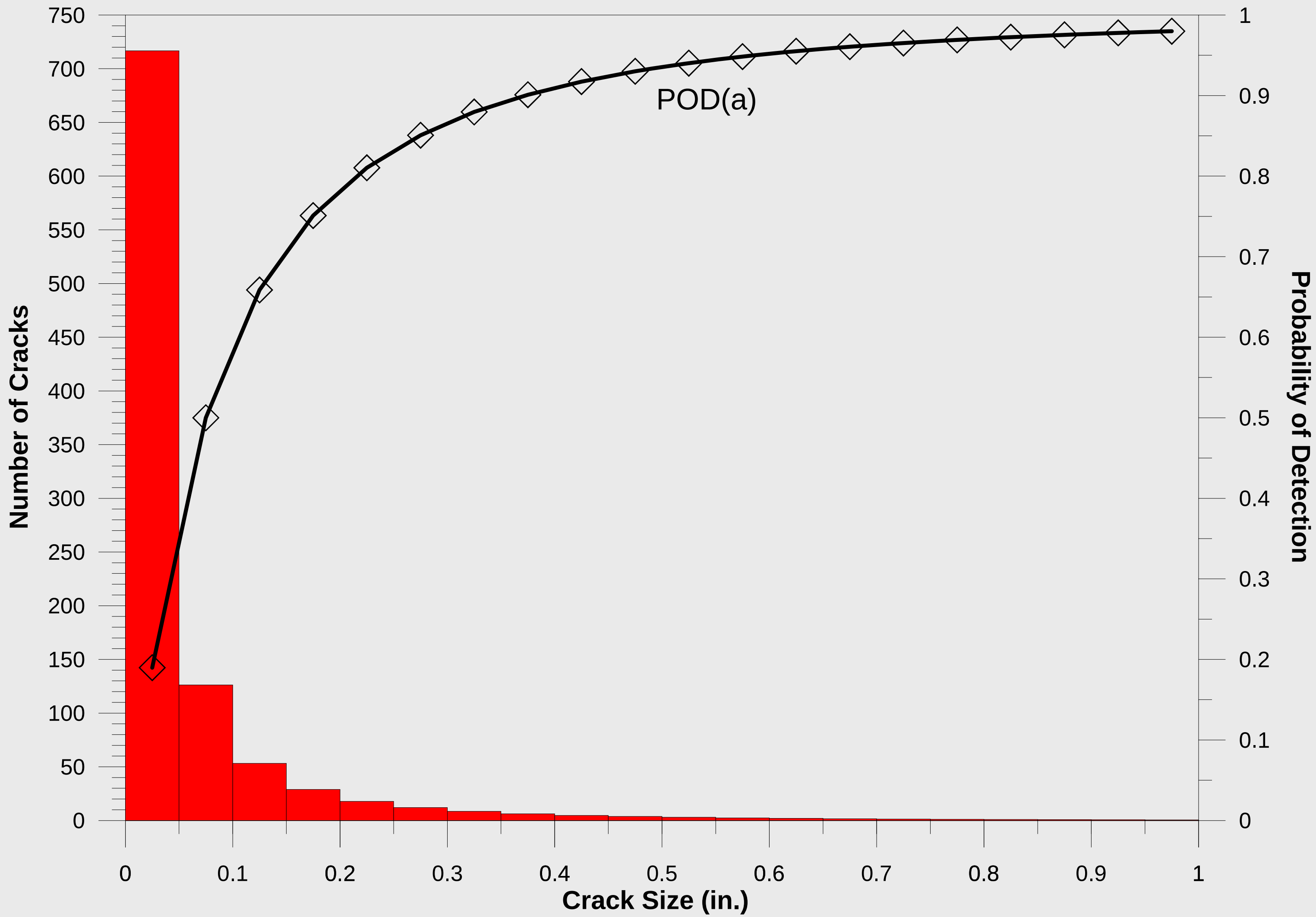
- Cracks in structure after inspection depend on both the cracks in the structure before the inspection and POD(a).
- Need effective POD(a).
- Need info on the sizes of cracks before an inspection.
  - Growth of equivalent initial flaw sizes?
  - Teardown inspection results?
  - In-service inspection results?

Detections at Inspection - Concept

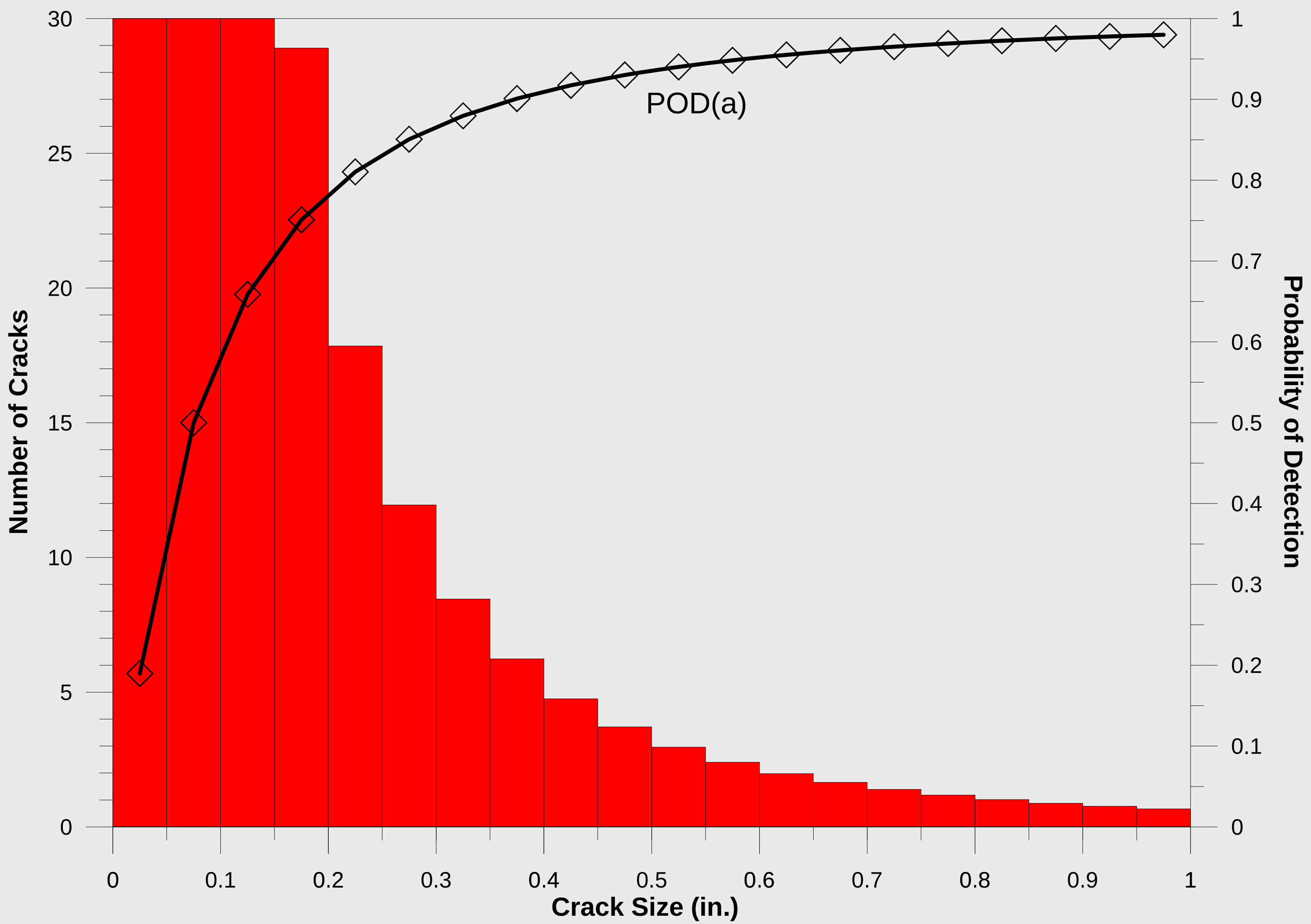
- 250 airframes in fleet with 4 identical critical locations (inspection sites) in each airframe for a total population of 1000 potential cracks.
- Crack size distribution, F(a) is Lognormal (0.020, 1.6).
- POD(a): a_{50} = 0.075, sigma = 1.25,

  a_{90} = 0.37.

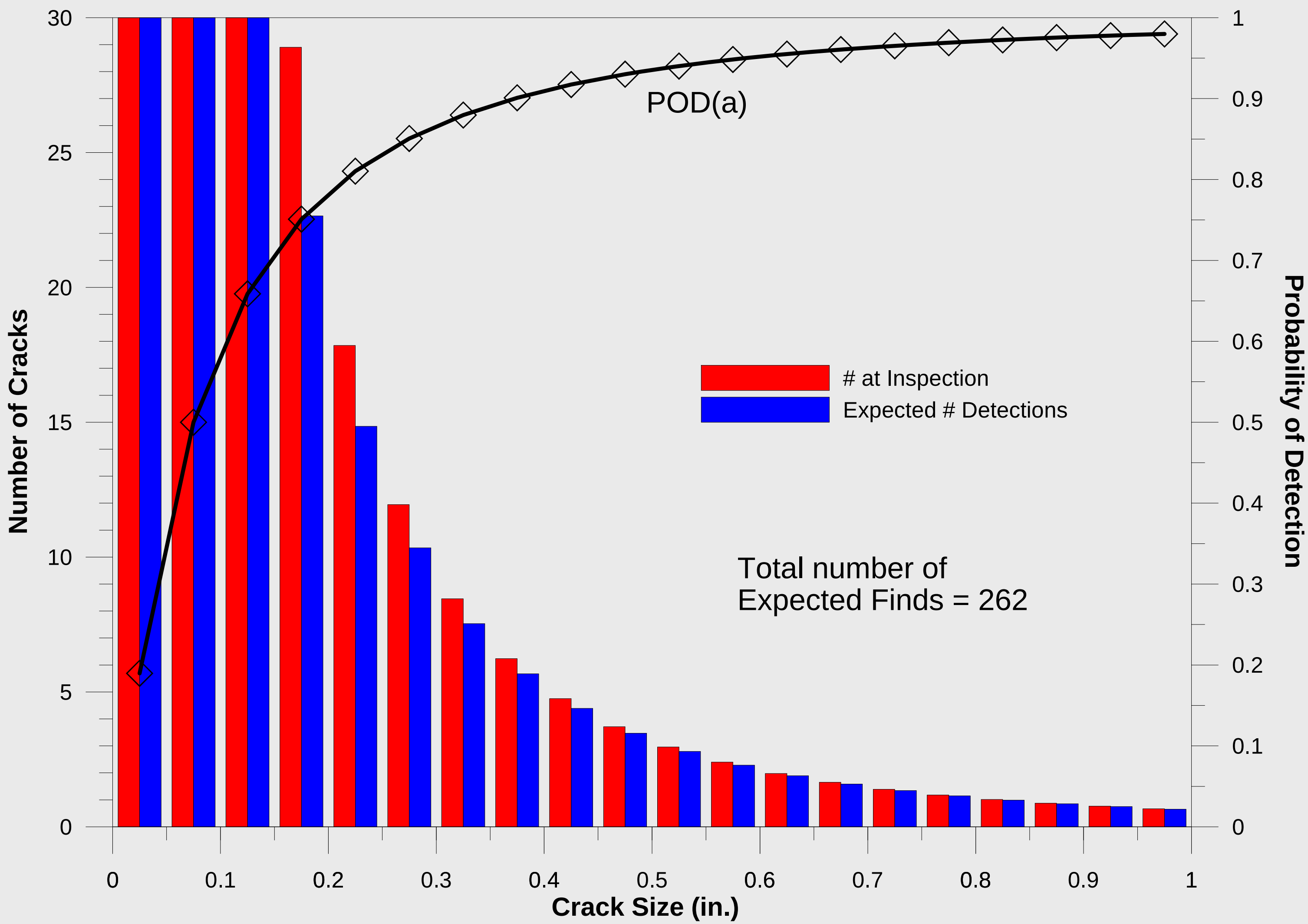
Histogram of Crack Sizes



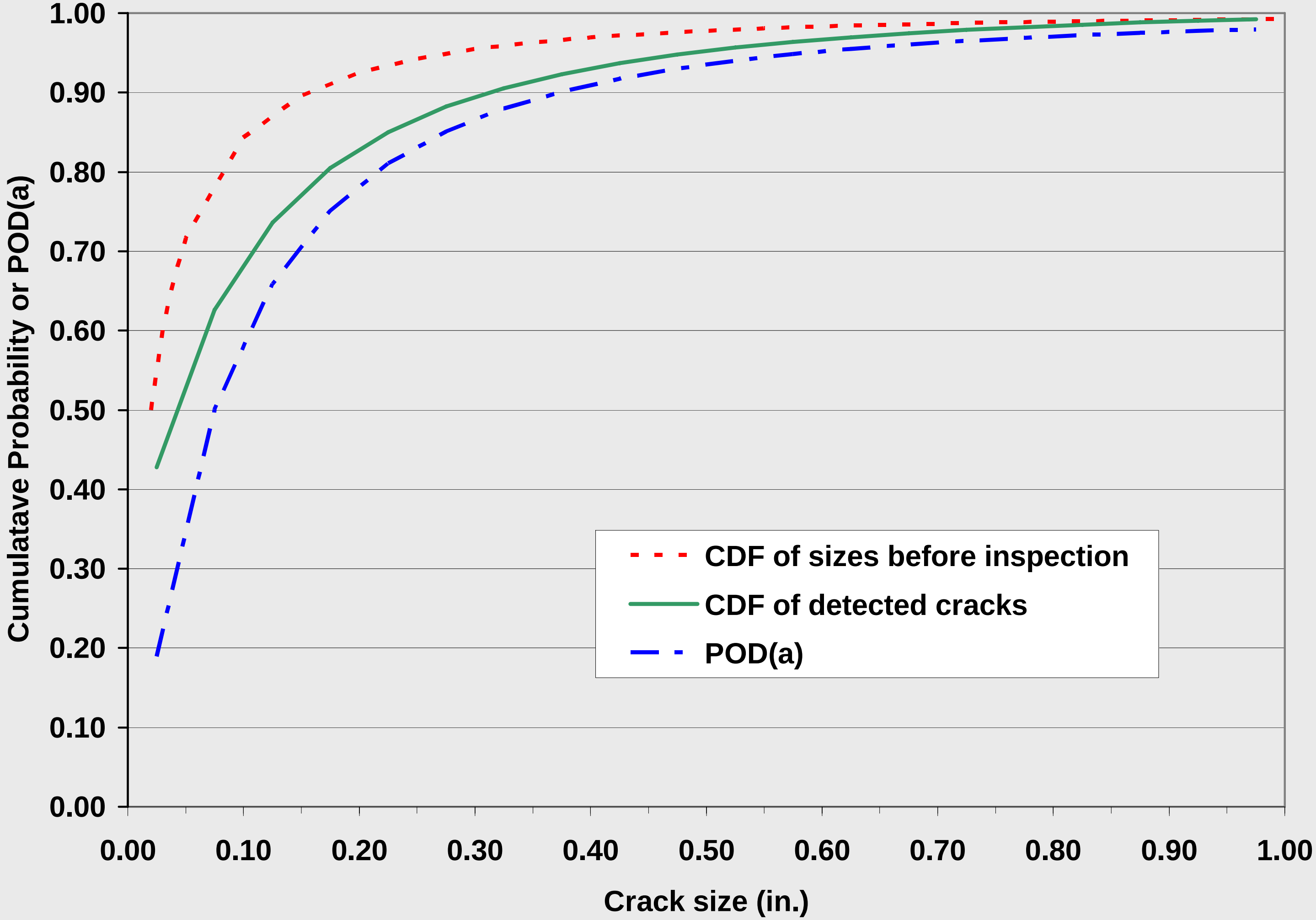
Histogram of Crack Sizes at Bigger Cracks



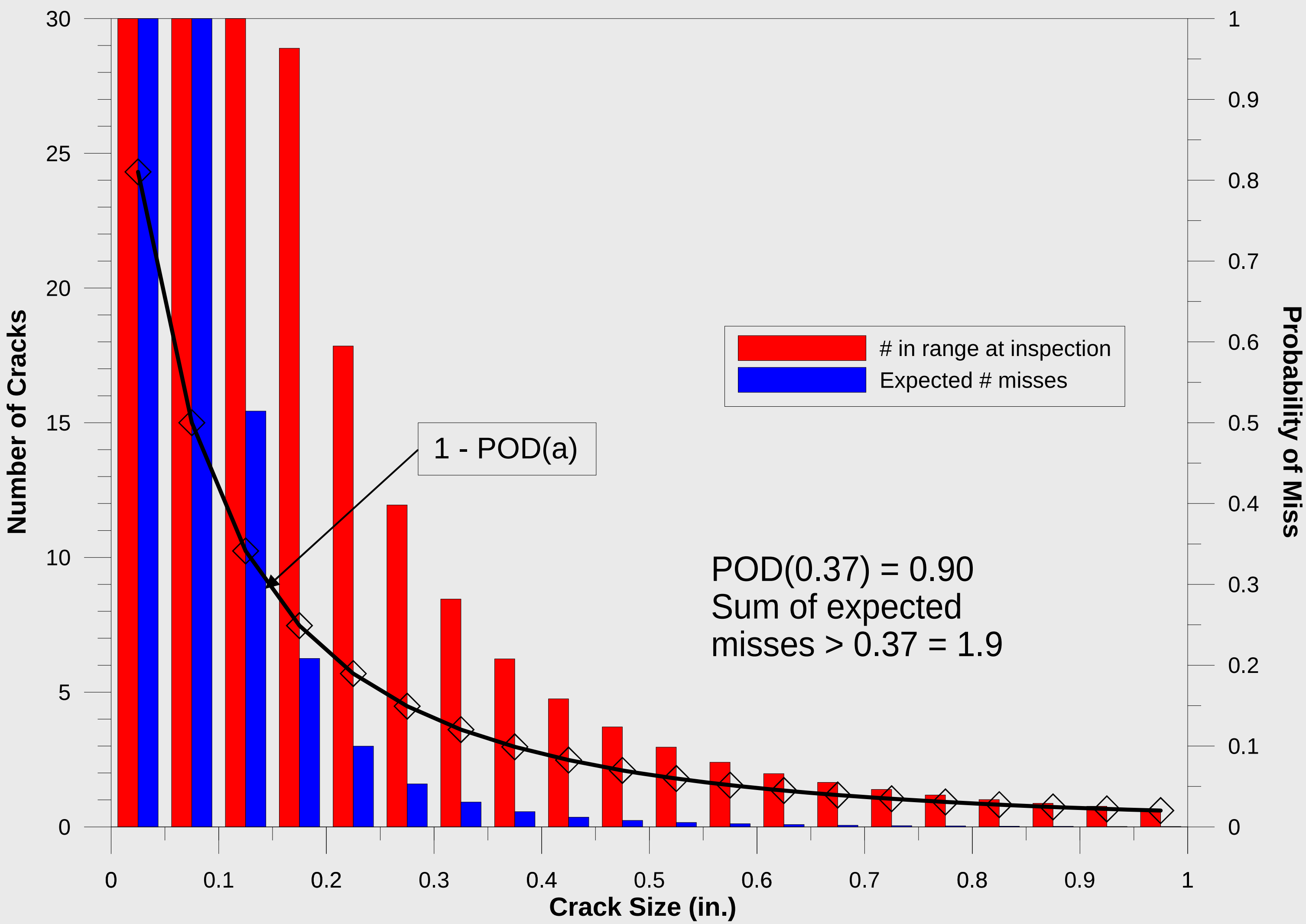
Expected Number of Detections



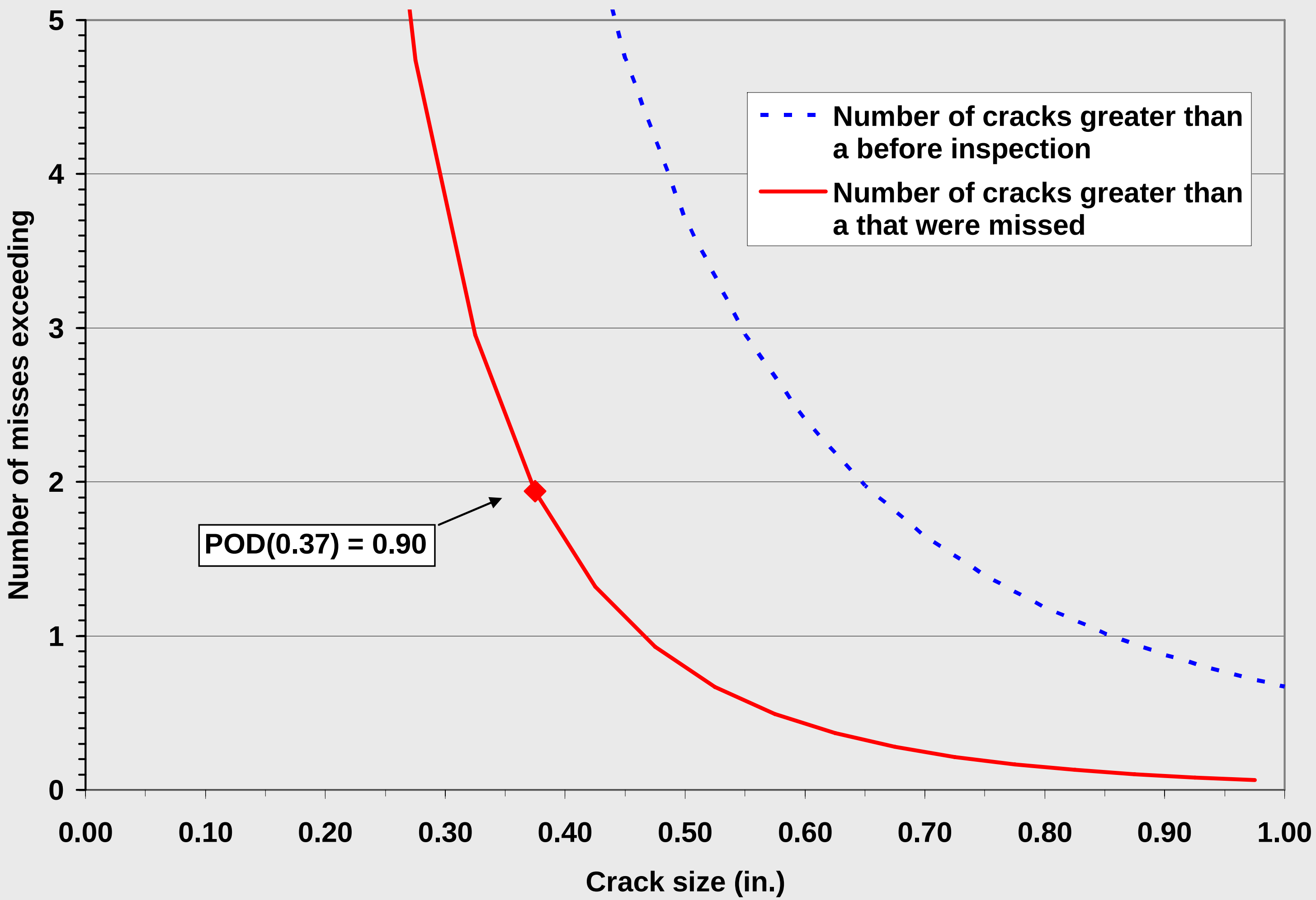
Cumulative Distributions (CDF) of Detections



Expected Number of Misses



Expected # of Misses Exceeding Size



Math Formulation

$$P_D(a) = \int_0^a f(x) POD(x) dx$$

$$P_M(a) = \int_0^a f(x)[1 - POD(x)] dx$$

$$P_D(a) + P_M(a) = F(a)$$

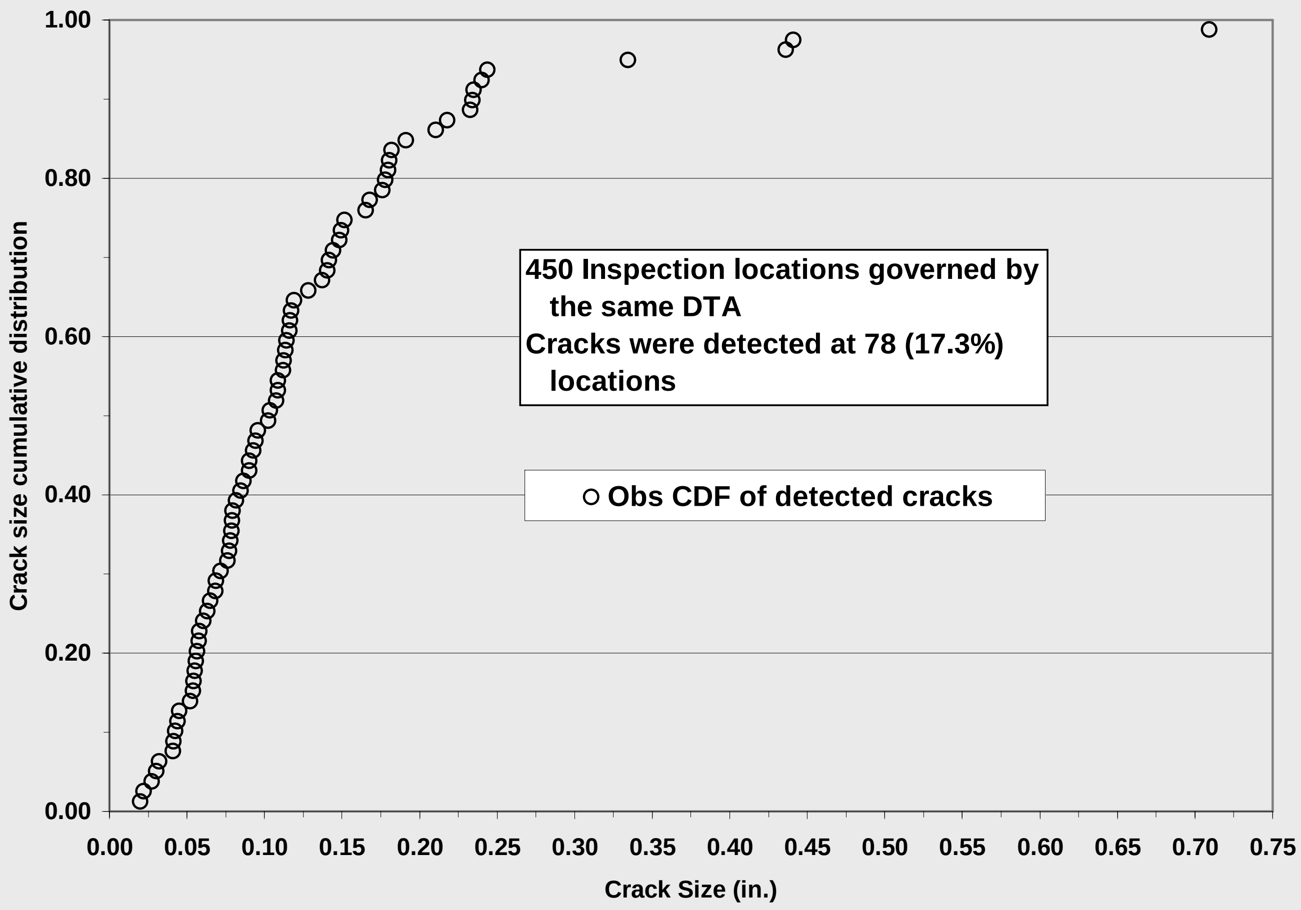
CDF's of the detected and missed cracks:

$$D(a) = P_D(a) / P_D(\infty)$$

$$M(a) = P_M(a) / P_M(\infty)$$

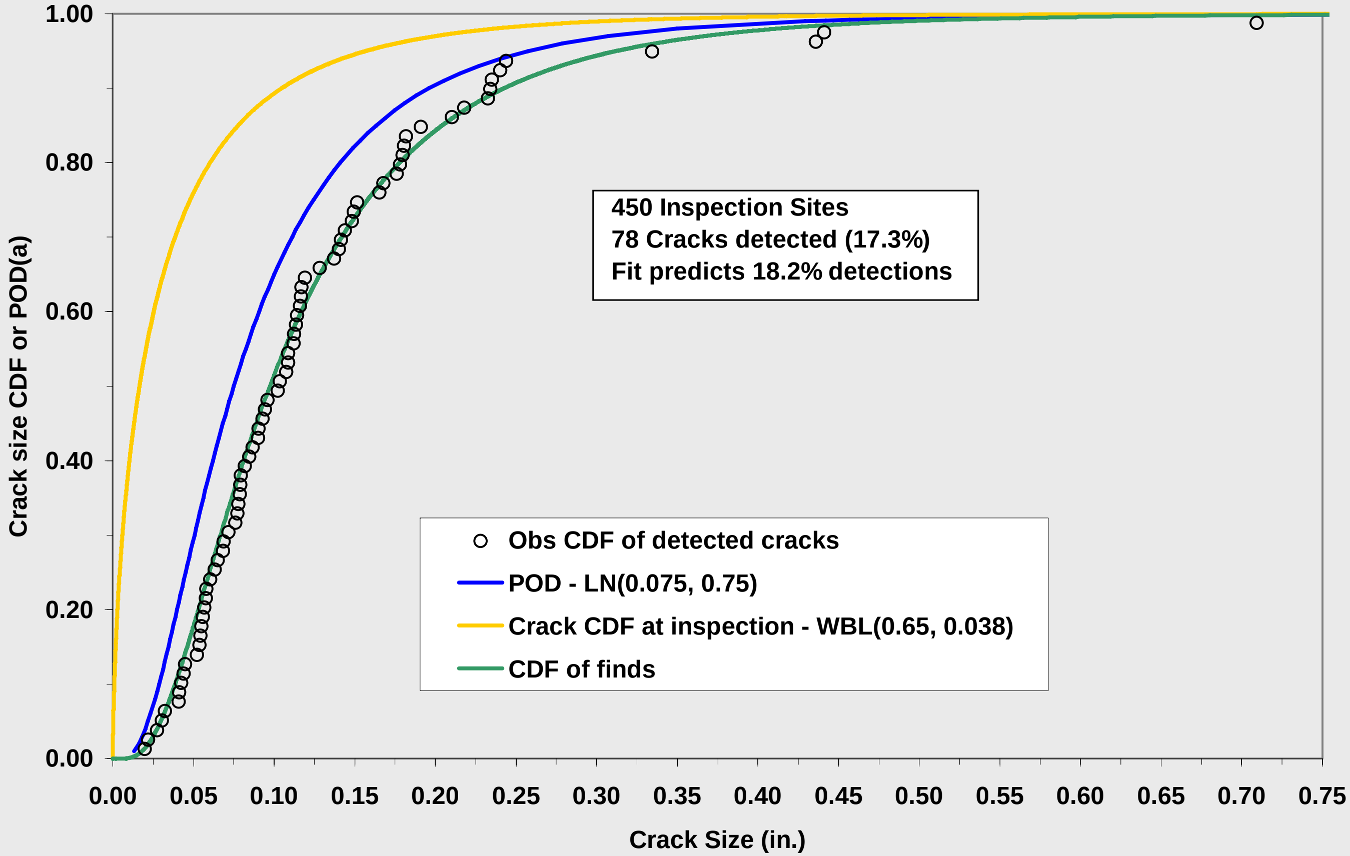
Reverse the Process

- The sizes of detected cracks reflect both the sizes at the critical locations at the time of the inspection and the effective POD(a).

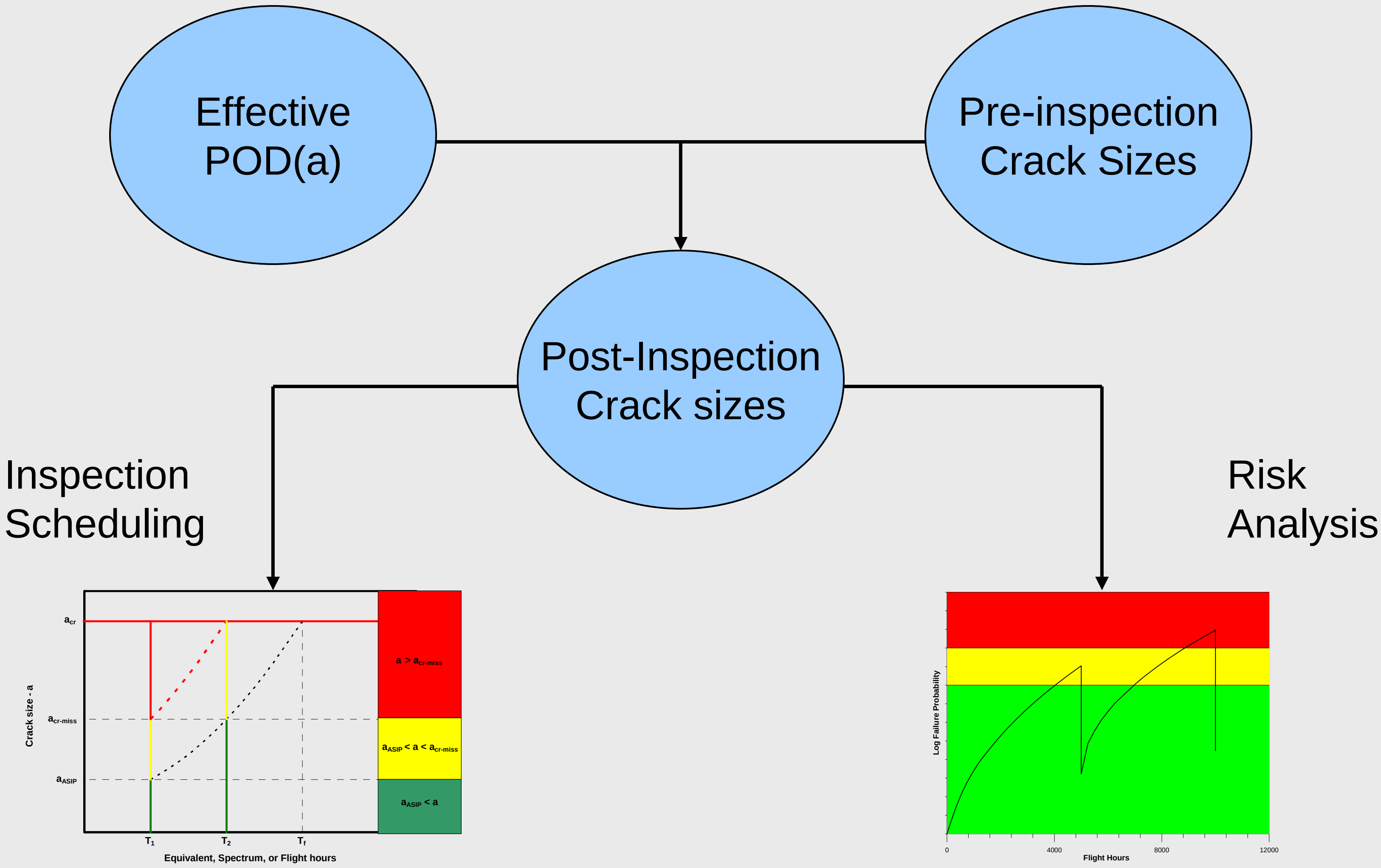


Find Fit to Observations

- Given distribution of detected cracks, what combination of pre-inspection crack size distribution and effective POD(a) could produce the result.

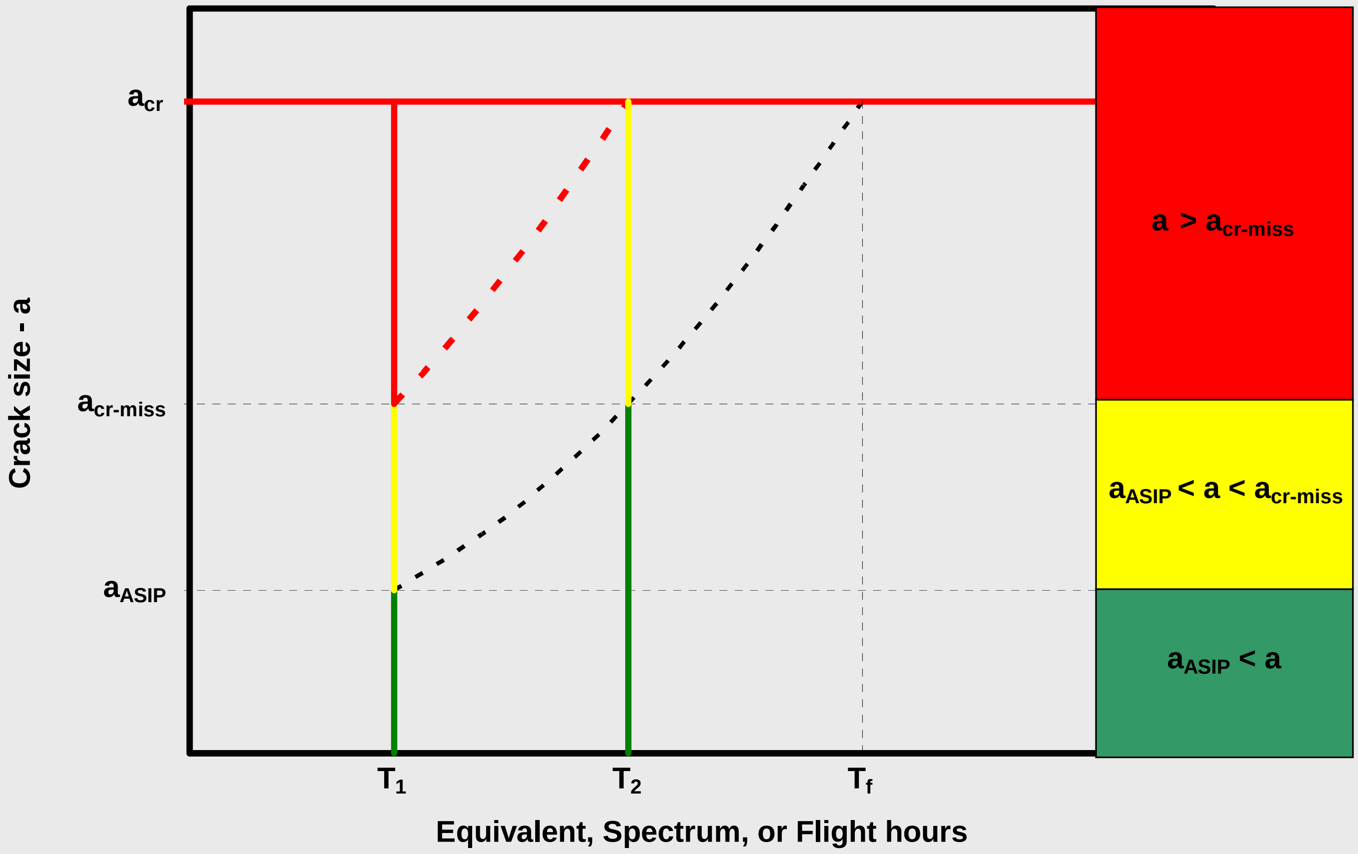


Fit to Found Cracks to Schedule



Missed Crack Significance

- Inspection at T_1. Next Inspection at T_2.

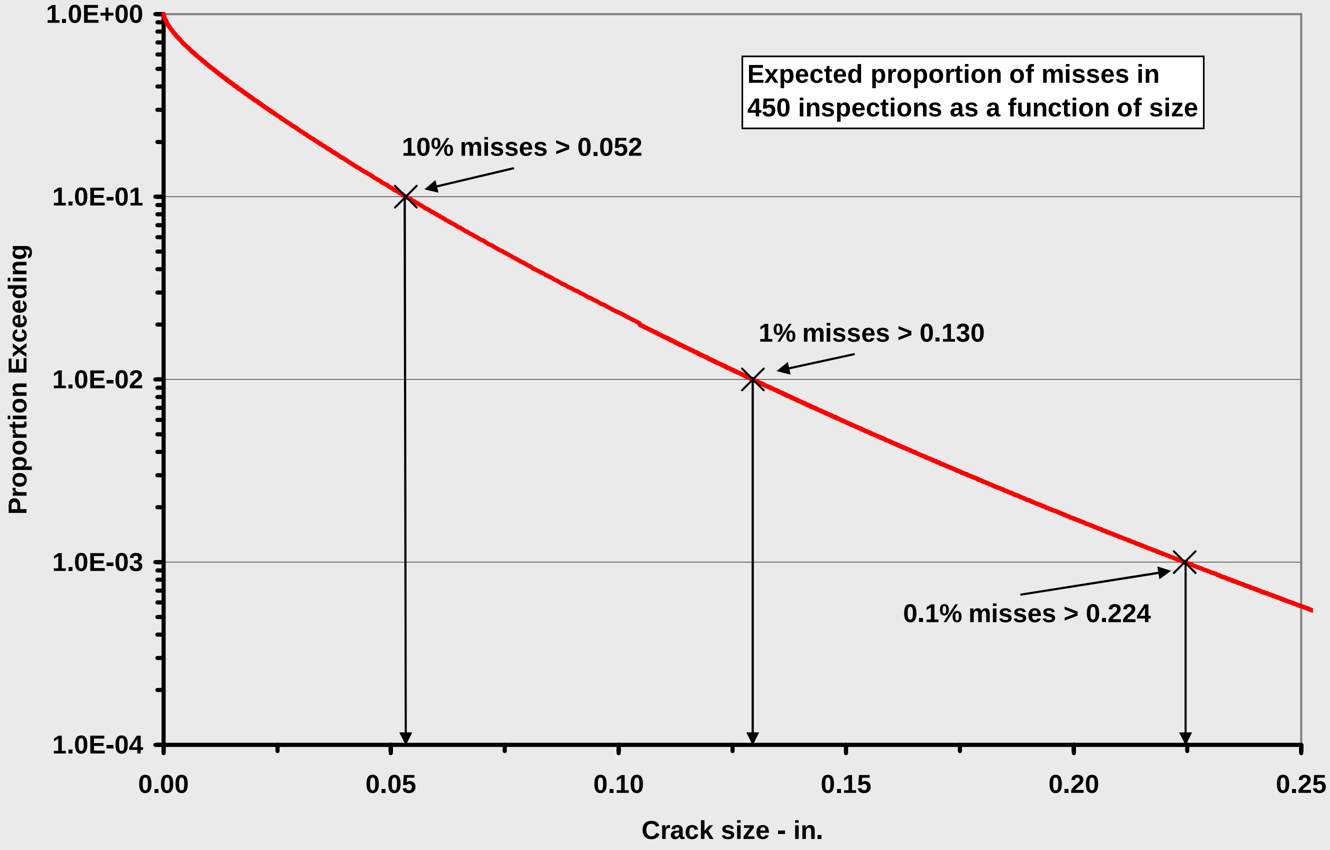


Re-Inspection Strategies

- Use pre-inspection crack size distribution and effective POD(a) to estimate post-inspection crack size distribution.
- Define a_{ASIP} in terms of a small chance of having a crack larger than a_{ASIP} at the location after the inspection.
  - Is P{post inspection crack > $a_{cr\text{-}miss}$} acceptable?
- Define a_{ASIP} in terms of a small chance of having a crack larger than $a_{cr\text{-}miss}$ at the location after the inspection.
  - Set inspection interval at hours for $a_{cr\text{-}miss}$ to reach a_f.
- Define a_{ASIP} based on judgment, i.e. a dictated inspection interval.
  - Determine $a_{cr\text{-}miss}$.
  - Is P{post inspection crack > $a_{cr\text{-}miss}$} acceptable?
- Define a_{ASIP} or $a_{cr\text{-}miss}$ in terms of expected number of misses for the population of interest rather than probability of a miss.

Post Inspection Crack Sizes

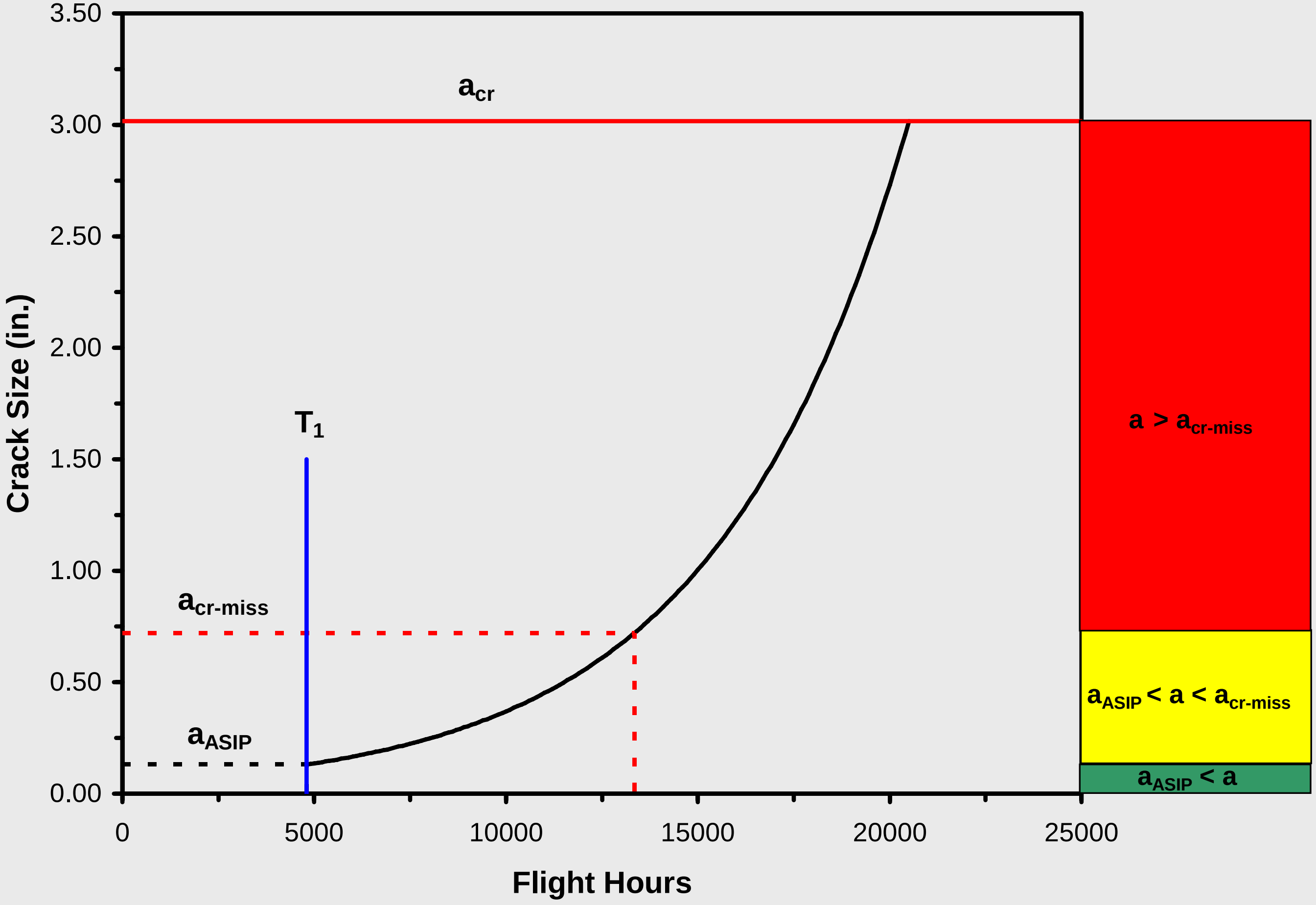
- From the fit, calculate the exceedance distribution of the sizes of the missed cracks – i.e., the post inspection crack sizes. Determine a_{ASIP} or $a_{cr\text{-}miss}$ for defined exceedance probability.



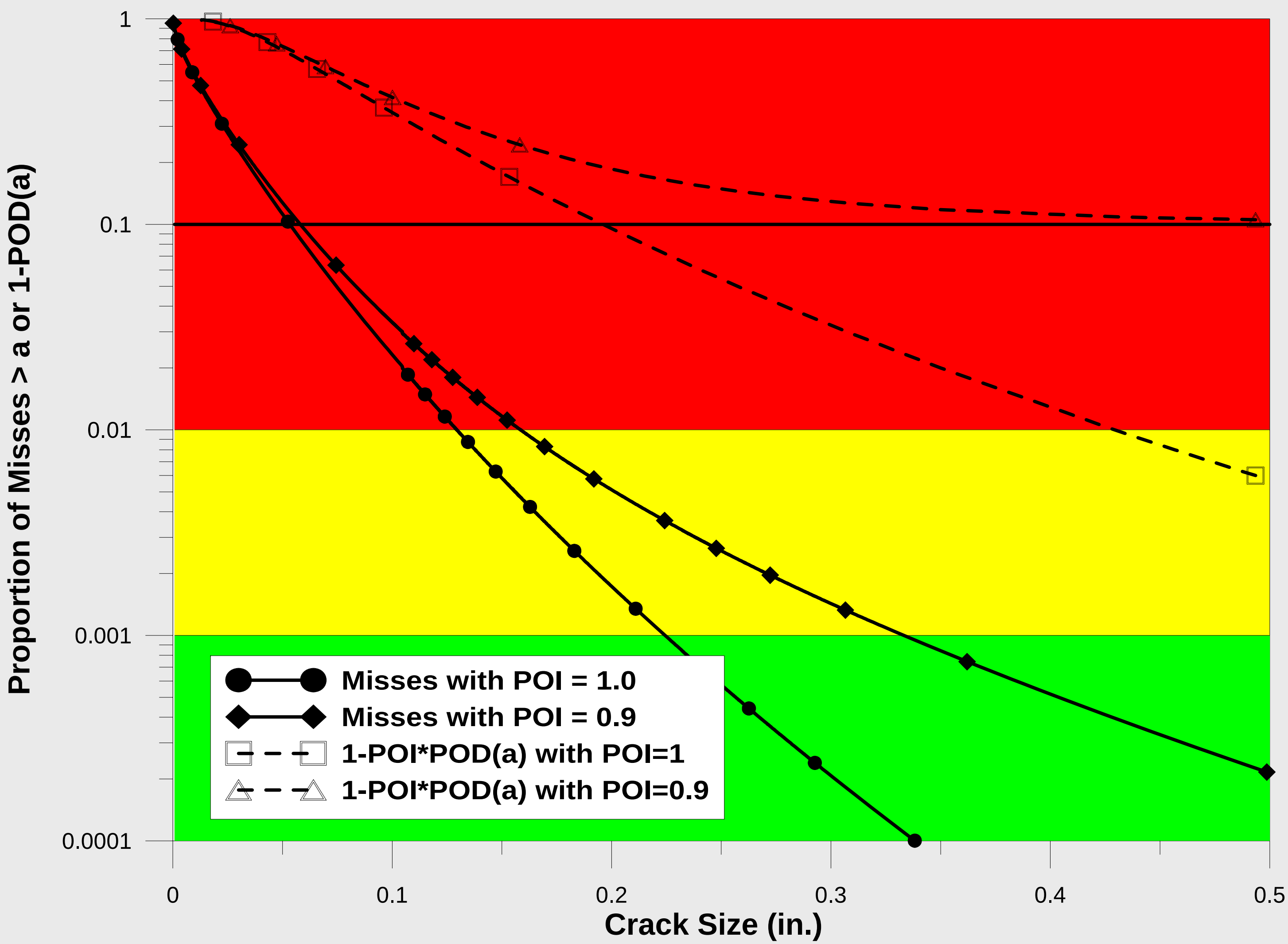
- Remember that the small probabilities from the tails of distributions are very sensitive to assumptions and sample sizes, i.e. subject to large errors.

Example $a_{cr\text{-}miss}$ from Crack Growth Curve

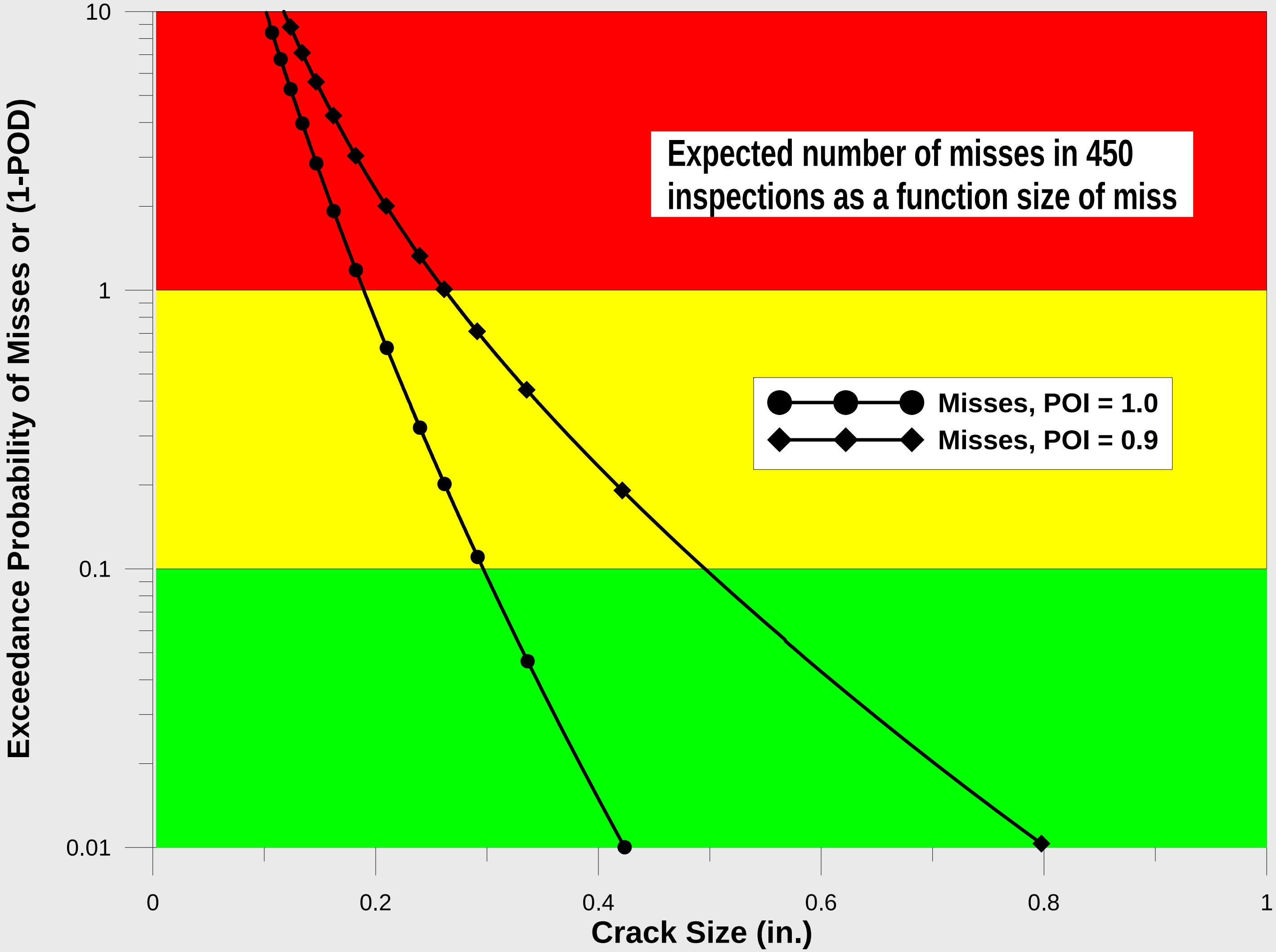
- For $p = 0.01$, $a_{ASIP} = 0.13$, T to failure = 17,100, T to next inspection = 8550, $a_{cr\text{-}miss} = 0.72$, $P(a_{cr\text{-}miss}) < 10^{-6}$.



Can Introduce POI Term



Account for Fleet Size – Expected # of Misses



Obvious Questions

- Availability of inspection results?
- Analytical approach to parameter estimation?
- Homogeneous crack populations?
  - Discipline in performing inspections at prescribed flight hours.
- No or very few cracks found?
- Rogue flaws?
- Quantify maintenance damage?
- Etc

Need Application Experience

- Pursue development of approaches with ASIP data.
  - Real examples. Do models fit real data?
  - Evaluate conjectured POD(a).
  - Use teardown inspections or other EIFS distributions for pre-inspection crack sizes?
  - Check calculated post-inspection crack sizes.
- Sensitivity of a_{ASIP} to pre-inspection crack sizes and POD(a).
- Develop/evaluate alternate definitions of a_{ASIP}.
- Evaluate approaches through risk analyses.

Summary or You Must Get the Data

- You don’t really know how many “big” cracks are at critical locations in the airframes of the aging fleets.
- You don’t want to inspect very often but you are afraid of the consequences if you don’t inspect often enough.
- You don’t really know how good you are at finding cracks outside the laboratory.
- Since the only sources of information about the cracks in the airframes are the cracks that are found, you must start preserving the number and sizes of the cracks that are showing up. But do it the easy way, i.e., without failures.
- Do it right and establish formal data bases for the inspection results from all ASIP critical locations before cracking problems become your problems.

Acknowledgements

- Lydia – My flight loads and lifelong partner
- Cy Peckham – Introduced me to statistics
- Pete Hovey – Statistician collaborator
- Joe Gallagher – Engineer collaborator (at the very least)

- The Structural Integrity Community