

3.2 Equivalent Initial Quality

The requirements of JSSG-2006 specify that initial flaws shall be assumed to exist as a result of manufacturing and processing operations. Small imperfections, equivalent to a 0.005 in. radius corner crack, resulting from these operations shall be assumed to exist in each hole of each element in the structure. These assumed cracks provide the basis for the fastener policy requirements as well as the continuing damage and remaining damage assumptions. However, if the contractor has developed initial quality data on fastener holes, these data may be submitted to the procuring activity for review and serve as a basis for negotiating a different size than the specified 0.005 in. radius corner flaw.

One method of accounting for the initial quality is to represent the quality in terms of an equivalent fatigue crack of a particular size and shape. Such a method of quantifying the initial quality is the Equivalent Initial Quality Method [Rudd & Gray, 1976; Rudd & Gray, 1978; Pinckert, 1976; Dumesnil, et al., 1977; and Potter, 1978]. The Equivalent Initial Quality method for characterizing manufacturing quality is described in the [Subsection 3.2.1](#) and demonstrated by example in [Subsection 3.2.2](#).

The concept of a distribution of flaw sizes for a population of structural details that will experience equivalent stresses in operational usage has been applied in more general contexts than characterizing initial quality. In particular, this concept plays a central role in a probabilistic approach to characterizing structural durability and in structural risk analyses. These uses of flaw size distributions will be briefly discussed in [Subsection 3.2.3](#)

3.2.1 Description of Equivalent Initial Quality Method

The Equivalent Initial Quality Method is presented for fastener holes since this is the most prevalent source of cracking in aircraft structures [Rudd & Gray, 1978]. Quality may be defined as a measure of the condition of the structure relative to imperfections, flaws, defects, or discrepancies that are either inherent in the material or introduced during manufacturing of the structure. The approach is to quantify these imperfections by representing them with fatigue cracks of a particular size and shape, such as the corner cracks illustrated in [Figure 3.2.1](#). Also illustrated in [Figure 3.2.1](#) are some of the parameters that can contribute to the initial quality of fastener holes. If an initial quality representation is performed for each of a number of fastener holes, an equivalent initial quality statistical distribution can be used to quantify the quality of the fastener holes produced by certain manufacturing and processing procedures [Potter, 1978].

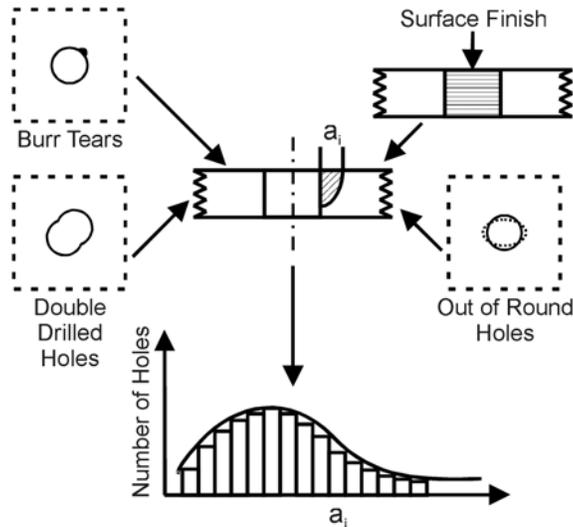


Figure 3.2.1. Parameters that Affect Fastener-Hole Initial Quality [Rudd & Gray, 1978]

The initial quality representation, defined as the equivalent initial quality, can be obtained in the following manner. Consider a piece of structure with a fastener hole containing the defect of characteristic dimension l (Figure 3.2.2). This defect results in fatigue crack initiation and propagation when subjected to some known load history. Upon failure of the structure, a fractographic examination of the fracture surface is performed to obtain as much of the crack growth curve as possible. Analytical crack propagation analyses are performed until there is good agreement between the analytical prediction and the fractographic test data. The initial crack length (crack length when the load history is first applied), a_i , of the analytical crack growth curve that correlates best with the fractographic test data is defined as the equivalent initial quality. Hence, a_i is said to be the analytical equivalent of the actual defect of characteristic dimension, l , if each results in a crack size a_e after N_e cycles of the same load history have been applied. Hence, fastener holes that contain actual crack lengths less than a_e after N_e cycles have been applied are of better quality than those that contain actual crack lengths equal to or greater than a_e after N_e cycles.

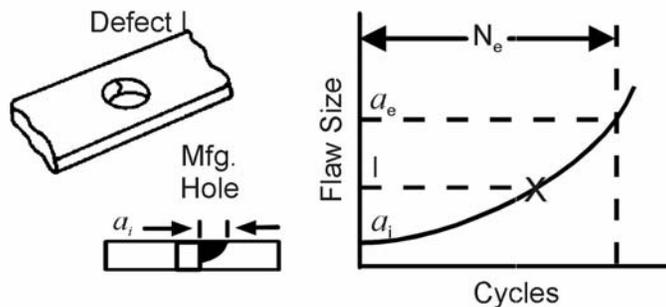


Figure 3.2.2. Definition of Equivalent Initial Quality [Rudd & Gray, 1978]

3.2.2 Example Application of Equivalent Initial Quality Method

Although Equivalent Initial Quality Method studies have been conducted on the F-4C/D [Pinckert, 1976], F-4E(S) [Pinckert, 1976], and A-7D [Dumesnil, et al., 1977], only a summary

of the quality assessment program by Rudd & Gray [1978] on the A-7D will be reviewed here. The remaining paragraphs in this subsection are taken directly from Rudd & Gray [1978]:

The purpose of the A-7D quality assessment was to establish the manufacturing quality (a_i) of the A-7D aircraft. This was accomplished using the Equivalent Initial Quality Method. The method was applied to a sample problem involving an A-7A wing fatigue test failure. Next, specimens were cut from an A-7D production aircraft and tested to failure under a selected block loading. The fracture surfaces were then fractographically examined and the equivalent initial quality was established.

A photograph of the failure area of a full-scale fatigue test of an A-7A wing was used as a sample problem to check out the Equivalent Initial Quality Method. The wing had been subjected to a 10-level, blocked, low-high stress spectrum. Fractographic measurements were taken from the photograph ([Figure 3.2.3](#)), making it possible to generate a large portion of the crack growth curve. Crack propagation analyses were performed using the computer routine EFFGRO and the Wheeler Retardation Model until the analytical crack growth curve correlated well with the fractographic test data. This correlation is presented in [Figure 3.2.4](#), which indicates that the manufacturing quality of the test hardware at the failure location was equivalent to an initial crack of length $a_i = 0.00109$ in. This excellent correlation of the analytical crack growth prediction with the fractographic test supported the validity of the Equivalent Initial Quality Method for this particular problem.

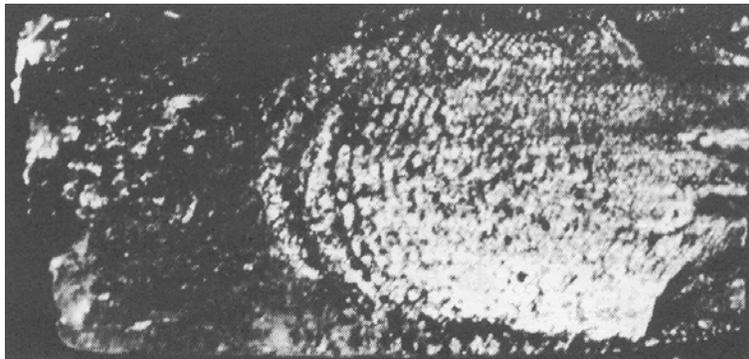


Figure 3.2.3. A-7A Wing Fatigue Test Fracture Surface [Rudd & Gray, 1978]

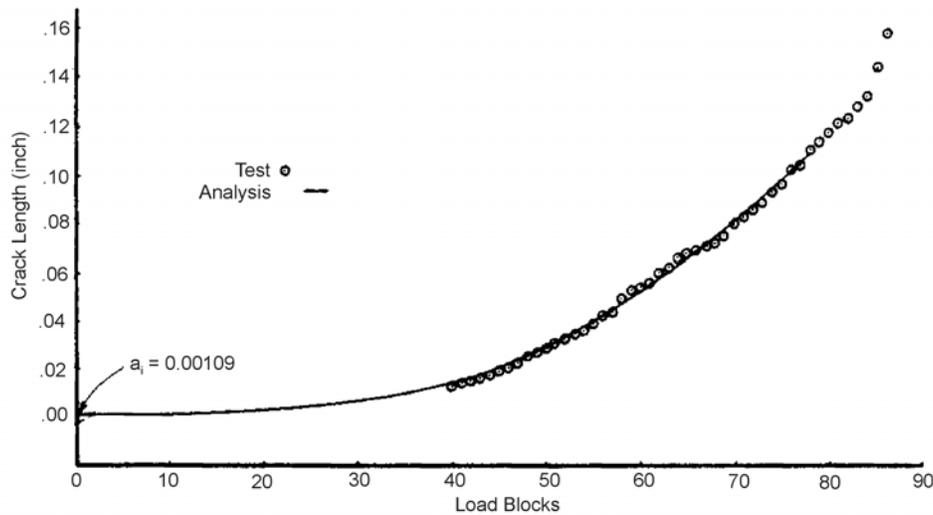


Figure 3.2.4. Equivalent Initial Quality Results for A-7A Wing [Rudd & Gray, 1978]

The Equivalent Initial Quality Method was next used to establish the A-7D quality assessment. This assessment was accomplished using test specimens cut from the lower wing skin of an A-7D production aircraft that had been used as a gunfire target. Because this particular aircraft had low flight time (691.9 hours), the probability of cracking in the wings was very low. The location of each specimen in the lower wing skin is illustrated in [Figure 3.2.5](#). Each specimen was made of 7075-T6 aluminum and contained multiple holes. The geometric details for each specimen are presented in [Table 3.2.1](#), indicating that the thickness ranged from approximately 3/16 in. to 1/4 in. and the nominal values of the width and hole diameter were 3 in. and 1/4 in., respectively. The specimens contained two types of holes – countersunk holes (wet-wing region) and straight-shank holes (dry-wing region).

The test specimens were subjected to a fatigue stress spectrum consisting of 5,000 cycles with a maximum stress of 20 ksi and a stress ratio of 0.1 followed by 100 cycles with a maximum stress of 30 ksi and a stress ratio of 0.1. The block spectrum was chosen because it produced test lives of reasonable length (less than 20 blocks) and fracture surfaces that were readily readable.

[Table 3.2.2](#) contains a summary of the number of fastener holes involved, the number of flaws detected, the number of flaws fractographically examined, the crack length range at the time of specimen failure (a_f), and the range of the equivalent initial quality (a_i). All but two of the 44 holes contained double flaws. One of these two holes contained one crack, while no crack was detected in the other hole. This resulted in a total of 85 flaws, of which 44 were examined fractographically. The flaws were arbitrarily chosen for fractographic examination at magnifications ranging from 30x to 400x using a universal measuring microscope. The equivalent initial quality range for all the holes was found to be 0.00015 - 0.0022 in. A statistical distribution of the A-7D equivalent initial quality was obtained.

Table 3.2.1. Geometric Details of A-7D Quality Assessment Specimens [Rudd & Gray, 1978]

Specimen	Thickness ^a	Width ^a	Hole Diameter ^a
101	0.226	2.93	0.253 ^b
201	0.226	2.93	0.253 ^b
301	0.217	3.00	0.253 ^b
401	0.231	3.00	0.253 ^b
501	0.183	2.90	0.253 ^c
502	0.176	3.00	0.253 ^c
601	0.263	3.00	0.253 ^c
602	0.264	3.00	0.253 ^c

^a Dimensions in inches

^b Countersunk hole

^c Straight-shank hole

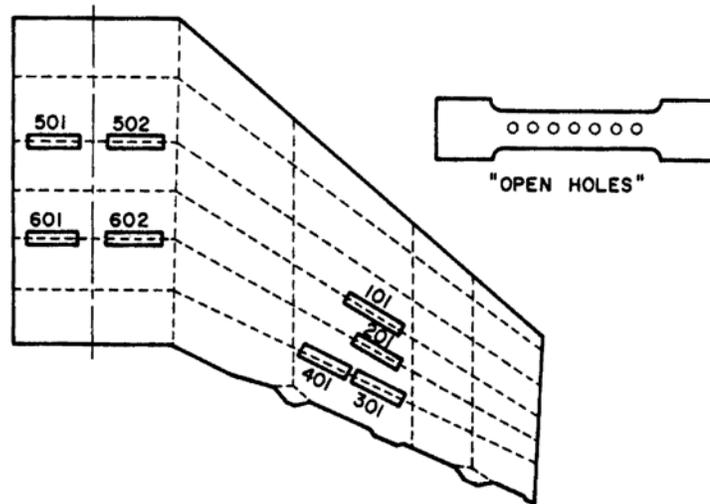


Figure 3.2.5. A-7D Quality-Assessment Specimen Locations [Rudd & Gray, 1978]

Table 3.2.2. A-7D Quality Assessment Test Results [Rudd & Gray, 1978]

Specimen	No. Holes	No. Flaws	a_f^a Range ^a	Flaws Tracked	a_i^a Range
101	7	14	0.05-0.75	14	0.0004-0.0022
201	6	12	<0.01-1.10	12	0.0004-0.0012
301	4	8	0.01-0.65	1	0.0003
401	3	6	0.02-0.50	1	0.0002-0.0014
501	8	14	0.00-0.60	1	0.0007
502	8	16	<0.01-0.62	6	0.0006
601	4	8	0.02-0.50	8	0.00015-0.0009
602	4	7	0.00-1.05	1	0.0006
Total	44	85		44	

^aDimensions in in.

The fractographic examinations revealed the origins of the flaws for both the straight-shank holes and the countersunk holes as illustrated in [Figure 3.2.6](#). There is equal possibility of flaw occurrence along the bore of the hole for the straight-shank hole, while the most frequently occurring flaw location for the countersunk hole is at the inside radius of the small-diameter portion of the hole. Typical flaw origins for each type of hole are shown on the fracture surfaces of [Figure 3.2.7](#). Also illustrated in [Figure 3.2.7](#) is the readability of the fracture surfaces for the selected stress spectrum, with the dark marking bands resulting from the application of the high-load (maximum stress of 30 ksi) portion of the specimen.

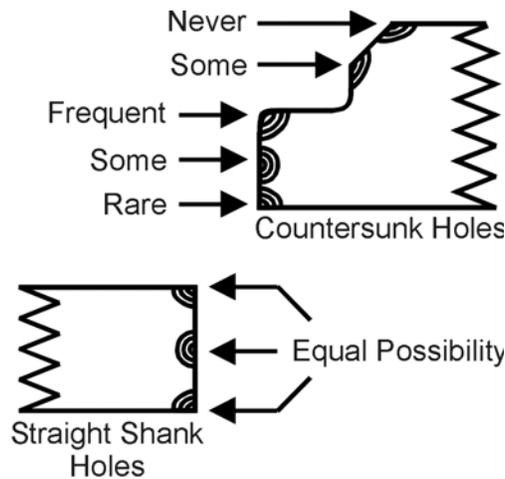


Figure 3.2.6. A-7D Flaws Origins [Rudd & Gray, 1978]

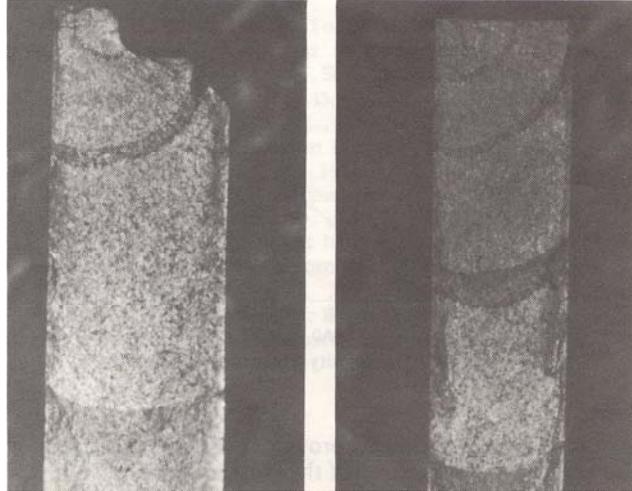


Figure 3.2.7. Fracture Surfaces for Countersunk (Left) and Straight-Shank (Right) Holes [Rudd & Gray, 1978]

Metallurgical investigations of the A-7D flaw origins revealed that the flaws were the result of two different sources-anodize pitting and mechanical sources. The majority of the flaws (86.4%) initiated from anodize pits in the following manner. Insoluble microconstituents were exposed along the bore of the hole during the hole-drilling operation. The anodizing ate away the microconstituents and caused pitting. The exposed pits were then filled with aluminum oxide, resulting in flaw initiation. The remaining flaws (13.6%) were due to the mechanical damage. Although anodizing provided corrosion protection, it also resulted in the majority of the fatigue cracks.

All but two of the holes contained double flaws, of which none were through-the-thickness flaws. The selected stress spectrum marked the fracture surfaces extremely well, making it possible to determine the crack length within each loading block. Hence, it was possible to fractographically determine the equivalent initial quality for each flaw examined.

[Figure 3.2.8](#) presents the probability density of occurrence versus the equivalent initial quality for the A-7D aircraft. It should be noted that the A-7D equivalent initial quality was determined by fractography alone, since it was possible to measure the crack length during the application of the first block of loading.

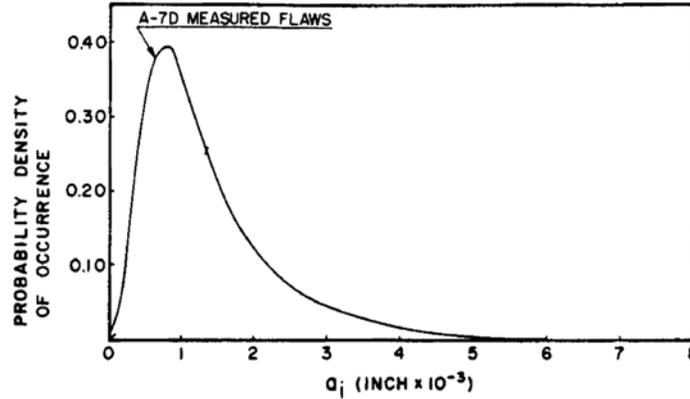


Figure 3.2.8. Probability Density of Occurrence of A-7D Equivalent Initial Quality [Rudd & Gray, 1978]

The probability density of occurrence ([Figure 3.2.8](#)) was used to determine the cumulative probability of occurrence for the A-7D aircraft. [Figure 3.2.9](#) presents the cumulative probability of occurrence versus the equivalent initial quality for the A-7D and F-4 C/D aircraft. Also presented in [Figure 3.2.9](#) is the cumulative probability of occurrence with 95% confidence for each aircraft. For example, [Figure 3.2.9](#) indicates that with 95% confidence, 99.9% of the A-7D flaws have an equivalent length less than 0.007 in. This means that one out of a thousand flaws have an equivalent length greater than 0.007 in.

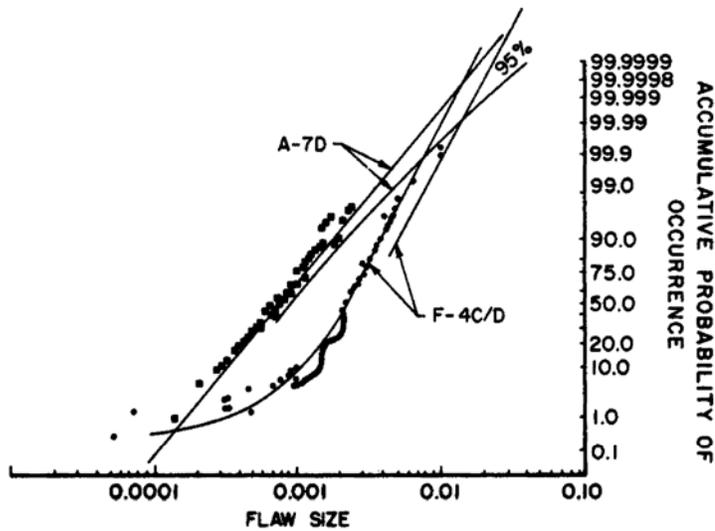


Figure 3.2.9. Cumulative Probability of Occurrence of A-7D Equivalent Initial Quality [Rudd & Gray, 1978]

3.2.3 Other Applications of Equivalent Flaw Size Distributions

The concept of a distribution of flaw sizes to model the physical condition of a population of structural details extends to areas other than manufacturing quality. In particular, characterizing

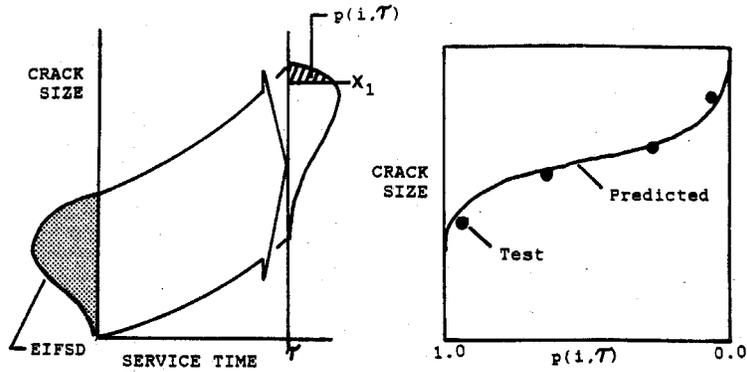
damage in terms of crack sizes has been applied to the demonstration of structural durability and the evaluation of structural failure probabilities in risk analyses.

3.2.3.1 Durability Analysis

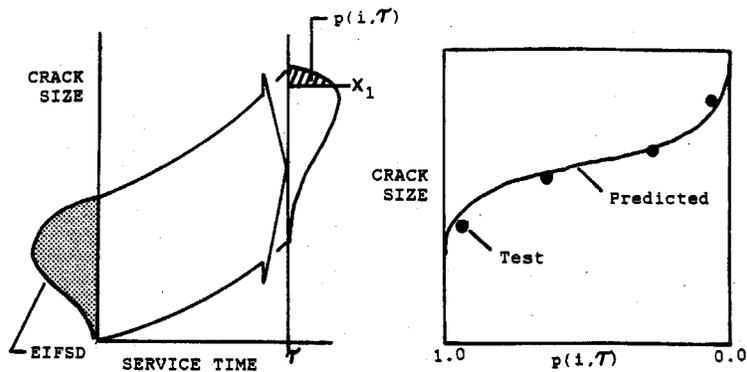
A probabilistic approach to characterizing structural durability has been extensively explored by Manning and Yang [1987, 1989]. For the durability analysis, the growth of a distribution of equivalent initial flaw sizes for a population of structural elements is calculated as a function of flight hours in the expected usage environment. Durability is then characterized in terms of either the expected number of cracks that will exceed a fixed size as a function of flight hours or in terms of the distribution of flights to reach a crack of given size. These concepts are illustrated in [Figure 3.2.10](#), from Manning & Yang [1989], in which:

- EIFSD represents the equivalent initial flaw size distribution of initial quality;
- $p(i, \tau)$ represents the distribution of number of cracks of a size larger than x ;
- $F_{T(x)}(\tau)$ represents the distribution of service time to reach a crack of size x .

The EIFSD must be projected forward based on a crack growth methodology that is compatible with that used to produce the EIFSD. Manning and Yang recommend a combined deterministic crack growth analysis (DCGA) and stochastic crack growth analysis (SCGA) for projecting the EIFSD.



a) Probability of Crack Exceedance at Service Time τ



b) Cumulative Distribution of Service Time at Crack Size x_1

Figure 3.2.10. Schematic Using the Equivalent Initial Crack Size Distribution (EIFSD) for Durability Analysis

3.2.3.2 Risk Analysis

A number of structural risk assessments have been performed in which damage in the structural detail is modeled in terms of the distribution of cracks or equivalent cracks. Examples of such risk analyses can be found in Lincoln [1985], Berens, et al. [1991], Alford, et al. [1992] and Lincoln [1997]. If the risk analysis calculations start with a virgin structure the crack sizes are equivalent initial cracks. If the risk analysis is being performed for in-service or aging aircraft, the crack size distribution is usually obtained either from the sizes of the cracks discovered during fleet inspections or from tear down inspections of structures removed from the fleet. The cracks detected during fleet inspections would have experienced different total service times and would have to be translated to a common service age to obtain a representative crack size distribution for the population of details. The cracks from tear down inspections may be from one or many airframes. In either case, the crack sizes usually need to be translated to a common or different service age. Typically, to locate the crack sizes at a common number of flight hours, the crack sizes are translated using a fracture mechanics based crack size versus flight hour curve for expected or observed usage. This process is illustrated in [Figure 3.2.11](#). After all cracks have

been translated to a common service age, a crack size distribution can be established for use in calculating probability of failure as a function of flight hours.

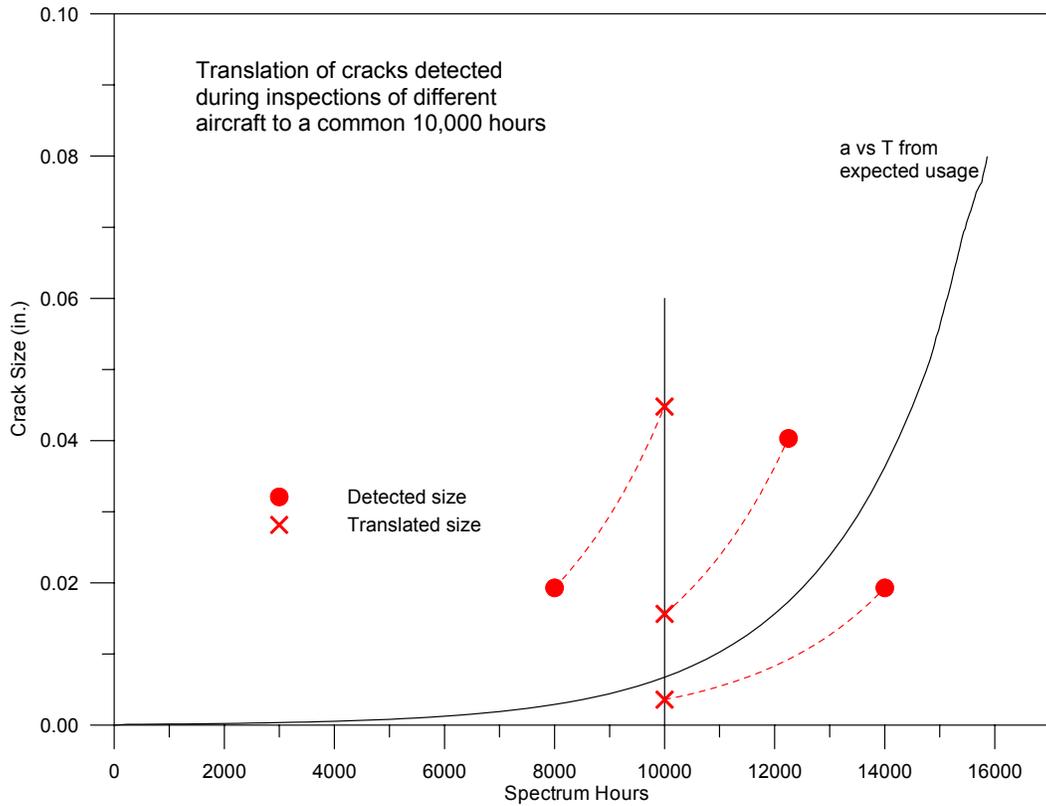


Figure 3.2.11. Schematic Demonstrating the Translation of Crack Sizes to a Common Size Using Predicted a versus T