AFRL-RX-WP-TP-2008-4045

U.S. AIR FORCE EFFORTS IN UNDERSTANDING AND MITIGATING THE EFFECTS OF "NDI MISSES" (PREPRINT)

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JUNE 2007

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UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
June 2007	Conference Proceedings Preprint	

4. TITLE AND SUBTITLE
U.S. AIR FORCE EFFORTS IN UNDERSTANDING AND MITIGATING THE EFFECTS OF "NDI MISSES" (PREPRINT)

5a. CONTRACT NUMBER F33615-03-D-5204
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER 62102F
5d. PROJECT NUMBER 4349
5e. TASK NUMBER 41
5f. WORK UNIT NUMBER 43494105

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8. PERFORMING ORGANIZATION REPORT NUMBER

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Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RXT

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RX-WP-TP-2008-4045

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Conference paper submitted to the proceedings of the 24th Symposium of the International Committee on Aeronautical Fatigue. The U.S. Government is joint author of this work and has the right to use, modify, reproduce, release, perform, display, or disclose the work. PAO Case Number: AFRL/WS 07-1294, 04 Jun 2007.

14. ABSTRACT
Recent events within the U.S. Air Force (USAF) have highlighted the reality that cracks large enough to be readily detected by non-destructive inspection (NDI) can be missed during in-service NDI actions. These so-called "missed crack" or "NDI miss" events may pose serious risks to the safety and integrity of aircraft structures. This paper will review USAF actions: 1) to understand the severity and ramifications of the NDI miss problem, 2) to minimize the probability that cracks will be missed, and 3) to mitigate the effects of undetected cracks. In this paper, the probability of detection (POD) concept will be described from the standpoint of the variables that govern the detectable crack size associated with a given POD. Examples will be presented that illustrate the ramifications missed cracks have on aircraft structural safety. A technique for estimating the probability distribution of missed cracks based on NDI findings (i.e., "found cracks") and on the knowledge of a specific NDI technique's POD capability will be described. In addition, a brief review of recent advances in NDI technologies and techniques designed to minimize NDI misses will be presented.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor) / 19b. TELEPHONE NUMBER *(Include Area Code)*
Unclassified	Unclassified	Unclassified	SAR	24	James C. Malas / N/A

U.S. AIR FORCE EFFORTS IN UNDERSTANDING AND MITIGATING THE EFFECTS OF "NDI MISSES"

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Abstract: Recent events within the U.S. Air Force (USAF) have highlighted the reality that cracks large enough to be readily detected by non-destructive inspection (NDI) can be missed during in-service NDI actions. These so-called "missed crack" or "NDI miss" events may pose serious risks to the safety and integrity of aircraft structures. This paper will review USAF actions: 1) to understand the severity and ramifications of the NDI miss problem, 2) to minimize the probability that cracks will be missed, and 3) to mitigate the effects of undetected cracks. Under the current USAF inspection philosophy, missed cracks that are larger than a crack that can grow to a critical size before the next scheduled inspection pose the greatest risk to structural safety. Significant challenges exist in understanding what causes cracks to be missed, in quantifying how many and how frequently cracks are missed based upon available maintenance data, in calculating the risk to flight safety of missed cracks, and, finally, in developing technologies that will minimize the future probability that cracks greater than a specified size will be missed. The probability that a structural component will be inspected as required and that a detectable crack will, indeed, be found, are both key factors affecting NDI misses. In this paper, the probability of detection (POD) concept will be described from the standpoint of the variables that govern the detectable crack size associated with a given POD. Special attention will be given to the utility of the "90/95" crack size (the size of a crack that can be found 90% of the time with 95% confidence). The discussion of the POD idea will be augmented to include the concept of a probability of miss (POM). POM, though computed simply by subtracting POD from unity, focuses attention on the size of a crack that can go undetected and, therefore threaten safety and structural integrity.

Examples will be presented that illustrate the ramifications missed cracks have on aircraft structural safety. A technique for estimating the probability distribution of missed cracks based on NDI findings (i.e. "found cracks") and on the knowledge of a specific NDI technique's POD capability will be described. In addition, a brief review of recent advances in NDI technologies and techniques designed to minimize NDI misses will be presented.

INTRODUCTION

This paper describes, in a general sense, actions being taken by the U.S. Air Force (USAF) in response to recent instances when it was discovered that normally detectable cracks in safety-of-flight (S-o-F) aircraft structures had been missed by non-destructive inspections (NDI). These so-called "NDI misses" are of particular importance for several reasons. First, the current damage tolerance approach which forms the basis of the USAF's Aircraft Structural Integrity Program (ASIP) depends upon accurate and capable inspections that enable effective aircraft maintenance and that ensure the safety of damaged aircraft structures. Second, the age of the USAF's fleet of military aircraft is increasing, current flight operations are steadily putting more hours on airframes and, therefore, the probability of cracks occurring in S-o-F structure is increasing. Finally, the NDI misses have raised new questions in the USAF regarding the true capabilities of its NDI systems and have also served to spur activities that are designed to understand NDI system capabilities as well as devise ways to prevent or at least mitigate the effects of potential future NDI misses.

Section 1 will describe the USAF's ASIP, the importance ascribed to inspections in the damage tolerance philosophy upon which ASIP is founded, and the resulting inspection schedule typical for today's USAF aircraft.

Section 2 will briefly summarize NDI misses that have recently occurred in the USAF.

Section 3 will explain the significance of NDI misses with, again, an emphasis on the USAF's ASIP approach, when inspections are required, to maintain structural safety.

Section 4 will describe the actions taken by the USAF in response to NDI misses.

Section 5 will discuss some of the factors the USAF found to be contributory to NDI misses.

Section 6 will describe mitigation efforts that the USAF is pursuing in the general topic areas of policy, technology, and procedures.

It is hoped that the reader will benefit from this paper by gaining a better understanding of how to assess NDI system capabilities, by considering the options for addressing NDI misses available to the aircraft structural integrity community, and by realizing that the cracks found by an inspection technique are often far less important that the cracks that are missed.

THE USAF AIRCRAFT STRUCTURAL INTEGRITY PROGRAM & INSPECTIONS

Since the loss of several B-47 strategic bombers in 1958, the structural safety of U.S Air Force (USAF) aircraft has been established and preserved by the Aircraft Structural Integrity Program (ASIP). [1, 2] The ASIP provides a formal, organized, and disciplined framework to achieve the desired level of structural safety, performance, durability, and supportability with the least possible economic burden throughout the aircraft's design service life. Governing documents for the ASIP include:

1. *AFPD 63-10 Air Force Policy Directive, Aircraft Structural Integrity* [3] which establishes an official policy by directing the establishment of the USAF ASIP.
2. *AFI 63-1001 Air Force Instruction, Aircraft Structural Integrity Program* [4] which provides direction to all affected organizations and implements the policy set forth in AFPD 63-10.
3. *MIL-STD-1530C(USAF) Department of Defense Standard Practice - Aircraft Structural Integrity Program (ASIP)* [5] which describes the ASIP and defines the requirements that must be met to ensurem the structural integrity of USAF aircraft.

The goal of the ASIP is to ensure the desired level of structural safety, performance, durability, and supportability with the least possible economic burden throughout an aircraft's design service life. To achieve this goal, the program consists of a series of five interrelated tasks (Figure 1). Although these tasks have evolved over the years, they have had essentially the same focus since approximately 1970. [6] The first four tasks are primarily associated with the acquisition of USAF aircraft, while the last task occurs after an aircraft becomes operational and lasts throughout the aircraft's sustainment phase until it is retired. Thus, the five ASIP tasks span the entire lifecycle of an aircraft, from conceptual design to retirement.

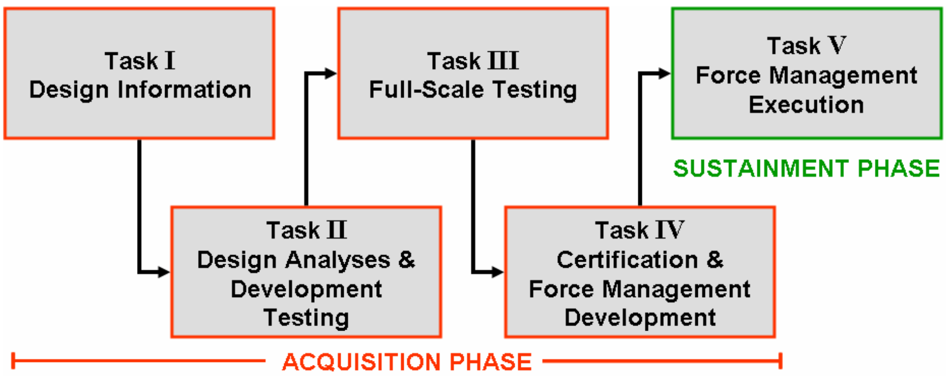


Figure 1: The Five Tasks of the USAF's Aircraft Structural Integrity Program (ASIP)

Originally, the safe life approach was employed for the design of USAF and served as the basis for the ASIP's fatigue life assessments. However, this changed with the December 1969 loss of an F-111 fighter-bomber due to a fatigue failure in a crucial wing pivot fitting. The component had been designed using a safe life methodology but, upon post-accident investigation, was found to be extremely sensitive to the presence of flaws arising from material impurities, manufacturing problems, and usage. The sensitivity to flaws in this F-111 component and premature failures in other safe life designs drove the USAF to adopt a damage tolerance (DT) approach to fatigue prevention and analysis. [7]

The USAF started to institutionalize damage tolerance (DT) as the approach for protecting airframe structure from crack damage when it created Mil-Spec-83444 and Mil-Std-1530A in 1974 and 1975, respectively [8, 9]. In design, the DT approach focuses on establishing structural configurations and stress allowables to control and mitigate the effects that potential crack-like damage could have on structural failures during the design lifetime. Contrary to popular belief, the focus of the DT design activities has not been to develop an inspection program, but to minimize all in-service maintenance actions during service by: 1) setting design allowables low enough, 2) defining structural configurations with sufficient redundancies and 3) choosing materials sufficiently tolerant to fatigue cracking so that real flaws will not grow to critical size during the airframe's lifetime [10]. In the current version of the DoD Joint Service Guide Specification 2006 [11], this intention is more clearly identified in §3.2.14.5 which states "By design, the airframe structure shall not require inspection during the service life specified in §3.2.14."

Despite this intent, because of inadequacies in structural design, analytical techniques, and aircraft mission usage and lifetime prediction, inspections do figure prominently in the ASIP as illustrated in Figure 2 which describes the main components of Task V.

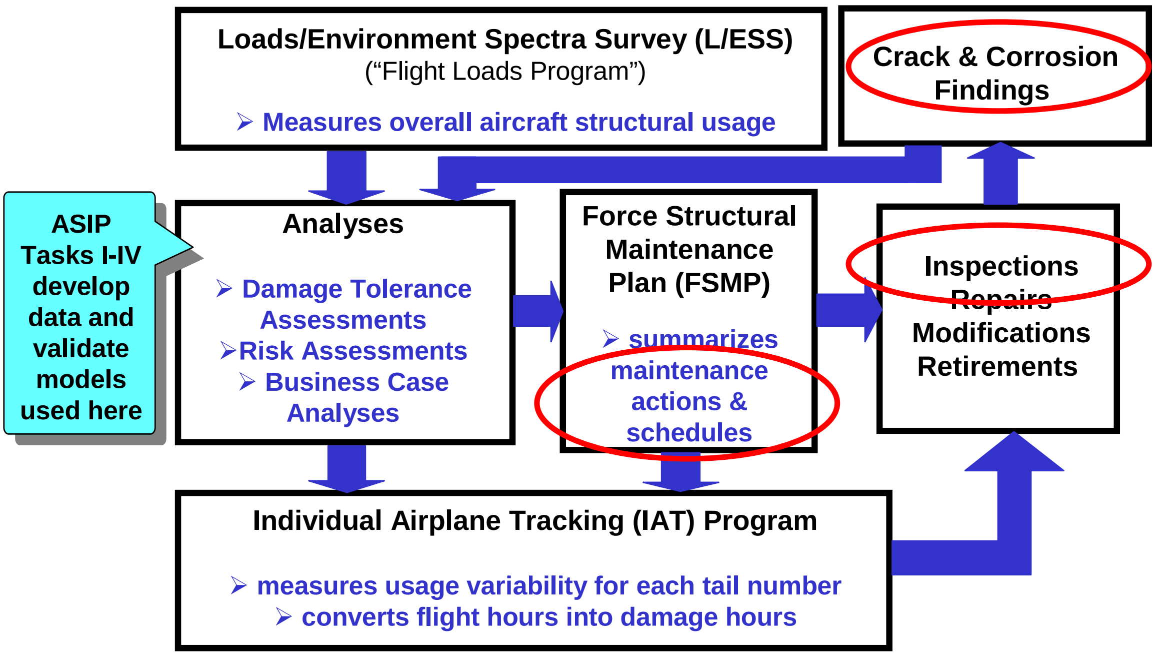


Figure 2. Inspections are a significant activity in Task V of the USAF's Aircraft Structural Integrity Program (ASIP)

In Task V, which occurs during the sustainment phase of an aircraft program, the Force Structural Maintenance Plan (FSMP) is executed and modified based on analyses and findings from fielded aircraft. The FSMP, in turn, specifies the scheduling and execution of various maintenance actions including inspections. This feedback process continues throughout the life of the aircraft to ensure that sufficient inspections are in place to prevent damage (e.g., a crack) from being undetected before it reaches a critical size.

Figure 3 illustrates a typical fatigue crack growth curve for a safety-of-flight (S-o-F) structure designed to meet DT requirements through using a slow crack growth approach. This figure also illustrates the USAF's policy, as specified in MIL-STD-1530C [5], of requiring the first inspection to occur at half the time it takes to grow a crack from its initial "rogue" size (a_0, typically assumed to be 1.3 mm [0.05 in.]) to the critical crack size (a_{cr}) at which point the aircraft will catastrophically fail due to the failure of the S-o-F structure. While cracks are sometimes found during these initial half-life inspections, such findings are rare since the assumed rogue flaw may not exist or because current inspection methods cannot detect the small cracks present at this early time in a component's life.

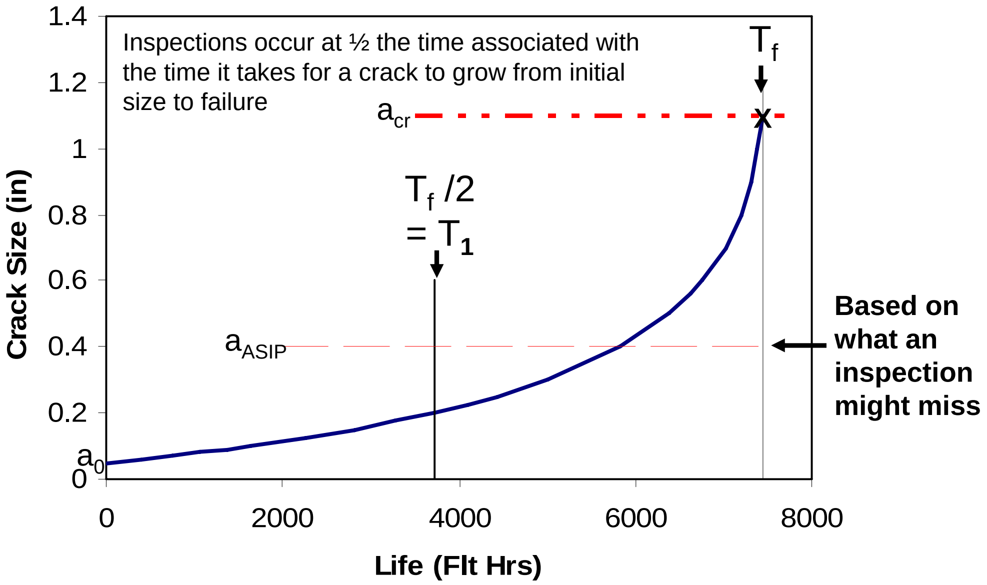


Figure 3. Slow crack growth curve from initial rogue flaw (a_0) at time zero to critical crack size (a_{cr}) at the time for catastrophic failure (T_f). Per USAF ASIP policy, the initial inspection of an S-o-F part is required at a time (T_1) occurring at half the crack growth life. The capability of an inspection systems may be defined by the length of crack that such a system might miss (a_{ASIP}).

Figure 4 illustrates the repeat inspection approach for the same fatigue crack growth curve for the safety-of-flight (S-o-F) structure shown in Figure 3.

Note that subsequent to the initial inspection, a second flaw size assumption is made that resets the assumed crack length existing in the S-o-F structure to a_{ASIP}. USAF ASIP policy requires that a second inspection must occur at half the time it takes to grow a crack from its "reset" size (a_{ASIP}), to the critical crack size (a_{cr}).

The choice of a_{ASIP} is made with an understanding of what might be appropriate for: 1) the inspection site, 2) the probability that an inspector may miss a certain sized crack, and 3) the potential for damage occurring during the disassembling/re-assembling process prior and subsequent to the inspection. Historically, the value of a_{ASIP} was established based on simple characterizations of the inspection equipment used for similar problems.

MIL-STD-1530 has traditionally suggested that the $a_{90/95}$ crack size, established from probability of detection (POD) experiments, be equivalent to the a_{ASIP} crack size (also referred to as the a_{NDE} crack size). (Recall that the $a_{90/95}$ crack size is determined based on a 90% POD (found 9/10 times) with a statistical confidence level of 95%.)

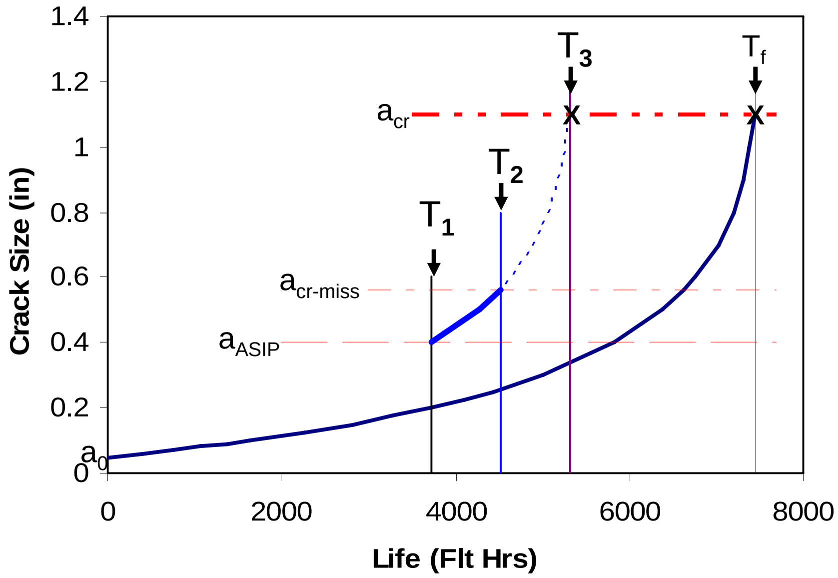


Figure 4. The slow crack growth curve from a post-inspection based rogue flaw (a_{ASIP}) growing from time (T_1) to the critical crack size (a_{cr}) for catastrophic failure at time (T_3) defines the inspection requirement for a situation where this rogue crack grows to critical size. Also shown in the figure are the time period (T_2) and the critical-miss crack size ($a_{cr-miss}$) associated with the crack that will grow to failure before the next inspection period if missed during a repeat inspection.

In summary, inspections are often required to detect cracks that potentially exist at known cracking locations in order to: 1) provide surveillance for determining if predicted cracking scenarios match observations, and 2) provide safety for those S-o-F structures where damage could grow to a critical size during the service life of the aircraft.

USAF NDI MISS EVENTS

During the last decade, there have been approximately six USAF aircraft fleets that experienced one or more NDI "misses." These misses have occurred on every major class of USAF aircraft: fighter/attack, transport, trainer, and helicopter.

An NDI miss is defined as a situation when a crack (normally detectable using standard NDI procedures) exists in a previously inspected location but was not detected by that previous inspection. Furthermore, analyses performed following the discovery of the crack by a subsequent inspection indicate that the crack was large enough to have been detected in the previous inspection. Thus, the conclusion is drawn that the first inspection failed to detect (i.e. "missed") the crack.

In the USAF cases, the missed cracks were determined to have been well above the stated $a_{90/95}$ inspection capability for the location. In fact, some missed cracks were even larger than the $a_{cr-miss}$ size defined in Figure 4.

Fortunately, these missed cracks were eventually found and corrective action was taken before any serious, catastrophic aircraft failures occurred. However, for one USAF aircraft fleet, missed cracks led to the condemnation of 11 shipsets of wings with cracked lower skins.

SIGNIFICANCE OF NDI MISSES

Obviously, if left undetected due to the NDI miss phenomenon, a missed crack could grow to critical size and result in the catastrophic loss of an aircraft. Figure 5 provides an illustration on how large a missed crack must be before it poses a threat to S-o-F structure and flight operations.

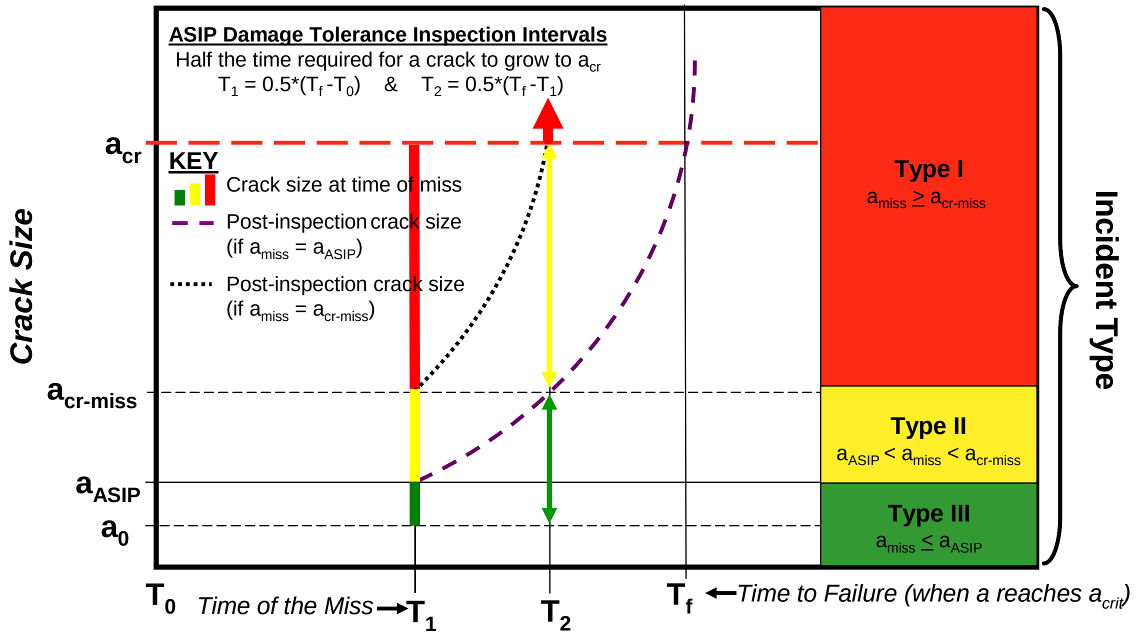


Figure 5. The three possible criticalities of missed cracks:

Type III (least critical) when a_{miss} (at inspection conducted at time T_1) $\leq a_{ASIP}$;

Type II when $a_{ASIP} < a_{miss}$ (at inspection conducted at time T_1) $\leq a_{cr\text{-}miss}$;

Type I (most critical) when a_{miss} (at inspection conducted at time T_1) $\geq a_{cr\text{-}miss}$

As shown this figure, if a crack (a_{miss}) smaller that a_{ASIP} went undetected during the initial inspetion of a S-o-F component at time T_1, then it could grow to a size of just less than $a_{cr\text{-}miss}$ by the time a second inspection were scheduled at time T_2. If, as unlikely as it may be, the crack went undetected during the second inspection at time T_2, a second chance of detecting the crack would occur during the third scheduled inspection at time T_3. This may be referred to as a “Type III” NDI miss which carries with it a relatively low risk of catastrophic failure since two chances (i.e. inspections) exist to detect a crack before it reaches the critical size. This is the preferred situation.

Correspodingly, if a crack (a_{miss}) with a size of between a_{ASIP} and $a_{cr\text{-}miss}$ went undetected during the initial inspection of a S-o-F component at time T_1, then it could grow to a size of just less than a_{cr} by the time a second inspection were scheduled at time T_2. This may be referred to as a “Type II” NDI miss which carries with it a relatively moderate risk of catastrophic failure since only one chance exists to detect a crack that was initially missed before the crack reaches the critical size.

Finally, if a crack (a_{miss}) of size equal to or greater than $a_{cr\text{-}miss}$ went undetected during the initial inspection of a S-o-F component at time T_1, then it could grow to failure before a second inspection could occur. This may be referred to as a "Type I" NDI miss which carries with it a high risk of catastrophic failure since no chances (i.e. no inspections) exist to detect a crack that was initially missed before the crack reaches the critical size.
The significance of an NDI miss is illustrated in Figure 6 which describes two missed crack events on USAF trainer aircraft. On two separate aircraft, cracks were found in wing skins with lengths that were approximately equal to a_{cr} and $2a_{cr}$, respectively. Upon detection of these cracks, the components were removed from service, the cracks broken open, and fractographic examinations made. Evidence on the crack surfaces pointed to instances of high loads which caused rapid crack growth approaching catastrophic failure. Despite the long lengths of the cracks, catastrophic failure did not occur because these aircraft were not flown on missions that subjected the structure to loads sufficient to cause catastrophic failure (even though such loads were within the operational spectrum of the aircraft).

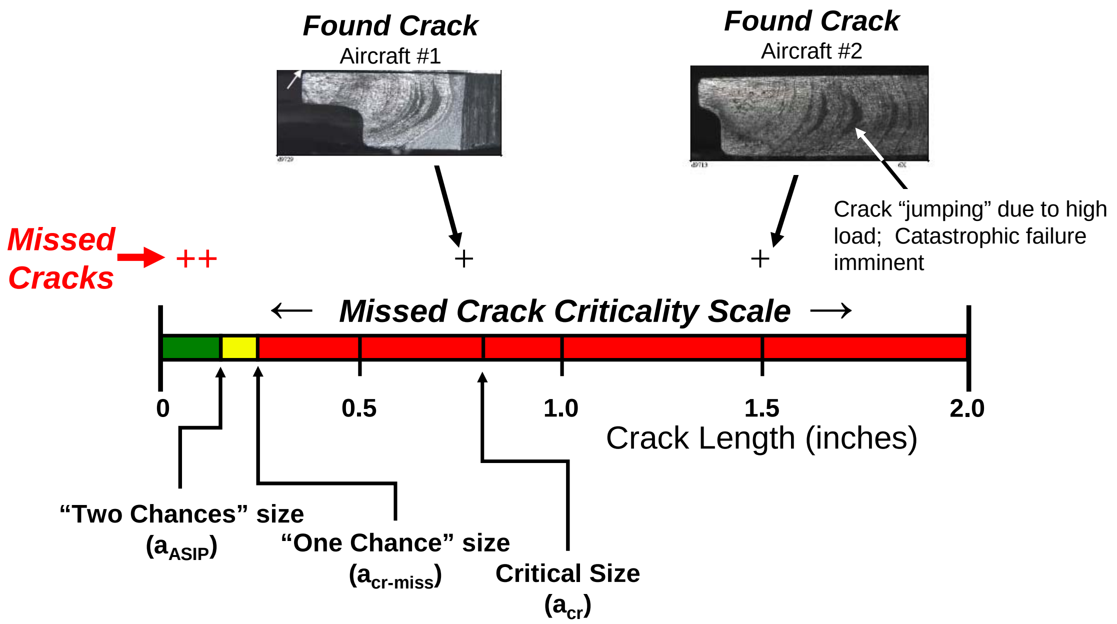


Figure 6. Two cracks taht were missed on two USAFseparate trainer aircraft were eventually found but not until they were of sufficient length to threaten structural integrity and safety.

Analyses, conducted after the cracks were discovered, showed that the cracks had initially been missed during inspections conducted when the cracks were smaller than a_{ASIP}. Subsequent inspections resulted in additional misses. Thus, as illustrated by this example, the significance of NDI misses or missed cracks is that such events may result in cracks growing long enough to lead to catastrophic failure of safety-of-flight components which, in turn, would lead to the loss of an aircraft.

U.S. AIR FORCE RESPONSE TO NDI MISSES

Following the discovery of NDI miss events on USAF aircraft in early 2005, Air Force Materiel Command (AFMC) senior leaders directed the formation of a multi-organizational "NDI Tiger Team" to study the problem and recommend actions that could be taken to mitigate the possible effects of missed cracks. Tiger Team membership included personnel from sustainment, acquisition, and research & development organizations within the USAF and was led by the USAF NDI Program Office. The Tiger Team concluded, based on reports of missed cracks from multiple aircraft fleets, that NDI misses were an institutional problem. Senior leaders then directed the formation of an NDI Action Team, chaired by the USAF Aircraft Structural Integrity Program (ASIP) Manager, to develop strategies for addressing the problem and to implement the recommendations of the Tiger Team. Activities of the NDI Action Team led to a multi-pronged effort within the USAF to address NDI misses (Figure 7).

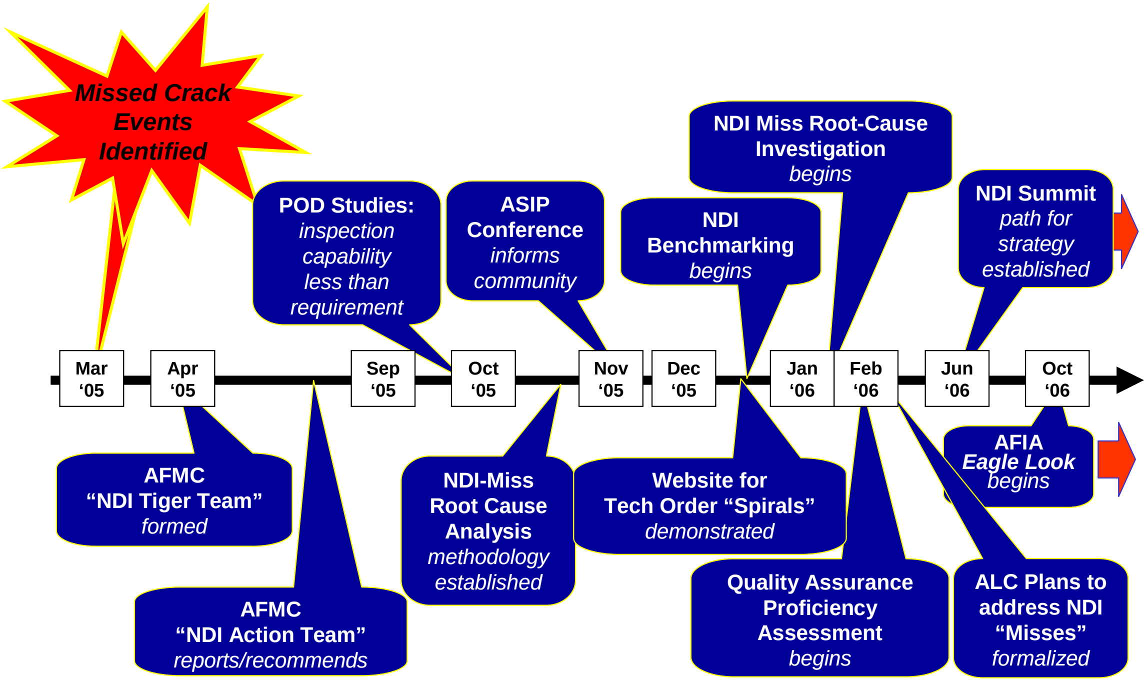
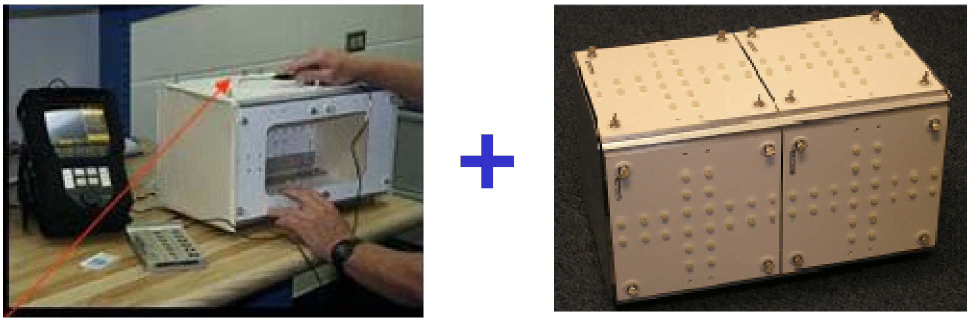


Figure 7. Activities comprising the USAF's multi-pronged effort to eliminate NDI misses and mitigate their possible effects.

The multiple USAF activities focused on eliminating NDI misses and mitigating their effects include:

1. Conducting probability of detection (POD) study and quality assurance proficiency assessments – To determine the capability of NDI system, controlled experiments using the surface scan eddy current technique were conducted using field and depot inspectors and standard mock-up components simulating crack aircraft structures (Figure 8). These studies were led by the USAF NDI Program Office. The initial POD study was conducted using a limited number of inspectors and indicated that the capability of the NDI system (inspectors + equipment + procedures) was less than the inspection requirement for a_{ASIP}. It was determined that the detectable crack size [$a_{90/95}$] was substantially larger than the crack sizes being used by USAF aircraft programs as their a_{ASIP} values This result was consistent with the occurrence of NDI misses. Because the POD study was based upon a limited number of inspectors a larger quality assurance proficiency assessment is now being conducted to determine if the POD study results are truly indicative of the eddy current surface scan capability of the entire USAF inspection community. Similar assessments of other NDI techniques will also be conducted in the future.
2. Informing the USAF's aircraft structural integrity community – Several sessions at the 2006 Aircraft Structural Integrity Program Conference (ASIP 06) were devoted to the

NDI miss issue in an attempt to provide the greatest amount of visibility possible to the problem. The use of the conference as a forum to highlight the NDI miss issue ensured that a wide cross-section of the ASIP community ranging from USAF engineers and managers to industrial technology developers and providers of maintenance services was informed and energized to devote resources to minimizing the likelihood of future NDI misses.



A. B.

Figure 8. The USAF Probability of Detection (POD) study used laboratory experiments that simulated aircraft structural configurations to characterize the capability of the surface scan eddy current inspection system

A. The equipment, instructions, probe, calibration and inspector were parts of the inspection system.
B. The experiment utilized multiple structural feature test articles (only one article shown) which had numerous details representative of aircraft hardware; some of the fastener holes were cracked but most were not.

3. Developing a website to aid in technical order (TO) development – One of the contributing factors to the 2005 NDI miss events was the rapid release of a number of USAF TOs that contained procedures that had not been properly validated and verified by maintenance and NDI organizations. In an effort to ensure that future TOs will not contribute to future NDI misses, a secure web-based tool is being tested for one aircraft fleet to enhance communication among the various organizations responsible for the development and validation/verification of vital instructions describing crucial NDI inspections. If this test effort is successful, other aircraft programs may adopt the concept to reduce the chance that flawed or sub-optimal inspection procedures are released to depot and field-level inspectors and, ultimately, to reduce the chance that future inspections fail to detect cracks.
4. Conducting a benchmarking study – In an effort to identify best practices used by organizations responsible for conducting NDI, a team of experienced USAF NDI inspectors and engineers conducted a benchmarking study at all three USAF Air Logistics Center, a U.S. Navy maintenance center, a commercial airline's maintenance center, and the combined U. S. Air Force/Navy tech school charged with training military NDI inspectors. This benchmarking study identified several policies, procedures, and techniques that were judged to be effective in reducing the probability that a normally detectable crack may be missed by an NDI inspection. Results from the study will be distributed across the USAF.
5. Developing and implementing root cause analysis methodology – The NDI misses discovered in 2005 revealed the USAF's lack of a formal root cause analysis

investigation procedure to identify the contributing and causal factors for missed crack events. To address this need, personnel from the Air Force Research Laboratory and the Aeronautical Systems Center's Engineering Directorate developed the *USAF Guide for Root Cause Analysis of NDI Misses.* Subsequently, this document has also been used to guide the investigation of the NDI misses that occurred in early 2005 and, has successfully identified contributing factors for these misses that the USAF is now taking steps to address.

6. Focusing Air Logistics Centers (ALCs) on developing plans that improve NDI processes – Because it is desirable to inspect aircraft under controlled conditions, a majority of non-destructive inspections are conducted at the ALCs when aircraft are brought in to undergo periodic heavy maintenance. Therefore it was recognized that "get well" plans needed to be developed and executed by the ALCs to improve the quality of their NDI processes and overall inspection system. Each ALC is organized in a slight different fashion, so these plans had to be tailored to account for organizational differences. However, a common thread in the development of these plans was the involvement of engineers, inspectors, and maintainers. These plans have been approved, are being executed, and are a foundation of the ALCs' individual and collective pursuit of continuous process improvement.
7. Conducting a USAF NDI Summit meeting – Following nearly a year of activity focused on eliminating NDI misses, representatives from engineering, inspection, maintenance, and technical policy organizations from across the USAF assembled to: 1) discuss progress on the various activities that addressed NDI misses, 2) exchange ideas and suggestions on the effectiveness of their actions, and 3) assist in crafting an Air Force-wide strategy to combat the risk of missed cracks. This summit meeting made a major contribution towards ensuring that USAF senior leaders remained informed of, and focused on, the necessity for continued effort to improve NDI processes and systems across the Air Force.
8. Conducting an independent internal USAF investigation – An independent investigation of the NDI miss issue conducted by the Air Force Inspection Agency (AFIA) commenced in October of 2006 and concluded in February of 2007. This AFIA *Eagle Look* investigation confirmed several contributing factors for NDI misses identified by previous efforts, recommended additional actions to be taken to minimized the probability of occurrence of future NDI misses, and informed the highest levels of leadership of progress towards the goal of eliminating NDI misses as well as of the requirement for continuing activity and vigilance in this effort.

These various activities have resulted in several key steps being taken towards improving NDI processes across the USAF including:

1. Understanding the true capability of NDI inspection systems (i.e. the probability that an NDI system may miss a crack of a given size in a given location on an aircraft)
2. Reconfirming which components must be considered safety-of-flight structures and conveying that information to the NDI community by way of TOs to ensure inspectors recognize the importance of their tasks
3. Developing improved NDI equipment to increase the probability of detecting cracks in S-o-F structures

The USAF continues to follow this multi-faceted approach towards eliminating NDI misses and mitigating their effects if they are found to have occurred.

FACTORS CONTRIBUTING TO NDI MISSES

During the multiple activities performed by various USAF organizations in response to the NDI miss events of 2005, a number of factors were found to be contributing to the problem.

The USAF's large fleet of aged and increasingly aging aircraft was determined to be a factor. As these aircraft age and as they continue to be operated under combat conditions, the number of cracks in structural components is expected to increase. Increasing age and an increasing number of cracks equate to more inspections and, thus, more chances of missed cracks. This situation may be exacerbated by an increasing workload being placed on a shrinking pool of qualified inspectors.

The instructions for performing inspections (technical orders or TOs) were also identified as a contributing factor for several reasons. TOs written in response to the 2005 discovery of the missed cracks were sometimes issued before the inspection procedures which they called out had been tested to ensure that they would actually aid in detecting cracks. In addition, TO descriptions of the areas to inspect were in some cases difficult to follow. The hasty issuance of inspection procedure TOs for which no validation/verification ("val/ver") dry runs were performed also resulted in inspectors being required to execute procedures that could not detect cracks of the size required to preserve structural integrity and safety. Training and familiarity with TO-required inspection technique also appeared to be an issue.

As indicated by the POD studies, the capability of NDI equipment coupled with human factors affecting its usage also plays a primary role in determining whether an inspection may miss a crack of an assumed detectable size. Current additional studies being conducted by the USAF are beginning to show that equipment performance variability is overshadowed by human factors. Thus, it is becoming increasingly evident that environmental conditions, body position, fatigue, vision, and other human factors may be the greatest threat to NDI system capability and, therefore, the primary factor contributing to NDI misses.

Finally, the traditional approach of using probability of detection (POD) and single point characterizations (a_{90} or $a_{90/95}$ crack sizes)_ of an NDI system's capability also appears to create an environment favorable for missing cracks during non-destructive inspections. Concentrating on the smallest crack that can be detected, i.e. concentrating on the probability of detecting a crack of a given size "a," POD(a), shifts our focus from the more important crack size, the largest crack that an inspection can miss. A focus on the probability of missing a crack of a given size, POM(a), on the other hand, is required. This may seem to be a subtle difference, but it represents a shift away from improving the resolution of NDI *equipment* towards improving the overall capability of the NDI *system*. Safety and structural integrity rely upon this system capability. As shown in Figure 9, use of the POD(a) - a_{90} approach may indicate, for example, that a crack size of 3.5 mm (0.135 in) may be detectable 90% of the time. While this appears to indicate a strong inspection system capability, shifting to the use of a POM(a) concept reveals some surprising results. This concept is developed further by Gallagher, et al. [10]

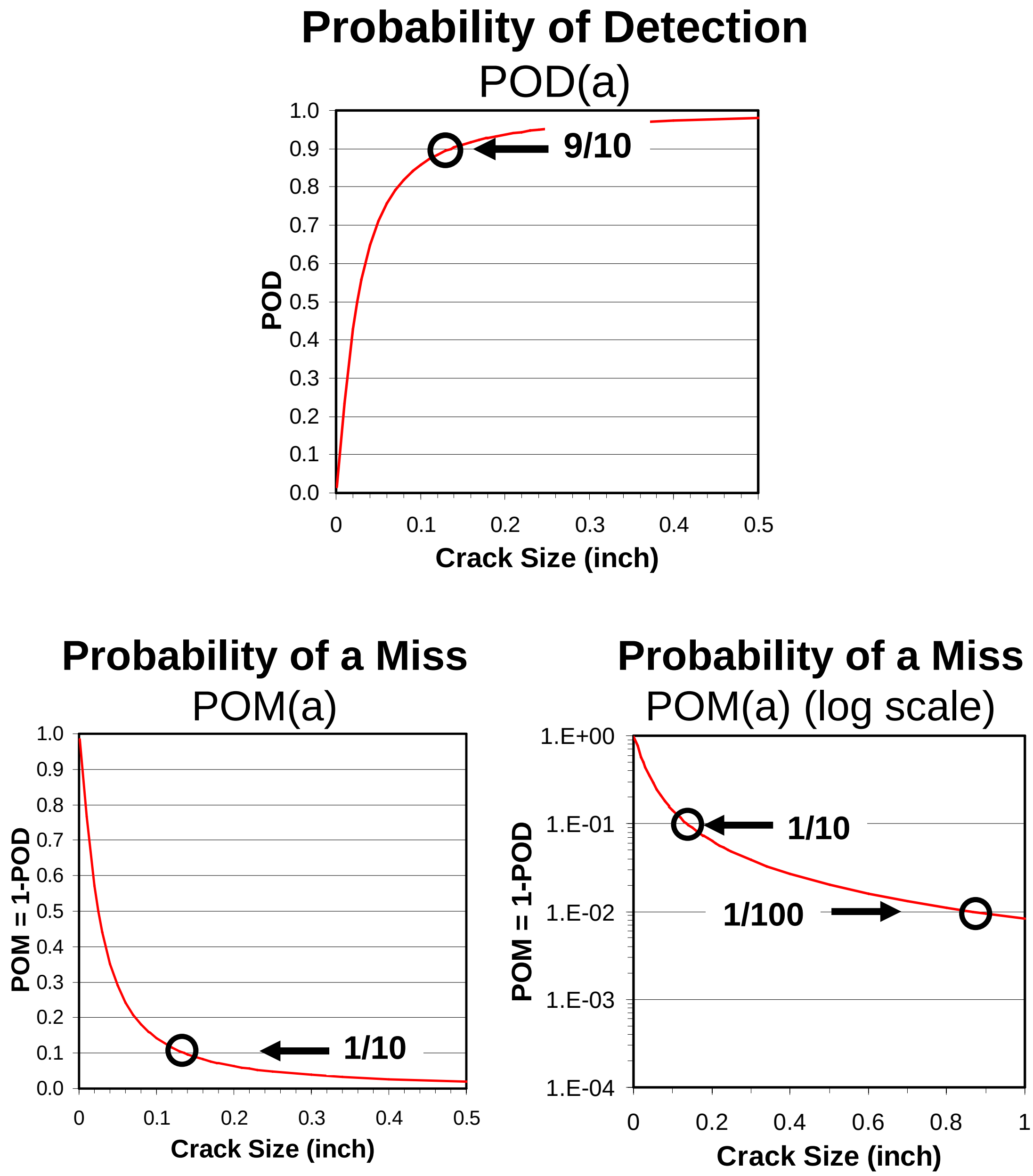


Figure 9. The POD(a) versus the POM(a) concept

When the POM(a) approach is used, the example crack with a length of of 3.5 mm (0.135 in) is now seen as being missed 10% of the time (POM[a] = 1 – POD[a]). However, the POM(a) approach highlights the fact that a crack with a length of 21.5 mm (0.85in) may be be missed 1% of the time. For USAF aircraft this relatively large probability (1%) of missing a crack of significant size, in relation to the emphasis on ensuring that the probability of failure per flight hour of S-o-F components is less than 10^{-7} (i.e. 0.00001%) is troubling and reflects a need to shift away from a focus on the smallest crack that can be detected towards the largest crack that can be missed.

MITIGATION ACTIONS

This shift of focus towards POM(a) has resulted in several mitigation actions underway within the USAF that are part of the activities described in Figure 7. The actions can be separated into three major categories: policy, technology, and procedures.

Policy

No completely new policy has been developed in the wake of the NDI miss events. However, there has been a renewed emphasis placed on certain requirements of MIL-STD-1530C that address inspections from the ASIP perspective.

First, recognizing the criticality of certain structural components is crucial to planning an effective and efficient inspection program. It must be clear to all parties involved with inspections which components requiring inspections are safety-of-flight (S-o-F) structure. Thus, greater emphasis is being placed on determining exactly which structural components are to be considered safety-of-flight-critical. Part of this effort is focused on defining the crack sizes in S-o-F structure that cannot be missed ($a_{cr\text{-}miss}$) in order to better determine the capability requirements for inspection systems. Furthermore, it must also be clear if the S-o-F structure can be characterized as “single load path” or “fail-safe” structure.

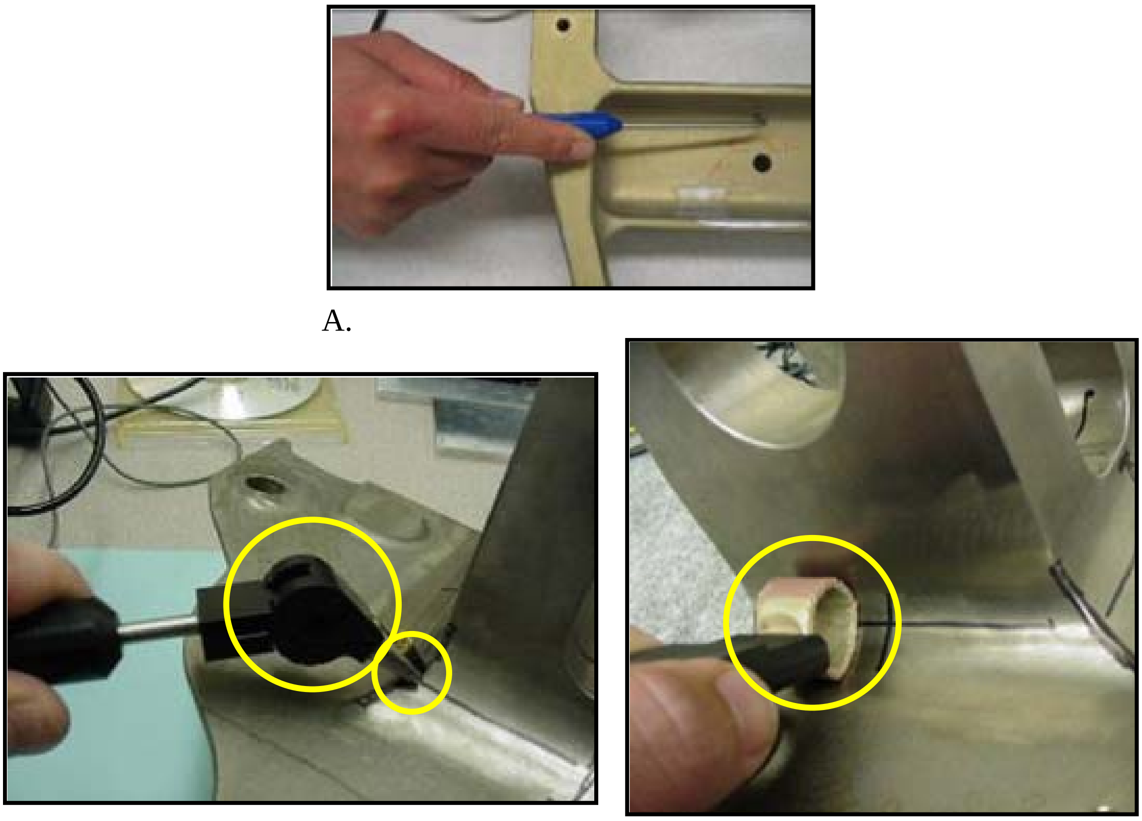
Secondly, following from this is a parallel requirement to clearly identify those components as S-o-F critical in USAF technical orders so that maintainers understand the importance of performing inspections on those critical components. This approach utiol;izes the practices successfully employed for many years by the world’s commercial airlines.

Third, efforts are underway to take advantage of modern database technology to collect, store, and make accessible the results of inspections of S-o-F structures. This will provide a better insight into the structural health of a single aircraft or an entire fleet and, thus, enhance commanders’ abilities to make decisions regarding sustainment and/or retirement of the aircraft.

Finally, though not driven specifically by the NDI miss events, the use of risk analysis in the design and maintenance of S-o-F structures to keep the probability of failure less than 10^{-7} per flight hour is also helping to mitigate the effects of NDI misses by preserving a level of conservatism that offsets increased risk posed by missed cracks.

Technology

Stemming from the USAF’s POD study and its quality assurance performance assessment which collectively focused on surface scan eddy current inspections and building upon lessons learned from NDI equipment developed for engine system components, an effort led by Air Force Research Laboratory personnel is underway to develop and field high frequency eddy current (HFEC) probes (Figure 10) that will minimize the detrimental effects of some human factors on the capability of the NDI systems. The existing pencil-type probe eddy current has multiple degrees of freedom in how it is positioned and how it is moved over a potentially cracked region. This type of probe substantially contributes to the challenge for interpreting eddy current instrument output. By employing articulating heads, conformal conductive ribbons, and other designs that assist the inspector in guiding the probe with better precision, these new probes are reducing performance variability resulting from lift-off and abnormal angularity between the probe head and the component being inspected. This reduced variability will aid in reducing POM(a). Several USAF aircraft ranging from new fighter aircraft to legacy bomber and transport aircraft have, or soon will, adopt these probes as their equipment of choice for surface scan eddy current inspections.



A.

B. C.

Figure 10. The evolution of surface scan eddy current probes. (A): tradition pencil-type probe, (B): probe with articulating head and edge-following guide for corners, (C) conformal head probe for fillets and radii.

Procedures

Past inspection procedures and schedules have been developed largely on the basis of laboratory experiments that provided estimates of an inspection system's capability or on the basis of OEM or NDI system manufacturer estimates of POD(a) curves or $a_{90/95}$ values. These types of estimates have contributed to NDI misses by providing an overly optimistic view of an NDI system's capability because the estimates have been produced without accounting for all variables that must be addresses when computing capability. All processes, procedures, personnel, equipment types, documentation, environmental factors, etc., contribute to the true probability of detecting or missing a crack during an inspection. Therefore, future inspections should use lab-based capabilities as baseline estimates and further refine those estimates using inspection data collected in the field or at the depots during teardown inspections, analytical condition inspections (ACIs) or other maintenance actions. Field/depot inspection results should be used to periodically re-evaluate POM(a) and POD(a) and these probabilities should be used in a risk-based approach to alter inspection intervals as necessary to maintain safety and structural integrity.

An example of this procedure based on Berens' work [12] in shown in Figure 11 which summarizes the process using crack detection results (data points) obtained by inspections of a single fatigue critical location (FCL) on multiple aircraft. These results were rank ordered as a cumulative distribution function (CDF) as a function of crack size. Also shown in Figure 11 are three curves: 1) an estimate of the *total* crack size distribution CDF(a), 2) an estimate of the CDF for the cracks detected, and 3) an estimate of the "effective" POD(a) curve associated with the inspection (referred to as the "effective" POD curve as opposed to one generated in a laboratory environment).

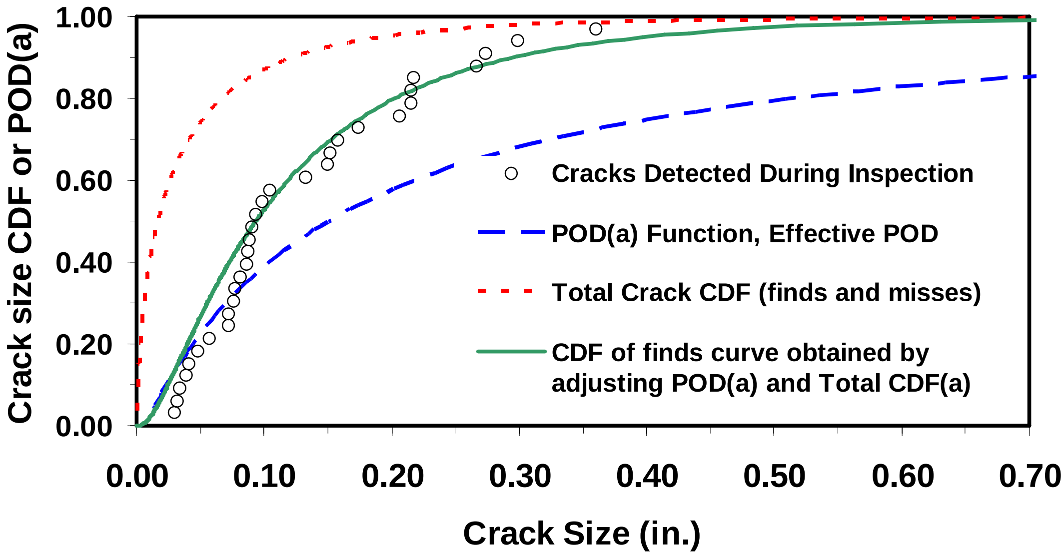


Figure 11. Crack Detections at Fatigue Critical Control Point identified as data points, shown with a "best estimate" cumulative distribution function (CDF) curve. Also shown are the effective POD(a) curve and estimated pre-inspection crack sizes curve CDF(a).

The three curves depicted in Figure 11 are interrelated. Changing the curves that represent the POD(a) function and the CDF of the total number of cracks will result in a change to the curve representing the "best estimate" CDF(a) for the cracks detected. In this manner, the CDF(a) curve for the detected cracks was obtained by iteratively changing the functional parameters associated with the "effective" POD(a) curve and the functional parameters associated with the total crack size distribution CDF(a) curve until a CDF(a) curve is found that accurately fits the detected crack data points obtained. The choice of optimizing parameters for the total crack size distribution and effective POD(a) curves was also subjected to a second constraint: collectively, the functions had to provide a match to the percentage of sites where cracks were detected (vs. not detected). In this manner, data on cracks found can be combined with knowledge of the "effective" probability of detecting those cracks to formulate an estimate of the number and size distribution of the total number of cracks present which can be then be used in risk analyses.

Note that the results in Figure 11 are the cracks detected, and do not represent the total crack size population present when the FCL was inspected. Additional cracks existed but were undetected either because they were below the detection threshold of the NDI system or they were detectable but were missed. We make this point because normally the detected cracks are used to define a site's fatigue crack size population for risk assessments. If a number of large cracks went undetected, the normal risk assessment assumption may lead to unconservative results. However, since it is probable that the distribution of detected cracks sizes is dominated by the more easily detectable large cracks, use of this distribution will likely be more conservative. A detailed comparison of using the *detected* crack distribution vs. the *total* crack distribution on airframe risk assessments has not yet been explored.

This example describes one possible new procedure being explored by the USAF that uses inspection results to refine estimates of a lab-based POD(a) curve to produce an aircraft's "effective" POD(a) curve which accounts for all components of an NDI system at a given crack site. In doing so, a much more accurate estimate of POM(a) can be generated which, in turn, will aid in the development of inspection schedules and techniques that can minimize the probability of future NDI misses.

SUMMARY

The DT-based inspection approach supports the USAF's execution of its mandated Aircraft Structural Integrity Program (ASIP) which is focused on ensuring structural safety. Recently, detectable cracks missed during safety-related nondestructive inspections (i.e. "NDI Misses") have forced the USAF to closely examine all aspects of its inspection processes. As a result of this examination, the USAF does not plan to take any action that would eliminate the use of its DT-based inspection approach as one of the mitigating options for addressing cracking problems that arise during the acquisition or sustainment phases of an aircraft.

The USAF has taken several additional actions to minimize future NDI misses and to mitigate their effects. New concepts of the largest crack that can be missed during an inspection (a_{ASIP}) and the size of a crack that can reach a critical length before the next inspection ($a_{cr\text{-}miss}$) have been introduced into USAF discussions, calculations, and maintenance planning. Renewed emphasis is being placed on: 1) confirming which structural components are safety-of-flight critical, 2) identifying the crack lengths that must be found in these parts during inspections, 3) utilizing laboratory POD experiments to systematically improve proeceses and equipment, and 4) documenting this information where engineers as well as inspectors can see it. Improved equipment is being constructed and fielded. Finally, new procedures are being developed that use actual inspection findings to refine laboratory-based estimates of NDI system capabilities.

Most importantly, the recent NDI misses and the US Air Force's reaction to them has begun to shift the focus from identifying the smallest crack an NDI system can find to identifying the largest crack it can miss. In addition, there is a corresponding shift from using a probability of detection (POD) approach to using a probability of miss (POM) approach. These changes in philosophy are foundational to a new way of thinking that is intended to minimize if not eliminate NDI misses in the future and contribute toward mitigating the effects of NDI misses should they occur.

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