ABSTRACT

Title of Thesis: AN INVESTIGATION ON THE AFFECT OF EXTERNAL CONDITIONS ON THE RELIABILITY OF AIRCRAFT INSPECTIONS

Adam David Blake Barrett, Master of Science, 2017

Thesis Directed By: Professor Mohammad Modarres
Department of Mechanical Engineering

The objective of this study is to develop an understanding of how external variables commonly encountered during an inspection affect an inspection systems detection capability. A probability of detection study was performed using representative structural samples, attached to a simulated naval flight asset. For the execution of these tests, common nondestructive testing equipment was utilized by multiple inspectors. For each test inspectors, test samples (with imbedded damage) and inspection locations around the test bed were varied to better simulate field inspection conditions. An understanding of how these variables affect inspection performance will give maintainers, designers, and planners a more realistic idea of what damage can be detected and quantified in field inspection conditions.

AN INVESTIGATION ON THE AFFECT OF EXTERNAL CONDITIONS ON THE RELIABILITY OF AIRCRAFT INSPECTIONS

by

Adam David Blake Barrett

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2017

Advisory Committee:
Professor Mohammad Modarres, Chair and Advisor
Professor Hugh A. Bruck
Assistant Professor Monifa Vaughn Cooke

Preface

Essentially, all models are wrong, but some are useful.

-George E. P. Box: *Empirical Model-Building and Response Surfaces* (1987)

Dedication

I dedicate this work and my life to you Sierra

Acknowledgements

I desire to acknowledge the following individuals for their guidance and support of me during this effort:

First I acknowledge and thank those who provided support from College Park:

- My advisor Professor Modarres for his support, mentoring and editorial reviews.
- Reuel Calvin Smith for his practical advice for a graduate student, and his guidance for the analytical modeling.

I would also like to acknowledge personnel at the Naval Air Warfare Center Aircraft Division in Patuxent River Naval Air Station. Their guidance and support was important to the execution of research. I would like to take the time to thank:

1. Those who took the time to intimately guide me:
    a. Jerry Rubinsky for his guidance on developing a successful funding proposal and for supporting the aspirations of younger personnel.
    b. Cheryl Bryon for her guidance and patience on aiding me in the development of a successful IRB package.
    c. Dr. Barry S. Shender for providing guidance on an alternate path of Human Reliability Analysis, thru NASA TLX survey.
    d. Brandi Briggs for providing guidance on how human research is conducted and advice on how to create a successful IRB package.
    e. Dave Rusk, Tony Posocco and Dave & Joshua Barrett, for providing stories of their personal thesis experiences and their advice and guidance on approaches to analyze the results.

2. The FY15 Section 219 Workforce Development Proposal Board, for their review, approval to fund this effort. This includes but is not limited to: Dr. James Sheehy, Jerry Rubinsky, Kristi Wiegman & Courtney Ross.
3. Aircraft Prototype Systems Division (5.4.6.1.). For their support in the fabrication of the test panels utilized for testing during this project, in spite of personal hardships: Will Farrell & Randy D Hagelin.
4. The following personnel from the inorganic (primer) and organic (painting) coaters & primers laboratories (4.3.4.2), for efforts of conditioning the test panels: Andy Schwartz & Frank Pepe.
5. The NAWCAD IRB board (4/21/16, IO 5/9/16) which approved the execution of "NAWCAD.2015.0007-IR: Analytical Multi-Variable Distribution Model to Assess the Reliability of Inspections to Detect Damage in Complex Aircraft Structures". This included the chair Mr. Stephen Coleman, the Institutional Official (IO), Rear Admiral Shane G. Gahagan and other members of the board.
6. Managers of the Materials Division: Division Head Darryl Tenney, Branch Head Gina Caudill, for their agreement to the risk of testing around the retired airframe. Paul Roser for providing permission to use test frame.
7. A special thanks to the Testers: Emily Currier, William Milan, Nicole Carlisle, Michael Giganti, Paul Kulowitch, Andy Magkasi.
8. Francis R. Smith, with the Air Force Research Laboratory, Materials and Manufacturing Directorate Wright-Patterson Air Force Base, OH,

Funding for this effort was obtained thru a NISE (Naval Innovation in Science & Engineering) BAR (Basic and Applied Research) Proposal: 219BAR-15-015. This effort directly addresses the following naval research goals:

- Naval Aviation Enterprise Science and Technology Objective: System Safety & Availability.
- Navy S&T Focus Areas: Total Ownership Cost.
- NAVAIR Core Capabilities: Advanced Airframe Structures & Materials.

Additionally, research was conducted within the guidelines established by the research protocol (NAWCAD.2015.0007-IR), which was approved by NAVAIR IRB in April 2016.

Table of Contents

List of Tables

List of Equations

List of Figures

List of Abbreviations

a_{NDI}- minimum defect size, which can be reliably detected by a technique.

ASTM- American Society for Testing and Materials

BAR- Basic and Applied Research

BS- British Standards

C- Degrees Celsius

EDM- Electro Discharge Machine

F- Degrees Fahrenheit

HRA- Human Reliability Analysis

IS- Inspection System

IRB- Institutional Review Board

MANPOD- Model Assisted Probability of Detection

MLE- Maximum Likelihood Estimate

NACRA- Naval Aviation Center for Rotorcraft Advancement

NDI- Non-Destructive Inspection

OWAS- Ovako Working Posture Analysis System

POD- Probability of Detection

PSA- Probabilistic Safety Assessment

SHEL- Software, Hardware, Environment, Liveware

SHMS- Structural Health Monitoring Systems

SSEC- Surface Scan Eddy Current

TLX- Task Load Index

Chapter 1: Introduction

1.1 Motivation and Background

Failures of structures and mechanical parts happen periodically, due to fatigue, wear, corrosion or other failure mechanisms. If the failures of critical systems are not managed properly, it can cause the loss of financial resources, time or even lives. Unexpected failures can lead to bankruptcy and lawsuits (in business) or unacceptable levels of unavailability of weapon systems (in military) during a critical moment of need.

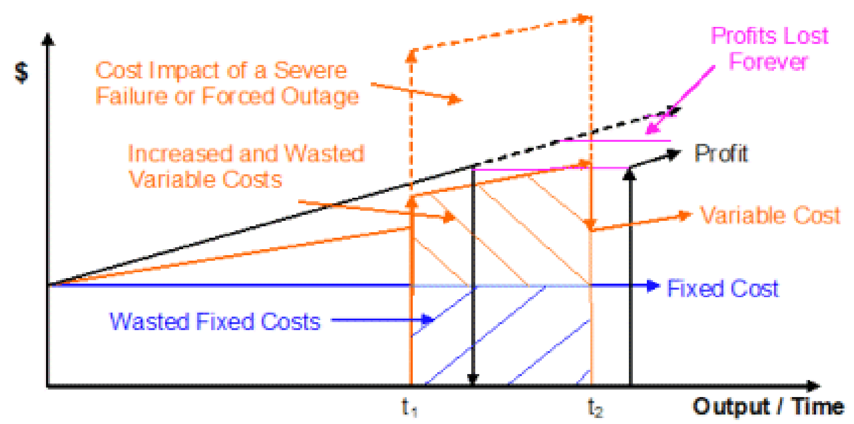


Figure 1: Consequences of a failure incident on operation costs /profit [1].

Figure 1 above demonstrates the potential cost of failures on an organization. The shaded areas in the graphic show that when a failure happens un-expectantly, the cost to the business is the loss of future profits, plus immediately wasted fixed costs variable costs, and the added variable costs needed to get the operation back into production [1]. However, an approach that is too conservative and retires assets too early can also be detrimental to operations. While a approach of a lower damage threshold of the safe life reduces the likelihood of catastrophic failure, the high safety factors tend to lead to premature retirement and a lower return on investment [2]

Typically, in naval aviation the primary structure (bulkheads, spars, ribs, etc.) are metallic. If these structures fail in flight, this can cause the air vehicle to crash. According to a naval report provided to CNN by the Naval Safety Center, from October 2014- April 2016, the Navy has reported accidents that total over $1 billion in damages [51]. These could have been primarily attributed to three major failure modes of metallic failure: ductile, brittle & fatigue fractures [3]. Other failure mechanisms common to naval structures are wearing, fretting and corrosion. According to a study performed by the U.S. Federal Highway Administration (FHWA) in 2002: the total annual estimated direct cost of corrosion in the U.S. is $276 billion (3.1% Gross Domestic Product (GDP) [4]. In 2013 the costs of corrosion, has grown to $500 billion [49] and is expected to increase in the future. Structures can fracture and fail by the growth of manufacturing flaws (defects) or in service damage. The damage will grow if the following loading stress and shape factor conditions are met:

Equation #1: Conditions under which damage will grow

$$\sigma \geq \frac{K_{I_c}}{\beta\sqrt{\pi a}}$$

$$\sigma = Fracture\ Stress$$

$$\beta = Shape\ Factor$$

$$a = Crack\ Length$$

$$K_{I_c} = Stress\ Intensity\ Factor$$

Crack propagation leads to failures, which cost money, time and availability of assets. However, cracks and other flaws can be detected before they propagate till failure. One way to detect damage before the advent of failure is thru the implementation of NDT (nondestructive testing). NDT is used to search for damage in structural materials and components, and this information can be used to determine if a material or component is safe or fit for its intended use [5]. The scope of NDT applications can range from detection of safety critical flaws, to preventive maintenance processes aimed at minimizing expensive maintenance [5].

Traditional NDT techniques include (but are not limited to) visual, eddy current, magnetic particle, penetrant, ultrasonic and radiography methods. Generally smaller damage is more difficult to detect than larger damage. One of the key features that helps to determine appropriate applications of an NDT method is the minimum damage size (a_{NDI}), that can be reliably detected by the method [5]. NDT can be utilized as an appropriate failure mitigation technique if it can possess the following relationship of detectability of damage versus damage that is large enough to be structurally significant (critical damage size).

Equation #2: Desired detectability of a IS (Inspection System)

$$a_{NDI} < a$$

Where:

$a_{NDI} = Smallest\ size\ damage\ that\ can\ be\ relibly\ detected$

$a = Critical\ damage\ size$

The a_{NDI} (minimum reliable detectable damage size) is commonly characterized as the probability of detection (POD) of a specific type of defect as a function of defect size [5]. Each method, technique, equipment and process has its own unique advantages, limitations and a_{NDI}. However, the POD information obtained from a representative trial is strictly applicable only to the exact conditions and defect types for which the POD trial inspections were performed [5]. These POD studies yield empirical data which is used to determine the a_{NDI} of an IS (Inspection System). The IS is the equipment, personnel, procedure and other elements of an inspection that work in concert together to perform an inspection. POD studies are typically conducted in a controlled environment. However many IS are utilized in field conditions where NDT will be implemented in varied conditions (such as physical space, access, viewability, environmental and other inspection limitations). These circumstances can influence IS capability and their varied affect is not typically accounted for in POD studies. It has been recognized that NDT techniques and instruments that have proven themselves in the laboratory do not always perform as well under field conditions [52]. As such, conventional POD studies may not be the best representation of in-field IS capabilities. Without an in-field study, this can lead to an overestimation of field a_{NDI}, leading to possible overconfidence in IS capabilities.

The IS in the field can be viewed as a collection of 4 smaller elements and each element interfaces with the human (in center box in black). A visual model of the relationship between these elements (and some but not all potential degradation factors) is displayed below in Figure 2:

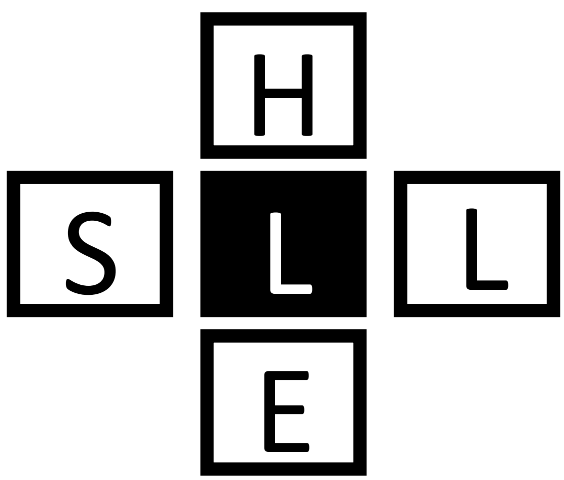


Figure 2: SHEL model [7]

S: Software- This includes the procedures, manuals, standards, etc. Degradation from misinterpretation of poorly written procedures, lack of training, poor communication [7].

H: Hardware- Tools/ equipment, physical structure of part, etc. Degradation from: unavailability of needed tools/ equipment, inadequate resources for required task [7].

E: Environment- Physical and work environments. Degradation from: Work area hazards and issues [7].

L: Live ware- The inspector and personnel in the work environment. Degradation from: Shortages of manpower, training, retention, lack of supervision, support. human physiology, psychology, workplace design, environmental conditions, human machine interface, anthropometrics [7].

The personnel interact with all elements of the IS and as such parameters that effect human performance also have an impact on other elements of the IS. There are some common maintenance personnel errors, which can be applied to analysis of NDI. These common maintenance errors are: Lack of communication, complacency, lack of knowledge, distraction, lack of teamwork, fatigue, lack of resources, lack of assertiveness, and stress [53]. According to a study executed in 2011 [6] Table 1 below displays the breakdown of the causes of aviation fatalities.

Table 1: Main causes of aircraft accidents [6]

Principle Cause of Fatality	Percentage of Deaths by Cause Category
Human Error	67.57%
Aircraft Failure	20.72%
Weather	5.95%
Sabotage	3.25%
Other	2.51%

Therefore, it is important to consider human factors in an assessment of IS capability to better understand its effect on inspection results. The approach of this effort is to quantity the effect of external variables on inspection capabilities. This will be done by performing an empirical (POD) study by evaluating input parameters that are factors present in most inspections. These variables are: The visibility of test surface, physical hindrances to the tester, comfort of inspection position, inspector backgrounds and size/ shape/ density of defects. Armed with information on how these variables affect IS capabilities and knowledge of the actual testing conditions in a field environment, an approximation can be made of the capabilities of the IS in that inspection space. This too can aid in the assessment of risk i.e. the potential for variation in cost, schedule or performance or its products [8].

1.2 Research Objectives and Methodology

The objectives of this research are to execute the following tasks:

1. Design and receive approval to test, monitor and record results on the capabilities of the IS. The POD will be executed by varying representative field inspection conditions, personnel, defect in test samples and inspection locations around the test bed (aircraft).
2. Ignoring the potential effects of external variables on IS capability, model the POD of the IS with a conventional 2 parameter model. Determine the best fit of a mathematical distribution to the empirical data and which parameter values are the best for an analytical model.
3. Assess the quantification capabilities of the IS by performing a linear regression analysis of the assessed size of damage vs. the actual size of the damage.
4. To publish during a future effort an investigation into the relationships between the assessed variables and their effect on IS capabilities. Use

these relationships to form the basis of a multivariate model that shows the effect of these variables on IS capabilities.

1.3 Thesis Contributions

The products of the research in this thesis are as follows:

1. Development of a new NDT inspection protocol that can be used as a guide (or be resurrected) for similar research in the future.
2. Collected NDT data thru empirical experiments that show the capabilities of common naval equipment in common operational environments. This data can be utilized to create an analytical damage detection model which displays the effect that common external variables have on inspection capabilities.
3. Development and utilization of a Maximum Likelihood Estimation approach to properly analyze POD data.
4. Generated data that describes the degree of relative comfort of common field inspection body positions.

1.4 Outline of Thesis

This thesis includes six chapters. The first chapter is the introduction to the motivation for the work, the methodology of investigation and the contributions of this work. The second chapter covers a review of applicable literature: Approaches to assess NDT capabilities, Assessments of HRA, an overview of NDT techniques and the theory of eddy current principles. Chapter 3 covers the process of fabrication and chosen design of testing specimens, the acquisition and use of a aircraft hull to use for testing, the test procedure and assessment process of the observed variables: Defect panels, inspection positions & hindrance, visibility (secondary access) of the test surface and inspector background (education and expertise) are also covered. Chapter 4 presents the assumptions made and the post experimental methods: censoring data (binary and assessment), using distributions to model the binary POD data and performing regression analysis on assessment data. Chapter 5 summarizes the results from the tests/experiments, including POD, measured vs. actual size of damage assessments. Lastly, chapter 6 discusses further analysis that can be explored/ executed in the future, regarding this effort.

Chapter 2: Literature Review

2.1 Assessment of Detection and Qualification Capabilities

2.1.1. Approaches to Assess NDT IS Capabilities

There are a variety of NDT methods and techniques and as such experts typically consider multiple options in determining an optimal testing solution. Applications of damage detection/assessment can be addressed in multiple ways. When planning to utilize NDT one should consider several factors:

- The requirements regarding reliable and safe operation.
- Quality assurance level that is desired to be achieved.
- Physical- chemical properties of materials to be inspected.
- Feasibility of NDT methods available.
- Economic criteria (time, cost, ect.).

In the selection of a suitable NDT method, experts should be involved to determine extent and frequency of required testing. [9]. In this consideration, they should assess all aspects of the IS (Inspection system), especially the qualification of the three constituent elements: Equipment, Personnel and Procedure **[10].**

There are multiple approaches to assess the capability of the elements of a IS all working together in concert:

1. Review data/information on method/instrumentation capability. Ensure the data was generated using a similar IS and conditions, to the current application. There are several sources for generic NDI capability; however application of such estimates to other inspection environments should be used with caution [39].

2. Perform an assessment/ simulation under the expected inspection conditions, with representative samples that possess expected damage. Assess the detection capability to a pre-defined qualification target. Keep in mind: The number of parameters that could be tested is immense. Ensure the solutions parameters are a reasonable representation of reality [11].
3. Incorporate a full POD that generates empirical data. For guidance and guidelines on how to execute an effective POD, the Navy uses the MIL-HDBK-1823. To determine a_{NDI}, thru an empirical study, the testing should include at least 60 damaged sites [11]. To assess measurement error (or other qualitative measurements) at least 40 sites are recommended [11].

For this study, we will incorporate a full POD study to assess overall IS capability under varied conditions.

2.1.2. POD to Assess IS Capability

The reliability of NDT is commonly characterized in terms of the Probability of Detection (POD) of a specified type of defect as a function of damage size: a_{NDI}[5]. Qualitative assessment of the reliability of NDT is an essential part of aircraft structural integrity management. Current practices for determining POD require large scale trials of NDT procedures on representative components to gather data for statistical analysis which can be prohibitively expensive [5]. Keep in mind:

- When POD is determined using a traditional POD then the conclusions from such information is only applicable to the exact conditions under which the POD trial inspections were performed.

- Broader application of the estimated POD to other inspection conditions is reliant on an engineering assessment to assume that the delta between test and field conditions will not reduce the POD.

2.1.3. Probability of Detection Model

As previously discussed there are multiple approaches to assessments of IS capabilities. An empirical approach to determine an a_{NDI} of an IS is not always feasible due to time, resources and other considerations/restrictions [5]. The tradeoff in planning and executing a POD study: Will the study focus on a specific environment and application to achieve greater accuracy & precision of a IS capabilities? Or will the assessment be focused on a broader, but more common inspection environment? The goal of this thesis is to explore the more holistic view, a general assessment of the effect common variables have on IS capabilities. The variables assessed are: varied operators, defects present in structure and inspection locations. With this understanding we can discover how these common variables influence IS capabilities in field inspection conditions.

2.2 Assessment of Human Factors on IS Capabilities

2.2.1. Approaches Considered to Assess Human Effects on IS Capabilities

As discussed in Section (1.1) human factors are a significant cause of failures and as such we will assess human effects on IS capabilities, however, this information will not be utilized in the analysis of detection capabilities in this thesis. To ensure our human tests are conducted in an ethical manner, the research protocol adhered to 3 basic principles contained in the Belmont Report: Respect for persons, benefice and justice [12]. No research was conducted until NAVAIR's IRB (Institutional Review Board) approved a research protocol. The purpose of the board is to review, approve and monitor naval research involving humans. This oversight by the board is required to ensure human testing is conducted in an ethical & safe manner.

Almost 80% of maintenance errors in aviation involve human factors [13] and as such it is important to observe the human effect on IS capabilities. HRA (human reliability analysis) is one area of study in PSA (probabilistic safety assessment) that has direct applications in many industries [14]. These studies are essential to understanding how the environment and inspection spaces affects personnel's ability to execute tasks in the areas they work [13]. For the execution of this study 2 approaches were identified and evaluated to quantify Human Factors effect on IS capability.

2.2.2 1st Approach to HRA: CAD & Avatar Modeling in SANTOS

NAVAIR possess an organic capability to perform HRA assessments. One approach is to partner with the Human Systems 4.6.5.3. Aircraft Accommodation/ Anthropometry/ Design for Maintainer Branch. This group offered to provide an assessment of psychophysical, anthropometric and spatial restrictions and their effect on inspector performance. They identified that over 500 distinct measures of human performance can be used to evaluate the functionality of the brain, limbs, and other body functions [42]. However, the group offered to provide the following analysis:

- Liberty Mutual psychophysical push and pull force limits- Evaluating lifting, lowering, pulling, pushing and carrying tasks on capability and limitations [41].
- Assessments of balance, flexibility and other human performance measures.

- Quantifying energy expenditure for conditions of static & dynamic fatigue.

We determined the best approach to assess effect of inspection position on IS capabilities were to:

1. Model the restrictions of each inspection space around the aircraft using FaroArm®. This is a tool that is a portable coordinate measuring machine, that can be used for 3D inspection, CAD comparison, dimensional analysis & more [43]. The device would create a dimensionally accurate scan of the physical space of each identified testing location. The technical data would be imported into a CAD format software, Verisurf® by utilizing reverse engineering with Verisurf Device Interface. Verisurf®'s model based definition lets users set a model for any surface or feature [44]. This would produce a 3D CAD solid model of each inspection space to aid in HRA of task loads on inspectors operating in test locations.
2. Obtain some basic biometric measurements of each human tester. Information on how to obtain these biometric measurements are contained in appendix A, Standard Biometric Measurements. To ensure that each dimension is measured accurately and consistently from subject to subject, dimensions are defined in terms of body landmarks, which serve as the origin, termination or level of measurement of a dimension [15]. An example of these measurements is shown below in Figure 3.
3. Standard Biometric measurements are shown below in Figure 3 & Appendix A: Acromial Height(3), Bideltoid Breadth(12), Buttock Depth(24), Chest Breadth(32), Chest Depth(36), Forearm Circumference Flexed(32), Forearm-Hand Length(54), Functional Leg Length(55), Hip Breadth(65), Overhead

Fingertip Reach(83), Shoulder-Elbow Length(91), Stature(99), Waist Depth(115), Weight, Acromial Height Sitting(3), Biacromial Breadth(10) , Buttock-Knee Length(26), Buttock-Popliteal Length(27), Gluteal Furrow Height(56), Knee Height(73), Sitting Height (93), Popliteal Height(86), Thumbtip Reach(105) [15].

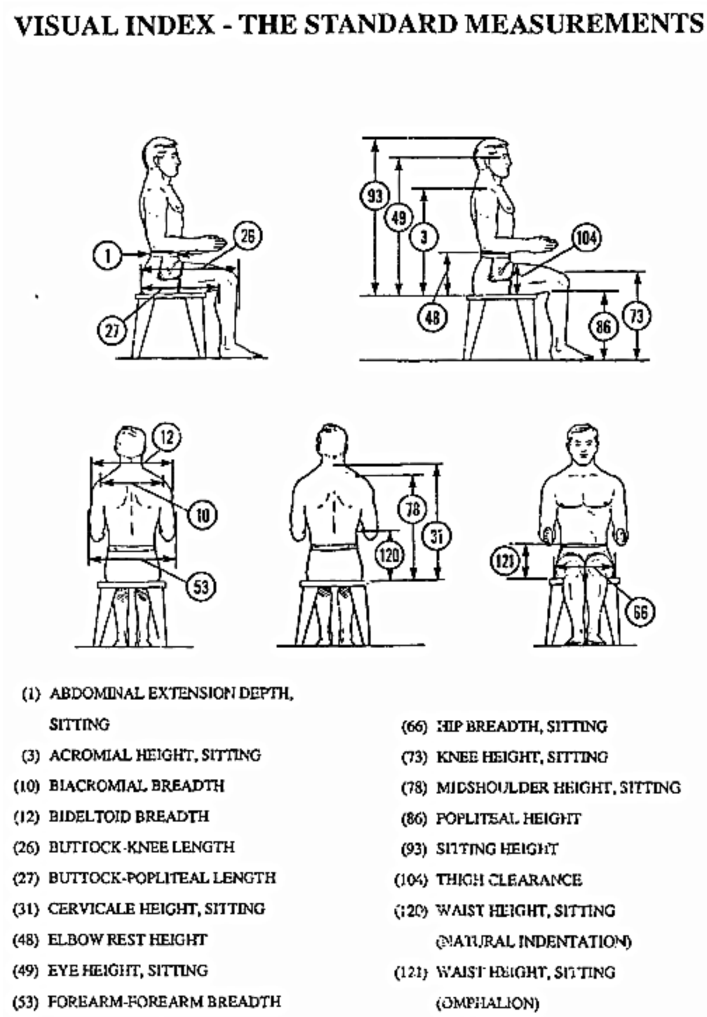


Figure 3: Standard biometric measurements [15]

4. Input the biometric measurement data of each tester into SANTOS software, to create a digital human avatar. SANTOS is a mathematical model based on the Denavit-Hartenberg method [16]. This method is used to analyze links of robot kinematics, and each link has two parameters: the link length and the link twist, used to define the relative location of the two attached joint axes in space [54].

This is used for kinematic and dynamic analysis and is used to predict human posture, motion and other functions in a physics based digital environment [16].

5. Generate a digital avatar (shown in Figure 4 below). Input the avatar into the 3D CAD solid model of the inspection space. Use the software to simulate each tester performing an inspection in each test location, to determine human performance measurements.

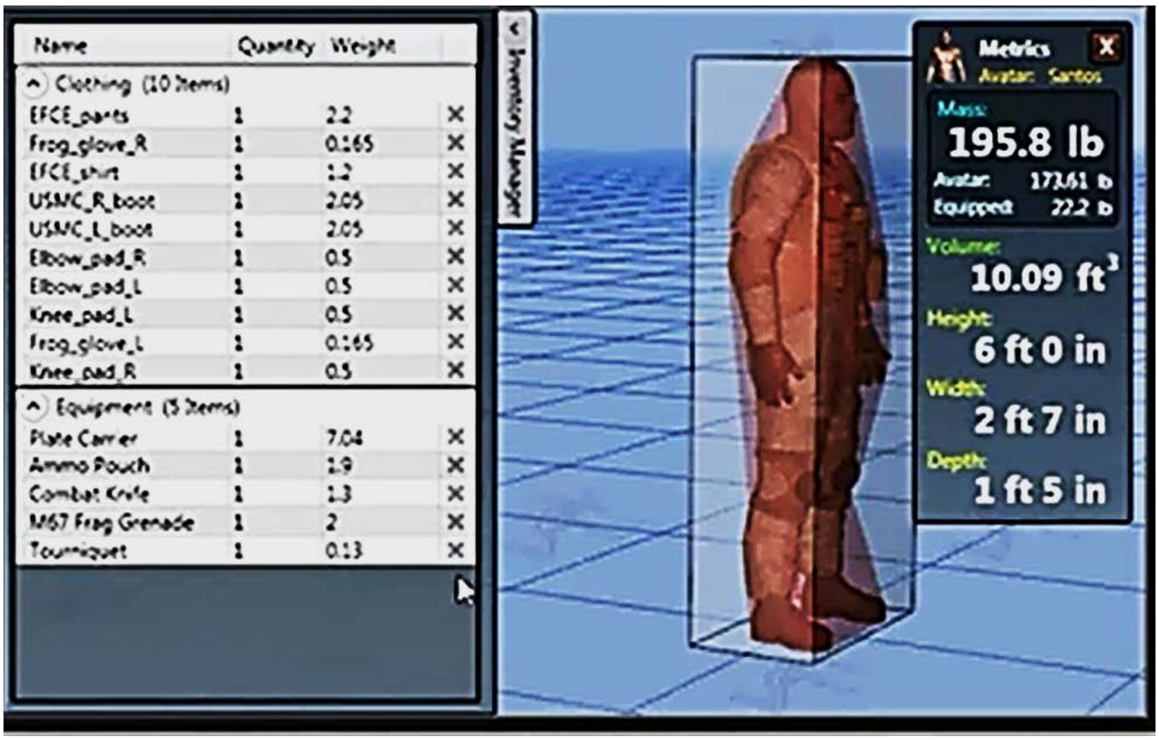


Figure 4: Representative avatar in SANTOS [16]

This process would evaluate comfort (endurance) of a specific tester in a specific inspection location. To provide future assessments on testing conditions, new biometric and inspection space parameters could be uploaded into the software code. If data on the tester and inspection space can be obtained, an assessment of an inspection condition could be provided remotely.

This method was not employed as it would increase the risk of testing. This would limit tester's willingness to participate as it required the collection of personal biometric information. The storage of this personal information would require stringent data storage processes. To be successful this approach would require a close coordination with the Human Systems Aircraft Accommodation/ Anthropometry/ Design for Maintainer Branch.

2.2.3. 2nd approach to HRA: Human Factors Assessment thru NASA TLX

This secondary approach had the testers provide a self-assessment on the inspection conditions they encountered and how they affected their ability to perform the needed task, during the testing process. This self-assessment was a modified NASA TLX survey. The NASA TLX is a multi-dimensional rating procedure that provides an overall workload score based on a weighted average of ratings on six subscales [45]. This survey is utilized to quantify the effort/cost incurred by human operators to achieve a specific level of performance [18]. The Official NASA Task Load Index (TLX) is a subjective workload assessment tool to allow users to perform subjective workload assessments on operator(s) working with various human-machine interface systems [17]. The approach and how to execute NASA TLX is available in the Appendix D: sections A-D.

This approach had several advantages:

1. It is a well-established and proven method of assessment. Developed by NASA Ames Research Center's (ARC) Sandra Hart in the 1980s, NASA TLX has become the gold standard for measuring subjective workload across a wide range of applications [17]. For example, it has been successfully used around the world to assess workload in various environments such as aircraft cockpits; command, control, and communication (C3) workstations; supervisory and process control as well as simulations/ laboratory tests [17].

2. It provides a quick and easy method of establishing workload and is reliably sensitive to experimentally important manipulations [18].
3. NASA TLX reports user generated answers, and therefore provides insight into the user's interpretation of workload/ performance limitations, using pairwise comparisons of subscales.

The primary disadvantage of implementation of this method is the potential introduction of a response bias [18]. For this effort the utilization of NASA TLX was the chosen approach to aid in the determination if limitations can be correlated with a decrease in inspection performance.

2.3 Selection of NDT Techniques to Utilize for Investigation

2.3.1. NDT Techniques of Consideration

NDT technology utilizes a diverse array of nondestructive processes to monitor/ measure direct material responses [46]. To select the proper method for any application, one should consider the following characteristics: The evaluation material, inspection environment, applied acceptance criteria, human factors and other considerations [46]. For our research purposes, the following selection criteria was used to select a test method and technique:

1. Must be used in naval aviation. Equipment and expertise currently available in NAVAIR Materials Division laboratory.
2. Easy to create appropriate test samples that represent naval aviation structures.
3. Easy to implement, set up & break down of test and equipment.
4. Subsurface detection capabilities, to allow detection to be solely from the equipment of the IS (no visual detection).

5. Sensitivity and reliability would change and be measurable as external variables of test change (produced quantifiable results for these tests).
6. Nonhazardous to testing personnel.

The following NDT methods were assessed for use in this investigation. Below in Table 2 is information on advantages/ disadvantages of each test method.

Table 2: Advantages and disadvantages of considered NDT techniques [19]

Method	Advantage	Disadvantage
Visual	Inexpensive, portable, minimum training and part preparation.	Surface detection only, not as sensitive as other methods.
Dye Penetrant	Inexpensive, portable, minimum training, sensitive.	Surface detection only, part preparation required.
Magnetic Particle	Potentially portable, inexpensive, sensitive, moderate skill required, subsurface detection capability.	Part preparation required, semi directional, ferro magnetic martials only, demagnetization process after test.
Eddy Current	Portable, subsurface detection capability, immediate results, sensitive.	Surface must be accessible to probe, only testable on electrically conductive materials. Skill and training required.
Ultrasonic	Portable, inexpensive, sensitive, immediate results, little part preparation, range of materials and thicknesses can be inspected, subsurface detection.	Surface must be accessible to probe, sensitive to discontinuity orientation, Skill required, couplant required.
Radiography	Subsurface detection, minimum part preparation, permanent test record	Safety hazard, very expensive, sensitive to flaw orientation, high degree of skill required.

Eddy Current became the chosen method for this study. Sensitivity and reliability of the equipment are highly dependent on the inspector's ability to keep probe normal to surface and as such physical hindrances can make it difficult to keep the probe of the instrument normal to the surface of test. The orientation of the probe with respect to the test object is critical [47]. Training, experience, and biometric considerations of testers could have a dramatic effect on IS performance, utilizing eddy current as a test method.

2.3.2. Eddy Current Principles

Eddy Current testing is widely used in all types of industries to evaluate the quality of materials and components, including both ferritic and nonferritic metals [47]. In an Eddy Current probe, alternating current flows through a wire coil and generates an oscillating magnetic field (a- See Figure 5 below) [20]. If the probe and its magnetic field are brought close to a conductive material like a metal test piece, a circular flow of electrons known as an eddy current will begin to move through the metal like swirling water in a stream (b) [20]. The Eddy Current flowing through the metal will in turn generate its own magnetic field, which will interact with the coil and its field through mutual inductance (c) [20]. Changes in metal thickness or defects like near-surface cracking will interrupt or alter the amplitude and pattern of the Eddy Current and the resulting magnetic field [20]. This in turn affects the movement of electrons in the coil by varying the electrical impedance of the coil [20].

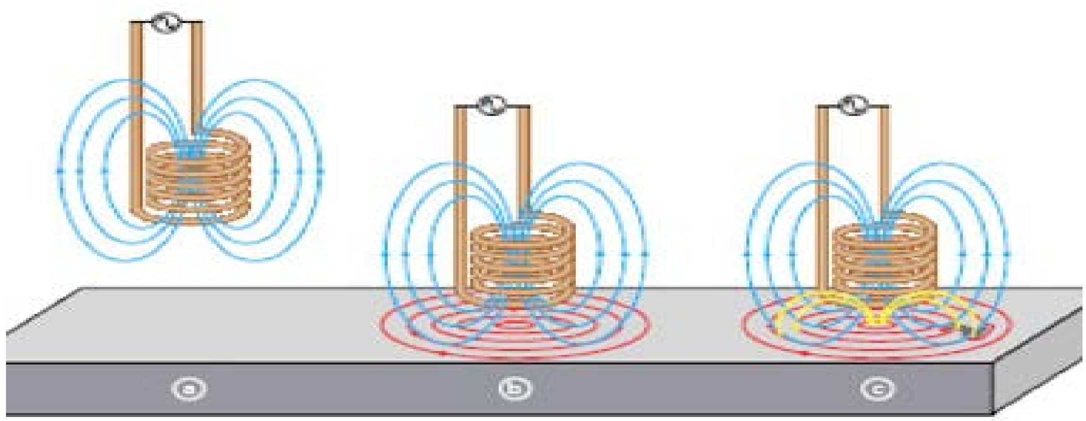


Figure 5: Eddy Current principles [20]

Eddy current density is highest near the surface of test (which is called "skin effect"). Because of the "skin effect", the depth of penetration of Eddy Currents is limited. However these Eddy Current's penetrate the structure of test and therefore the method has subsurface detection capabilities. Eddy Current testing is limited to surface and near surface evaluation of materials and products [47].

The permeability and conductivity of the test material as well as the frequency of the coil rotation, affect the current density of the eddy's in the tests material [21]. As shown below in Figure 6, increasing frequency, conductivity or permeability, increases eddy current density on the surface but decreases depth of penetration into the part.

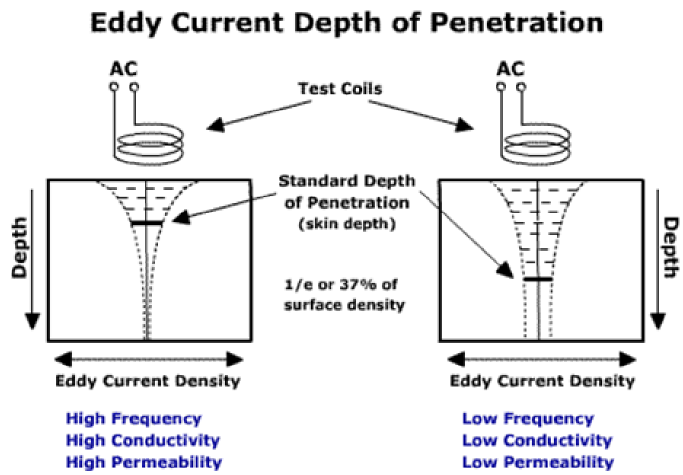


Figure 6: Eddy Current depth of penetration [21]

To understand the subsurface detection capabilities, the standard depth of penetration is defined as the depth at which the Eddy Current density is 37% of its surface value and is determined to be the maximum depth to reliably detect a defect [21]:

Equation 3: Eddy Current depth of penetration

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

Where:

$\delta = Standard\ Depth\ of\ Penetration\ (mm)$

$f = Test\ Frequency\ (Hz)$

$\mu = Magnetic\ Permability\ of\ test\ structure\ (\frac{H}{mm})$

$\sigma = Electrical\ Conductivity\ of\ test\ structure\ (\%\ IACS)$

In most Eddy Current instruments, the incoming signal is processed to obtain amplitude and phase components [47]. Changes in the impedance amplitude and phase angle can be detected by a trained operator (or triggered by pre-determined gates/ thresholds) to identify changes in the test piece. An impedance plane plot that graphs coil resistance on the x-axis versus inductive reactance on the y-axis for use in pencil probe inspections as shown below in Figure 7.

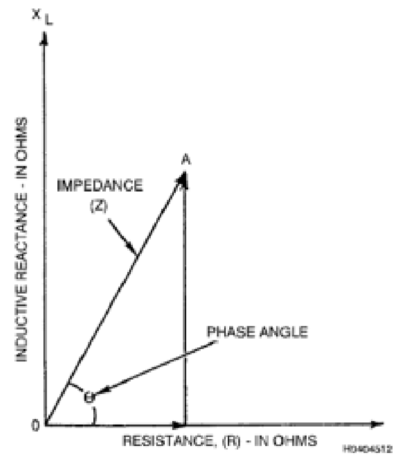


Figure 7: Vector diagram showing the relationship between resistance, reactance and impedance [55].

As you can see the electrical resistance & inductive reactance (opposition that an electric component offers to alternating current) components in Figure 7 above, can be combined to produce a net impedance of the coil [55]. The amplitude of impedance may be determined from the known values of resistance and inductive reactance [55]. Inductive reactance can be calculated by:

Equation 4: Impedance magnitude

$$Z = (X_L^2 + R^2)^{1/2}$$

Where:

$Z = Impedance\ magnitude\ (ohms)$

$X_L = Inductive\ reactance\ (ohms)$

$R = Resistance\ \ (ohms)$

It is common for the operator to choose a frequency at which the liftoff (distance probe is from test surface) lies on the horizontal axis of the display and the desired discontinuity signal displays vertically [47]. The larger the defect the greater the signal response that is created, due to the larger impedance of the eddy's. Figure 8 below shows the equipment response due to a .04" notch (1), .02" notch (2) and a .01" notch (3).

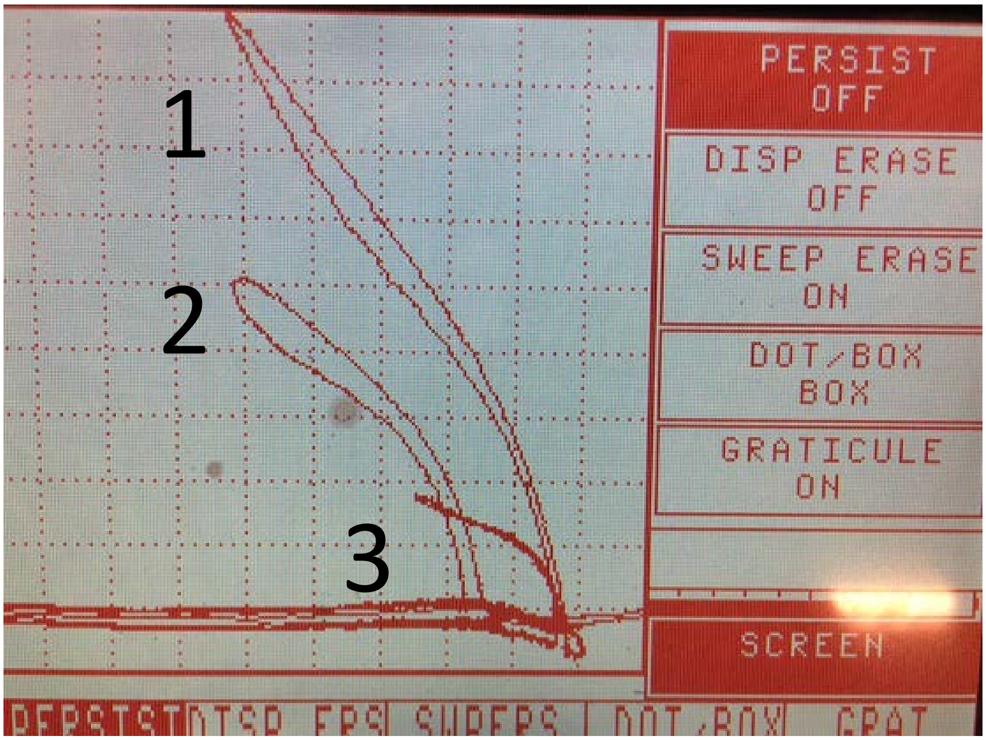


Figure 8: Eddy Current instrument responses of (1) .04", (2) .02", (3) .01" surface cracks.

Keep not that variations in the conductivity of the test material, its magnetic permeability, the frequency of the AC pulses driving the coil, and coil geometry will all influence the test sensitivity, resolution, and penetration during Eddy Current inspections.

2.4 Review Thoughts

POD studies are used to quantify capabilities of IS, however in these studies the effect of external variables on detection capabilities is typically not quantified. This could result in POD studies that may not reflect IS capabilities in operational conditions. The variables effect of these on the reliability- capability of a IS can be understood in the following equation:

Equation 5: Reliability of NDT IS [22]

$$R = f(IC) - g(AP) - h(HF)$$

Where:

$IC - Intrinsic\ Capability\ (Optimal\ performance\ ) of\ a\ NDT\ tecnique.$

$AP - Effect\ of\ Applipicaiton\ Parameters\ that\ reduce\ capability\ of\ IS.$

$HE - Effect\ of\ Human\ Factors\ on\ capability\ of\ IS.$

The intrinsic capability (physics based) of the technique & instrumentation is typically well known [22]. Effect of application parameters such as access restrictions, test structure surface conditions and human factors on IS performance are the subject of the treatise. The application parameters that will be studied are positioning oneself for an inspection (primary access), viewability of test surface (secondary access) [55]. The effect of human factors that will be studied are the tester backgrounds: experience and education. Other variables include differences in inspection samples and external variables of testing (such as ambient temperature). For this study, the IS will consist of a trained operator utilizing a common Eddy Current system in a representative operation area. After recording observations and inspection results, correlations will be assessed in the data to determine their effect on the IS capabilities. This information will give maintainers, designers, and planners a more realistic idea of what size/types of flaws that can be reasonably found- detected in field inspection conditions with the IS. For conditions that yield low detection results, alternate solutions will be assessed to address monitoring issues (such as the use of SHM's (Structural Health Monitoring Systems)) or automated IS to ensure capability and reliability of inspections.

Chapter 3: Experimental Procedure

This chapter covers all aspects of the testing and data collection of the effort. This chapter will cover in the following order, the design of test samples and final design, test bed assessment as well as testing locations to utilize for the study. General background information about the testers and pre-and post-test procedures to provide an overview of the method and type of data collection employed during testing.

3.1 Preparation of Test Specimens

3.1.1. Factors of Consideration in Determination of Sample Design

Damage size is a target characteristic but there are other characteristics that influence probability of detection, such as orientation of damage, morphology, density, defect locations and test structure shape [23]. While these factors can influence POD, the single most influential factor, is the size of damage and as such this parameter is predominantly used and assessed in POD studies [23]. Size and other aspects of design were considered in the design of test specimens as described below:

- *Size of Test Panels*- A large flat surface was used to ensure there would be no visual aids to judge progress on the inspection. Larger surface areas are more difficult to adhere to aircraft and take the inspector longer to test. However, the desired test length is > 30 minutes to ensure the inspector will not maintain sustained attention and will experience a vigilance decrement during the inspection. After the first 15 minutes of a scan looking for simple signals, the tester's sustained attention will probably decrease by 50%, and their attention does not significantly deteriorate after 30 minutes [24]. Almost all NDI techniques have an element of visual inspection [25]. For these tests the inspector monitors the signals from the equipment and keeps track of where the probe is on the structure and which areas have yet to be inspected. Performance for a visual inspection, measured by the probability of detecting a signal or imperfection in a given time is predictable (assuming a random search model) [25]. The probability of detection of a single imperfection in a time t is:

Equation 6: POD of a single imperfection in time

$$p_1 = 1 - \exp(-\frac{t}{\bar{t}})$$

$Where$

$P_1 = Probability\ of\ Detection$

$t = Length\ of\ Search\ Time$ (Sec)

$\bar{t} = Mean\ Search\ Time$ (Sec)

To create an estimate of the time required to inspect a surface: the mean search time for a visual inspection can be expressed as:

Equation 7: Mean search time

$$\bar{t} = \frac{t_0 A}{aPn}$$

Where:

$t_0 = Average\ time\ for\ one\ fixaiton$ (Sec)

$A = Area\ of\ object\ searched$ (Sec)

$a = Area\ of\ visual\ lobe$

$P = Probability\ that\ inspector\ will\ detect\ signal\ indicating\ damage$

$n = Total\ number\ of\ damage\ sites$[25]

- *Material Composition*- Choose a material that is common in Naval structures, inducing artificial damage into material is relatively easy, lightweight for portability, adherence compatibility with testbed and inexpensive.

- *Thickness*- Panels must be thick enough to sustain machining of damage, without creating additional damage or severely weakening the structure of the sample. However, if the samples are too thick, the weight may make it difficult to adhere panels to aircraft.
- *Depth of Damage*- There is a balance that must be maintained. It is desired that fabricated defects do not create a protuberance that is visually detectable on the test surface. However, if the bottom of drilled holes is not close enough to the test surface, they will not be detected with eddy current inspection techniques.
- *Size/ Types of Defects*- Utilized are a spectrum of sizes and defects that are barely detectable to ones that are easy to detect with eddy current inspection techniques.
- *Coatings to Apply to the Surface of the* Panel- Should exhibit or represent coatings and paints applied to Naval aircraft structures.

3.1.2. Determined Design of Testing Samples

The following characteristics were incorporated into the final design of the panels:

- *Size of Test Panels*- a 12" by 12" panel was deemed to be optimal, for portability, adherence to aircraft and desired inspection duration.
- *Material Composition*- Aluminum 7075 was chosen to be the sample material of choice. This alloy is used in aerospace structures such as stringers, skins, bulkheads, rivets and extruded sections [13]. Aluminum is relatively light and inexpensive compared to steel and titanium.
- *Thickness*- For this application, 1/8" inch thick panels were deemed optimal which allowed for safe machining of defects and provided enough material to ensure strong eddy currents did not propagate to the back surface of material. If

this propagation were allowed (due to utilizing a thin panel), it could cause erroneous results in inspections.

- *Depth of Damage*- By testing the eddy current response from scanning over holes of different depths, the optimal depth was determined to be approximately (.01”) deep (from the inspection surface). As shown in Figure 9 below, damage holes at this depth would be detectable by eddy current and would not create a protuberance on the test surface, revealing their location.

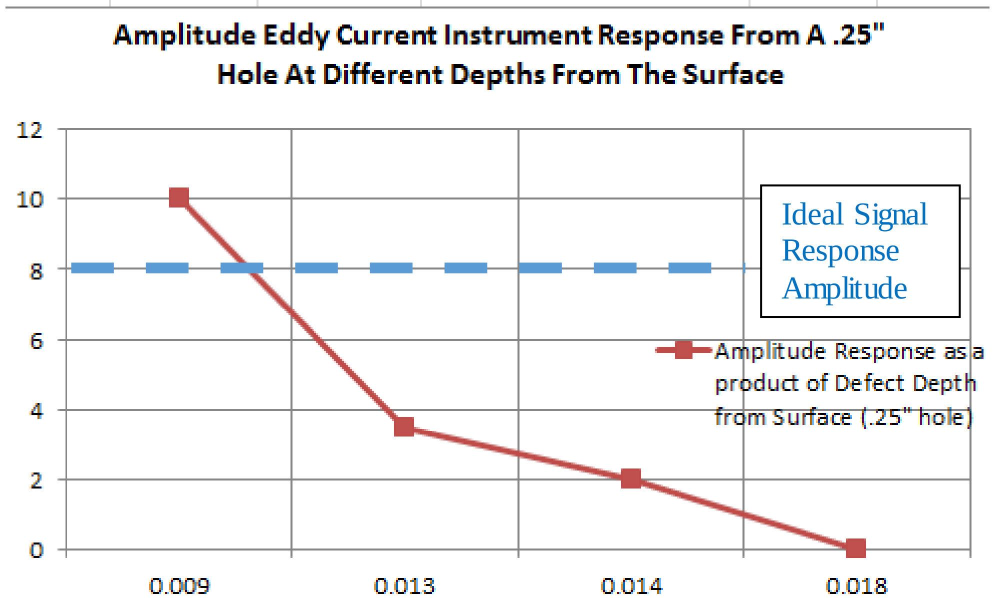


Figure 9: Amplitude response (dB) as a function of damage depth from inspection surface (in).

- *Size/ Types of Defects*- It was economical to create flat bottomed holes (using drill press) and slots (elongated linear defects, using a mandrel) at approximately .01” deep. There is one instance of a defect created on the test surface of a panel using a saw cut. This panel was utilized for blind inspections (positions where the inspector could not see the surface of the test panel). Sizes of defects ranged from .06” (1/16”) all the way to 5” in length. Defects larger than .25” were slots (and in one case a saw cut). Defects less than .25” were holes. Defects of size .25 were either slots or holes. Figure 10 below shows the damage size distribution from all the test samples.

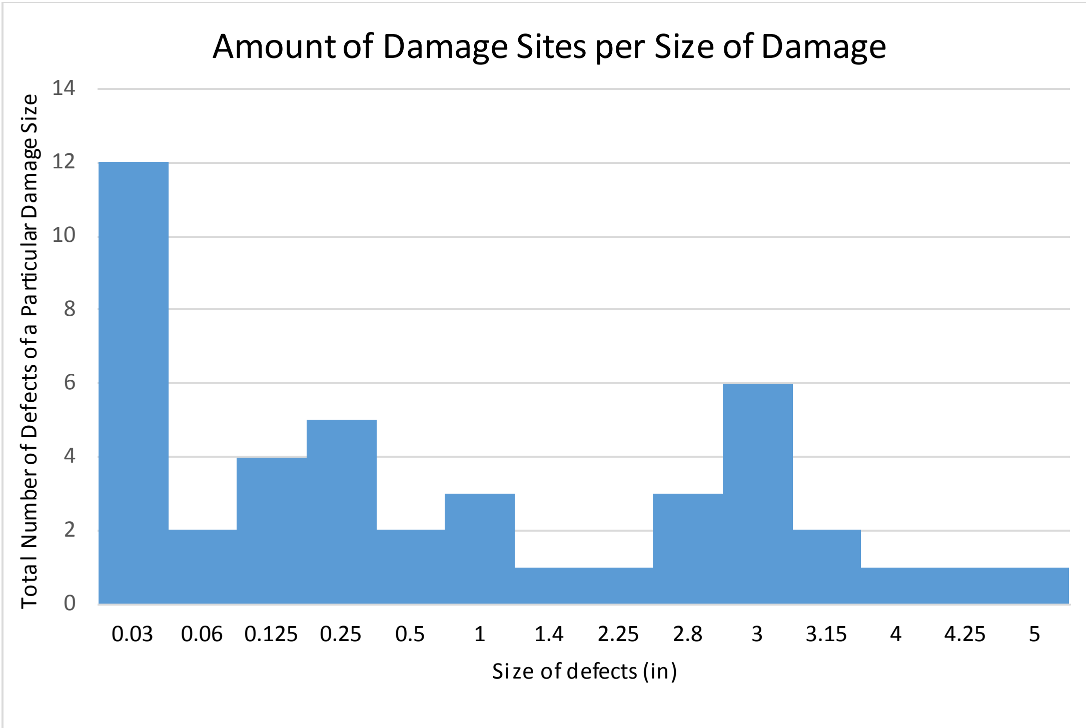


Figure 10: Distribution of damage sizes (in) fabricated in the combined test panels.

- *Coatings to Apply to the Surface of the Panel*- For coating aluminum and aluminum alloys, the Department of Defense follows guidance contained in:
  - MIL-PRF-85285E [26]: Coating- Polyurethane, Aircraft & Support Equipment. The topcoat on these panels was approximately 2.22 mills thick (average).
  - MIL-PRF-85582E [27]: Primer Coatings- Epoxy, Waterborne. The waterborne primer on these panels was approximately .83 mills thick (average).
  - MIL-DTL-5541F [28]: Chemical Conversion Coatings on Aluminum and Aluminum Alloys.

- The paintings- coatings on these panels were pretreated first with chromate conversion coating then painted the next day with a conversion coating (following guidance of MIL-C-5541 Type 1, compositions containing hexavalent chromium).

The test samples were ten 12” x 12” x 0.125” 7075 aluminum panels purchased from McMaster-Carr (Product #: 885K15). After receipt of these panels, technicians from the Machining Branch in AVMI (Air Vehicle Modification & Instrumentation) fabricated damage in each panel per guidance contained in Appendix F (Panel Design) which shows the damage layout (position & size) in each panel. After fabricating defects, the inspection surface was sprayed with a thin nonconductive coating by technicians from the Inorganic Coatings Lab. For the application of this coating they adhered to the guidance in MIL-DTL-5541F. The coatings were applied to the surface with a total thickness of approximately .003” thick.

3.2 Assessment of Testing Locations

3.2.1. Test Bed Utilized for Study

As discussed earlier it is important that the tests were executed in a representative operational environment, to accurately determine IS capabilities in Naval field conditions. There were two different considerations of testing platforms to utilize for this effort, both located at Patuxent River Naval Air Station.

- Option 1: The T-Rex helicopter test bed. These were 2 UH-1N Helicopters, owned by NACRA (Naval Aviation Center for Rotorcraft Advancement). The organization’s purpose is to demonstrate and develop technologies in a naval rotary wing environment. These flying test assets are equipped with instrumentation racks and electrical systems that allow them to become system simulators for virtually any rotary wing type platform [29]. Figure 11 below is a picture of one of the test assets.

Figure 11: NACRA test asset

- Option #2: A retired MH-60, located behind building 2188. The airframe is used to test new sacrificial laminates that protect windscreens against erosion. The US Navy has contracted VTOL LLC to develop an improved version of the protective laminate that would be suitable for the marine environment. Improvements made to the V1 product during this effort include: an increased adhesive bond strength, extended UV life, easier installation and removal, improved moist/humid performance, and increased total light transmission [30]. The sacrificial laminate film is composed of a PET polymer and has no HAZMAT issues and therefore was not detrimental to the testers on the aircraft. Permission to use test bed was given by Paul Roser (who acquired the test bed) and 4.3.4 management. As a condition of the permission, it was required that testers did not climb on aircraft and that their feet never left the ground during the testing process. Figure 12 below shows pictures of the test asset.

Figure 12: MH-60 test bed.

The MH-60 was chosen as the best testing option as it was structurally identical to actual aircraft flown in the Navy. Currently there are more than 500 MH-60's in the Navy and they are utilized for anti-submarine warfare, search and rescue, vertical replenishment & medical evacuation [50]. Additionally, there was no competition with flight test schedules and the location of the test bed was very close to normal work location. However, some testing locations inside the aircraft were disqualified for study to accommodate the risk requirements of management.

3.2.2. Testing Locations Around Aircraft

Discrete areas of test were chosen around the aircraft. The chosen positions had to represent a spectrum of possible inspection positions encountered for inspections of aircraft structures. The following were the variables assessed of the testing locations:

- Physical Restrictions- From no restriction to severe restrictions that limit movement/ accessibility.
- Visual- Secondary access (the ability to see the inspection surface). The degree of blocking of site of the test surface. Objects partially or totally blocking the tester's ability to view the inspection surface. This also investigates the angle of view of

the inspection surface (see Figure 13 below). If θ = 90 degrees, the inspection surface is perpendicular to the line of site of the inspector. As θ decreases, it becomes more difficult to view the inspection surface.

Figure 13: Spatial viewing angle.

- Anthropometric Accommodation:
    - The comfort of the assumed anatomical position of test. Positions that are relatively neutral (see Figure 14 below) to ones more complex and taxing.
    - Fatigue- From positions that are comfortable to others that invoke fatigue in test subject.

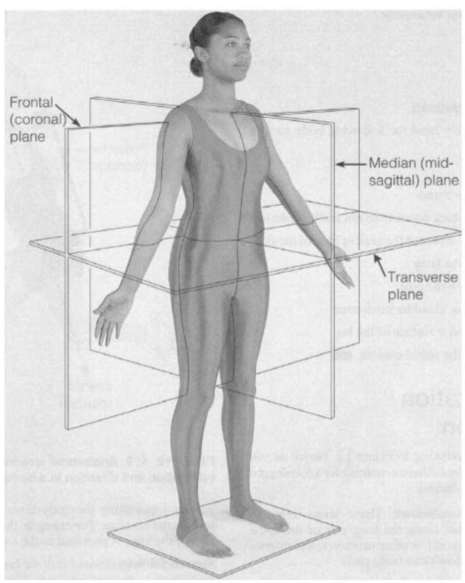


Figure 14: Planes of the body. [31]

Each inspection position chosen for tests is shown in Appendix E, Part A. For each position a corresponding OWAS (Ovako Working Posture Analysis System) value was used to determine the relative harm and discomfort of each inspection position.

OWAS has been used in other domains to analyze the postures of workers. It is a simple observational method for analyzing and controlling poor postures at a worksite [32]. These observations are contained in the Appendix E, Part B.

3.3 *Assessment of Testers*

Information on the testers was gathered by observation and thru a survey completed by testers (Survey is contained in Appendix G, Part A). Some general information about the inspectors is contained below:

1. Age: Ages ranged from mid-twenties to late fifties. Four of the testers were younger than the late thirties and 2 of the inspectors were older than their mid-forties.
2. Sex: Two were female the rest were male.
3. Education Level: One tester possessed a master's degree & another attended the Navy NDI School. The rest of the testers possessed bachelor degrees. All testers had some training on eddy current inspection techniques. Four of the testers has ASNT III certifications in ET testing.
4. Attitude: Inspectors were volunteers and were asked a week ahead of time when they could devote 2 hours to support a test.
5. Experience level: This varied- 2 testers had over 20 years of experience in NDT either in military or government service. The rest of the testers (4) had 10 years or less working for the government in NDT.
6. Unique Techniques Implemented: For half of the blind inspections, a linear guide was used (see tester notes). This may have aided in the detection and assessment capabilities of these inspections.

3.4 Testing/ Inspection Procedure

3.4.1. Pre-Testing Procedures

To prepare, set up and execute a test, the first step was to determine which test points to obtain, utilizing the test matrix shown in Table3.

Table 3: Initial Test Matrix*

Defects	Easy				Hard	Explanation
	1	2	3	4	5	Panels
Quantity	1 or 2	3 or 4	5 or 6	7 or 8	9 or 10	Amount
Quality	>2.5	2.25 to 2	1.9 to 1	.9 to 0.51	<.51	Ratio of small defects to large defects
	Ratio of defects >1.1" to defects <1.1"					
Test Condition	Easy				Hard	Explanation
	1	2	3	4	5	
Access	none	Slight	Non Optimal	High Hin	Cannot Reach all of Panel	Hinderance
Bod Pos	Very Con	Confortabl e	Slight Disconfort	Unconfortabl e	Very Unconfortable	Confort
Fatigue	0	few	few long	multiple	frequent	Breaks
Visual	No Block	tiny block	partly block	extens block	total block	% block
Angle	90-75	75-50	50-35	35-20	20 to 0	Theta
Inspector	Easy				Hard	Explanation
	1	2	3	4	5	
Background	EC III	Basic III	FLT Test EC I	EC II or School	EC II>	Training
Yrs of Exp	>15	10 to 15	5-10	2-4	<2	Experience

***Top table shows the variables in the test panels, middle table shows the variables from testing locations, and the bottom table shows the variables from the tester**

The test philosophy was to create useful data points under various conditions and repeated tests under similar conditions. This information help generate a better understanding of the IS capabilities under varied field conditions. Testing was executed in the following fashion: The test designer had to assess if outdoor conditions would allow for safe testing, if personnel, equipment (IS) and test needs (tester, panel and location involved in test) were available and set up. The test designer asked the tester to clear 2 hours in their schedule to support a test. This included the time to calibrate equipment, inspect, report findings and to fill out NASA TLX Assessment. Testing was commenced only under the following conditions:

- Within ambient temperatures of 40-100 F (4.5- 38 C). This limitation was incorporated to ensure safe testing conditions, but also to limit the effect of temperature conditions on human performance of these tasks. A study was performed to assess the effect of temperature on performance of tasks and they observed: a decrease in performance by 2% per degree C increase in temperature of the range 25-32 C (77 -90 F) and no effect on performance in temperatures ranging of 21-25 C (70-77 F). [33]
- For safety testing would be halted if lightning was in the immediate vicinity or there was heavy precipitation.
- All participants were: At least 18 years of age and were civilian government employees. It was desired that testers had a technical background in NDT & that they were: an employee and/or rotational assignee of NAVAIR 4.3.4.3 AND/OR a graduate of the Navy NDI School in Pensacola Florida AND/OR possessed a technical interest in participating in the project and received training in basic Eddy Current Principles and Inspection Techniques.
- At any time, a tester could refuse to test or ask for changes to be implemented to the inspection (such as changing the location of testing). In the unlikely event of an incident requiring medical attention for a participant, the experimenter will cease all testing, call Emergency Services and inform the Internal Review Board (IRB) of the event. No further testing could take place until the IRB has approved a restart after such an event.

A pre- test check was performed of the inspection area before a participant executed a test:

1. Test panel was firmly secure to the surface of the aircraft.

2. Testing area was safe and to assess, mitigate or note of any potential hazards.

3. The tester monitor was an individual required to complete Collaborative Institutional Training Initiative (CITI) and was listed in the protocol package. Their task was to ensure that test equipment is ready: a thermometer, watch, clipboard with a rating scale, Modified NASA TLX Survey and Defect Nomenclature Sheet were available and ready to use.

3.4.2. Testing Procedures

The following steps were followed in the order shown:

1. Tester was shown the location of the panel on the aircraft. This allowed the tester to assess which probe was the most appropriate to use for the test.
2. Tester was given the following equipment which consisted of:
    a. EC Instrument Nortec 2000D+ EMI. The instrument offers a frequency range of 50 Hz to 12 MHz for Eddy Current test applications. [34].
    b. SPCK-429-1, Surface Probe Kit: PAB0030: 3 Pencil probes with ABS bridge (TRIAX LEMO). Shaft is 3” in length and made of stainless steel. Exhibits a frequency range of 50-500KHz. Probes were either straight, 45 or 90 degree probes. All made by EC NDT.
    c. Eddy Current Standard: VMA. 01-0-07T (for 7075 Aluminum Alloy).
    d. Grease Pencil
3. Tester was given the following paperwork:
    a. Procedure (located in Appendix B): Inspection Procedure.

    b. Defect Nomenclature Worksheet (Appendix C)
    c. NASA TLX (Appendix D, Parts A-C) which consist of the following worksheets:
        i. Ratings of Descriptors of Inspection
        ii. Weightings of Descriptors
        iii. Inspection Descriptor Rating Scale Definitions

4. Tester then calibrates the equipment in an outdoor area and as per the guidance in inspection procedure (Appendix B).
5. Execution of test: Tester transports the calibrated equipment to the identified testing location and commences with the inspection of the test panel. Any damage that is detected, the locations is marked with a grease pencil. In route to the inspection location the test observer informs the tester of potential hazards that may be encountered while testing. During the test the test monitor takes a measurement of the temperature 20 minutes into test and assists the tester if there are questions or concerns. The test monitor indicates if there are any deviations from a normal test i.e. hindrances from wildlife, distractions from coworkers, test areas wet from previous rain all are to be recorded.
6. Report Inspection Results: At the conclusion of each test, the panel is removed from the aircraft and the tester uses a ruler to measure the size and position of the discovered damage. This information as well as characterization of the flaws is put on the Defect Nomenclature Worksheet (located in Appendix C: Defect Nomenclature Worksheet).
7. Lastly the tester fills out a post inspection NASA TLX questionnaire that helps to assess the overall hindrance encountered during the inspection.

3.4.3. Post Test Procedures

The participant's assessment will be compared to the known status of the panel. This "Grade" will be used to determine the effectiveness of the inspection.

1. The information in the filled-out Defect Nomenclature Worksheet is compared to actual defects in the test panel.
2. There were a few circumstances where the test data was censored from further analysis if it met the following conditions:
    a. When the tester reported the position of the defect and that reported position covered the locations of more than one damage area in the test panel. Also in cases where it was unclear which defect was detected by the tester, the data of the defects was censored.
    b. Censoring of Measured vs True Size of Damage Areas- In cases where a single defect was reported as multiple defects, it was unclear how to assess the tester's reported size of the defect, therefore the tester was given credit on discovering the defect, but the data on their assessment of sizing was censored.
3. The following information could be obtained from the recorded data:
    a. Position:
        i. For a slot: the length and the position of each of the endpoints.
        ii. For a hole: the position of the center of the hole and the diameter.
    b. Amplitude response: The tester indicated the observed response of the instrument.
    c. Characterization: Indicated if tester thought the damage was circular or elongated, was it a slot or a hole?

d. Detection: was the defect detected?

The results of the tests are listed in: Chapter 5, tables 5 & 6 as well as appendix H & I.

Chapter 4: Analytical Approach

In this chapter, the following information will be covered: The assessment process an inspector utilizes to discover and interpret potential defects. Also the assumptions made during the creation of analytical models that were utilized to assess probability of detection. In the analysis three potential distributions were used to model the parameters of detection probability vs damage size. These analytical distributions are: the lognormal, logistic and log logistic. The approach adopted to assess actual vs measured defects and potential sources of measurement error.

4.1 Assessment of the POD of IS

4.1.1. Introduction to the Assessment Process

When a tester is inspecting a structure and assessing the output of equipment (either continuously or discrete intervals) one of the results are obtained in Table 3:

- True Positive: Flaw is found when a flaw is indeed present (Correct Reject)
- False Positive: Flaw is found when no Flaw is Present (False Call)
- False Negative: No Flaw found when a Flaw is Present (Miss)
- True Negative: No Flaw found when no Flaw is Present (Correct Accept)

Table 4: Conditional probability in damage detection [35]

NDE Signal Flaw Response	Flaw Present	Flaw Not Present
POS A	True Positive (T.P.-flaw present and detected). NO ERROR	False Positive (F.P.-flaw is detected, but not present). TYPE II ERROR
NEG N	False Negative (F.N.-flaw is present but not detected). TYPE I ERROR	True Negative (T.N.-no flaw present and detected). NO ERROR

After an inspection, the Probability of Detection (POD) of the IS may be expressed as:

Equation #8 Probability of Detection

$$POD = \frac{T.P. = Total\ Number\ of\ Positive\ Calls\ (Rejects)}{T.P. + F.N. = Total\ Number\ of\ Oppourtunities\ for\ Rejection}$$

The POD will be calculated for each defect size that was tested. A distribution is assumed and the maximum likelihood is used to estimate the parameters of the model, based from the data generated by the tests and data observed.

The likelihood L of P (detection) follows a Bernoulli model:

Equation #9: The likelihood of P(detection):

$$L(P_i : a_i, x_i) = P_i^{x_i}(1 - P_i)^{1-x_i}$$

$P_i = Probability\ of\ Detection\ of\ Crack\ Size\ a_i$

$x_i = Inspection\ Outcome\ (0 = miss, 1 = hit)$

Equation #10: Maximum Likelihood POD

$$\ell = \prod_{i=1}^{N_D} POD(a_i|\theta) \prod_{j=1}^{N_D} [1 - POD(a_j|\theta)]$$

$a_i = Truth$

$N_D = Detected$

$P_{FD} = Probability\ of\ False\ Detection$

4.1.2. Assumptions

One of the most widely used methods of estimation is the Maximum Likelihood Estimate (MLE) [57]. This analysis utilizes MLE and the experimental data to determine the maximum likelihood parameters of the POD model. This approach is not only to determine the parameters but also which mathematical distribution will best fit the data. 3 different mathematical distributions will be investigated: Lognormal, Logistic and Log Logistic.

The model will be based on the following assumptions:

1. The assumed minimum detectable flaw size is .005”. For the experiments the instruments were set up to allow for the optimal detection of a .02” flaw, which would create an 8-deviation signal on the machine. Damage of half that size for the same calibration would create half as high of a signal (.01” flaw would create a 4-deviation signal response). A 2-deviation response (.005”) would be barely discernable above noise in the signal. This is an estimate of the lower threshold of detection capability but there are many factors that affect this value: size of the probe, frequency of rotating coil, material of inspection, surface finish and other characteristics.
2. That there is no inspection ceiling, (as damage gets larger the probability of detection increases). However, the POD never reaches 100%).

4.1.3. Lognormal Distribution

The Lognormal probability distribution function is described as:

Equation #11: Lognormal probability distribution function [48]

$$f(t) = \frac{1}{\sigma_N t\sqrt{2\pi}}\exp[-.5\left(\frac{\ln(t) - \mu_N}{\sigma_N}\right)^2]$$

With a scale parameter of μ_N & a shape parameter of σ_N

The Lognormal Cumulative Distribution Function is:

Equation #12: Lognormal cumulative distribution function [48]

$$F(t) = \Phi(\frac{\ln(t)-\mu_N}{\sigma_N})$$

Where Φ is the standard cumulative normal distribution function.

Then using MLE to find parameters:

Equation #13 Lognormal MLE

$$\ln(l) = \sum_{i=1}^{N_c} n_i * \ln[f(t_i:\theta_M)] + \sum_{j=1}^{N_r} n_j \ln[1 - [F(t_j:\theta_M)]]$$

Find: $\frac{\partial ln(l)}{\partial \theta_M} = 0$

4.1.4. Logistic Distribution

The Logistic probability distribution function is:

Equation #14: Logistic probability distribution function [48]

$$f(t) = \frac{1}{4s} sech^2 (\frac{t-\mu}{2s})$$

With a scale parameter of <u>s</u> & location parameter of <u>μ.</u>

Logistic Cumulative Distribution Function is:

Equation #15: Logistic cumulative distribution function [48]

$$F(t) = \frac{1}{2} + \frac{1}{2} tanh(\frac{t-\mu}{2s})$$

4.1.5. Log Logistic Distribution

The log-logistic_probability distribution function is:

Equation #16: Log logistic probability distribution function

$$f(t) = \frac{(^{\beta}/_{\alpha})(^{x}/_{\alpha})^{\beta-1}}{(1+(^{x}/_{\alpha})^{\beta})^2}$$

With a scale parameter of <u>α </u>& a shape parameter of<u> β.</u>

<u>*Log- logistic Cumulative Distribution Function*</u> of:

Equation #17: Log logistic cumulative distribution function

$$F(t) = \frac{1}{1+(^{x}/_{\alpha})^{-\beta}}$$

The POD model is a simple, broadly applicable model for qualitative validation of statistical parameters [36]. According to source [11] the data used to create the POD model should exhibit the following characteristics:

- Minimum number of data point for Hit/ Miss is N=60
- A uniform distribution of target sizes
- Target range should result in POD coverage from 3% to 97%
- Possibility of a POD floor or ceiling should be kept in mind [37]

4.2 Measured vs. True Defect Sizes

Not all the data obtained during these tests is Bi-modal. Testers were instructed to assess the size of the defects they discovered during the tests. The analysis of measurement error is based on evaluating the deviation of the measured defect size from the actual or true defect size. Systematic Error (bias) may indicate overestimation (positive bias) or underestimation (negative bias) [39]. The analysis of error is based on:

Equation #18: Measurement error

$$E_M = a^* - a$$

$E_M = Measurement\ Error$

$a^* = measured\ size$

$a = actual\ size$

A linear regression model was used to model the measurement error as shown in equation #19:

Equation #19 Linear Regression Measurement Error:

$$a^* = ma + c + \varepsilon(0, \sigma_a)$$

$m\ \&\ c = Regression\ Coefficients$

$\varepsilon = Random\ Error\ in\ Measurement$

4.3 Summary

In summary, the following analysis is provided:

1. Assessments on the following POD analytical distribution models: Logarithm, Logistic and Log Logistic. An assessment will be made on the ML value of the parameters of each distribution.
2. Assessment of measured vs the true size of defects. Discussion will include;
    a. True size of defects vs measured size.
    b. True size of defect vs percent error of measurement.
    c. True size of defect vs oversizing/ under sizing defect.

Chapter 5: Results

This chapter covers the following: The analysis of the POD test data; and a comparison of different analytical distributions to model these relationships. Next the linear regression analysis of the relationship between measured vs actual damage sizes is covered. Discussed last will be the sources of potential errors in sizing of the IS.

5.1. POD Analysis

5.1.1. Assessment of POD

Out of 25 executed tests, 124 data points (on POD) were collected. Five of these data points have been censored because the testers marked one defect over the position of many defects and as such it was unclear which damage areas were detected by the IS. For additional information on censoring refer to section 3.4.3. To support the POD analysis, 119 data points were used that were obtained from the tests as shown in the data table below, Table 4.

Table 5: POD results

Size of Flaw (in)	Hits (detections)	Total Tested	Averaged POD
.03”	14	28	.5
.06”	3	4	,75
.125”	11	12	.92
.25”	9	10	.9
.5”	1	1	1
1”	2	2	1
1.4”	11	11	1
2.25”	4	4	1
2.8”	15	15	1
3”	15	15	1
3.15”	6	6	1
4”	5	5	1
4.24”	5	5	1
5”	1	1	1

This table displays the total amount of POD data points for each size of tested defect. In the leftmost column is the size of the damage area is displayed. The next column shows the total damage areas detected of a particular damage size. The 3rd column display the number of tested damage areas of a particular size. The last column displays the averaged POD (column 2/ column 3). What is observed is an expected trend, as damage size increases; the damage has a higher likelihood to be detected. The one exception is the comparison between damage sizes of .125” to .25”. In both circumstances one flaw of a particular damage size was not detected, however the smaller flaws had a greater number of tests (and thus yielded a higher averaged POD). Figure 15 shows the size and quantity of damage areas that were tested.

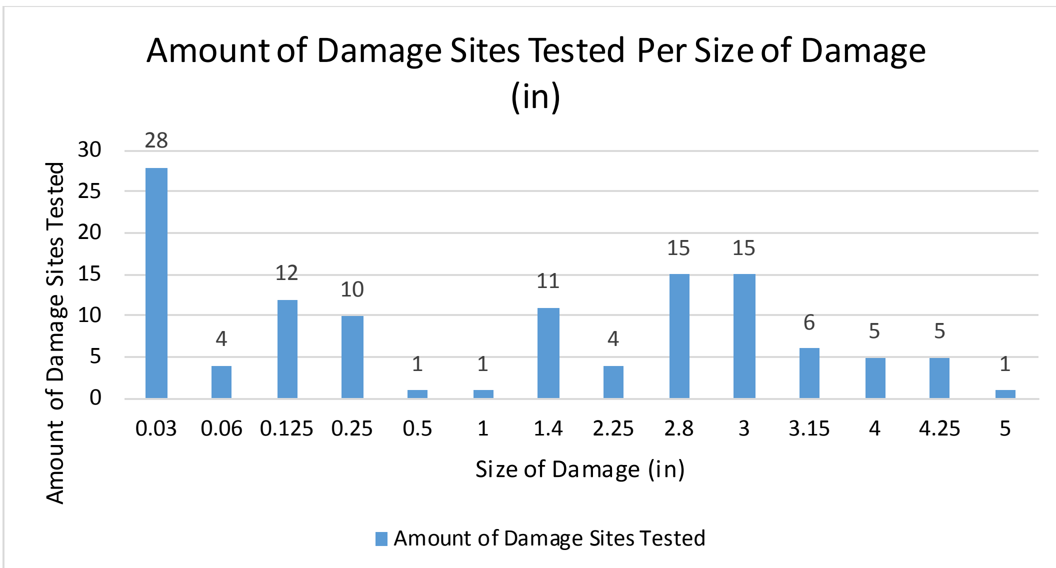


Figure 15: The amount of damage sites tested per size of damage area

5.1.2. Modeling of POD

Using data obtained from testing (Table 4), assessments were made on the fit of mathematical distributions to the data to model the behavior/ relationship between damage size and the IS POD in the varying testing conditions. The Matlab code utilized for these models can be found in the appendix: J, parts A-C. Below are the analytical models, with confidence intervals, the MLE value of parameters and a brief discussion. The model results for damage size <.005” will be ignored as this is the deemed minimum detectable flaw size.

Lognormal Fit

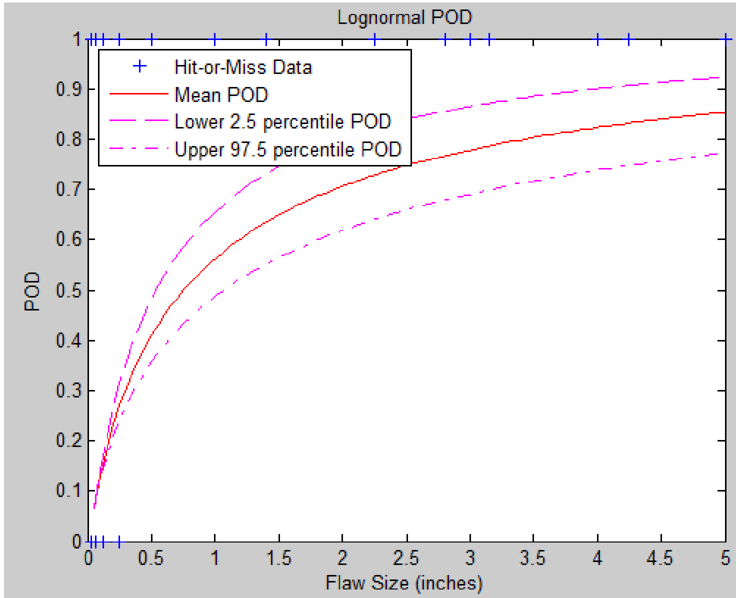


Figure 16: Lognormal fit of the POD data

ML mean parameter μ_N = -.31

ML standard deviation parameter of σ_N= 3.1

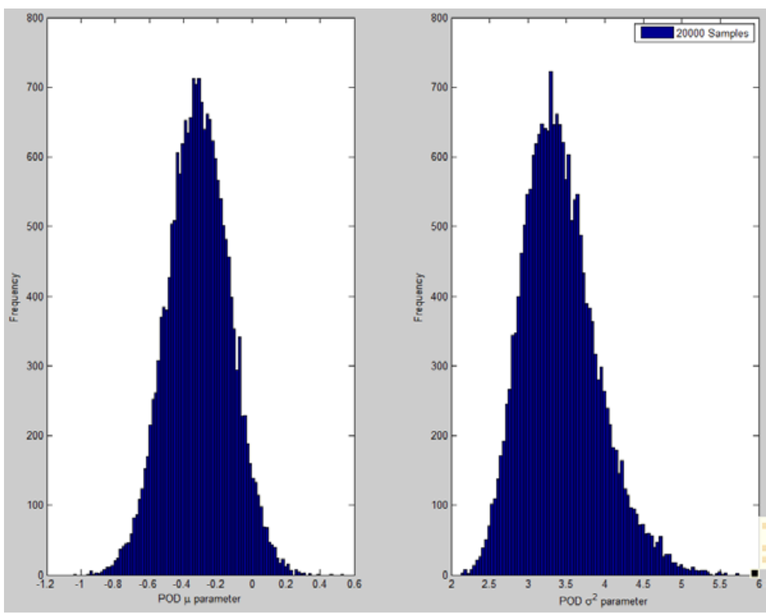


Figure 17: ML mean parameter (left) & ML standard deviation parameter (right) of a lognormal fit to the POD data

Discussion of Lognormal Fit: There are no significant issues in modeling the behavior of the IS with this distribution.

Logistic Fit

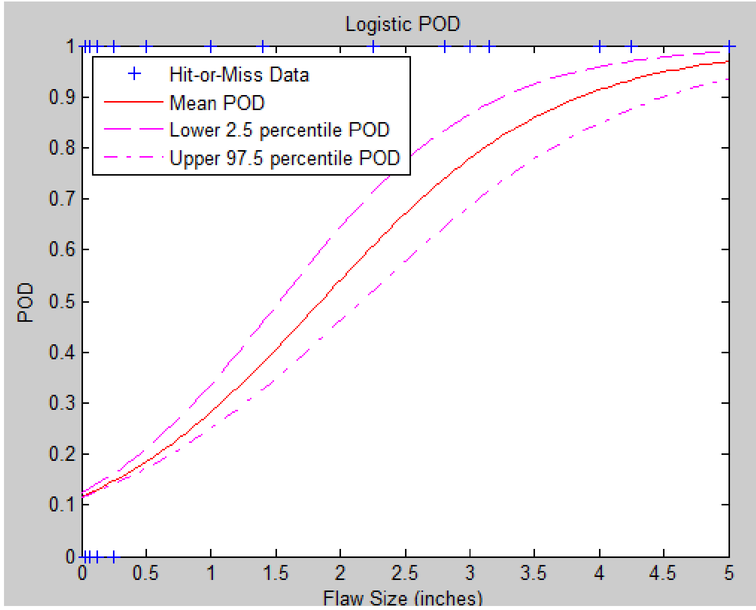


Figure 18: Logistic fit of the POD data

ML scale parameter of s = .9

ML location parameter of μ.= 1.8

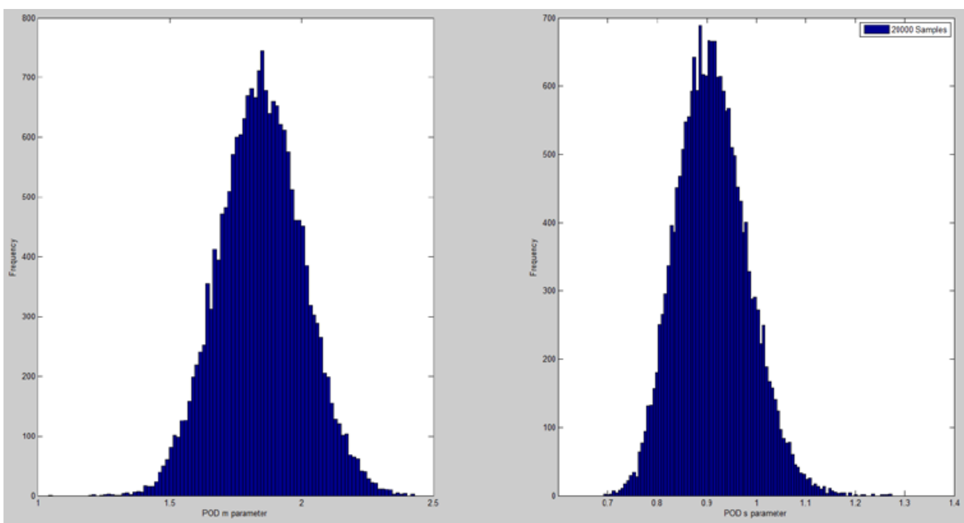


Figure 19: ML scale parameter (Left) & ML location parameter (Right) of a logistic fit to the POD data.

Discussion of Logistic Fit: As the flaw size approaches zero, the POD does not converge to zero. Instead it reaches an asymptote at approximately 10% POD. Assuming that model is valid for damage >.005" it is therefore a candidate for a good fit.

Log Logistic

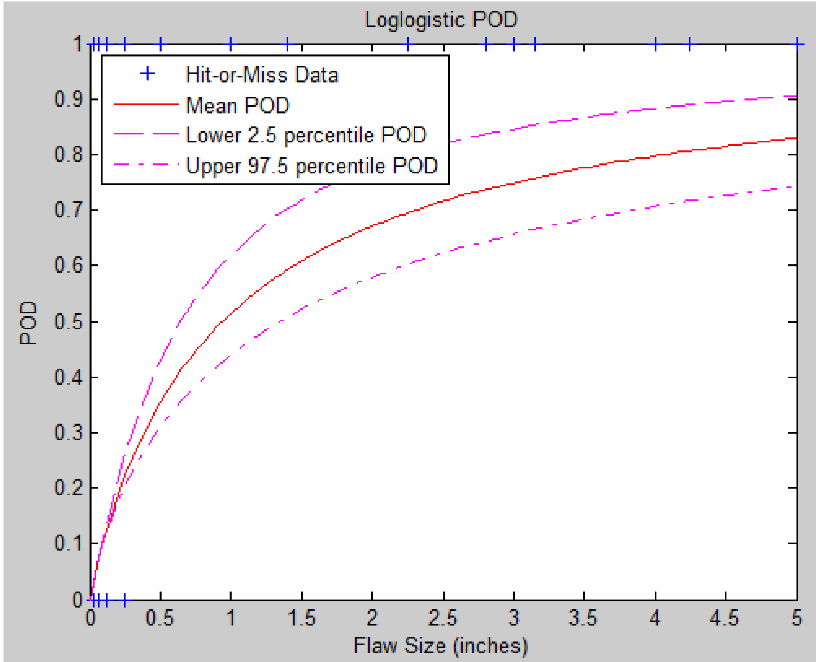


Figure 20: Log logistic fit of the POD data

ML scale parameter of α = -.5

& a shape parameter of β.= 1.03

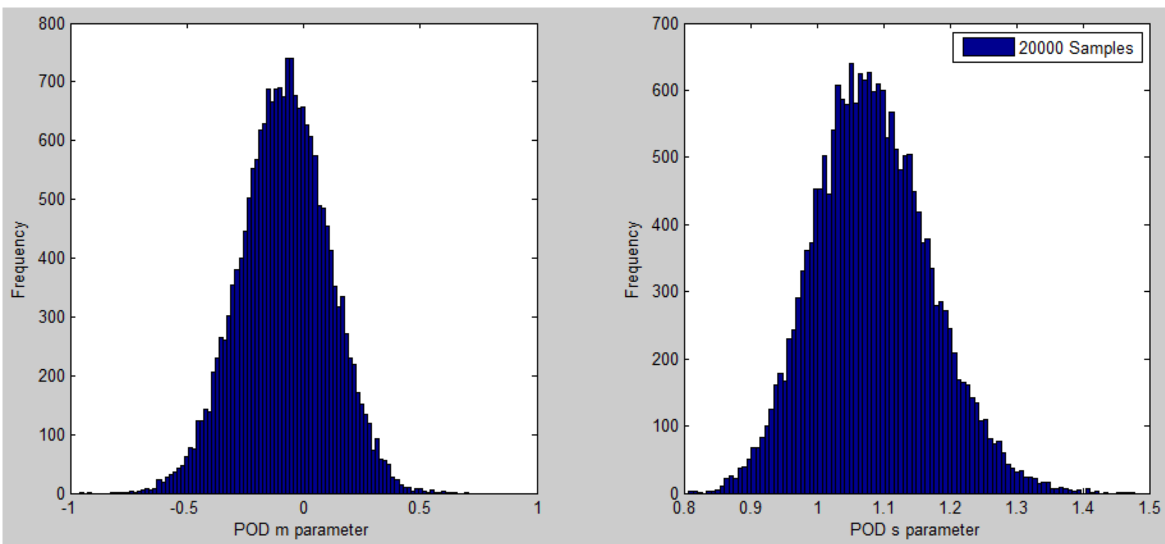


Figure 21: ML scale parameter (Left) & ML location parameter (Right) of a log logistic fit to the POD data

Discussion of Log Logistic Fit: There are no significant concerns to the fit of this distribution to the data.

5.2.3. Assessment of Models

To determine if the models do a good job of depicting IS behavior, compare their results to past data of similar IS. It is expected that for a conventional eddy current IS utilizing a pencil probe for free hand scanning of a flat open aluminum surface less than 4" square that a crack of length .25" and depth of .125" has a $a_{90/95}$ of being detected [40] (where $a_{90/95}$ is equivalent to saying the IS can find (out of 10 flaws of that size with a 95% confidence). Our analytical models predict:

Lognormal $a_{90/95}$ = 10" (Estimated)

Logistic $a_{90/95}$= 3.85"

Log Logistic $a_{90/95}$=10" (Estimated)

In comparison to past data and the current testing, the results of the created models show either:

1. The IS utilized in testing has less capability (or testing conditions had an significant impact on test results).
2. Error in the models or testing process
3. Combination of the above

Further Discussion:

1. IS tested possesses less capability or experienced more difficult testing conditions: The Wright Patterson Study gives an idea on similar IS capabilities, let's compare the results of the two.
    a. Similarities: the equipment, inspection techniques, general design of test samples (flat lightly coated aluminum panels including surface roughness), test procedures validated & verified by NDI Level 3 Engineer & conducted according to source 58.

b. Differences:

Table 6: Differences between Pax River testing conditions and Source 40 dependency conditions

	Pax River Tests	Source 40
Inspection area	100" Sq	4" Sq
Visual Access	Unhindered to completely blocked.	Ability to monitor signal & ensure positive contact with surface.
Physical Access	Varied.	Accommodates inspector, sensor, unencumbered manipulation.
Placement of Damage	.01" deep from surface, mainly drilled from opposite surface.	Unknown.

The differences between testing conditions shown above in table 5 could account for the discrepancy between the expected results and the obtained results.

2. Error in Models or Tests:
    a. Possible error in model development: Improper distributions to model relationship, errors in code or incorrect assumptions.
    b. Possible error in tests: Incorrect reading or recording of data.

All models created from these tests indicate much more conservative detection capabilities however theses tests involved an inspection area 25x's the reference area.

Additionally, external conditions were varied and in most cases had a detrimental effect on IS capabilities and as such, it was expected this effort would produce a more conservative detection capability.

5.3 Measured Defect Sizes vs. True Defect Sizes

During the tests, there were a total of 102 detected damage areas. Of the 102 detected damage areas, 89 of those provide valid data points to assess measured vs true damage size (see table 7 below). 13 defects were censored: In cases where a single defect was reported as multiple defects, it was unclear how to assess the testers reported size of the defect. Therefore, the test point yielded POD data that was not censored, but the data on their assessment of sizing was censored.

The actual size of the tested damage ranged from .06" to 5" in length. The below table (Table 6) contains the information obtained during the testing on these defects. The very left column indicates the actual size of the defects while the other columns indicate the measured sizes of the defects.

Table 7: Measured vs true damage sizes (in).

Actual Size (in)	Measured Size (in)													
.03	0.1	0.25	0.2	0.2	0.4	0.125	0.125	0.2	0.125	0.25	0.25	0.15	0.125	0.125
.06	0.5	.2	.125											
.125	0.2	.5	.25	.375	0.2	0.5	0.25	0.2	0.3	0.25	0.25			
.25	0.5	0.5	0.25	.25	0.4	0.25	0.3	0.3	0.5					
.5	.5													
1	1	1.1												
1.4	1.5	1.75	1.4	1.5	1	1	1.1	1.13	1	1				
2.25	0.3	0.5												
2.8	2.9	2.31	2.75	2.75	2.8	2.8	2.75	2.75	2.38	2.75	2.75	2.75	3	3
3	3	3	3	3	3	3	3	2	3	3	3			
3.15	3.2	3.25												
4	4	4	4.1	4										
4.25	4.3	3.5	1	4.25	3.61									
5	5													

Below is a linear regression model (where the relationship between the dependent variable and the independent variable is: Y= a* X + b). This linear regression model fits the data. This model is shown below in Figure 22. The data is marked in black dots, the X position indicates the actual size of the defect, and the Y position indicates the measured size according to the IS (both are in inches).

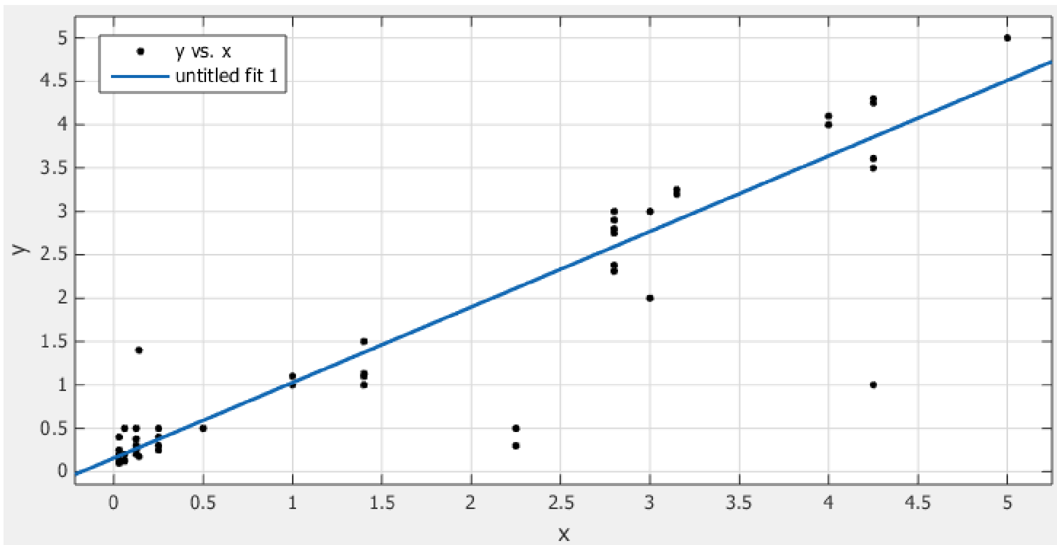


Figure 22: True damage size (x-Axis in inches) Vs measured damage size (y-Axis in inches)

The blue line indicates a best fit line to the data. The equation for a linear regression relationship is (Equation 19):

$$a^* = ma + c + \varepsilon(0, \sigma_a)$$

In this case the discovered parameters are:

	95% Confidence Interval	
$m = .8708$	Lower Bound: .8043	Upper Bound: .9373
$c = .1566$	Lower Bound: .0092	Upper Bound: .3039

With a coefficient of determination of .8861, 88.6% of the total variation in the measured size of defects can be explained by the equation obtained on the linear relationship between the actual sizes of defects vs the measured defects sizes.

Here is a closer look at the ability of the IS ability to measure defect size:

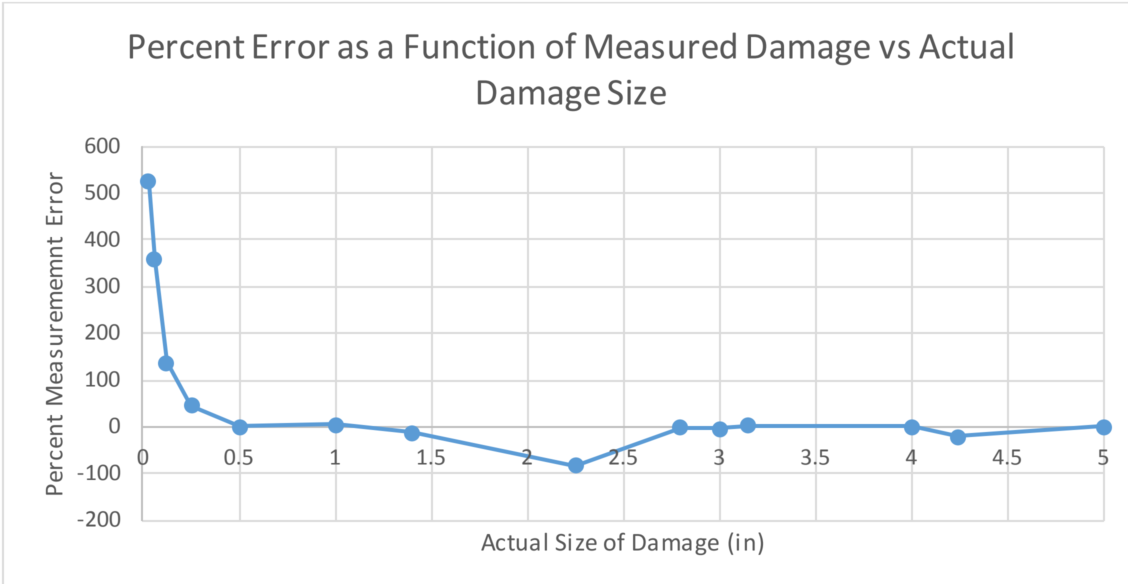


Figure 23: Percent difference between measured damage size (by IS) vs true damage size

In Figure 23 above, the data shows the total percent difference between measured damage size (by IS) to true damage size in all the experiments.

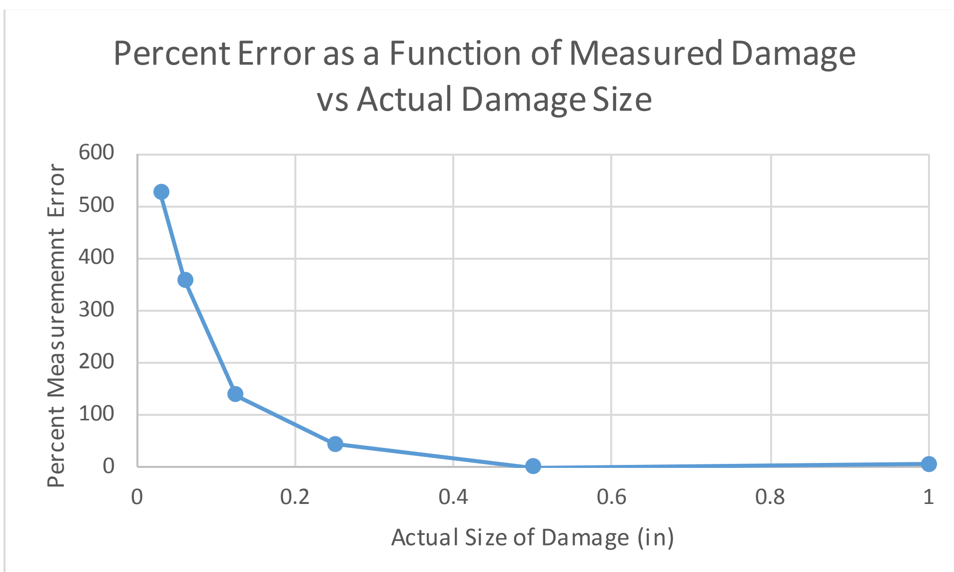


Figure 24: Measured vs. true defect sizes, for defects <1".

Figure 24 suggests the smallest damage areas were greatly oversized (in some cases almost 500% greater than their actual size). As damage size increases, the percent difference between measured and actual damage size, tended to decrease.

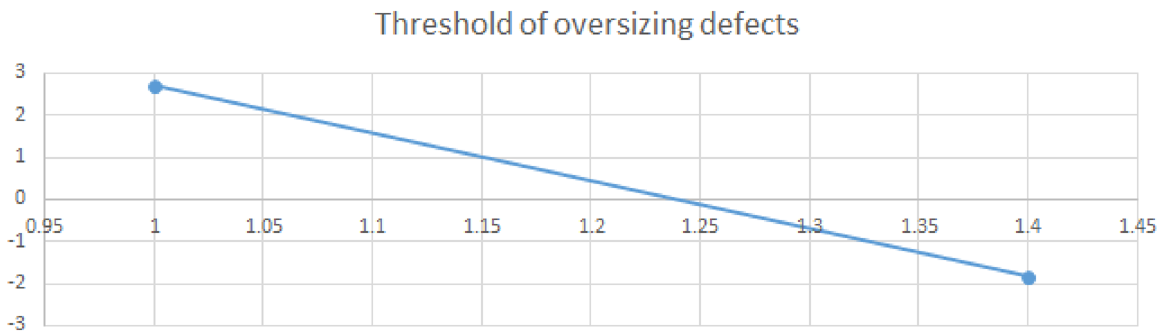


Figure 25: Threshold of Oversizing vs Under Sizing of Damage Areas by IS.

As seen in Figure 25 above, defects <1.25" tended to be oversized by the IS while defects >1.25" were undersized.

5.4 Discussion of Errors

The eddy current coil size is approximately 1/8" = .125". Ideally an inspector could determine the length of a defect up to half the coil diameter of the probe. For our IS, the probe utilized had a diameter of 1/8", therefore a defect could be sized to 1/16" =.0625". This IS having an expected systematic error in sizing flaws of <.0625".

For larger defects, there is a systematic error present; however, this does not explain the total error of measurement detected. If we subtract the systematic error from the total error, we obtain an idea of the error from other sources. The difference (or random error) of each defect size is shown in the below in Table 7.

Table 8: Expected IS error per true size of damage

Size of Flaw (in)	% error Expected	Actual Error Percentage	Differen ce
0.250	25.000	50.588	25.588
0.500	12.500	18.670	6.170
1.000	6.250	2.712	3.538
1.400	4.464	1.848	2.616
2.250	2.778	6.154	3.377
2.830	2.208	7.608	5.400
3.000	2.083	7.928	5.844
3.150	1.984	8.181	6.197
4.000	1.563	9.258	7.695
4.240	1.474	9.483	8.009
5.000	1.250	10.056	8.806

5.5 Discussion of Test Implementation

To providing a better understanding of the overall difficulty of implementing an inspection for each test, the data in Table 9 provides information on the conditions of tests.

Table 9: Conditions of test

1	2		3					4		5	6		
Test #	Panel		Hinderance	Anthro Accomodation		Viewing Conditions		Inspector Background		Median	Testing Conditions		
	Quantity	Quality	Accessibillity	Body	Fatigue	Visability	Angle of	Training	Years of	Overall	Panel	Test Location	Tester
1	2	5	2	3	3	1	5	1	3	3	6	6	6N
2	2	2	2	3	3	1	5	4	4	3	7	6	4Z
3	5	5	1	5	4	1	2	1	3	3	1	7	6N
4	3	1	3	2	2	2	3	4	4	3	5	8	4Z
5	3	5	1	1	2	1	1	1	3	1	2	1	6N
6	2	5	2	3	3	1	5	1	4	3	6	6	4V
7	2	2	1	5	4	1	2	1	4	2	7	7	4V
8	3	1	4	2	2	5	3	1	4	3	5	5B	4V
9	3	5	1	1	2	1	1	4	4	2	2	1	4Z
10	3	1	4	2	2	5	3	1	3	3	5	5B	6N
11	2	2	2	3	3	1	5	1	3	2	7	6	3C
12	4	3	3	2	2	2	3	1	4	3	4	8	4V
13	2	5	4	2	2	5	3	1	1	2	6	5B	1Z
14	3	1	4	2	2	5	3	1	3	3	5	5B	3C
15	2	2	1	5	4	1	2	4	4	2	7	7	4Z
16	2	2	3	2	2	2	3	1	3	2	7	8	3C
17	5	5	1	2	4	2	1	1	3	2	1	3	6N
18	1	5	1	5	4	1	2	1	3	2	8	7	3C
19	3	1	2	3	3	1	5	4	1	3	5	6	2C
20	3	2	1	1	2	1	2	4	4	2	3	9	4Z
21	3	2	1	1	2	1	2	1	3	2	3	9	3C
22	3	2	1	1	2	1	2	1	3	2	3	9	6N
23	3	2	1	1	2	1	2	4	1	2	3	9	2C
24	3	2	1	1	2	1	2	1	1	1	3	9	1Z
25	3	2	1	1	2	1	2	1	4	2	3	9	4V

	7									8	
Duffi	Amount										Sum
1	1	5	13	8	0	17	3	18	4	Easy	69
2	8	11	5	8	15	4	10	0	0		61
3	13	1	3	5	5	0	7	0	11		45
4	1	0	4	0	5	0	0	7	10		27
5	2	8	0	4	0	4	5	0	0	Dufficult	23

This data in Table 9 shows the following information in each section. For rated variables, this is on a scale from 1 to 5, with 1 indicating low likelihood effect on IS performance, 5 indicating a high likelihood on IS performance:

- Section 1: test number (1, 2, etc.).
- Section 2: rated variables of panel (quantity and quality of defects).

- Section 3: rated variables of testing location (Accessibility, body positions, fatigue, viability & angle of panel).
- Section 4: rated variables of inspector's background (training and years of experience).
- Section 5: median rating of each test (of all variables of Sections 2-4).
- Section 6: actual testing conditions: The panel, location and tester used in each test.
- Section 7: the number and difficulty of each variable that was tested for total tests.
- Section 8: the total number of variables of test and their relative hindrance to a successful test.

With limitations on the availability of inspectors, testing positions and test samples, randomization of variables was not possible. There were instances where the test plan for the week needed to change last minute (due to unavailability of inspectors, either conditions or other considerations)

Median values are used to in Section 5 of table 9 to give an overall (but not necessarily accurate) picture of the difficulties encountered at each test. For example, a journeyman inspector inspecting a medium panel in a medium inspection area, may produce better results than a new inspector using an easy panel in an easy to test location. Further analysis should be considered in the development of a multivariate model.

Chapter 6: Recommendations & Conclusion for Future Work

6.1 Summary

Probability of detection studies were performed with a variety of samples, testers and inspection areas around a test bed to determine the effects of external conditions on IS capability. These tests were performed in an operationally representative environment and test data was recorded including: Detection, positional, characterization, sizing errors. Variables recorded are temperature, probe used, position in aircraft, time to execute test, NASA TLX results. The analysis in this effort is focused specifically on assessment of detection capabilities and sizing errors.

Detection capabilities of the IS were modeled with a POD. The model used MLE (maximum likelihood estimate) to assess the parameters of a Lognormal, Logistic and Log Logistic distributions. Results from this study show lower detection capabilities of this IS than previously estimated, according to source 40.

Further analysis was conducted from the same data set to determine capability of the IS to quantify defects detected. A regression model was created to observe IS measurement trends. It was observed that flaws less than 1.25" tended to be oversized (reported larger than they actually are, and that flaws greater than 1.25" tended to be reported undersized. For the smallest defects a great part of the error can be contributed to the sizing limitations of the equipment. For larger flaws the errors are more random in nature.

6.2. Summary of Quantitative Assessments

The following are contributed assessments from this work:

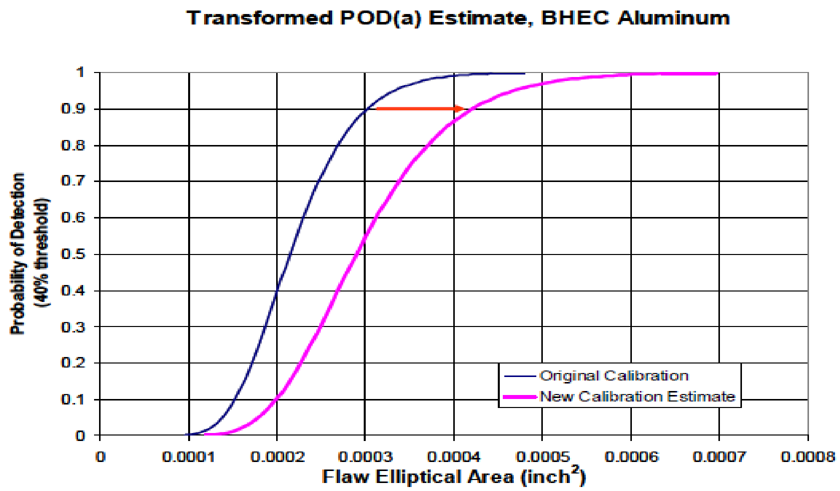
1. A better understanding of this IS degree of random sizing error as a function of damage area size.

2. An investigation into the source of error in sizing small damage areas: The inspection equipment. Also, the degree of systematic error by the limitations of the equipment.
3. The probability of detection under common varying field inspection conditions.
4. A testing process to assess detection capability as a function of inspection conditions (tester, inspection area, visibility, temperature and other considerations).

6.3. Future Work

6.3.1. Utilize Database to Perform Single Parameter Transfer for $\hat{\boldsymbol{a}}\ \boldsymbol{vs}\ \boldsymbol{a}$ Data for Various Inspection Conditions.

As a result of this work there is now a database of Eddy Current inspection data obtained under various inspection conditions. If there is a desire to determine the POD with a similar IS under non-assessed inspection conditions one could use a transfer function to obtain new estimates of the inspection capability. If all variables with a capability estimate are known and the inspection data used to generate these estimates are available, it is possible to use existing data to apply a transfer function in order to provide a reasonable detection estimate [39]. In Figure 26 below, a transfer function is used for a IS that has been calibrated with a larger notch (lower sensitivity) than normally used for an inspection. One must have an understanding of all the factors used to develop the original data set as well as the factors that may influence the capability of the inspection application under consideration in order to appropriately apply a transfer function [39].



-Figure 26: The use of a transfer function on POD data [39].

6.3.2. Assessment of TLX on IS capability

To understand the relationship between TLX assessment and degradation of inspection performance, one can show this relationship with Qualitative Adjustment Factors (inspect ability factor). The inspect ability factor is assigned based on qualitative assessment of inspection difficulty and human factor challenges only [39]. For use a a_{NDI} should be adjusted by multiplying it with the appropriate factor. These factors can be calculated with the data obtained by this study. Quantifying the relationship between TLX and their corresponding effect on IS capabilities would be of value and can used as an assessment tool to assess IS capabilities in field inspection conditions.

6.3.2. Assessment of TLX on HRA

Earlier (in section 2.2.2.) we covered 2 approaches to HRA assessment of an inspection space. Modeling each tester in SANTOS would yield more accurate results of the anatomical effect each inspection space has on a tester. This information can be correlated with the TLX responses and can be utilized to make assumption on IS capability degradation for future inspections that involve TLX responses after the inspection.

6.3.3. Assessment of random error in sizing defects

In this study, there were random errors in sizing larger defects. An investigation into the potential causes of this measurement error would be of value. Were physical variations, parallax, personal errors the most significant factors? How can these errors be mitigated in future inspection to ensure more promising IS results and capabilities?

6.3.4. Improve POD model

Enough data was generated to form a basis of an analytical model. Interesting observations from the model indicate that the 90% detection crack length is estimated to be above 3.8" for all 3 models. However, all damage areas larger than ¼" were all detected in this study. This could be an indication of a poor fit or that more data needs to be acquired and assessed by the model. A verification of the models can be obtained by inputting the data into modeling software (POD-Q2) to compare model outputs.

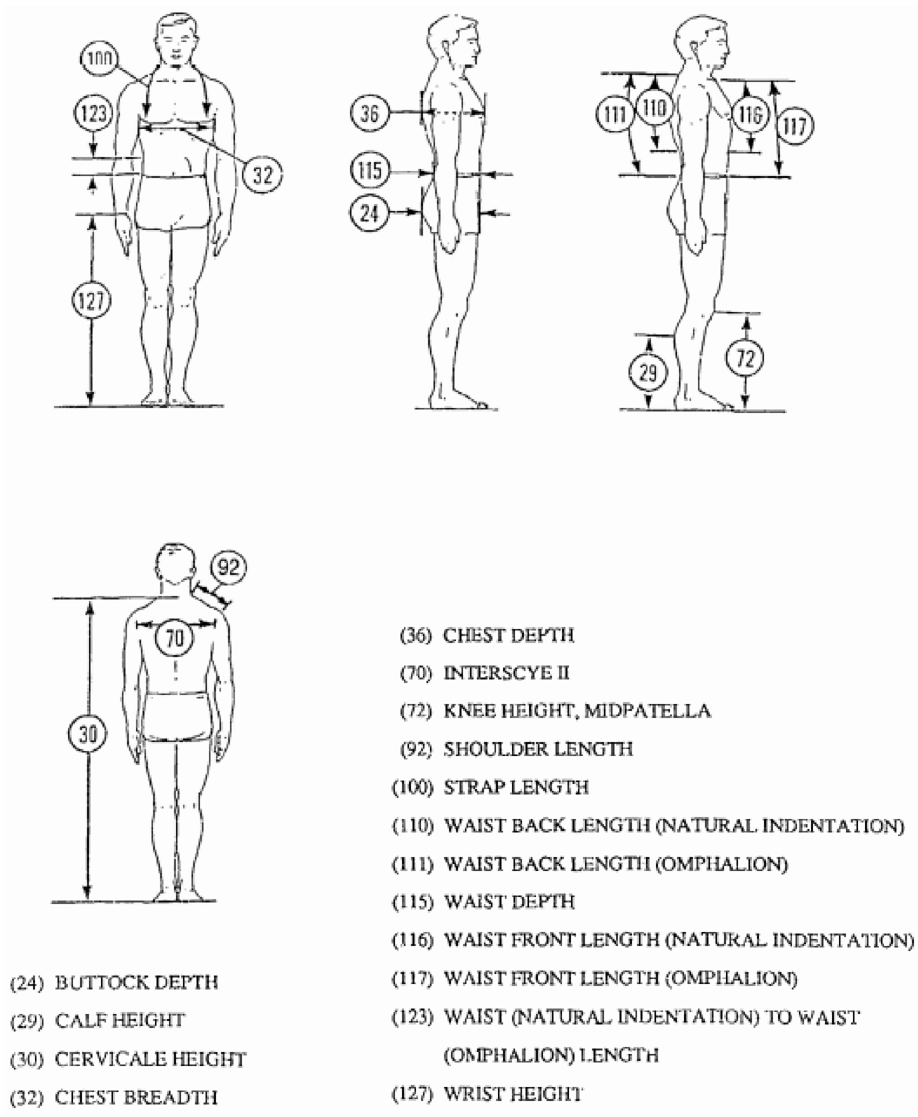
6.3.5. Utilize model to assess reliability of inspection methods

These models / analyses were created to aid in the development of an assessment tool, to determine the best approach structural health monitoring approach (automated, remote (SHM) or inspector) for a specific application. For future Eddy Current inspections of large flat aluminum structures, use the data to communicate detection and characterization capabilities.

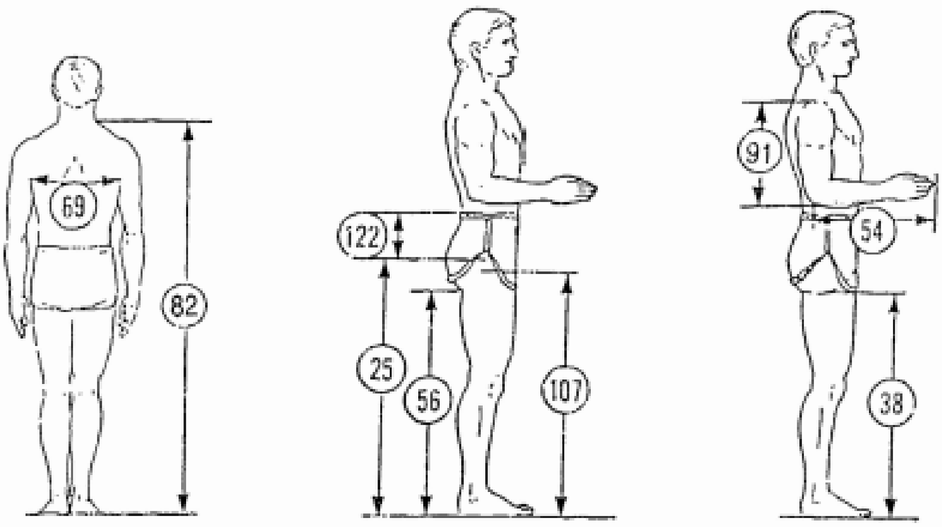
Appendices

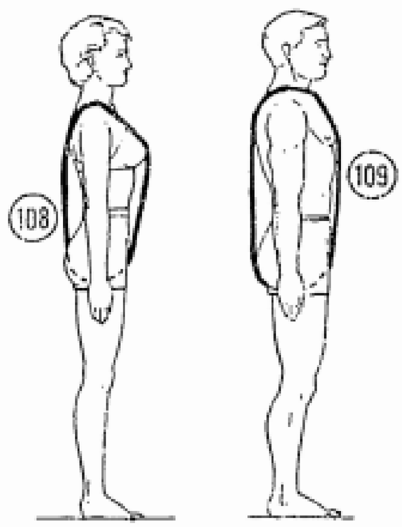
Appendix A- The Standard Biometric Measurements

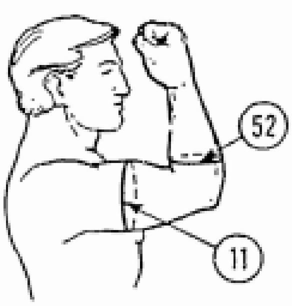
Explanation: These are some of the standard biometric measurements, designed and utilized by the Army to incorporated biometric data into designs as quickly as possible. Below are diagrams of measurements that can be taken to import biometric data into SANTOS.



VISUAL INDEX - THE STANDARD MEASUREMENTS (Continued)







(11) BICEPS CIRCUMFERENCE, FLEXED

(25) BUTTOCK HEIGHT

(38) CROTCH HEIGHT

(52) FOREARM CIRCUMFERENCE, FLEXED

(54) FOREARM-HAND LENGTH

(56) GLUTEAL FURROW HEIGHT

(69) INTERSCYE I

(82) NECK HEIGHT, LATERAL

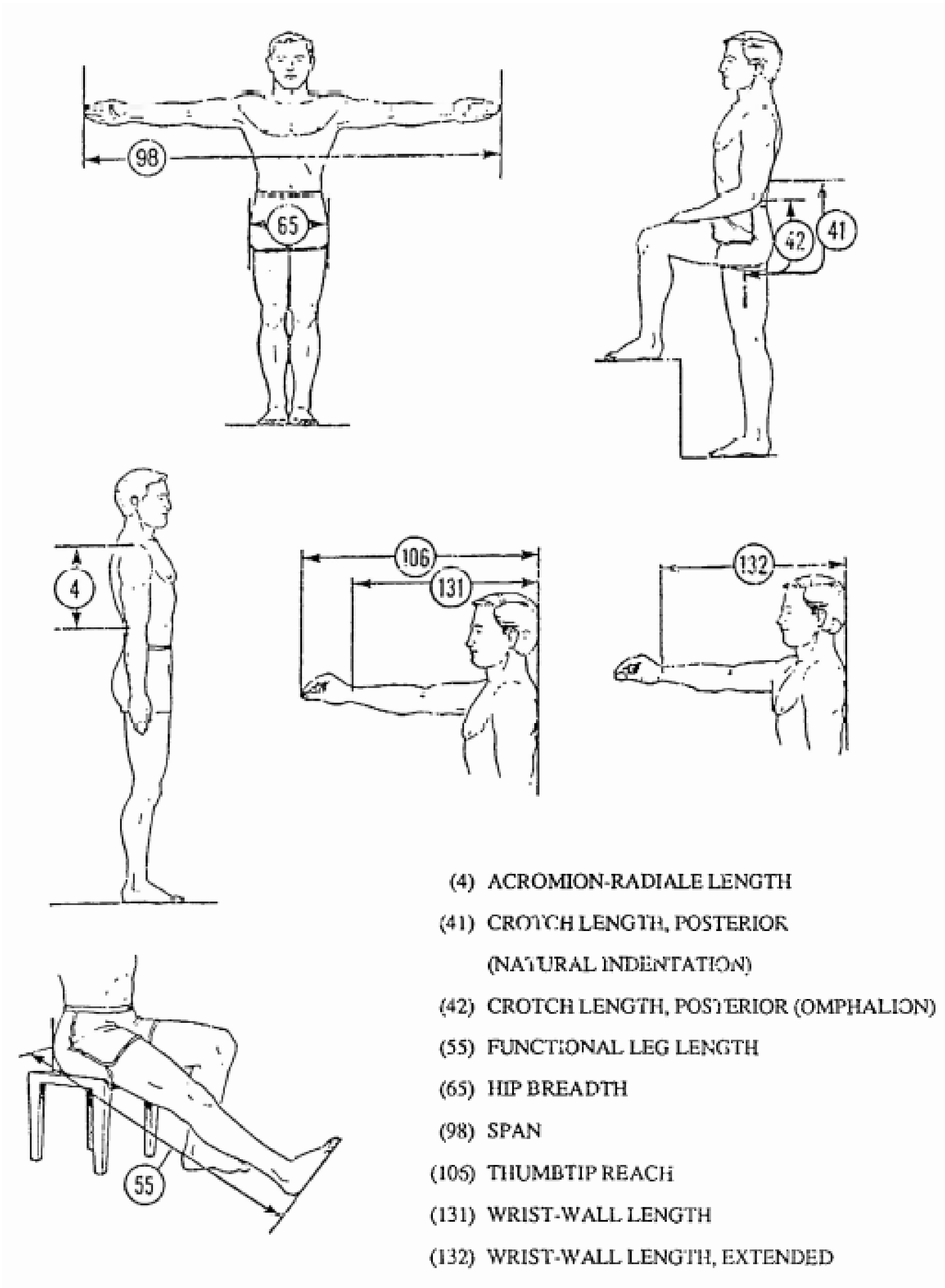
(91) SHOULDER-ELBOW LENGTH

(107) TROCHANTERIC HEIGHT

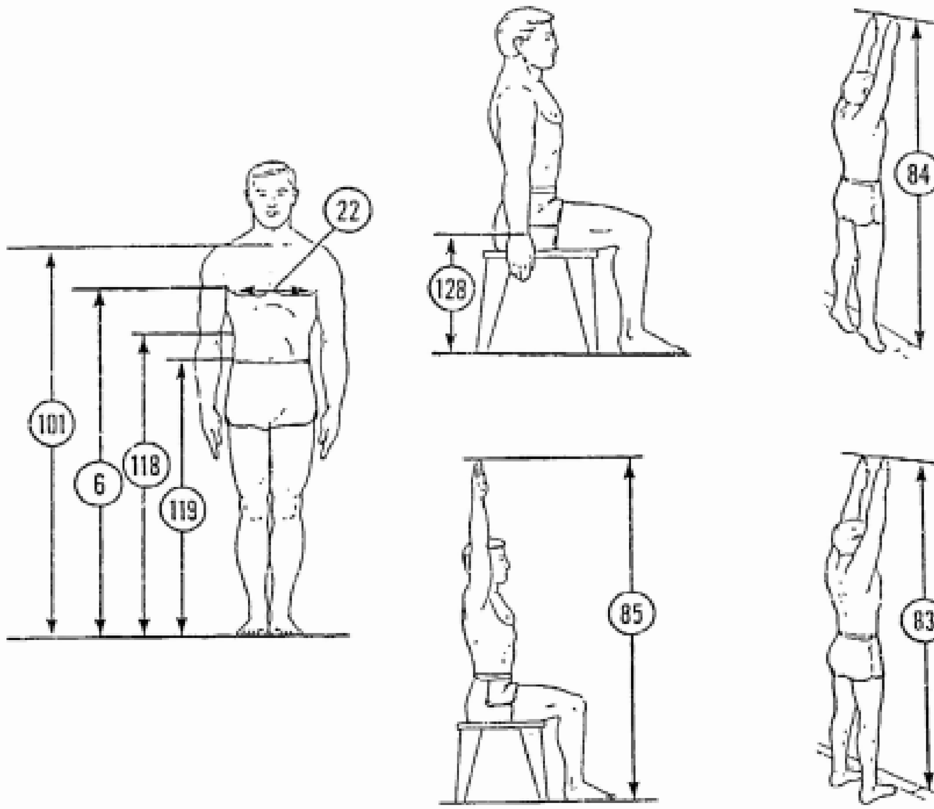
(108) VERTICAL TRUNK CIRCUMFERENCE (ASCC)

(109) VERTICAL TRUNK CIRCUMFERENCE (USA)

(122) WAIST-HIP LENGTH


98
65
42
41
4
106
131
132
55
(4) ACROMION-RADIALE LENGTH
(41) CROTCH LENGTH, POSTERIOR (NATURAL INDENTATION)
(42) CROTCH LENGTH, POSTERIOR (OMPHALION)
(55) FUNCTIONAL LEG LENGTH
(65) HIP BREADTH
(98) SPAN
(106) THUMBTIP REACH
(131) WRIST-WALL LENGTH
(132) WRIST-WALL LENGTH, EXTENDED

VISUAL INDEX - THE STANDARD MEASUREMENTS (Continued)



(6) AXILLA HEIGHT

(22) BUSTPOINT/THELION-BUSTPOINT/THELION BREADTH

(83) OVERHEAD FINGERTIP REACH

(84) OVERHEAD FINGERTIP REACH, EXTENDED

(85) OVERHEAD FINGERTIP REACH, SITTING

(101) SUPRASTERNALE HEIGHT

(118) WAIST HEIGHT (NATURAL INDENTATION)

(119) WAIST HEIGHT (OMPHALION)

(128) WRIST HEIGHT, SITTING

Appendix B- Inspection Procedure

Explanation: This is the inspection procedure that was given to tester before they executed the test.

EDDY CURRENT NONDESTRUCTIVE TESTING PROCEDURE
MATERIALS ENGINEERING DIVISION, CODE 4343
PATUXENT RIVER, MD

Eddy Current Method:	Surface
Nomenclature:	POD Aluminum Panel
Material:	7075 Aluminum Alloy
References:	NAVAIR 01-1A-16, NAS410
Inspector Certification:	Varies

EQUIPMENT

Instrument:	Nortec 2000D+ or equivalent
Probe Kit	SPCK-429-1, Surface Probe Kit or equivalent
Reference Standard:	VMA. 01-0-07T or equivalent

EQUIPMENT SETTINGS

MAIN

Frequency:	200 kHz
Angle:	96
H-Gain:	70.0 dB
V-Gain:	85.0 dB
Probe Drive:	Mid

FILTER

LP Filter:	100
HP Filter:	OFF
Cont Null	OFF
Auto Lift	OFF
Balance	OFF

DISPLAY

Sweep	OFF
V-Pos	20.0%
H-Pos	80.0%
SCREEN	
Persist	ON: 1 s
Disp Erase	OFF
Sweep Erase	ON
Dot/Box	BOX
Graticule	ON

ALARM

Type	BOX
+/-/off	OFF
Horn	OFF

SPECIAL

Alarm Dwell	0.0
Scan RPM	1500
Sync Angle	0
WATERFALL	
Waterfall	OFF
Sweep min	1
Sweep max	32
Waterfall angle	96
Depth	01

PROCEDURE

CALIBRATION:

1. Load DEFAULT settings.
2. Adjust the phase and gain settings to reflect the above values.
3. Position probe on the reference block.
4. Null the probe.
5. Adjust lift-off to go horizontal and left. Adjust angle if needed to produce a horizontal response for lift off.
6. Cover the 0.020" notch with a piece of Teflon tape. Scan across the 0.020" notch (see Figure 1). Adjust Gain/V-Gain/H-Gain, persist and other settings as necessary to achieve a calibration response of approximately 8 divisions (similar to Figure 2) & to allow for a comfortable inspection.

INSPECTION TO FIND/ QUANTIFY DEFECTS:

1. Place probe on part.
2. Re-Null if necessary and confirm lift-off direction. Note: If lift-off direction has changed by more than 5 degrees or dot is not on the screen when the probe is placed on the part, the reference standard may not be close enough in conductivity for this inspection.
3. Scan around the test panel as shown in Figure 3.
4. Note any areas where the signal deflects vertically more than ½ division and NOTE the maximum amplitude height.
5. To quantify Characteristics:
    a. Is defect a slot or a flat-bottomed hole?
        i. Scan along defect. If width = length then defect is a FBH. Otherwise the defect is a slot.
    b. Position: Scan along defect, determining where on surface maximum signal response decreases by approximately ½ signal height (6 dB's). Find and mark these points on the surface with a grease pencil. At the conclusion of the inspection, note the found defects information (position, type, signal response, ect.) on the inspection sheet.
        i. FBH, report position of the center of the FBH.
        ii. Slot: Mark ends of slot. Record these positions as well as length of slot.
    c. Response: Record maximum amplitude of defect found.
6. Document information: Defect type, position, response in Figure 4: Table 1.
7. Ensure the instrument is still calibrated properly approximately every 15 minutes by scanning standard and observing responses. If necessary Re-Null the probe on the reference block.

ACCEPTANCE CRITERIA:

Accept/Reject Criteria:	No defects allowed
Inspection Location:	Surface area 10"X10"
Method of Marking/Documentation:	Grease Pencil on surface of panel. Mark/ record defect nomenclature on inspection sheet.

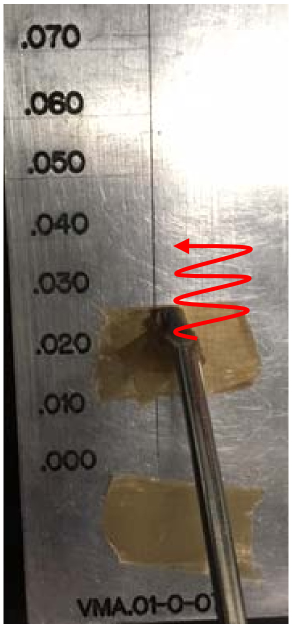


Figure 1. Scanning across .020” Teflon coated notch.

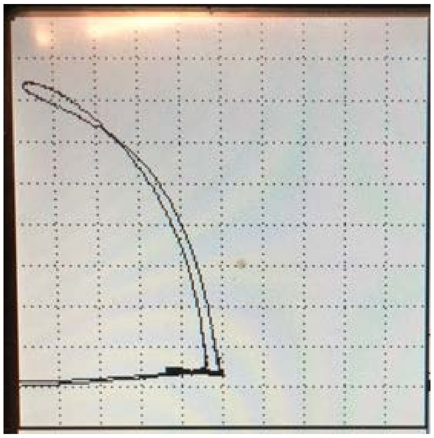


Figure 2. Calibration standard response over a 0.020” notch.

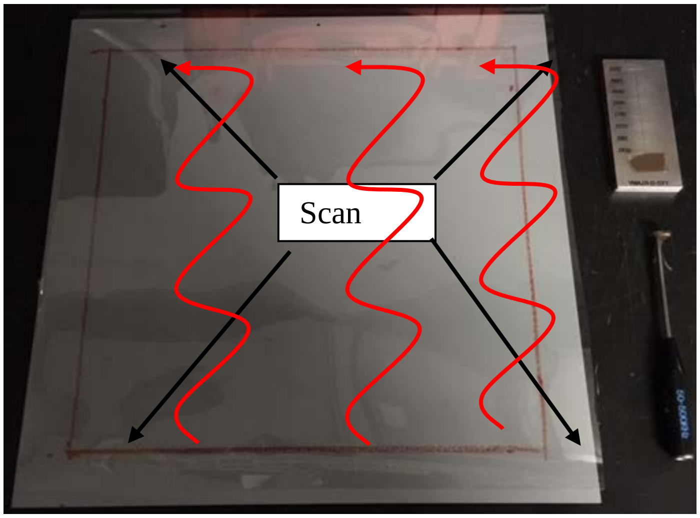


Figure 3. Scan area of panel.

I. TABLE 1. CRACK INDICATION DOCUMENTATION

#	Defect Location (center & radius for circle, endpoints for slot)	Signal Amplitude No. of Divisions	Defect Size (Diameter for hole,	Type of Defect
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Figure 4. Table to record defects found in inspection.

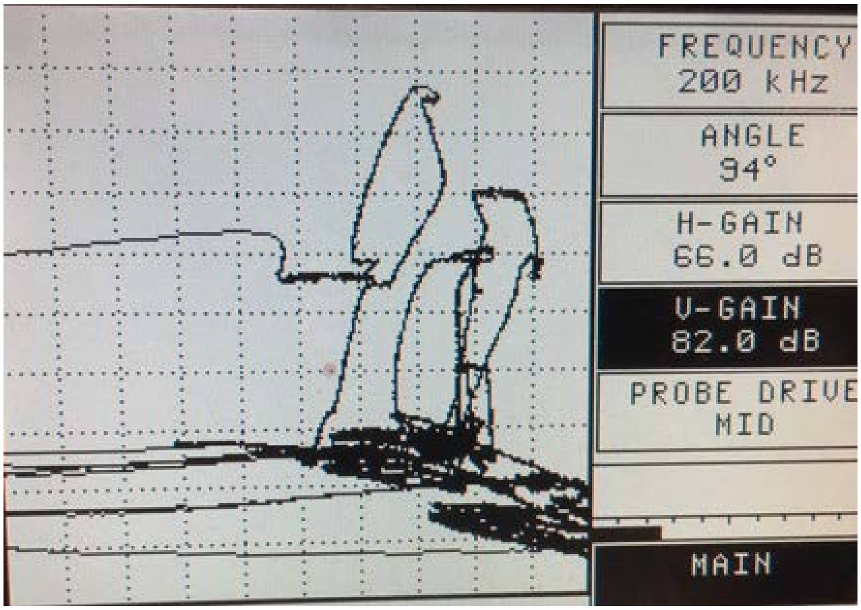


Figure 5. Signal Response of .25, .125, .062, .032 FBH's.

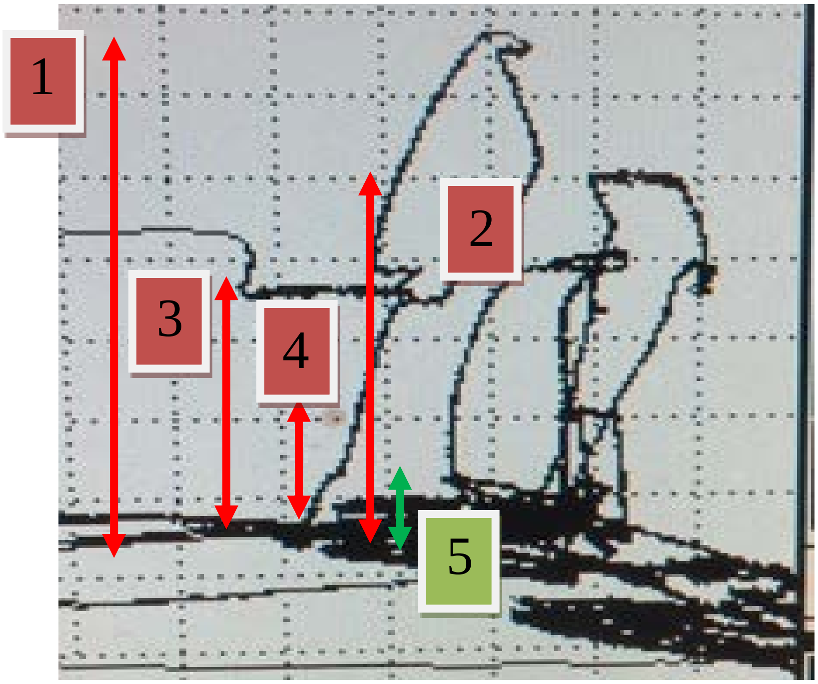


Figure 6: 6 deviation response for a .25" FBH, **2**: 4 deviation response for a .125" FBH, **3:** 3 deviation response for a .062" FBH, **4:** 1.5 deviation response for a .032" FBH, **5:** ½ deviation: Typical noise variation over good material.

Appendix C- Defect Nomenclature Worksheet

Explanation: This is the worksheet that testers used to report their inspection results.

Date:

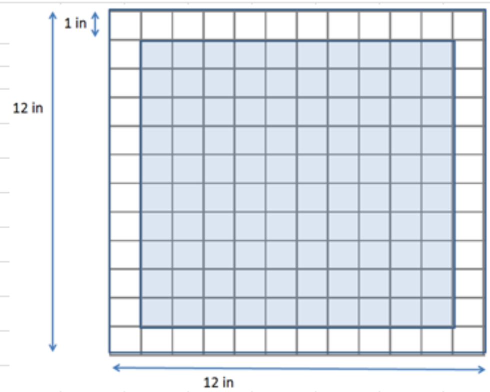
Defect Nomenclature Worksheet

	Defect Location from bottom left hand of panel (Center & Radius for circle, endpts for slot)						Signal Amp (No. of Divisions)	Defect Size (diameter: hole, length: Slot	Type of Defect (hole, slot, ect.)
	Slot (end #1)		Slot (end #2)		Holes				
	x value	y value	x value	y value	x value	y value			
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
ex1	2	9	5	9			10+	3"	Slot
ex2					5	7	8	.5" Dia	Hole

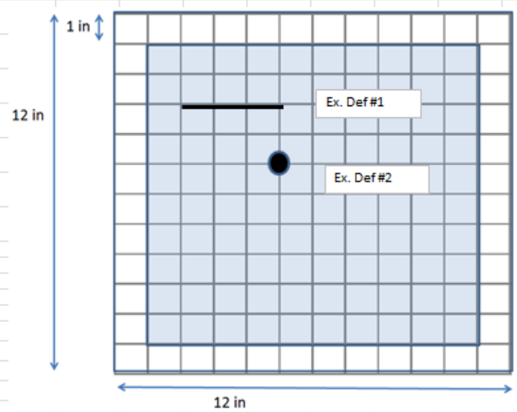
Notes:

Date:

Defect Nomenclature Worksheet



Example



Appendix D- NASA TLX

Part A: Description of how to implement NASA TLX tool.

Description: After the filled out a defect nomenclature worksheet, the tester filled out a TLX worksheet for workload evaluation. On this worksheet, the tester quantified their expected performance and testing experience. It was executed in this fashion:

1. The tester read the descriptors of the scales (see part b) to get and understanding of their meanings.
2. The tester then assessed the effect of 6 distinct factors on their effect on their ability to execute an effective inspection, rated on a scale from 0 to 100 (refer to part c).
3. The tester then was presented with several pairwise rating scales and asked to choose with of the factors most restricted their ability to execute a successful inspection (refer to part d).
4. The TLX was then graded using the TLX calculator (part e).
    a. In row A, the results of step 2 were entered.
    b. In area B, the answers to the pairwise comparisons were placed.
    c. In row C, you
    d. In row D, the values are automatically calculated, each is the corresponding answer in A multiplied by answer in C.
    e. In cell E, the value is automatically calculated. $E = \frac{Total\ Sume\ of\ D}{Total\ Sum\ of\ C}$. The value in cell E gives the overall TLX value of test.

Part B: Inspection Descriptor Rating Scale Definitions

INSPECTION DESCRIPTOR RATING SCALE DEFINITIONS	
	PROVIDE A VALUE FROM
	Low to High
	(or Good to Poor for Performance)
MENTAL DEMAND (Difficulty of Characterization)	How much mental and perceptual activity was required (e.g., interpreting, deciding, measuring, calculating, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Restrictions (Hindrance)	How hindered were you in the execution of your task? Did you feel unrestricted or Closter phobic? Did you have free range of motion or were you hindered in performance of your task?
BODY POSITIONAL DEMAND (Anthropometric Accommodation)	How uncomfortable was your assumed body position? Did you desire to assume a different body position in the execution of the task or were you content with position? Did you have to frequently adjust your position or were you comfortable?
PHYSICAL DEMAND (Fatigue)	How much physical activity/exertion was required (e.g., were you fatigued and took breaks often/ did the task make you tired)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
VISUAL DEMAND (Viewing Conditions)	How difficult was it to view the surface of inspection? Was it fully viewable or restricted? Did you have to adjust regularly to see the surface or did you frequently change position/ stop inspection to see the surface?
PERFORMANCE	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals? Were you frustrated or secure in your results?

Part C: Ratings of Descriptors of Inspection Worksheet (sheet 2)

RATINGS OF DESCRIPTORS OF INSPECTION WORKSHEET

Evaluate the specific task(s) you performed by placing a '|' at the point on each of the 6 scales below which matches your latest experience with it. Consider each scale individually and refer to the scale descriptions provided. Questions are allowed.

Subject: ____________________ Date: ____________

RATING SHEET

MENTAL DEMAND

Low — High

PHYSICAL RESTRICTIONS

Low — High

BODY POSITIONAL DEMAND

Low — High

PHYSICAL DEMAND

Low — High

VISUAL DEMAND

Low — High

PERCEIVED PERFORMANCE

Good — Poor

Notes:

Part D: Weightings of Descriptors Worksheet (sheet 1)

WEIGHTINGS OF DESCRIPTORS WORKSHEET

For each pair of scale titles listed below, circle the title that you believe that represents the greatest obstacle to the execution of a successful inspection for your inspection

Performance	or	Mental Demand
Physical Restricitions	or	Visual Demand
Physical Demand	or	Physical Restrictions
Body Position	or	Performance
Visual Demand	or	Performance
Physical Restrictions	or	Performance
Body Position	or	Physical Demand
Physical Restrictions	or	Body Position
Physical Demand	or	Visual Demand
Body Position	or	Mental Demand
Visual Demand	or	Mental Demand
Mental Demand	or	Physical Restrictions
Visual Demand	or	Body Position
Performance	or	Physical Demand
Mental Demand	or	Physical Demand

JSAM001

WEIGHTINGS OF DESCRIPTORS WORKSHEET

For each pair of scale titles listed below, circle the title that you believe that represents the greatest obstacle to the execution of a successful inspection for your inspection

Visual Demand	or	Performance
Visual Demand	or	Mental Demand
Body Position	or	Physical Demand
Performance	or	Mental Demand
Physical Restrictions	or	Visual Demand
Mental Demand	or	Physical Demand
Physical Restrictions	or	Performance
Physical Demand	or	Physical Restricitons
Performance	or	Physical Demand
Body Position	or	Mental Demand
Physical Demand	or	Visual Demand
Physical Restrictions	or	Body Posiitonal
Visual Demand	or	Body Posiitonal
Mental Demand	or	Physical Restricitons
Body Position	or	Performance

JSAM002

Part D: TLX Calculator

1. Enter weights from TLX Sheet 2

Weights:

	Mental	Hinderance	Positional	Physical	Visual	Performance
A	20	20	20	30	20	20

2. Enter letter(s) corresponding to subject's choices from TLX Sheet 1

B	p	m = Mental Demand
	d	r = Physical Restrictions
	d	b = Body Position
	r	d = Physical Demand
	p	v = Visual Demand
	b	p = Performance
	r	
	d	
	p	
	b	
	d	
	d	
	b	
	m	
	b	

3. TLX Score provided below

C	1	2	4	5	0	3

Weighted Counts:

D	20	40	80	150	0	60

Score:

E	23.33

Date:	22-Dec

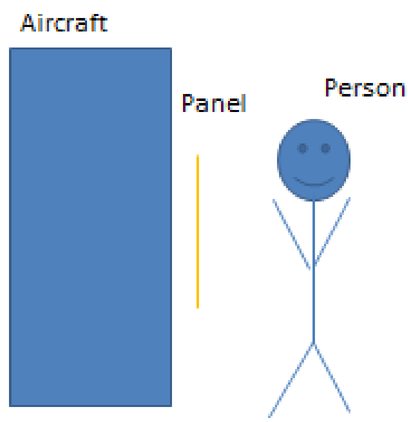
Appendix E- Inspection Positions Around Test Bed

Explanation: Below are the inspection locations around the test frame.

Part A: Positions

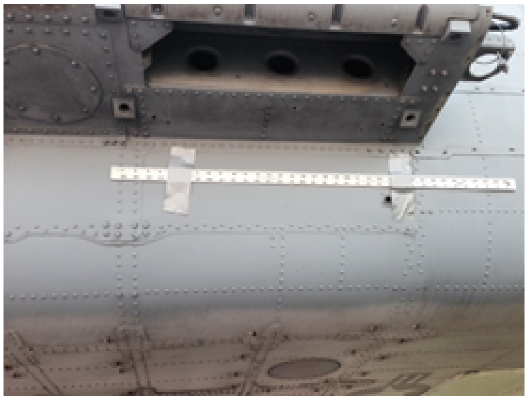
Testing Areas on Airframe

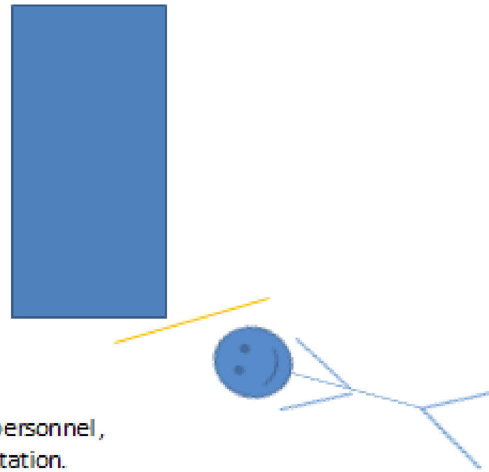
Area #1 (wall inspection): Vertical panel, Easy Access



Panel attached to outside of aircraft within easy reach of personnel, in a vertical orientation

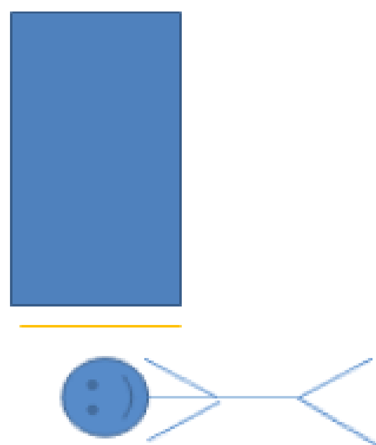
Area #2 (Lower angled inspection) : Angled panel, Easy Access, non optimal position





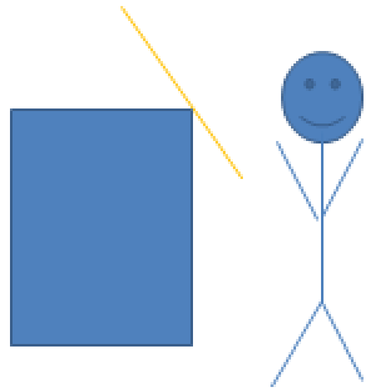
Panel attached to aircraft within easy reach of personnel, near the underside of aircraft, in a angled orientation.

Area #3 (Horizontal Overhead Inspection): Horizontal panel, Easy Access, non optimal position



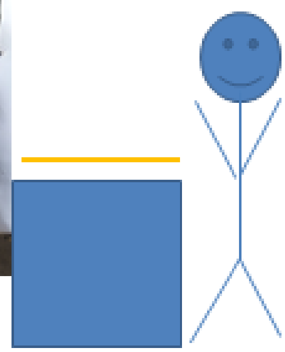
Panel attached to underside of aircraft within easy reach of personnel, in a horizontal position.

Area #4 (sloped and restricted wall inspection): Angled panel, Moderately difficult access, slightly high position



Panel attached to tail of aircraft, within reach of personnel, in a angled position.

Area #5 (Far Reach Table): Horizontal panel, can barely reach all of panel.

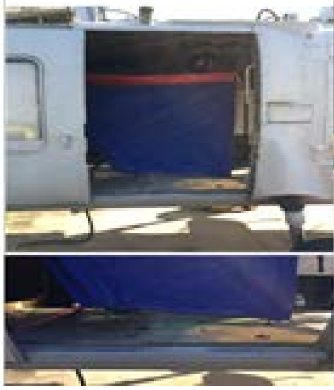


Panel attached to top of composite structure inside aircraft (but below ceiling, within reach of personnel, in a horizontal position.

Area #5 (Far Reach Table) Variations:

- 5R- Restricted View

#1: Configuration: Blind Inspection

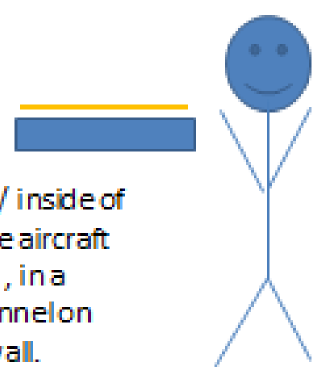


#2 Configuration: Restricted access/ visibility

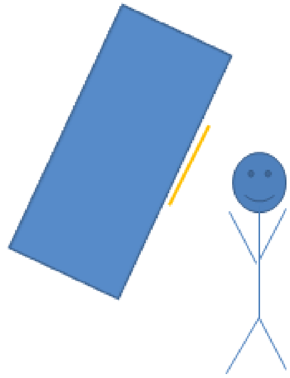
- 5R- Restricted

Area #6 (High Countertop): Horizontal panel, restricted access and viewing,

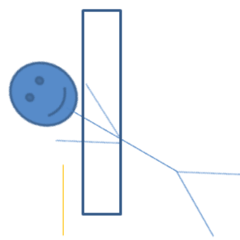
Panel attached to bottom/ inside of composite structure inside aircraft within reach of personnel, in a horizontal position. Personnel on other side of composite wall.



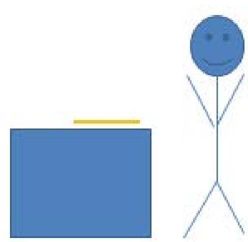
Area #7 (overhead inspection): Above head panel, slight angle toward inspector.



Area #8 (kneeling/ sitting inspection): Slight restrictions/ accessibility issue.



Area #9: Tabletop Inspection



Part B: Positions and correlated OWAS Values

OWAS (Ovako Working Posture Analysis System) was created in the 1970's to evaluate current or future positional domains on humane workers [32]. It has been used to determine if postural demands are acceptable, establishes baseline to evaluate effectiveness of interventions, and the concepts of this system have been incorporated into other posture analysis systems. Simple observations are made about the trunk, arm, lower body, head and neck to determine relative discomfort [32]. Below are the results of 1 relative assessment made on each inspection position.

Pos #1

Trunk Posture	5	#	20	30	40	50	60	70	80	90	##	1
Neutral											x	100
Bent Forward												0
Twisted												0
Bent/ Twisted												0

Arm Posture	5	#	20	30	40	50	60	70	80	90	##	1
2 Arms Blw Shd											x	100
1 Arm Abv Shd												0
2 Arms Abv Shd												0

Lower Body	5	#	20	30	40	50	60	70	80	90	##	2
Sitting												0
Std 2 legs											x	100
Std 1 leg												0
Std kns bent												0
Kneeling												0
Walking												0

Head and Neck	5	#	20	30	40	50	60	70	80	90	##	1
Neutral									x			80
Fwd (> 20 deg)			x									20
Side (> 20 Deg)												0
Bkwd (>20 Deg)												0
Twst (>20 deg)												0

	Result	Result
Trunk Posture	Acceptable	1.25
Arm Posture	Acceptable	
Lower Body	Slightly Harmful	
Head and Neck	Acceptable	

Pos #3

Trunk Posture	5	#	20	30	40	50	60	70	80	90	###	2
Neutral						x						50
Bent Forward						x						50
Twisted												0
Bent/ Twisted												0

Arm Posture	5	#	20	30	40	50	60	70	80	90	###	3
2 Arms Blw Shd												
1 Arm Abv Shd										x		90
2 Arms Abv Shd		x										10

Lower Body	5	#	20	30	40	50	60	70	80	90	###	2
Sitting												0
Std 2 legs											x	100
Std 1 leg												0
Std kns bent												0
Kneeling												0
Walking												0

Head and Neck	5	#	20	30	40	50	60	70	80	90	###	4
Neutral			x									20
Fwd (> 20 deg)												0
Side (> 20 Deg)												0
Bkwd (>20 Deg)									x			80
Twst (>20 deg)												0

	Result	Result
Trunk Posture	Slightly Harmful	2.75
Arm Posture	Distinctly Harmful	
Lower Body	Slightly Harmful	
Head and Neck	Extremly Harmful	

Pos #4

Trunk Posture	5	#	20	30	40	50	60	70	80	90	##	1
Neutral											x	100
Bent Forward												0
Twisted												0
Bent/ Twisted												0

Arm Posture	5	#	20	30	40	50	60	70	80	90	##	1
2 Arms Blw Shd											x	100
1 Arm Abv Shd												0
2 Arms Abv Shd												0

Lower Body	5	#	20	30	40	50	60	70	80	90	##	2
Sitting												0
Std 2 legs											x	100
Std 1 leg												0
Std kns bent												0
Kneeling												0
Walking												0

Head and Neck	5	#	20	30	40	50	60	70	80	90	##	1
Neutral									x			80
Fwd (> 20 deg)			x									20
Side (> 20 Deg)												0
Bkwd (>20 Deg)												0
Twst (>20 deg)												0

	Result	Result
Trunk Posture	Acceptable	1.25
Arm Posture	Acceptable	
Lower Body	Slightly Harmful	
Head and Neck	Acceptable	

Pos #5B

Trunk Posture	5	#	20	30	40	50	60	70	80	90	###	2
Neutral			x									20
Bent Forward									x			80
Twisted												0
Bent/ Twisted												0

Arm Posture	5	#	20	30	40	50	60	70	80	90	###	1
2 Arms Blw Shd											x	100
1 Arm Abv Shd												0
2 Arms Abv Shd		x										0

Lower Body	5	#	20	30	40	50	60	70	80	90	###	2
Sitting												0
Std 2 legs											x	100
Std 1 leg												0
Std kns bent												0
Kneeling												0
Walking												0

Head and Neck	5	#	20	30	40	50	60	70	80	90	###	3
Neutral												0
Fwd (> 20 deg)											x	100
Side (> 20 Deg)												0
Bkwd (>20 Deg)												0
Twst (>20 deg)												0

	Result	Result
Trunk Posture	Slightly Harmful	2
Arm Posture	Acceptable	
Lower Body	Slightly Harmful	
Head and Neck	Distinctly Harmful	

Pos #6												1
Trunk Posture	5	#	20	30	40	50	60	70	80	90	##	
Neutral											x	100
Bent Forward												0
Twisted												0
Bent/ Twisted												0
												3
Arm Posture	5	#	20	30	40	50	60	70	80	90	##	
2 Arms Blw Shd												0
1 Arm Abv Shd											x	100
2 Arms Abv Shd												0
												2
Lower Body	5	#	20	30	40	50	60	70	80	90	##	
Sitting												0
Std 2 legs											x	100
Std 1 leg												0
Std kns bent												0
Kneeling												0
Walking												0
												3
Head and Neck	5	#	20	30	40	50	60	70	80	90	##	
Neutral					x							40
Fwd (> 20 deg)							x					60
Side (> 20 Deg)												0
Bkwd (>20 Deg)												0
Twst (>20 deg)												0

	Result	Result
Trunk Posture	Acceptable	2.25
Arm Posture	Acceptable	
Lower Body	Slightly Harmful	
Head and Neck	Acceptable	

Pos #7												2
Trunk Posture	5	#	20	30	40	50	60	70	80	90	###	
Neutral						x						50
Bent Forward						x						50
Twisted												0
Bent/ Twisted												0
												3
Arm Posture	5	#	20	30	40	50	60	70	80	90	###	
2 Arms Blw Shd												0
1 Arm Abv Shd											x	100
2 Arms Abv Shd												0
												2
Lower Body	5	#	20	30	40	50	60	70	80	90	###	
Sitting												0
Std 2 legs											x	100
Std 1 leg												0
Std kns bent												0
Kneeling												0
Walking												0
												3
Head and Neck	5	#	20	30	40	50	60	70	80	90	###	
Neutral												0
Fwd (> 20 deg)								x				70
Side (> 20 Deg)												0
Bkwd (>20 Deg)				x								30
Twst (>20 deg)												0

	Result	Result
Trunk Posture	Slightly Harmful	2.5
Arm Posture	Distinctly Harmful	
Lower Body	Slightly Harmful	
Head and Neck	Extremly Harmful	

Pos #8												3
Trunk Posture	5	#	20	30	40	50	60	70	80	90	##	
Neutral												0
Bent Forward											x	100
Twisted												0
Bent/ Twisted												0
												1
Arm Posture	5	#	20	30	40	50	60	70	80	90	##	
2 Arms Blw Shd											x	100
1 Arm Abv Shd												0
2 Arms Abv Shd												0
												2
Lower Body	5	#	20	30	40	50	60	70	80	90	##	
Sitting								x				70
Std 2 legs												0
Std 1 leg												0
Std kns bent												0
Kneeling				x								30
Walking												0
												3
Head and Neck	5	#	20	30	40	50	60	70	80	90	##	
Neutral												0
Fwd (> 20 deg)											x	100
Side (> 20 Deg)												0
Bkwd (>20 Deg)												0
Twst (>20 deg)												0

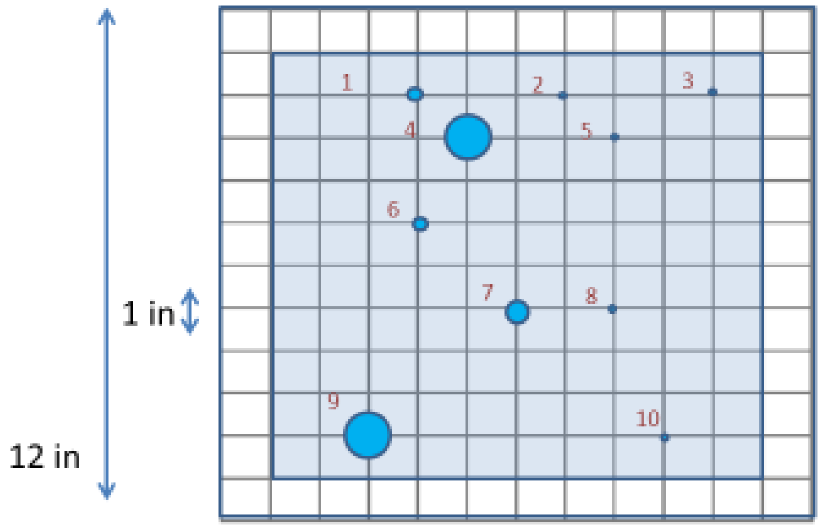
	Result	Result
Trunk Posture	Distinctly Harmful	2.25
Arm Posture	Acceptable	
Lower Body	Slightly Harmful	
Head and Neck	Distinctly Harmful	

Pos #9												1
Trunk Posture	5	#	20	30	40	50	60	70	80	90	###	
Neutral									x			80
Bent Forward			x									20
Twisted												0
Bent/ Twisted												0
												1
Arm Posture	5	#	20	30	40	50	60	70	80	90	###	
2 Arms Blw Shd											x	100
1 Arm Abv Shd												0
2 Arms Abv Shd		x										0
												2
Lower Body	5	#	20	30	40	50	60	70	80	90	###	
Sitting												0
Std 2 legs											x	100
Std 1 leg												0
Std kns bent												0
Kneeling												0
Walking												0
												3
Head and Neck	5	#	20	30	40	50	60	70	80	90	###	
Neutral												0
Fwd (> 20 deg)											x	100
Side (> 20 Deg)												0
Bkwd (>20 Deg)												0
Twst (>20 deg)												0

	Result	Result
Trunk Posture	Acceptable	1.75
Arm Posture	Acceptable	
Lower Body	Slightly Harmful	
Head and Neck	Distinctly Harmful	

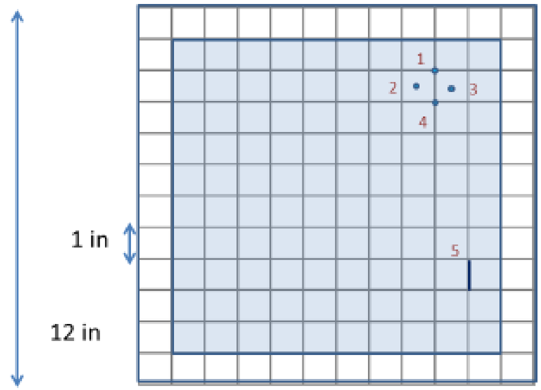
Appendix F- Panel Design

Contained in this section of the appendix are drawings which indicate information on the positions and types of defects in each panel.



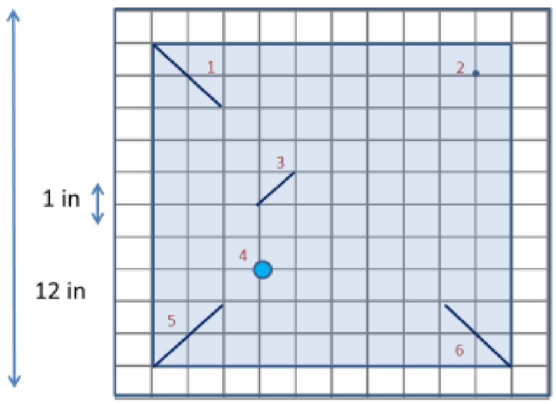
Panel #1 (view from top surface)

- 1: FBHS approx. .062" (+-.005") diameter & .115" (+-.005") deep from top surface.
- 2: FBHS approx. .032" (+-.005") diameter & .115" (+-.005") deep from top surface.
- 3: FBHS approx. .032" (+-.005") diameter & .115" (+-.005") deep from top surface.
- 4: FBHS approx. .25" (+-.005") diameter & .115" (+-.005") deep from top surface.
- 5: FBHS approx. .032" (+-.005") diameter & .115" (+-.005") deep from top surface.
- 6: FBHS approx. .062" (+-.005") diameter & .115" (+-.005") deep from top surface.
- 7: FBHS approx. .125" (+-.005") diameter & .115" (+-.005") deep from top surface.
- 8: FBHS approx. .032" (+-.005") diameter & .115" (+-.005") deep from top surface.
- 9: FBHS approx. .25" (+-.005") diameter & .115" (+-.005") deep from top surface.
- 10: FBHS approx. .032" (+-.005") diameter & .115" (+-.005") deep from top surface.



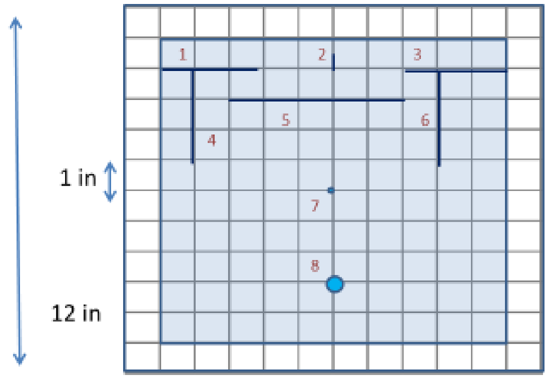
Panel #2 (view from top surface)

- 1: FBHS approx. .032" (+-.005") diameter & .12" (+-.005") deep from top surface.
- 2: FBHS approx. .032" (+-.005") diameter & .12" (+-.005") deep from top surface.
- 3: FBHS approx. .032" (+-.005") diameter & .115" (+-.005") deep from top surface.
- 4: FBHS approx. .032" (+-.005") diameter & .115" (+-.005") deep from top surface.
- 5: A slot cut from the top surface 1" long (+-.2") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.



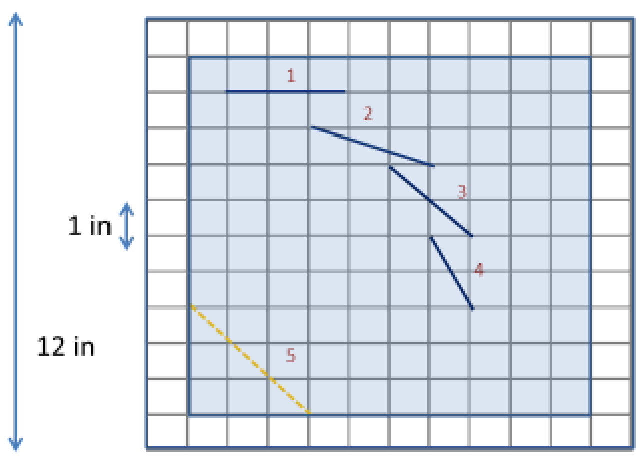
Panel #3 (view from top surface)

- 1: A slot cut from the top surface 2.83" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.
- 2: FBHS approx. .032" (+-.005") diameter & .115" (+-.005") deep from top surface.
- 3: A slot cut from the top surface 1" long (+-.2") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.
- 4: FBHS approx. .125" (+-.005") diameter & .115" (+-.005") deep from top surface.
- 5: A slot cut from the top surface 2.8" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.
- 6: A slot cut from the top surface 3" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.



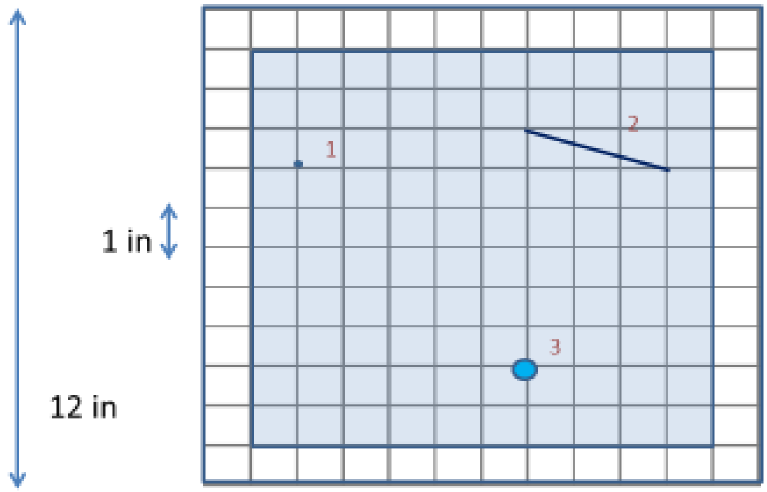
Panel #4 (view from top surface)

- 1: A slot cut from the top surface 3" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.
- 2: A slot cut from the top surface .5" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.
- 3: A slot cut from the top surface 3" long (+-.2") and .05"(+-.01") wide and .115" (+-.005") deep from top surface.
- 4: A slot cut from the top surface 3" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.
- 5: A slot cut from the top surface 5" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.
- 6: A slot cut from the top surface 3" long (+-.1") and .05"(+-.01") wide and .115" (+-.005") deep from top surface.
- 7:FBHS approx. .032" (+-.005") diameter & .115" (+-.005") deep from top surface.
- 8:FBHS approx. .125" (+-.005") diameter & .115" (+-.005") deep from top surface.



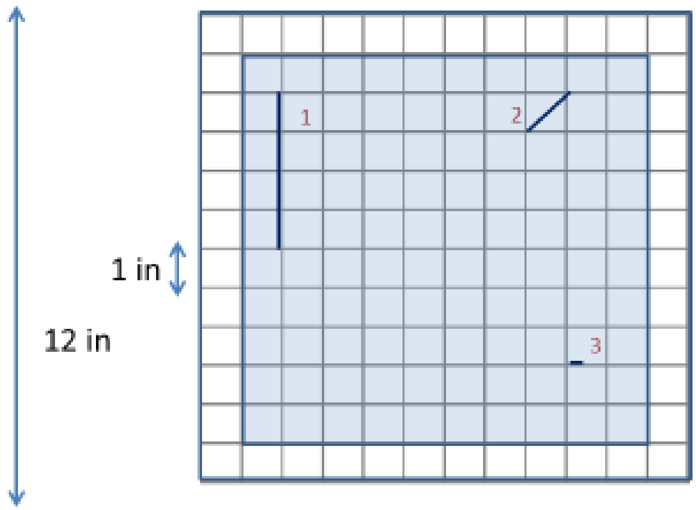
Panel #5 (view from top surface)

- 1: A slot cut from the top surface 3" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.
- 2: A slot cut from the top surface 3.16" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.
- 3: A slot cut from the top surface 2.83" long (+-.2") and .05"(+-.01") wide and .115" (+-.005") deep from top surface.
- 4: A slot cut from the top surface 2.24" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.
- 5: A saw cut from the bottom surface 4.24" long (+-.2") and .031"(+-.005") wide and .01" (+-.005") deep from the bottom surface.



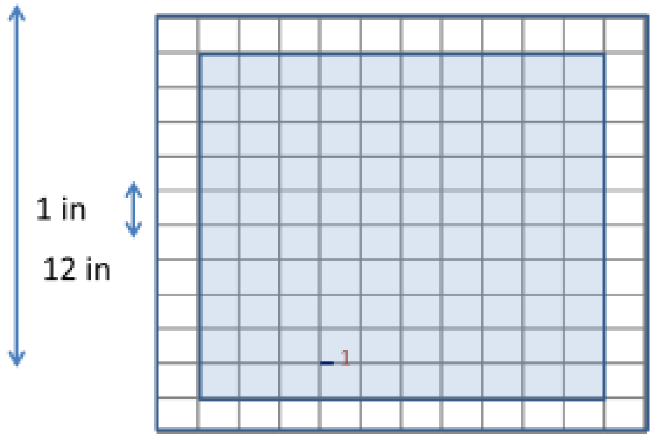
Panel #6 (View from top surface).

- 1: FBHS approx. .032" (+-.005") diameter & .115" (+-.005") deep from top surface.
- 2: A slot cut from the top surface 3.16" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.
- 3: FBHS approx. .125" (+-.005") diameter & .115" (+-.005") deep from top surface.



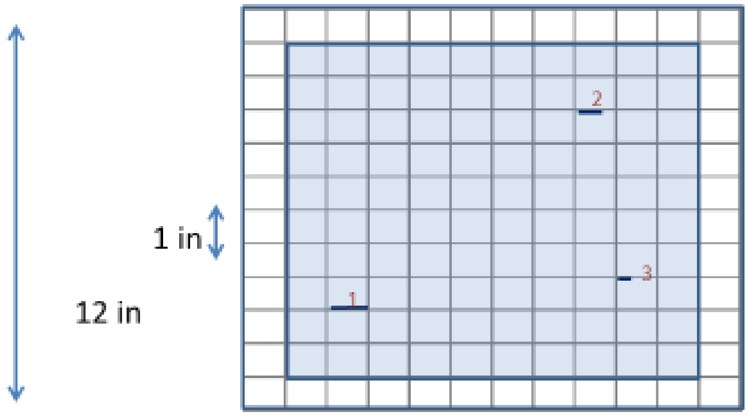
Panel #7 (View from top surface).

- 1: A slot cut from the top surface 4" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.
- 2: A slot cut from the top surface 1.4" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.
- 3: A slot cut from the top surface .25" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.



Panel #8 (View from top surface).

- 1: A slot cut from the top surface .25" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.



Panel #9 (View from top surface).

- 1: A slot cut from the top surface 1" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.
- 2: A slot cut from the top surface .5" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.
- 3: A slot cut from the top surface .25" long (+-.1") and .093"(+-.01") wide and .115" (+-.005") deep from top surface.

Appendix G- Tester Surveys

Part A; Tester Survey

Each tester was instructed to fill out a survey that helped to assess their background experience and training in NDT. The following were the questions:

Question #1 NAVAIR Experience		
Years at NAVAIR		ANSWER
0	3	
3	6	
6	10	
10	15	
15	30	

Question #2 NDT Experience		
Years of NDT Experience		ANSWER
0	3	
3	6	
6	10	
10	15	
15	30	

Question #3 NDT Training	
Eddy Current Training Completed	ANSWER
EC Level I	
EC Level II	
NDI Tech School	
Basic ASNT III Certification	
EC ASNT III	

Question #4 Total EC Experience		
Total Hours of EC Testing Experience		ANSWER
0	25	
25	50	
50	100	
100	250	
250	1000	

Question #5 Present EC Experience		
EC Testing Experience Within Past 3 Years		ANSWER
0	20	
20	50	
50	100	
100	200	
200	500	

Part B: Tester Survey Results

Explanation- Below are the results of each testers responses to the survey questions.

Tester	3C	4V	1Z	4Z	2C	6N
Rating	3	3	1	5	3	
Q1: Yrs at NAVAIR	0-4	0-4	>15	0-4	4-8	6-10
Q2: Yrs of NDT Exp	4-8	0-4	15-30	0-4	15-25	6-10
Q3: EC Training Completed	ET III	ET III	ET III	ET II	NDI School	ET III
Q4: Total ET Exp Hrs	100-500	100-500	1000-5000	0-50	500-1000	100-500
Q5: EC EXP Past 5 Yrs	100-500	100-500	200-500	0-50	0-50	50-100

Appendix H- Rating of Test Factors

Variable	#	Damage in Panel		Hinderance	Anthropometric		Viewing Condition		Inspector Background	
		Quantity	Quality	Access	Position	Fatigue	Visability	Angle of View	Training	Experience
Panel	1	5	5							
	2	3	5							
	3	3	2							
	4	4	3							
	5	3	1							
	6	2	5							
	7	2	2							
	8	1	5							
	9	2	5							
Position	1			1	1	2	1	1		
	2			1	4	4	1	3		
	3			1	2	4	2	1		
	4			2	2	2	1	2		
	5			2	2	2	1	3		
	5B			4	2	2	5	3		
	6			2	3	3	1	5		
	7			1	5	4	1	2		
	8			3	2	2	2	3		
	9			1	1	2	1	2		
	1Z								1	1
Personnel	3C								1	3
	4V								1	4
	6N								1	3
	4Z								4	4
	2C								4	1

The above table displays the difficulty rating for each factor. The very left column identifies each test panel, inspection location and tester. The following columns display the rating for each factor: quantity and quality of each test panel. Hindrance, body position, fatigue, viability, angle of view of each testing location. Degree of training and years of experience for each tester. Each of these are rated on a scale of 1 to 5 with 1 indicating a low chance of a negative inspection affect to 5 indicating a high chance of a negative affection on inspection performance.

Appendix I- Test Execution Information

	Test Execution Informaiton								
Inspect #	Name	Date	Panel #	Temp	Loc in testbed	Probe	Start Time	End Time	Notes/ Tester Comments
1	6N	8-Jul	6	85	6	90	9:10	10:18	Sunlight affected visual (T)
2	4Z	22-Jul	7	86	6	90	8:00	8:51	Inspected on tiptoes. 24 min in broke to get sunglasses.
3	6N	22-Jul	1	93	7	45	9:48	10:40	Streatched, sunglasses, dufficult to determine location (T)
4	4Z	25-Jul	5	92	8	90	8:57	9:34	Sunglasses, in shade, breeze
5	6N	25-Jul	2	97	1	45	10:05	10:37	Sunglasses, partly shaded
6	4V	26-Jul	6	83	6	45	8:04	8:30	Sunglasses, rained night before
7	4V	10-Aug	7	92	7	90	9:08	9:34	Sunglasses, Frequent Breaks
8	4V	23-Aug	5	82	5B	90	8:38	8:53	Blind Inspection
9	4Z	24-Aug	2	77	1	90	8:28	8:46	Mosquitos
10	6N	30-Aug	5	81	5B	45	9:05	9:41	Could have false indications due to gromets
11	3C	4-Oct	7	72	6	90	2:45	3:26	Windy (10<), inspection on toes, bugs
12	4V	1-Nov	4	62	8	90	1:25	2:02	Moved from one side of aircraft to another, foot fell asleep
13	1Z	3-Nov	6	87	5B	90	1:58	2:48	Used folder as guide, took a couple of breaks
14	3C	3-Nov	5	80	5B	90	3:30	4:16	Light Rain, used folder as guide
15	4Z	8-Nov	7	53	7	45	8:33	9:00	Used Sunglasses
16	3C	8-Nov	7	60	8	90	9:49	10:14	Moved from one side of the aircraft to another.Played music
17	6N	10-Nov	1	57	3	0	1:14	2:32	Wind > 7 MPH, Inspector Gridded Surface of Panel
18	3C	10-Nov	8	57	7	45/ 90	3:10	3:33	Inspected on tiptoes, arm got tired.
19	2C	17-Nov	5	59	6	90	1:51	2:27	twice during inspeciton (potentially distracted). Wind >9 MPH
20	4Z	5-Dec	3	72	9	45	2:55	3:45	
21	3C	13-Dec	3	72	9	45	12:33	1:13	Neck got sore during inspection
22	6N	15-Dec	3	70	9	90/45	9:42	10:42	Gridded surface, distracted (1 Min)
23	2C	20-Dec	3	70	9	0	9:25	10:20	Used Ruler, Took Breaks
24	1Z	21-Dec	3	71	9	45	3:25	4:05	instrument alarm
25	4V	22-Dec	3	72	9	45	8:44	9:10	Disturbed by multiple people

Appendix J- Test Data

	Test#	Date	Tester	Panel#	Pos#	WAS	TLX	Men	Phy	Pos	Dem	Vis	Per	Temp	TotT	Def#	Det	Cen	Ass	One?	Char	Mesd	Cen	Ass	Size	Notes
1	1	7/8	6N	6	6	2	28	5	0	1	3	7	13	85	68	1	1		1	1	1	0.1		1	0	
2																2	1		1	1	1	3.2		1	3	
3																3	1		1	1	1	0.2		1	0	
4	2	7/22	4Z	7	6	2	70	2	0	27	21	12	8	86	51	1	1		1	0			1	0	4	
5																2	1		1	0			1	0	1	
6																3	0		1					0	0	
7	3	7/22	6N	1	7	3	57	3	0	22	17	6	9	93	52	1	1		1	1	1	0.5		1	0	
8																2	0		1					0	0	
9																3	0		1					0	0	
10																4	1		1	1	1	0.5		1	0	
11																5	0		1					0	0	
12																6	0		1					0	0	
13																7	0		1					0	0	
14																8	0		1					0	0	
15																9	1		1	1	0	0.5		1	0	Hole Char as slot
16																10	1		1	1	1	0.3		1	0	
17	4	7/25	4Z	5	8	2	39	17	4	1	0	10	8	92	37	1	1		1	0			1	0	3	
18																2	1		1	0			1	0	3	
19																3	1		1	1	1	2.9		1	3	
20																4	1		1	1	0	0.3		1	2	Slot Char as hole
21																5	1		1	1	1	4.3		1	4	
22	5	7/25	6N	2	1	1	23	3	0	0	1	15	4	97	32	1	1		1	1	1	0.2		1	0	
23																2	0		1					0	0	
24																3	0		1					0	0	
25																4	1		1	1	0	0.2		1	0	Holes Char as slot
26																5	1		1	1	1	1		1	1	
27	6	7/26	4V	6	6	2	38	1	4	17	13	3	0	83	26	1	0		1					0	0	
28																2	1		1	1	1	3.3		1	3	
29																3	1		1	1	1	0.5		1	0	
30	7	8/10	4V	7	7	3	49	2	3	13	23	8	0	92	26	1	1		1	1	1	4		1	4	
31																2	1		1	1	1	1.5		1	1	
32																3	1		1	1	1	0.3		1	0	
33	8	8/23	4V	5	5B	2	71	12	16	3	0	33	7	82	15	1	1		1	1	1	3		1	3	Notes
34																2	0	1	0	0				0	3	
35																3	0	1	0	0				0	3	
36																4	0	1	0	0				0	2	Defects 1-3 char
37																5	1		1	1	1	3.5		1	4	as single defect
38	9	8/24	4Z	2	1	1	28	15	4	1	0	6	3	77	18	1	1		1	1	0	0.4		1	0	
39																2	0		1					0	0	
40																3	0		1					0	0	Defects 1-4 char
41																4	0		1					0	0	as single defect
42																5	1		1	1	1	1.1		1	1	
43	10	8/30	6N	5	5B	2	70	20	20	0	1	11	17	81	36	1	1		1	0			1	0	3	
44																2	0	1	0	0				0	3	XX
45																3	0	1	0	0				0	3	XX
46																4	1		1	0			1	0	2	
47																5	1		1	1	1	1		1	4	
48	11	10/4	3C	7	6	2	73	27	1	8	14	24	0	72	41	1	1		1	1	1	4		1	4	
49																2	1		1	1	1	1.8		1	1	
50																3	1		1	1	0	0.3		1	0	Slot Char as hole

	Tes t#	Date	Tes ter	Pan el #	Po s #	W AS	TL X	Me n	Ph y	Po s	De m	Vis	Pe r	Te mp	To t T	De f #	De t	Ce n	Ass	On e?	Cha r	Mes d	Ce n	As s	Siz e	Notes
51	12	11/1	4V	4	8	2	42	1	11	23	4	3	0	62	37	1	1		1	1	1	3		1	3	
52																2	1		1	1	1	0.5		1	1	
53																3	1		1	1	1	3		1	3	
54																4	1		1	1	1	3		1	3	
55																5	1		1	1	1	5		1	5	
56																6	1		1	1	1	3		1	3	
57																7	1		1	1	1	0.1		1	0	
58																8	1		1	1	1	0.3		1	0	
59	13	11/3	1Z	6	5B	2	52	0	17	15	9	6	5	87	50	1	1		1	1	1	0.1		1	0	
60																2	1		1	0			1	0	3	
61																3	1		1	1	1	0.4		1	0	
62	14	11/3	3C	5	5B	2	82	0	6	9	9	33	25	80	46	1	1		1	0			1	0	3	
63																2	1		1	0			1	0	3	
64																3	1		1	0			1	0	3	
65																4	1		1	1	0	0.5		1	2	Slot Char as hole
66																5	1		1	1	1	4.3		1	4	
67	15	11/8	4Z	7	7	3	53	12	0	3	5	20	13	53	27	1	1		1	1	1	4.1		1	4	Indicates as non
68																2	1		1	1	1	1.4		1	1	linear line
69																3	1		1	1	1	0.4		1	0	
70	16	11/8	3C	7	8	2	17	3	3	8	2	0	1	60	25	1	1		1	1	1	4		1	4	
71																2	1		1	1	1	1.5		1	1	
72																3	1		1	1	0	0.3		1	0	Slot Char as hole
73	17	11/10	6N	1	3	3	36	5	3	18	9	0	0	57	78	1	1		1	1	1	0.2		1	0	
74																2	0		1					0	0	
75																3	0		1					0	0	
76																4	1		1	1	1	0.3		1	0	
77																5	1		1	1	1	0.2		1	0	
78																6	1		1	1	1	0.1		1	0	
79																7	1		1	1	1	0.2		1	0	
80																8	1		1	1	1	0.1		1	0	
81																9	1		1	1	1	0.3		1	0	
82																10	0		1					0	0	
83	18	11/10	3C	8	7	3	29	3	1	7	13	0	5	57	23	1	1		1	1	1	0.5		1	0	
84	19	11/17	2C	5	6	2	24	3	3	5	3	11	0	59	36	1	1		1	1	1	3		1	3	
85																2	1		1	0			1	0	3	
86																3	1		1	1	1	2.3		1	3	
87																4	1		1	0			1	0	2	
88																5	1		1	1	1	3.6		1	4	
89	20	12/5	4Z	3	9	2	46	16	0	1	1	8	20	72	50	1	1		1	1	1	2.8		1	3	
90																2	1		1	1	1	0.3		1	0	
91																3	1		1	1	1	1		1	1	
92																4	1		1	1	0	0.5		1	0	Hole Char as slot
93																5	1		1	1	1	2.8		1	3	
94																6	1		1	1	1	3		1	3	
95	21	12/13	3C	3	9		14	3	1	8	1	0	0	72	40	1	1		1	1	1	2.8		1	3	
96																2	1		1	1	0	0.3		1	0	Hole Char as slot
97																3	1		1	1	1	1		1	1	
98																4	1		1	1	1	0.3		1	0	
99																5	1		1	1	1	2.8		1	3	
100																6	1		1	1	1	2		1	3	
101	22	12/15	6N	3	9		8	1	0	1	4	0	2	70	60	1	1		1	1	1	2.8		1	3	

	Test#	Date	Tester	Panel#	Pos#	WAS	TLX	Men	Phy	Pos	Dem	Vis	Per	Temp	TotT	Def#	Det	Cen	Ass	One?	Char	Mesd	Cen	Ass	Size	Notes
102																2	0		1					0	0	
103																3	1		1	1	1	1.1		1	1	
104																4	1		1	1	1	0.2		1	0	
105																5	1		1	1	1	2.8		1	3	
106																6	1		1	1	1	3		1	3	
107	23	12/20	2C	3	9		40	16	1	1	0	3	19	70	55	1	1		1	1	1	2.4		1	3	
108																2	1		1	1	1	0.2		1	0	Pot .15
109																3	1		1	1	1	1.1		1	1	
110																4	1		1	1	1	0.3		1	0	Pot .3
111																5	1		1	1	1	2.8		1	3	
112																6	1		1	0			1	0	3	
113	24	12/21	1Z	3	9		44	22	0	2	5	15	0	71	40	1	1		1	1	1	2.8		1	3	
114																2	1		1	1	0	0.1		1	0	
115																3	1		1	1	1	1		1	1	
116																4	1		1	1	1	0.3		1	0	
117																5	1		1	1	1	2.8		1	3	
118																6	1		1	1	1	3		1	3	
119	25	12/22	4V	3	9		23	1	3	5	10	0	4	72		1	1		1	1	1	3		1	3	
120																2	1		1	1	0	0.1		1	0	
121																3	1		1	1	1	1		1	1	
122																4	1		1	1	1	0.3		1	0	
123																5	1		1	1	1	3		1	3	
124																6	1		1	1	1	3		1	3	
125																										
150																										
Stats				Average			42	8	4	8	7	9	6	75	40	SUM	###	5	###	89		SUM	13	89		
				St Dev			20	8	6	8	7	10	7	13	16											

Conclusions: 124 data points (defects) were sought out in this study. From this study has been obtained: 119 data points for probability of detecion study (5 data points are censored), with a total of 102 detected defects. Of the 102 detected defects, 89 produced viable data for a hat vs a studies (with 18 having to be censored due to desired characterizaiton criteria. 5 of those were censored because the marked area of a defect covered multiple defect and it was dufficult to judge which one of them was actually detected

1. If a defect is detected, but not assessed correctly as a single defect, the data point will be assessed for POD, but not A hat vs A. **2.** If a defect is detected, assessed correctly as a single defect, but mis characterized, the data point will be assessed for POD, and A hat vs A. **3.** If detected but will be censored, put 0 for detected.

For POD

1. If defect is or is not detected, the data is used for POD. **2.** If it is dufficult to determine which defect is detected in a cluster of defects, then the data is censored

Appendix K-Matlab Code for POD Models

Explanation:

The code for the Lognormal, Logistic and Log Logistic runs in the following manner:

1. Loads the detection data which indicates the true size of the defect and binary information: if the defect was detected by the IS or not.
2. Sequences 20,000 random samples of a probability distribution using Metropolis Hastings Maximum likelihood estimates. It has a lower threshold of .005" and makes an initial guess of each parameter. Each guess gets closer and closer to the estimate and the end result approximates the mean & confidence bounds of the POD parameters.
3. It returns the Maximum Likelihoods Estimate for the parameters of the lognormal, logistic and log logistic distributions, using the empirical experimental data. It approximates the distribution and provides a confidence bound of 95% (from 2.5% to 97.5%).

Part A: Logistic

```matlab
% Parameter Definitions
% x(1) - Logistic POD m parameter
% x(2) - Logistic POD s parameter
clear
clc
%% Load Detection Data
% Load the total detection data.  Column 1 - Detection (1 = D, 0 = ND),
% Column 2 - Censored (0 = not censored, 1 = censored), Column 3 - measured
% flaw size, Column 4 - actual flaw size
load detectiondata;
i2 = 1;
i3 = 1;
i4 = 1;
for i = 1:124
    % Isolation of the detection data (D)
    if Ddata(i,1) == 1 && Ddata(i,2) == 0
        D(i2,1) = Ddata(i,4);
        i2 = i2 + 1;
    end
    % Isolation of the non-detection data (ND)
    if Ddata(i,1) == 0 && Ddata(i,2) == 0
        ND(i3,1) = Ddata(i,4);
        i3 = i3 + 1;
    end
    % Isolation of the censored data (cens)
    if Ddata(i,1) == 0 && Ddata(i,2) == 1
        cens(i4,1) = Ddata(i,4);
        i4 = i4 + 1;
    end
end
n_D = length(D);
n_ND = length(ND);
Hitmiss = [zeros(n_ND,1);ones(n_D,1)];
Dhitmiss = [ND;D];
% =====================================================
%% Constants
% =====================================================
significance=0.05;
alow = .005;                 % lower threshold of flaw detection size (inches)
nsamples = 20000;         % Number of samples (higher number of samples increases the acceptance rate)
K = 1000;                 % Burn-in value for MH sampling
M = 10;                   % This Thinning parameter controls the size of the new markov chain which omits M-1 out of M values
n = 2;                    % Number of parameters
% init_param=[40 10];    % First initial parameter guess
init_param=[1.9945 1.0120];    % Better initial parameter guess
% NOTE: The initial parameter guess must be such that the pdf(init_param)
% is greater than zero.  When it equals zero the MH Sampling function won't
% function.  Note that the first init_param guess results in the mean
% estimate being far off from that guess.  The second initial parameter is
% closer to that estimate and therefore produces better results.
% =====================================================
%% MH Sampling and Likelihood Setup
% =====================================================
prop_sig=eye(n);              % sigma for the proposed PDF
% The Logistic POD function
logisticpodcdf=@(x2,m,s) exp((x2 - m - alow)./s)./(1 + exp((x2 - m - alow)./s));
% The Left Side of the likelihood representing the failures (Detections)
pdfD1 = @(x2,m,s) exp((x2 - m - alow)./s)./(s.*((1 + exp((x2 - m - alow)./s)).^2));
% The Right Side of the likeiihood representing the survivors
% (Non-detections)
pdfD0 = @(x2,m,s) 1./(1 + exp((x2 - m - alow)./s));
% The Prior estimates for the parameters m and s
PODpriors = @(x) unifpdf(x(1),-100,100)*unifpdf(x(2),0,100);
% The Likelihood x Priors
pdf = @(x) PODpriors(x)*prod(pdfD1(D,x(1),x(2)))*prod(pdfD0(ND,x(1),x(2)));
% define proposal distribution and r.n. generator
proppdf = @(x,y) mvnpdf(x,y,prop_sig);
proprnd = @(y) [normrnd(y(1),0.1),normrnd(y(2),0.1)];
% ===========================================================
%% MH Sampling Routine
% ===========================================================
% Routine without Burn-in or thinning
% [result,accept] = mhsample(init_param,nsamples,'pdf',pdf,'proppdf',proppdf,'proprnd',proprnd);
% Routine with Burn-in and thinning (recommended)
[result,accept] = mhsample(init_param,nsamples,'pdf',pdf,'proppdf',proppdf,'proprnd',proprnd,'burnin',K,'thin',M);
% ===========================================================
% Calculation of the autocorrelation values for lagged values (Optional)
% ===========================================================
AC = zeros(n,1);
lag = 1;
for i=1:n
    me = mean(result(:,i));
    v = var(result(:,i));
    m2 = result(:,i)-me;
    ACfactor = zeros(nsamples-lag,1);
    for j=1:(nsamples-lag)
        ACfactor(j) = m2(j)*m2(j+lag);
    end
    AC(i) = 1/(v*(nsamples-lag))*sum(ACfactor);
end
```

```
% ============================================================
%% POD Parameter Distributions
% ============================================================
[mF,mresult] = ecdf(result(:,1));    % Nonparametric distribution for parameter m
[sF,sresult] = ecdf(result(:,2));    % Nonparametric distribution for parameter s
% Confidence bounds of the parameters m and s according to the significance
% chosen
for i = 1:length(mF)
    if mF(i) <= significance/2
        mlow = mresult(i);
    end
    if mF(i) <= 0.5
        mmed = mresult(i);
    end
    if mF(i) <= 1 - significance/2
        mhigh = mresult(i);
    end
end
for i = 1:length(sF)
    if sF(i) <= significance/2
        slow = sresult(i);
    end
    if sF(i) <= 0.5
        smed = sresult(i);
    end
    if sF(i) <= 1 - significance/2
        shigh = sresult(i);
    end
end
% Mean and standard deviation of the parameters
[mmean,mSD] = normfit(result(:,1));
[smean,sSD] = normfit(result(:,2));
% Table: rows - m,s; columns - mean, SD, low%, median, high%
TABLE = [mmean mSD mlow mmed mhigh;smean sSD slow smed shigh];

% POD Curve data
a = linspace(alow,max(Dhitmiss),100);
PODmean = logisticpodcdf(a,mmean,smean);
PODlow = logisticpodcdf(a,mlow,slow);
PODhigh = logisticpodcdf(a,mhigh,shigh);
PODmed = logisticpodcdf(a,mmed,smed);

% ============================================================
%% Plots
% ============================================================
```

```
figure(1)
subplot(1,2,1)
hist(result(:,1),100)
xlabel('POD m parameter')
ylabel('Frequency')
subplot(1,2,2)
hist(result(:,2),100)
xlabel('POD s parameter')
ylabel('Frequency')
legend([num2str(nsamples),' Samples'])

figure(2)
pod = plot(Dhitmiss,Hitmiss,'b+',a,PODmean,'r-',a,PODlow,'m--',a,PODhigh,'m-.');
legend(pod,'Hit-or-Miss Data','Mean POD',['Lower ',num2str(100*(significance/2)),' percentile POD'],['Upper ',num2str(100*(1 - significance/2)),' percentile POD'],'Location','Northwest')
xlabel('Flaw Size (inches)')
ylabel('POD')
title('Logistic POD')
```

Part B: Log Logistic

```
% Parameter Definitions
% x(1) - Loglogistic POD m parameter
% x(2) - Loglogistic POD s parameter
clear
clc
% ====================================================
%% Load Detection Data
% ====================================================
% Load the total detection data.  Column 1 - Detection (1 = D, 0 = ND),
% Column 2 - Censored (0 = not censored, 1 = censored), Column 3 - measured
% flaw size, Column 4 - actual flaw size
load detectiondata;
i2 = 1;
i3 = 1;
i4 = 1;
for i = 1:124
    % Isolation of the detection data (D)
    if Ddata(i,1) == 1 && Ddata(i,2) == 0
        D(i2,1) = Ddata(i,4);
        i2 = i2 + 1;
    end
    % Isolation of the non-detection data (ND)
    if Ddata(i,1) == 0 && Ddata(i,2) == 0
        ND(i3,1) = Ddata(i,4);
        i3 = i3 + 1;
    end
    % Isolation of the censored data (cens)
    if Ddata(i,1) == 0 && Ddata(i,2) == 1
        cens(i4,1) = Ddata(i,4);
        i4 = i4 + 1;
    end
end
n_D = length(D);
n_ND = length(ND);
Hitmiss = [zeros(n_ND,1);ones(n_D,1)];
Dhitmiss = [ND;D];
% =====================================================
%% Constants
% =====================================================
significance=0.05;
alow = .005;               % lower threshold of flaw detection size (inches)
nsamples=20000;         %Number of samples (higher number of samples increases the acceptance rate)
K = 1000;               % Burn-in value for MH sampling
M = 10;                 % This Thinning parameter controls the size of the new markov chain which omits M-1 out of M values
n=2;                    % Number of parameters
% init_param=[40 10];   % First initial parameter guess
init_param=[1.9945 1.0120];   % Better initial parameter guess
% NOTE: The initial parameter guess must be such that the pdf(init_param)
% is greater than zero.  When it equals zero the MH Sampling function won't
% function.  Note that the first init_param guess results in the mean
% estimate being far off from that guess.  The second initial parameter is
% closer to that estimate and therefore produces better results.
% =====================================================
%% MH Sampling and Likelihood Setup
% =====================================================
prop_sig=eye(n);                % sigma for the proposed PDF
% The Loglogistic POD function
loglogisticpodcdf=@(x2,m,s) exp((log(x2 - alow) - m)./s)./(1 + exp((log(x2 - alow) - m)./s));
% The Left Side of the likelihood representing the failures (Detections)
pdfD1 = @(x2,m,s) exp((log(x2 - alow) - m)./s)./(s.*((1 + exp((log(x2 - alow) - m)./s)).^2));
% The Right Side of the likeiihood representing the survivors
% (Non-detections)
pdfD0 = @(x2,m,s) 1./(1 + exp((log(x2 - alow) - m)./s));
% The Prior estimates for the parameters m and s
PODpriors = @(x) unifpdf(x(1),-100,100)*unifpdf(x(2),0,100);
% The Likelihood x Priors
pdf = @(x) PODpriors(x)*prod(pdfD1(D,x(1),x(2)))*prod(pdfD0(ND,x(1),x(2)));
% define proposal distribution and r.n. generator
proppdf = @(x,y) mvnpdf(x,y,prop_sig);
proprnd = @(y) [normrnd(y(1),0.1),normrnd(y(2),0.1)];
% ===========================================================
%% MH Sampling Routine
% ===========================================================

% Routine without Burn-in or thinning
% [result,accept] = mhsample(init_param,nsamples,'pdf',pdf,'proppdf',proppdf,'proprnd',proprnd);
% Routine with Burn-in and thinning (recommended)
[result,accept] = mhsample(init_param,nsamples,'pdf',pdf,'proppdf',proppdf,'proprnd',proprnd,'burnin',K,'thin',M);
% ===========================================================
% Calculation of the autocorrelation values for lagged values (Optional)
% ===========================================================
AC = zeros(n,1);
lag = 1;
for i=1:n
    me = mean(result(:,i));
    v = var(result(:,i));
    m2 = result(:,i)-me;
    ACfactor = zeros(nsamples-lag,1);
    for j=1:(nsamples-lag)
        ACfactor(j) = m2(j)*m2(j+lag);
    end
    AC(i) = 1/(v*(nsamples-lag))*sum(ACfactor);
```

```
end
% ============================================================
%% POD Parameter Distributions
% ============================================================
[mF,mresult] = ecdf(result(:,1));    % Nonparametric distribution for parameter m
[sF,sresult] = ecdf(result(:,2));    % Nonparametric distribution for parameter s
% Confidence bounds of the parameters m and s according to the significance
% chosen
for i = 1:length(mF)
    if mF(i) <= significance/2
        mlow = mresult(i);
    end
    if mF(i) <= 0.5
        mmed = mresult(i);
    end
    if mF(i) <= 1 - significance/2
        mhigh = mresult(i);
    end
end
for i = 1:length(sF)
    if sF(i) <= significance/2
        slow = sresult(i);
    end
    if sF(i) <= 0.5
        smed = sresult(i);
    end
    if sF(i) <= 1 - significance/2
        shigh = sresult(i);
    end
end
% Mean and standard deviation of the parameters
[mmean,mSD] = normfit(result(:,1));
[smean,sSD] = normfit(result(:,2));
% Table: rows - m,s; columns - mean, SD, low%, median, high%
TABLE = [mmean mSD mlow mmed mhigh;smean sSD slow smed shigh];

% POD Curve data
a = linspace(alow,max(Dhitmiss),100);
PODmean = loglogisticpodcdf(a,mmean,smean);
PODlow = loglogisticpodcdf(a,mlow,slow);
PODhigh = loglogisticpodcdf(a,mhigh,shigh);
PODmed = loglogisticpodcdf(a,mmed,smed);

% ============================================================
%% Plots
% ============================================================
```

```
% ============================================================
figure(1)
subplot(1,2,1)
hist(result(:,1),100)
xlabel('POD m parameter')
ylabel('Frequency')
subplot(1,2,2)
hist(result(:,2),100)
xlabel('POD s parameter')
ylabel('Frequency')
legend([num2str(nsamples),' Samples'])

figure(2)
pod = plot(Dhitmiss,Hitmiss,'b+',a,PODmean,'r-',a,PODlow,'m--',a,PODhigh,'m-.');
legend(pod,'Hit-or-Miss Data','Mean POD',['Lower ',num2str(100*(significance/2)),' percentile POD'],['Upper ',num2str(100*(1 - significance/2)),' percentile POD'],'Location','Northwest')
xlabel('Flaw Size (inches)')
ylabel('POD')
title('Loglogistic POD')
```

Part C: Lognormal

```
% x(1) - Lognormal POD mu parameter
% x(2) - Lognormal POD sigma parameter
clear
clc
% Load the total detection data.  Column 1 - Detection (1 = D, 0 = ND),
% Column 2 - Censored (0 = not censored, 1 = censored), Column 3 - measured
% flaw size, Column 4 - actual flaw size
load detectiondata;
i2 = 1;
i3 = 1;
i4 = 1;
for i = 1:124
    % Isolation of the detection data (D)
    if Ddata(i,1) == 1 && Ddata(i,2) == 0
        D(i2,1) = Ddata(i,4);
        i2 = i2 + 1;
    end
    % Isolation of the non-detection data (ND)
    if Ddata(i,1) == 0 && Ddata(i,2) == 0
        ND(i3,1) = Ddata(i,4);
        i3 = i3 + 1;
    end
    % Isolation of the censored data (cens)
    if Ddata(i,1) == 0 && Ddata(i,2) == 1
        cens(i4,1) = Ddata(i,4);
        i4 = i4 + 1;
    end
end
n_D = length(D);
n_ND = length(ND);
Hitmiss = [zeros(n_ND,1);ones(n_D,1)];
Dhitmiss = [ND;D];
% ====================================================
%% Constants
% ====================================================
significance=0.05;
alow = .005;                % lower threshold of flaw detection size (inches)
nsamples=20000;          %Number of samples (higher number of samples increases the acceptance rate)
K = 1000;                % Burn-in value for MH sampling
M = 10;                  % This Thinning parameter controls the size of the new markov chain which omits M-1 out of M values
n=2;                     % Number of parameters
% init_param=[40 10];    % First initial parameter guess
init_param=[1.9945 1.0120];   % Better initial parameter guess
% NOTE: The initial parameter guess must be such that the pdf(init_param)
% is greater than zero.  When it equals zero the MH Sampling function won't
% function.  Note that the first init_param guess results in the mean
% estimate being far off from that guess.  The second initial parameter is
% closer to that estimate and therefore produces better results.
% ====================================================
%% MH Sampling and Likelihood Setup
% ====================================================
prop_sig=eye(n);            % sigma for the proposed PDF
% The Lognormal POD function
lognormalpodcdf=@(a,mu,sigP2) quadgk(@(x) (1./((x-alow)*sqrt(2*pi*sigP2))).*exp(-0.5*(1/sigP2).*(log(x-alow)-mu).^2),alow,a);

% The Left Side of the likelihood representing the failures (Detections)
pdfD1 = @(x2,mu,sigP2) (1./((x2 - alow).*sqrt(2*pi*sigP2))).*exp(-0.5.*(((log(x2 - alow) - mu).^2)/sigP2));
% The Right Side of the likeiihood representing the survivors
% (Non-detections)
pdfD0 = @(x2,mu,sigP2) 0.5 - 0.5.*erf((log(x2 - alow) - mu)./sqrt(2*sigP2));
% The Prior estimates for the parameters m and s
PODpriors = @(x) unifpdf(x(1),-100,100)*unifpdf(x(2),0,100);
% The Likelihood x Priors
pdf = @(x) PODpriors(x)*prod(pdfD1(D,x(1),x(2)))*prod(pdfD0(ND,x(1),x(2)));
% define proposal distribution and r.n. generator
proppdf = @(x,y) mvnpdf(x,y,prop_sig);
proprnd = @(y) [normrnd(y(1),0.1),normrnd(y(2),0.1)];
% ============================================================
%% MH Sampling Routine
% ============================================================

% Routine without Burn-in or thinning
% [result,accept] = mhsample(init_param,nsamples,'pdf',pdf,'proppdf',proppdf,'proprnd',proprnd);
% Routine with Burn-in and thinning (recommended)
[result,accept] = mhsample(init_param,nsamples,'pdf',pdf,'proppdf',proppdf,'proprnd',proprnd,'burnin',K,'thin',M);
% ============================================================
% Calculation of the autocorrelation values for lagged values (Optional)
% ============================================================
AC = zeros(n,1);
lag = 1;
for i=1:n
    me = mean(result(:,i));
    v = var(result(:,i));
    m2 = result(:,i)-me;
    ACfactor = zeros(nsamples-lag,1);
    for j=1:(nsamples-lag)
        ACfactor(j) = m2(j)*m2(j+lag);
    end
    AC(i) = 1/(v*(nsamples-lag))*sum(ACfactor);
end
% ============================================================
%% POD Parameter Distributions
```

```
% ============================================================
[muF,muresult] = ecdf(result(:,1));   % Nonparametric distribution for parameter mu
[sigP2F,sigP2result] = ecdf(result(:,2));   % Nonparametric distribution for parameter sigP2
% Confidence bounds of the parameters m and s according to the significance
% chosen
for i = 1:length(muF)
    if muF(i) <= significance/2
        mulow = muresult(i);
    end
    if muF(i) <= 0.5
        mumed = muresult(i);
    end
    if muF(i) <= 1 - significance/2
        muhigh = muresult(i);
    end
end
for i = 1:length(sigP2F)
    if sigP2F(i) <= significance/2
        sigP2low = sigP2result(i);
    end
    if sigP2F(i) <= 0.5
        sigP2med = sigP2result(i);
    end
    if sigP2F(i) <= 1 - significance/2
        sigP2high = sigP2result(i);
    end
end
% Mean and standard deviation of the parameters
[mumean,muSD] = normfit(result(:,1));
[sigP2mean,sigP2SD] = normfit(result(:,2));
% Table: rows - mu,sigP2; columns - mean, SD, low%, median, high%
TABLE = [mumean muSD mulow mumed muhigh;sigP2mean sigP2SD sigP2low sigP2med sigP2high];

% POD Curve data
a = linspace(alow,max(Dhitmiss),100);
PODmean = arrayfun(@(q1) lognormalpodcdf(q1,mumean,sigP2mean),a);
PODlow = arrayfun(@(q1) lognormalpodcdf(q1,mulow,sigP2low),a);
PODhigh = arrayfun(@(q1) lognormalpodcdf(q1,muhigh,sigP2high),a);
PODmed = arrayfun(@(q1) lognormalpodcdf(q1,mumed,sigP2med),a);
% ============================================================
%% Plots
% ============================================================
figure(1)
subplot(1,2,1)
hist(result(:,1),100)
xlabel('POD \mu parameter')
```

```
ylabel('Frequency')
subplot(1,2,2)
hist(result(:,2),100)
xlabel('POD \sigma^2 parameter')
ylabel('Frequency')
legend([num2str(nsamples),' Samples'])

figure(2)
pod = plot(Dhitmiss,Hitmiss,'b+',a,PODmean,'r-',a,PODlow,'m--',a,PODhigh,'m-.');
legend(pod,'Hit-or-Miss Data','Mean POD',['Lower ',num2str(100*(significance/2)),' percentile POD'],['Upper ',num2str(100*(1 - significance/2)),' percentile POD'],'Location','Northwest')
xlabel('Flaw Size (inches)')
ylabel('POD')
title('Lognormal POD')
```

Appendix L- Matlab Code for Regression Analysis of Measured vs Actual Defect sizes

```
>> % actual defect size
x = [.03 .03 .03 .03 .03 .03 .03 .03 .03 .03 ...
    .03 .03 .03 .03 .06 .06 .06 .125 .125 .125 ...
    .125 .125 .125 .125 .125 .125 .125 .125 .25 .25 ...
    .25 .25 .25 .25 .25 .25 .25 .5 1 1 ...
    1.4 .14 .14 1.4 1.4 1.4 1.4 1.4 1.4 1.4 ...
    2.25 2.25 2.8 2.8 2.8 2.8 2.8 2.8 2.8 2.8 ...
    2.8 2.8 2.8 2.8 2.8 2.8 3 3 3 3 ...
   3 3 3 3 3 3 3 3.15 3.15 4 ...
   4 4 4 4.25 4.25 4.25 4.25 4.25 5]';
% Measured defect size
y = [.1 .25 .2 .2 .4 .125 .125 .2 .125 .25 ...
    .25 .15 .15 .125 .5 .2 .125 .2 .5 .25  ...
    .375 .2 .5 .25 .2 .3 .25 .25 .5 .5 ...
    .25 .25 .4 .25 .3 .3 .5 .5 1 1.1 ...
    1.5 .175 1.4 1.5 1 1 1.1 1.13 1 1 ...
    .3 .5 2.9 2.31 2.75 2.75 2.8 2.8 2.75 2.75 ...
    2.38 2.75 2.75 2.75 3 3 3 3 3 3 ...
    3 3 3 2 3 3 3 3.2 3.25 4 ...
    4 4.1 4 4.3 3.5 1 4.25 3.61 5]';
```

Utilized curve fitting app to obtain the following results:

```
Results

Linear model Poly1:
   f(x) = p1*x + p2
Coefficients (with 95% confidence bounds):
     p1 =     0.8708  (0.8043, 0.9373)
     p2 =     0.1566  (0.009225, 0.3039)

Goodness of fit:
  SSE: 20.03
  R-square: 0.8861
  Adjusted R-square: 0.8848
  RMSE: 0.4798
```

Bibliography

[1] Sondalini, Mike. (2006) *Defect & Failure True Cost*. Retrieved from http://feedforward.com.au/costoffailure.htm.

[2] Hoffman, M. E., & Hoffman, P. C. (2001). Corrosion and fatigue research — structural issues and relevance to naval aviation. *International Journal of Fatigue,* 23, 1-10. doi:10.1016/s0142-1123(01)00115-3.

[3] Zamanzadeh, M., Larkin, E. , & Gibbon, D. (2004) *A Re-Examination of Failure Analysis and Root Cause Determination*. Matco Associates. Retrieved from http://az276019.vo.msecnd.net/valmontstaging/knowledge-center/a-re-examination-of-failure-analysis-and-root-cause-determination.pdf?sfvrsn=6.

[4] Kosh, Gehardus H., Brongers, Michael P.H., Thompson, Neil G., Virmani, Y. Paul., Payer, J.H. (2002). Corrosion Costs and Preventive Strategies in the United States. *NACE International*. Publication No. FHWA-RD-01-156.

[5] Harding, C.A., & Hugo, G.R., (2011, November). Guidelines for Interpretation of Published Data on POD for NDT. Maritime Platforms Division: Defense Science & Technology Organization.

[6] Alcorn, John B. Air Safety Fundamentals- Lessons Learned from the Deadliest Disasters in Aeronautics. American Institute of Aeromechanics and Astronautics. Retrieved from http://space.uah.edu/publications/aiaa_region2_2012/Alcorn_AirSafetyFundamentals_Manuscript.pdf.

[7] Rais, Anas Hassan El. (2015, January). Basic Human Factors and Nondestructive Testing. *The NDT Technician*, Vol. 14, No. 1, pp. 1-4.

[8] (2013, October) *NAVAIR Acquisitions Guide 2014/15*. 25th edition.

[9] Rihar, Gabriel. D Sc., varilstvo,Institut za., Ptujska 19, Ljubljana. (1997, April) Selection of an NDT Method and the Extent of Testing. *The 4th International Conference of Slovenian Society for Non Destructive Testing*. Ljubljana, Slovenia

[10] Algernon, Daniel (2017, March). *Assessment of the Capabilities of NDE Inspection Systems*. Retrieved from https://www.svti.ch/fileadmin/SVTI/NUK/Publikationen/Assessment_of_the_Capabilities_of_NDE_Inspection_Systems-07.07.1758-_J000007763.pdf.

[11] MIL HDBK-1823A Department of Defense Handbook. (2009, April). Nondestructive Evaluation System Reliability Assessment.

[12] The Belmont Report: Ethical Principles and Guidelines for the Protection of Human Subjects of Research. (1978). The National Commission for the Protection of Human Subjects of Biomedical and Behavioral Research.

[13] Aviation Maintenance Technician Handbook. *US Department of Transportation, Federal Aviation Administration*., ok, pp. 8-1-8-34, 2008. Oklahoma City

[14] Pyy, Pekka.(2000, December) Human Reliability Analysis Methods for Probabilistic Safety Assessment. Technical Research Centre of Finland, *Vtt Publications* 422. 63 p. + app. 64 p.

[15] Gordon, Claire C., Churchill, Thomas., Clauster, Charles E., Bradtmiller, Bruce., McConville, John T., Tebbetts, Ilse., Walker, Robert A., (1989, September) 1988 Anthropometric Survey of U.S, Personnel: Methods and Summary Statistics. *United States Army*, Natick Research, Development and Engineering Center

[16] The University of Iowa College of Engineering (2017, April). *Virtual Soldier Research*. Retrieved from http://www.ccad.uiowa.edu/vsr/.

[17] National Aeronautics and Space Administration. (2017, February). *NASA TLX Task Load Index*. Retrieved from https://humansystems.arc.nasa.gov/groups/tlx/.

[18] Hart, S.G., & Staveland, L.E. (1968). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. North Holland Press. Amsterdam

[19] Engineers Edge. (2017). *Disadvantages and Advantages of Selected Non-Destructive Inspection Methods (NDI)*. Retrieved from *http://www.engineersedge.com/inspection/inspection_pro_con.htm*

[20] (2004) *Nondestructive Testing Handbook, Electromagnetic Testing (ET).* Third Edition: Volume 5. ASNT

[21] NDT Education Resource Center, (2014). *NDT Resource Center*. Retrieved from https://www.nde-ed.org/EducationResources/CommunityCollege/EddyCurrents/Physics/depthcurrentdensity.htm

[22] Hayo, T., Frankenstein, B., Boller, C., Bockenheimer, C. (2011, November) Approach to the Technical Qualification of a SHM System in Terms of Damage Detection in Aerospace Industry. *International Workshop: Smart Materials, Structures & NDT in Aerospace*.

[23] Annis, Charles., Gandossi, Luca., Martin, Oliver. Optimal Sample Size for Probability of Detection Curves. *Statistical Engineering*.

[24] Teichner, W. H. (1974). The Detection of a Simple Visual Signal as a Function of Time of Watch. *Human Factors*. 16(4), 339-353.

[25] Drury, Colin G., Watson, Jean. (2002, May) Good Practices in Visual Inspection.

[26] (2012, January). MIL-PRF-85285E Coating: Polyurethane, Aircraft and Support Equipment.

[27] (2012, October). MIL-PRF-85582E: Primer coatings: Epoxy, Waterborne.

[28] (2006, July) MIL-DTL-5541F: Chemical Conversion Coatings on Aluminum and Aluminum Alloys.

[29] Nelms, Douglas. (2012, October). *T-Rex Lives! NACRA Flying Testbed Proves Worth. Oct 2012*. Retrieved from http://www.rotorandwing.com/2012/10/09/t-rex-lives-nacra-flying-testbed-proves-worth/.

[30] VTOL. (2015). *Protective Laminates*. Retrieved from https://vtolfilms.com/about.html.

[31] Saddleback College (2017, April) *BIO 113 Lab 1*. Retrieved from https://www.saddleback.edu/faculty/thuntley/bio113/labs/lab1.pdf. 4/12/2017

[32] Lee, TZU-Hsien., Han, Chia-Shan. (2013). Analysis of Working Postures at a Construction Site Using the OWAS Method. *International Journal of Occupied Safety and Ergonomics*. Vol 19, No.2.

[33] Seppanen, Olli; Fisk, William J.; Lei, Q.H. (2006, July). Effect of Temperature on Task Performance in Office Environment". Lawrence Berkley National Laboratory

[34] (2017, April) *Olympus Corporation* Retrieved from http://www.olympus-ims.com/en/2000ds/.

[35] Matzkanin, George A., Yolken, H.Thomas., (2001 August). Probability of Detection (POD) for Nondestructive Evaluation (NDE). *Nondestructive Testing Information Analysis Center*. NTIAC-TA-00-01.

[36] Wehling, P., LaBudde, R.A., Brunelle, S.L., & Nelson, M.T., (2012). Appendix H: Probability of Detection (POD) as a Statistical Model for the Validation of Qualitative Method. *AOAC International*.

[37] Annis, Charles & Gandossi, Luca. (2012). Influence of Sample Size and Other Factors on Hit/ Miss Probability of Detection Curves. *ENIQ Report No 47*.

[38] McCullagh, Peter. (1980). Regressional Models for Ordinal Data. *Journal of the Royal Statstical Society*.

[39] Brausch,John., Butkus, Lawrence., Campbell, David., Mullis, Tommy., & Paulk, Michael. (2008, October). Recommended Processes and Best Practices for NDE of Safety of Flight Structures. *Materials Integrity Branch System Support Division*.

[40] (2008, October). Structures Bulletin: EN-SB-08-012. *Wright Patterson AFB*.

[41] Snook, Stover H. & Ciriello, Vincent M. (2007, May). The Design of Manual Handling Tasks: Revised Tables of Maximum Acceptable Weights and Forces. Pgs. 1197-1213,

[42] Malek, Karim Abdel., Yang, Jingzhou., Yu, Wei & Duncan, Jerry. Human Performance Measurements: Mathematics. *Human Factors/Ergonomics Deere & Company Technical Center*. Moline, IL.

[43] (2017, April). Faro *Arm*. Retrieved from http://www.faro.com/en-us/products/metrology/measuring-arm-faroarm/overview

[44] (2017, April). Verisurf: Software-CAD. Retrieved from https://www.verisurf.com/software/cad

[45] (2017, April). NASA Task Load Index (NASA TLX) Version 1.0 Paper and Pencil Package. *Human Performance Research Group, NASA Ames Research Center*, Moffett Field, California.

[46] Rummel, Ward D. & Matzkanin, George A. (1997, November). Non Destructive Evaluation (NDE Capabilities Data Book) 3rd Edition. *Nondestructive Testing Information Analysis Center (NTIAC).*

[47] Workman, Gary L. & Moore, Patrick O. (2012). *Non Destructive Testing Handbook*. Volume 10, 3rd edition. ASNT.

[48] O'Connor, Andrew N. (2011). Probability Distributions Used in Reliability Engineering. *The Center for Risk and Reliability Engineering*, UMD

[49] Dr. Jackson, (2017, April) *G2MT Laboratories*. Retrieved from: http://www.g2mtlabs.com/corrosion/cost-of-corrosion/

[50] (2012) *MH-60 R/S*. Retrieved from http://www.mh-60.com/mh-60r/

[51] Browne, Ryan. (2016 June). *Military Aircraft Accidents Costing Lives, Billions of Dollars*. Retrieved from http://www.cnn.com/2016/06/20/politics/military-aviation-crash/index.html

[52] Spencer, Floyd W. (1998, April). Identifying Sources of Variation for Reliability Analysis of Field Inspections. *Sandia National Laboratories*.

[53] Hagemaier, Don. (1998). Factors Influencing Eddy Current POD in the Field Environment". *Boeing Phantom Works*. Long Beach CA.

[54] Corke, Peter I. (2002, November). A Simple and Systematic Approach to Assigning Denavit-Hartenberg Parameters. *Journal of LATEX*, Vol 1 No. 11,

[55] NAVAIR 01-1A-16-1_15. (2014, May). Nondestructive Inspection Methods, Basic Theory. *NAVAIR*

[56] Lock, MWB. (1998, May). The Effect of Aircraft Maintenance on Human Factors. *School of Industrial and Manufacturing Sciences*, Cranfield University

[57] Modarres, Mohammad. Kaminskiy, Mark. Krivtsov, Vasiliy. (2011, August).

Reliability Engineering and Risk Analysis, a Practical Guide. 2ed. T&F/Crc

[58] NAVAIR 01-1A-16-2. (2014, May). Nondestructive Inspection General Procedures and Process Controls