HUMAN FACTORS GOOD PRACTICES IN BORESCOPE INSPECTION

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1.0 EXECUTIVE SUMMARY

Inspection error has been blamed for a number of engine failures in civil aviation, such as the one at Pensacola in July 1998. One of the inspection techniques most used in engine inspection is the borescope, a tool that allows remote viewing and thus obviates the need to disassemble the engine for routine inspections. This report provides an analysis of the tasks of borescope inspection in human factors terms to derive effective interventions aimed at improving inspection reliability.

This report closely follows an earlier work on Fluorescent Penetrant Inspection (FPI) in that it uses detailed task analyses to discover potential human / system mismatches that could lead to error. As in the earlier report (Drury, 1999)1, the main technique is Hierarchical Task Analysis (HTA), where the whole job of borescope inspection is broken into successively smaller components, so that existing knowledge of human factors in inspection can be applied logically.

At each of two visits to engine inspection facilities the HTA model of Borescope Inspection was further developed, and both good and poor human factors practices noted. The HTA had seven major tasks:

1. Initiate inspection
2. Access inspection task
3. Initiate engine rotation
4. Search for indications
5. Decision on indications
6. Respond on inspection
7. Return borescope to storage

The HTA was used to break each task down until potential human errors could be derived. These errors (active failures) were analyzed for the factors driving the error rate (latent failures). Using this process, a set of YY human factors good practices was generated, and is presented in Appendix 1. Each good practice is keyed to one of the seven major tasks listed above. Each is also keyed to the potential errors that the good practice can prevent. In this way, users are given the reasons for our recommendations, so that they can develop a knowledge base in addition to the rule-based good practices. This will allow users to apply these recommendations better to their specific process.

Additionally, there were general control mechanisms needing to be addressed. Examples are the difficulties in controlling tip movement direction and extent, loss of orientation and situational awareness through the use of a limited field of view, interactions between field of view movements and eye movements, issues of repetitive inspection of almost-identical objects such as fan blades, and computer interface design issues with more modern borescopes. Each is discussed to show how human factors can be applied at a higher level than the YY specific recommendations.

Applying human factors good practices to engine borescope inspection can be expected to improve engine inspection reliability by addressing issues not typically found in the borescope literature.

2.0 OBJECTIVES AND SIGNIFICANCE

This study was commissioned by the Federal Aviation Administration (FAA), Office of Aviation Medicine with the following objectives for the following reasons.

2.1 Objectives

Objective 1. To perform a detailed Human Factors analysis of borescope inspection, particularly as applied to aircraft turbine engines.

Objective 2. To use the analysis to provide Human Factors guidance (best practices) to improve the overall reliability of borescope inspection

2.2 Significance

This research helps to ensure that the inspection of engine components, particularly rotating components, reaches the highest possible level of reliability. Incidents such as the Sioux City DC-10 crash and the Pensacola MD-80 damage have shown that engine component inspection is not perfectly reliable and that the human element in the inspection system is a primary cause of concern. Borescope inspection was chosen as it is used in a number of engine applications, it can also be used for airframe inspection (e.g. behind cabin insulation), and there are no known human factors guidelines available. The human factors analysis brings detailed data on human characteristics to the solution of inspection reliability problems. As a result of this research, a series of best practices are available for implementation. These can be used in improved training schemes, procedures, design of equipment and the inspection environment so as to reduce the overall incidence of inspection error in borescope inspection tasks for critical components.

3.0 INTRODUCTION

This report uses the same techniques as an earlier report (Drury, 1999)1 on Fluorescent Penetrant Inspection (FPI), and some of the sections applicable to both have been adapted directly for the current report. Thus the background data and models of inspection reliability and human inspection performance follow closely the earlier study.

This project used accumulated knowledge on human factors engineering applied to Nondestructive Inspection (NDI) of critical rotating engine components. The original basis for this project, and the previous FPI project, was the set of recommendations in the National Transportation Safety Board (NTSB) report (N75B/AAR-98/01)2 concerning the failure of the inspection system to detect a crack in a JT-8D engine hub. As a result Delta Flight 1288 experienced an uncontained engine failure on take-off from Pensacola, Florida on July 6, 1998. Two passengers died. Previous reports addressing the issue of inspector reliability for engine rotating components include the United Airlines crash at Sioux City, Iowa on July 19, 1989 (NTSB/AAR-90/06)3, and a Canadian Transportation Safety Board (CTSB) report on a Canadian Airlines B-767 failure at Beijing, China on September 7, 1997. Inspection failure in engine maintenance continues to cause engine failures and take lives.

Federal Aviation Administration (FAA) responses to these incidents have concentrated on titanium rotating parts inspection through the Engine and Propeller Directorate (FAA/TRCTR report, 1990, referenced in NTSB/AAR-98/01).2 These responses have included better quantification of the Probability of Detection (PoD) curves for the primary NDI techniques used, and drafts of Advisory Circulars on visual inspection (AC 43-XX)4 and nondestructive inspection (AC 43-ND).5   Note that nondestructive inspection (NDI) is equivalent to the alternative terminology of nondestructive testing (NDT) and nondestructive evaluation (NDE). However, there are still no PoD curves available relating specifically to Borescope inspection, despite borescopes being the main instruments for NDI of engines in flight line operations.

In order to control engine inspection failures, the causes of inspection failure must be found and addressed. Treating the (inspector plus inspection technology plus component) system as a whole, inspection performance can be measured by probability of detection (PoD). This PoD can then be measured under different circumstances to determine which factors affect detection performance, and quantify the strength and shape of these relationships. An example is the work reported by 6 on repeated testing of the same specimens using penetrant, ultrasonic, eddy current and X-ray inspection. Wide differences in PoD were found. It was also noted that many factors affected PoD for each technique, including both technical and inspector factors. Over many years (e.g. 7 a major finding of such studies has been the large effects of the inspector on PoD. Such factors as training, understanding and motivation of the inspector, and feedback to the inspector were considered important.6

Borescope inspection has been a mainstay of the engine inspector for many years, and borescope specifications and instructions are included in most inspection texts and manuals. For example, both the older Advisory Circular on visual inspection (AC 43-13-1B)8 and the more recent AC-43-XX4 provide a section on use of borescopes and a classification of the different types available. This project was designed to apply human factors engineering techniques to enhance the reliability of inspection of rotating engine parts using borescopes. In practice, this means specifying good human factors practice primarily for the borescope technique. Human factors considerations are not new in NDI, but this project provided a more systematic view of the human/system interaction, using data on factors affecting human inspection performance from a number of sources beyond aviation, and even beyond NDI.

FAA Advisory Circular 43-13-1B8 (Section 5.17) defines a borescope and its use as:

> *These instruments are long, tubular, precision optical instruments with built-in illumination, designed to allow remote visual inspection of internal surfaces or otherwise inaccessible areas. The tube, which can be rigid or flexible with a wide variety of lengths and diameters, provides the necessary optical connection between the viewing end and an objective lens at the distant, or distal tip of the borescope. Rigid and flexible borescopes are available in different designs for a variety of standard applications and manufacturers also provide custom designs for specialized applications. Borescopes are used in aircraft and engine maintenance programs to reduce or eliminate the need for costly tear-downs. Aircraft turbine engines have access ports that are specifically designed for borescopes. Borescopes are also used extensively in a variety of aviation maintenance programs to determine the airworthiness of difficult- to-reach components. Borescopes typically are used to inspect interiors of hydraulic cylinders and valves for pitting, scoring, porosity, and tool marks; inspect for cracked cylinders in aircraft reciprocating engines; inspect turbojet engine turbine blades and combustion cans; verify the proper placement and fit of seals, bonds, gaskets, and sub-assemblies in difficult to reach areas; and assess Foreign Object Damage (FOD) in aircraft, airframe, and power plants. Borescopes may also be used to locate and retrieve foreign objects in engines and airframes.*

To summarize, the need for improved NDI reliability in engine maintenance has been established by the NTSB. Human factors has been a source of concern to the NDI community as seen in, for example, the NDE Capabilities Data Book (1997).8 This project is a systematic application of human factors principles to one NDI technique most used for rotating engine parts, particularly for on-wing inspection.

4.0 TECHNICAL BACKGROUND: NDI RELIABILITY AND HUMAN FACTORS

There are two bodies of scientific knowledge that must be brought together in this project: quantitative NDI reliability and human factors in inspection. These are reviewed in turn for their applicability to borescope inspection.

4.1 NDI Reliability

Over the past two decades there have been many studies of human reliability in aircraft structural inspection. All of these to date have examined the reliability of Nondestructive Inspection (NDI) techniques, such as eddy current or ultrasonic technologies.

From NDI reliability studies have come human/machine system detection performance data, typically expressed as a Probability of Detection (PoD) curve, e.g. (Rummel, 1998).10 This curve expresses the reliability of the detection process (PoD) as a function of a variable of structural interest, usually crack length, providing in effect a psychophysical curve as a function of a single parameter. Sophisticated statistical methods (e.g. Hovey and Berens, 1988)11 have been developed to derive usable PoD curves from relatively sparse data. Because NDI techniques are designed specifically for a single fault type (usually cracks), much of the variance in PoD can be described by just crack length so that the PoD is a realistic reliability measure. It also provides the planning and life management processes with exactly the data required, as structural integrity is largely a function of crack length.

A typical PoD curve has low values for small cracks, a steeply rising section around the crack detection threshold, and level section with a PoD value close to 1.0 at large crack sizes. It is often maintained (e.g. Panhuise, 1989)12 that the ideal detection system would have a step-function PoD: zero detection below threshold and perfect detection above. In practice, the PoD is a smooth curve, with the 50% detection value representing mean performance and the slope of the curve inversely related to detection variability. The aim is, of course, for a low mean and low variability. In fact, a traditional measure of inspection reliability is the “90/95” point. This is the crack size which will be detected 90% of the time with 95% confidence, and thus is sensitive to both the mean and variability of the PoD curve.

In NDI reliability assessment one very useful model is that of detecting a signal in noise. Other models of the process exist (Drury, 1992)13 and have been used in particular circumstances. The signal and noise model assumes that the probability distribution of the detector’s response can be modeled as two similar distributions, one for signal-plus-noise (usually referred to as the signal distribution), and one for noise alone. (This “Signal Detection Theory” has also been used as a model of the human inspector, see Section 4.2). For given signal and noise characteristics, the difficulty of detection will depend upon the amount of overlap between these distributions. If there is no overlap at all, a detector response level can be chosen which completely separates signal from noise. If the actual detector response is less than the criterion or “signal” and if it exceeds criterion, this “criterion” level is used by the inspector to respond “no signal.” For non-overlapping distributions, perfect performance is possible, i.e. all signals receive the response “signal” for 100% defect detection, and all noise signals receive the response “no signal” for 0% false alarms. More typically, the noise and signal distributions overlap, leading to less than perfect performance, i.e. both missed signals and false alarms.

The distance between the two distributions divided by their (assumed equal) standard deviation gives the signal detection theory measure of discriminability. A discriminability of 0 to 2 gives relatively poor reliability while discriminabilities beyond 3 are considered good. The criterion choice determines the balance between misses and false alarms. Setting a low criterion gives very few misses but large numbers of false alarms. A high criterion gives the opposite effect. In fact, a plot of hits (1 – misses) against false alarms gives a curve known as the Relative Operating Characteristic (or ROC) curve which traces the effect of criterion changes for a given discriminability (see Rummell, Hardy and Cooper, 1989).6

The NDE Capabilities Data Book 9 defines inspection outcomes as:

		Flaw Presence	
		Positive	**Negative**
NDE Signal	**Positive**	True Positive No Error	False Positive Type 2 Error
	Negative	False Negative Type 1 Error	True Negative No Error

And
defines

PoD = Probability of Detection
=

PoFA = Probability of False Alarm
=

The ROC curve traditionally plots PoD against (1 – PoFA). Note that in most inspection tasks, and particularly for engine rotating components, the outcomes have very unequal consequences. A failure to detect (1 – PoD) can lead to engine failure, while a false alarm can lead only to increased costs of needless repeated inspection or needless removal from service.

This background can be applied to any inspection process, and provides the basis of standardized process testing. It is also used as the basis for inspection policy setting throughout aviation. The size of crack reliably detected (e.g. 90/95 criterion), the initial flaw size distribution at manufacture and crack growth rate over time can be combined to determine an interval between inspections which achieves a known balance between inspection cost and probability of component failure.

The PoD and ROC curves differ between different techniques of NDI (including visual inspection) so that the technique specified has a large effect on probability of component failure. The techniques of ROC and PoD analysis can also be applied to changing the inspection configuration, for example the quantitative study of multiple FPI of engine disks by Yang and Donath (1983)14 Probability of detection is not just a function of crack size, or even of NDI technique. Other factors can assume great importance, particularly in visual-based inspection techniques. This points to the requirement to examine closely all of the steps necessary to inspect an item, and not just those involving the inspector.

4.2 Human Factors in Inspection

Note: There have been a number of recent book chapters covering this area,13,15 which will be referenced here rather than using the original research sources.

Human factors studies of industrial inspection go back to the 1950's when psychologists attempted to understand and improve this notoriously error-prone activity. From this activity came literature of increasing depth focusing an analysis and modeling of inspection performance, which complemented the quality control literature by showing how defect detection could be improved. Two early books brought much of this accumulated knowledge to practitioners: Harris and Chaney (1969)16 and Drury and Fox (1975).17 Much of the practical focus at that time was on enhanced inspection techniques or job aids, while the scientific focus was on application of psychological constructs, such as vigilance and signal detection theory, to modeling of the inspection task.

As a way of providing a relevant context, we use the generic functions which comprise all inspection tasks whether manual, automated or hybrid.13 Table 1 shows these functions, with an example from borescope inspection. We can go further by taking each function and listing its correct outcome, from which we can logically derive the possible errors (Table 2).

Humans can operate at several different levels in each function depending upon the requirements. Thus in Search, the operator functions as a low-level detector of indications, but also as a high-level cognitive component when choosing and modifying a search pattern. It is this ability that makes humans uniquely useful as self-reprogramming devices, but equally it leads to more error possibilities. As a framework for examining inspection functions at different levels the skills/ rules/knowledge classification of Rasmussen (1983)18 will be used. Within this system, decisions are made at the lowest possible level, with progression to higher levels only being invoked when no decision is possible at the lower level.

Table 1. Generic Task Description of Inspection Applied to Borescope Inspection	
Function	**Description**
1. Initiate	All processes up to accessing the component through the borescope. Get and read workcard. Choose borescope configuration. Assemble and test borescope.
2. Access	Locate and access inspection area, e.g. through inspection ports on engine. Insert borescope to reach inspection area. Set up engine rotation system.
3. Search	Move engine to locate next blade to inspect. Move borescope field of view to render next area visible. Carefully scan component using a good strategy. Stop search if an indication is found.
4. Decision	Identify indication type. Compare indication to standards for that indication type.
5. Response	If indication confirmed, then record location and details. Complete paperwork procedures. Remove borescope and return to storage

For most of the functions, operation at all levels is possible. Access to an item for inspection is an almost purely mechanical function, so that only skill-based behavior is appropriate. The response function is also typically skill-based, unless complex diagnosis of the defect is required beyond mere detection and reporting. Such complex diagnosis is often shared with others, e.g. engineers or managers, if the decision involves expensive procedures such as changing or overhauling engines.

Table 2. Generic Function, Outcome, and Error Analysis of Test Inspection		
Function	**Outcome**	**Logical Errors**
Initiate	Inspection system functional, correctly calibrated and capable.	1.1 Incorrect equipment 1.2 Non-working equipment 1.3 Incorrect calibration 1.4 Incorrect or inadequate system knowledge
Access	Item (or process) presented to inspection system	2.1 Wrong item presented 2.2 Item mis-presented 2.3 Item damaged by presentation

Search	Individuals of all possible non-conformities detected, located	3.1 Indication missed 3.2 False indication detected 3.3 Indication mis-located 3.4. Indication forgotten before decision
Decision	All individuals located by Search, correctly measured and classified, correct outcome decision reacted	4.1 Indication incorrectly measured/confirmed 4.2 Indication incorrectly classified 4.3 Wrong outcome decision 4.4 Indication not processed
Response	Action specified by outcome decision taken correctly	5.1 Non-conforming action taken on conforming item 5.2 Conforming action taken on non-conforming item

4.2.1 Critical Functions: access, search and decision

The functions of search and decision are the most error-prone in general, although for much of NDI, setup can cause its own unique errors. Search and decision have been the subjects of considerable mathematical modeling in the human factors community, with direct relevance to borescope inspection in particular. For borescope inspection, access is also a critical task so that models of human control /guidance need to be presented. The sections on search and decision are adapted from Drury (1999)1 but the section on access is specific to this borescope report.

Access: Critical borescope access tasks consist of guiding the borescope tip along a specified path to reach a specified position. For example, using a flexible borescope the tip must be guided through the access port and around obstacles to reach the vicinity of a blade on a given disk. The final position with respect to the blade must be in a given location and a given distance from the blade.

For many years, human factors engineers have modeled such guidance tasks, where a "vehicle" must be moved in two or three dimensions, using various forms of control theory, from linear control systems (McReur, 1980)19 to optimal control (Barron, 1983)20. Useful summaries of such models can be found in Wickens, Mavor and McGee (1996)[21] and Salvendy (1998).22 For our purposes, the borescope tasks do not require the full complexity of such models as borescope movement is self-paced in that the inspector can choose the movement speed of the borescope tip. Conversely, in the full control models, it is assumed that the vehicle being guided (e.g. a gun or missile or aircraft) moves so as to track an object (e.g. enemy aircraft) that moves independently of the pilot's actions. Self-paced tasks are simpler as the main issue is the relationship between accuracy of control and speed of performance. Two relevant tasks need to be considered here:

(a) how to control the path traversed by an object such as the borescope tip so as to avoid damage to the tip (path control), and

(b) how an object such as the borescope tip is stopped at a fixed distance from a given object such as the blade (terminal aiming).

Self-paced path control tasks are defined as those tasks requiring movement along a path defined by its width. Examples are driving a car along a road of fixed width, or sewing a seam within quality limits. A suitable model for such tasks is the path control model of Drury (1971)23 that states simply that the maximum speed the "driver" can choose is related to the effective width of the "road" as:

Speed (for constant accuracy) = Controllability X Effective Width

This formulation has been applied in many laboratory tasks, such as drawing between lines or cutting with scissors, but also to more realistic tasks such as negotiating doorways, pushing carts, driving cars and driving fork-lift trucks (see Drury, 1985, for summary).24 The controllability of the task (or "vehicle") is a measure of how easy it is to control. Obviously the controllability also depends on the person performing the task, so that a skilled operator finds the vehicle easier to control than a novice. Models of such tasks can be derived from first principles, assuming that the operator acts so as to maximize speed while keeping errors low, i.e. not contacting the boundaries of the path (Drury, Montazer and Karwan, 1987).25 Such models provide the same speed / width relationship given above. Note that in general, the effective width of the path is the actual width minus the width of the vehicle, although more complex cases can be found (Defazio, Wittman and Drury, 1992).26 Note also that the speed is defined at a fixed error rate: operators can only increase speed by increasing probability of error. Conversely, any improvement in performance, e.g. by increasing the controllability, can result in a faster speed, or a reduced error rate, or both, depending on how the operator chooses to trade off speed and accuracy.

Applying this model to movement of a flexible borescope along a given path inside an engine shows that the speed and accuracy trade off in that higher speeds inevitably lead to higher probability of contact between the borescope tip and the adjacent structures. The speed may be increased where there is a broad path, e. g. across an open space, but must decrease where the path is laterally restricted, e.g. through a small hole. Again, people can trade speed for accuracy, meaning that if speed is not reduced enough as path width decreases, errors will occur. The other deduction from the speed relationship is that controllability directly influences speed, and thus error rate. The more controllable the tip, the faster and/or more accurate the inspector will be. This means that the controls over direction of travel are critical to the controllability, and hence to task performance, i.e. speed and accuracy. Because the controllability is specific to the inspector, then individual skills and training are important to the task of access.

The second model of interest is that of stopping a movement at a desired point. Such tasks have been characterized as terminal aiming tasks and were first accurately modeled as Fitts'Law (Fitts, 1954).27 In such tasks the operator must move a given distance (A) and stop at a point within a target width (W). Note that the target width is defined in the direction of the movement, e.g with the borescope tip at a specific distance from a blade surface in an engine. The time required for such a movement is given by:

Movement time = (Index of Difficulty)/(Information processing Rate)

Where the Index of Difficulty (ID) is defined as:

$$ID = \text{Log}_2 (2A/W)$$

The information processing rate is the speed at which people process movement control information, often about 10 bits/s for free hand movements. The Index of Difficulty is constant if both A and W change in proportion, e.g. if they both double. Thus it is the relative accuracy that controls the movement time rather than the absolute accuracy.

Again, Fitts' Law, or one of its many modifications, has been validated on many tasks. These range from laboratory tasks of moving to targets or placing pins in holes, to more realistic tasks such as foot movements between car pedals, inserting components into a printed circuit board, moving between keys on a keypad, manipulation of components under a microscope or even stopping fork-lift trucks at a stack of pallets. For a recent review of such terminal aiming tasks, see for example Drury and Hoffman (1992).28

In the borescope access task, terminal aiming can occur when a borescope tip is placed into an access port, with the target width being the difference between the port diameter and the tip diameter. Another task is that already mentioned of stopping at a given distance in front of an area to be inspected, such as a blade. Here the effective target width is a function of the area desired to include in the field of view, or it can be the depth of focus required for adequate viewing of the surface.

Search: In borescope work, as in visual inspection and X-ray inspection, the inspector must move his/her eyes around the item to be inspected to ensure that any defect will eventually appear within an area around the line of sight in which it is possible to have detection. This area, called the visual lobe, varies in size depending upon target and background characteristics, illumination and the individual inspector's peripheral visual acuity. As successive fixations of the visual lobe on different points occur at about three per second, it is possible to determine how many fixations are required for complete coverage of the area to be searched.

Eye movement studies of inspectors show that they do not follow a simple pattern in searching an object. Some tasks have very random appearing search patterns (e.g., circuit boards), whereas others show some systematic search components in addition to this random pattern (e.g., knitwear). However, all who have studied eye movements agree that performance, measured by the probability of detecting an imperfection in a given time, is predictable assuming a random search model. The equation relating probability () of detection of an imperfection in a time (t) to that time is

where is the mean search time. Further, it can be shown that this mean search time can be expressed as

where

= average time for one fixation

A = area of object searched

a = area of the visual lobe

p = probability that an imperfection will be detected if it is fixated. (This depends on how the lobe (a) is defined. It is often defined such that p = ½. This is an area with a 50% chance of detecting an imperfection.

n = number of imperfections on the object.

From these equations we can deduce that there is speed/accuracy tradeoff (SATO) in visual search, so that if insufficient time is spent in search, defects may be missed. We can also determine what factors affect search performance, and modify them accordingly. Thus the area to be searched is a direct driver of mean search time. Anything we can do to reduce this area, e.g. by instructions about which parts of an object not to search, will help performance. Visual lobe area needs to be maximized to reduce mean search time, or alternatively to increase detection for a given search time. Visual lobe size can be increased by enhancing target background contrast (e.g. using the correct lighting for the borescope) and by decreasing background clutter. It can also be increased by choosing operators with higher peripheral visual acuity29 and by training operators specifically in visual search or lobe size improvement.30 Research has shown that there is little to be gained by reducing the time for each fixation, t_0 , as it is not a valid selection criterion, and cannot easily be trained.

The equation given for search performance assumed random search, which is always less efficient than systematic search. Human search strategy has proven to be quite difficult to train, but recently Wang, Lin and Drury (1997)31 showed that people can be trained to perform more systematic visual search. Also, Gramopadhye, Prabhu and Sharit (1997)32 showed that particular forms of feedback can

Decision: Decision-making is the second key function in inspection. An inspection decision can have four outcomes, as shown in Table 3. These outcomes have associated probabilities, for example the probability of detection is the fraction of all nonconforming items that are rejected by the inspector shown as in Table 3.

Table 3. Attributes Inspection Outcomes and Probabilities		
	True State of Item	
Decision of Inspector	**Conforming**	***Nonconforming***
Accept	Correct accept,	Miss, (1 - p_2)
Reject	False alarm, (1 - p_1)	Hit,

Just as the four outcomes of a decision-making inspection can have probabilities associated with them, they can have costs and rewards also: costs for errors and rewards for correct decisions. Table 4 shows a general cost and reward structure, usually called a "payoff matrix," in which rewards are positive and costs negative. A rational economic maximizer would multiply the probabilities of Table 3 by the corresponding payoffs in Table 4 and sum them over the four outcomes to obtain the expected payoff. He or she would then adjust those factors under his or her control. Basically, SDT states that and p_2 vary in two ways. First, if the inspector and task are kept constant, then as p_1 increases, p_2 decreases, with the balance between and together by changing the discriminability for the inspector between acceptable and rejectable objects. and p_2 can be changed by the inspector. The most often tested set of assumptions comes from a body of knowledge known as the theory of signal detection, or SDT (McNichol, 1972).33 This theory has been used for numerous studies of inspection, for example, sheet glass, electrical components, and ceramic gas igniters, and has been found to be a useful way of measuring and predicting performance. It can be used in a rather general nonparametric form (preferable) but is often seen in a more restrictive parametric form in earlier papers (Drury and Addison, 1963).34 McNichol33 is a good source for details of both forms.

Table 4. Payoff Matrix for Attributes Inspection		
	True State of Item	
Decision of Inspector	**Conforming**	**Nonconforming**
Accept	A	-b
Reject	-c	d

The objective in improving decision-making is to reduce decision errors. There can arise directly from forgetting imperfections or standards in complex inspection tasks or indirectly from making an incorrect judgement about an imperfection's severity with respect to a standard. Ideally, the search process should be designed so as to improve the conspicuity of rejectable imperfections (nonconformities) only, but often the measures taken to improve conspicuity apply equally to nonrejectable imperfections. Reducing decision errors usually reduces to improving the discriminability between imperfection and a standard.

Decision performance can be improved by providing job aids and training that increase the size of the apparent difference between the imperfections and the standard (i.e. increasing discriminability). One example is the provision of limit standards well-integrated into the inspector's view of the item inspected. Limit standards change the decision-making task from one of absolute judgement to the more accurate one of comparative judgement. Harris and Chaney (1969)16 showed that limit standards for solder joints gave a 100% performance improvement in inspector consistency for near-borderline cases.

One area of human decision-making that has received much attention is the vigilance phenomenon. It has been known for half a century that as time on task increases, then the probability of detecting perceptually-difficult events decreases. This has been called the vigilance decrement and is a robust phenomenon to demonstrate in the laboratory. Detection performance decreases rapidly over the first 20-30 minutes of a vigilance task, and remains at a lower level as time or task increases. Note that there is not a period of good performance followed by a sudden drop: performance gradually worsens until it reaches a steady low level. Vigilance decrements are worse for rare events, for difficult detection tasks, when no feedback of performance is given, where the task is highly repetitive and where the person is in social isolation. All of these factors are present to some extent in borescope inspection of engines (e.g. the repetitive nature of inspecting a whole disk of blades, so that prolonged vigilance is potentially important here.

A difficulty arises when this body of knowledge is applied to inspection tasks in practice. There is no guarantee that vigilance tasks are good models of inspection tasks, so that the validity of drawing conclusions about vigilance decrements in inspection must be empirically tested. Unfortunately, the evidence for inspection decrements is largely negative. A few studies (e.g. for chicken carcass inspection)35 report positive results but most (e.g. eddy current NDI)36,37 find no vigilance decrement.

It should be noted that inspection is not merely the decision function. The use of models such as signal detection theory to apply to the whole inspection process is misleading in that it ignores the search function. For example, if the search is poor, then many defects will not be located. At the overall level of the inspection task, this means that PoD decreases, but this decrease has nothing to do with setting the wrong decision criteria. Even such devices as ROC curves should only be applied to the decision function of inspection, not to the overall process unless search failure can be ruled out on logical grounds.

5.0 RESEARCH OBJECTIVES

1. Review the literature on (a) NDI reliability and (b) human factors in inspection.

2. Apply human factors principles to the use of borescopes of engine inspection, so as to derive a set of recommendations for human factors good practices.

6.0 METHODOLOGY

The methodology developed was based on the knowledge of human factors in inspection and the accumulated data on borescope technology and application, e.g. the ASNT's Handbook of NDI volume on Visual Inspection, Part 2: Optically Aided Visual Testing of Aircraft Structures (pages 292-301).38 No data has been found to date on Probability of Detection curves for borescope inspection. In the absence of such quantitative data, we have had to rely more on the descriptive information and observations to discover the important factors likely to affect detection performance. Data on specific error possibilities, and on current control mechanisms was collected initially in site visits. Each visit was used to further develop a model linking errors to interventions, a process that eventually produced a series of human factors good practices.

6.1 Site Visits

Visits were made to two engine inspection operations where borescopes were in use. In addition, the author was able to study and use borescopes provided by manufacturers and discuss their use and potential errors with manufacturers' technical representatives. Finally, at one site the author was invited to attend a borescope training class for inspectors. This covered a new computer-assisted borescope system. At each engine inspection site the author was given an overview of borescope inspection by a manager. Facility personnel were briefed on the purpose of our visit, i.e. to better understand human factors in borescope inspection of rotating engine components rather than to inspect the facility for regulatory compliance. We emphasized that engine borescope inspection was usually a well-controlled process, so that we would be looking for improvements aimed at reducing error potential even further through application of human factors principles.

Following the management overview, the author spent one or two shifts working with personnel in each process. In this way he could observe what was being done and ask why. Notes were made and, where appropriate, photographs taken to record the findings.

6.2 Hierarchical Task Analysis

After each visit, the function analysis of Table 2 was progressively refined to produce a detailed task description of the borescope inspection process. Additionally, other sources of task description were sought to help structure the borescope process. One example is from *The Science of Remote Visual Inspection*, a comprehensive manual on borescopes written for one manufacturer by P. G. Lorenz (1990).39 On page 4-20 of that publication is the following set of steps:

Step 1: Become familiar with borescope and light source

Step 2: Check light source

Step 3: Locate Access port

Step 4: Insert probe, thread to area to be inspected, focus, inspect to plan

Step 5: Enter findings via notebook or computer (attach video or camera)

Step 6: Remove borescope

This task listing also includes many tips for safety of the inspector and of the borescope itself. Damage to the borescope is one error mode of great concern to both users and manufacturers.

Because each function and process is composed of tasks, which are in turn composed of subtasks, a more useful representation of the task description was needed. A method that has become standard in human factors, Hierarchical Task Analysis (HTA) was used.40,41 In HTA, each function and task is broken down into sub-tasks using the technique of progressive re-description. At each breakdown point there is a plan, showing the decision rules for performing the sub-tasks. Often the plan is a simple list ("Do 3.1 to 3.5 in order") but at times there are choices and branches. Figure 1 shows the highest-level breakdown for borescope of engine components, while Figure 2 shows one major process (responding).

One requirement before the HTA can begin is for a classification system for borescopes. Most manufacturers have a coding scheme for their borescopes, defining for example the type of borescope, its diameter, and the tip to use. For this report a more generic system is required so that we can, for example, consider both direct viewing borescopes and computerized borescopes by considering both as different example of "display". The following five-factor classification was developed for this report:

Function: View Only

View and Measure

View and Repair

Shaft: Rigid

Flexible (includes both optical fiber and electrical connection)

Tip: Fixed (Can be at different angles, e.g. forward, side, backward)

Moveable

Display: Direct Optical

Video Image (from sensor at tip or from sensor viewing optical fiber)

Computer-Mediated

Capture No capture

Photographic / video

Computer file

Note that this system is functional rather than hardware oriented, so that it differs from the systems used by manufacturers to specify borescopes. In the context of this analysis it allows us to separate, for example, display and image capture. Typically, a borescope will have a particular combination, for example (1) direct optical viewing and photographic image capture or (2) computer-mediated display and computer file image capture. However, Display and Capture are separate functions and there is no reason in principle why novel combinations cannot be used.

The HTA applied to borescope inspection of engines can be found in Appendix 1. The overall level (Figure 1) is broken into its branches (Figure 2) each of which is then carried further in a tabular form to provide the link to human factors knowledge. The tabular form of part of one branch (6.0 Respond) is given in Table 5. What this shows is a more complete task description of each sub-task under "Task Description". The final column, headed "Task Analysis" shows the human factors and other system reliability issues in the form of questions that must be asked in order to ensure reliable human and system performance. Essentially, this column gives the human factors issues arising from the task, making the link between the human factors literature in Section 3 and the original Function level description in Table 2.

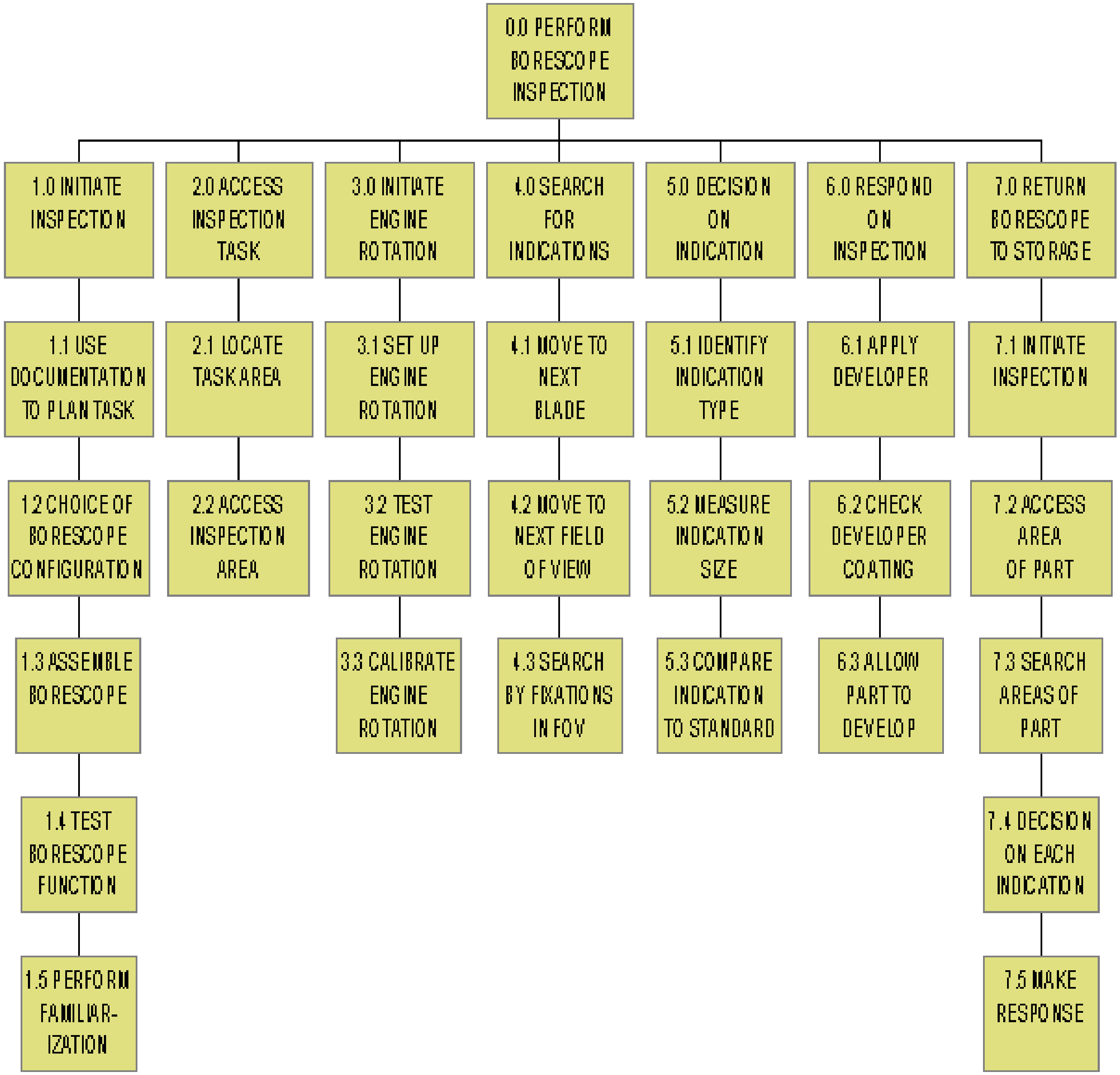


Figure 1. Highest Level Breakdown for Borescope Inspection

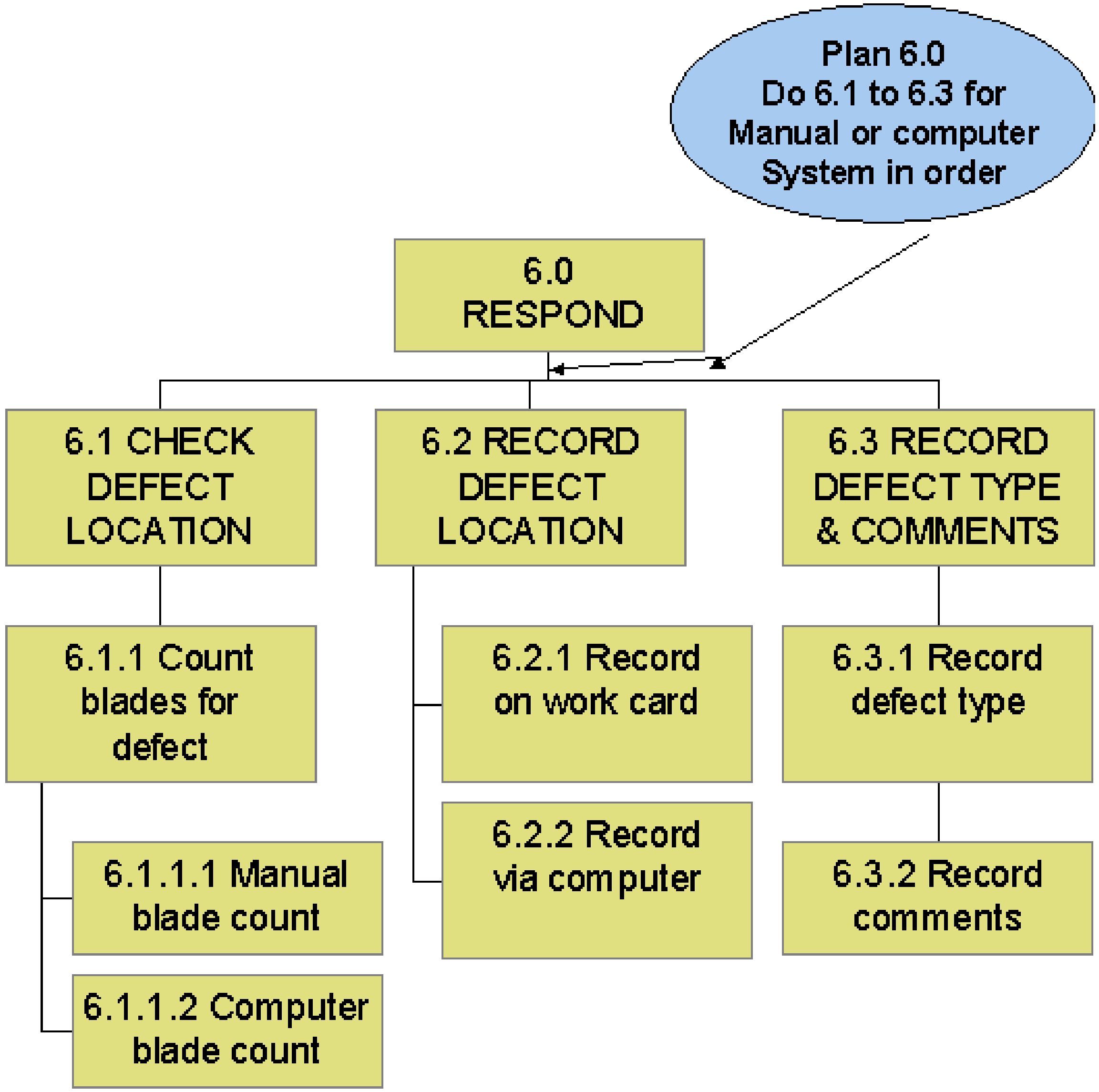


Figure 2. One Major Process (Responding) for Borescope Inspection

Finally, for each process in Table 5 there is a list of the errors or process variances that must be controlled. Each error is one logically possible given the process characteristics. It can also represent a process variance that must be controlled for reliable inspection performance.

To derive human factors good practices, two parallel approaches were taken. First, direct observation of the sites revealed good practices developed by site management and inspectors. For borescope inspection, most users and manufacturers think in terms of new models of borescopes with more features and functions. Thus, borescopes that record images can be useful to give a visual record to accompany the written record of each defect. This can be used, for example, to EMAIL an image to company maintenance headquarters for a second opinion on a particular defect. Here, more people can become involved in a critical decision directly, for example whether or not an aircraft should continue flying with a given indication in one engine.

The second set of good practices came from the HTA analysis. As an overall logic, the two possible outcome errors (active failures) were logically related to their antecedents (latent failures). A point that showed a human link from latent to active failures was analyzed using the HTA to derive an appropriate control strategy (good practice). For example, it was found repeatedly that the control over direction and extent of movement using flexible borescopes was a source of human factors problems (latent failure). Damage could occur to the borescope tip, or to the surrounding structure, as well as defects being missed (active failures). Controls that are better human-engineered, e.g. joysticks for two-dimensional control in place of concentric rings, would be an appropriate control strategy (good practice).

Two representations of human factors good practice were produced. First, a list of 59 specific good practices is given, classified by process step (Initiate, Access, …., Return). Second, a more generic list of major issues was produced to give knowledge-based guidance to borescope designers and managers. Here, issues were classified by major intervention strategy (workplace design, lighting, training, etc.) under the broad structure of a model of human factors in inspection. For both representations, the good practices are tied back directly to the active failures they were designed to prevent again to help users understand why an action can reduce errors.

Finally, there are a number of latent failures that will require some additional research to produce direct interventions. These are listed, again with error-based rationales, to give guidance to industry

7.0 RESULTS

As noted under methodology, these two sets of interventions comprise the main findings of this study. The following three sections provide the results in detail.

Table 5. Detailed level of HTA for 6.0 Respond

	Task Description	Task Analysis
6.1 Check Defect Location	**6.1.1 Count Blades for defect** 6.1.1.1 Manual Blade count: Start from blade with defect, count from known reference mark	Has known reference mark been determined correctly? Does human inspector count blades correctly? Can each blade be viewed unambiguously as it passes the counting point?
	6.1.1.2 Computer blade count: use computer interface to note current blade count.	Does the computer interface show blade count in its normal inspection mode?

6.2 Record Defect location	6.2.1 Record on work card 6.2.2 Record via computer	Should a workcard or an NRR be used for recording? Is workcard/NRR conveniently located with respect to the inspection site? Is there enough room on workcard /NRR to allow writing all defect locations? Is computer conveniently located with respect to the inspection site? Is computer program in correct mode for recording? Does computer program allow room for all defects to be recorded?
6.3 Record Defect type and comments	6.3.1 Record Defect Type 6.3.2 Record defect comments	Are defect types classified unambiguously? Is there a checklist of proper defect types? Is there room for comments on the workcard / NRR / computer program? Are inspectors encouraged to write sufficient comments for later use of data?
(For continuation, see Appendix 1)		
	Errors/Variances for 6.0 Respond Defect location not recorded Defect type not recorded Defect comments not recorded. Defect location incorrectly recorded Defect type incorrectly recorded Defect comments incorrectly recorded.	

7.1 DETAILED HUMAN FACTORS GOOD PRACTICES

The direct presentation of human factors good practices is found in Appendix 2. It is given as Appendix 2 because it is so lengthy, with 59 entries. It is organized process-by-process following the HTA in Figure 1 and Appendix 1. For each good practice, there are three columns:

1. Process: Which of the seven major processes is being addressed?

2. Good Practice: What is a recommended good practice within each process? Each good practice uses prescriptive data where appropriate, e.g. for time ob task. Good practices are written for practicing engineers and managers, rather than as a basis for constructing legally-enforceable rules and standards.

3. Why? The logical link between each good practice and the errors it can help prevent. Without the "why" column, managers and engineers would be asked to develop their own rationales for each good practice. The addition of this column helps to train users in applying human factors concepts, and also provides help in justifying any additional resources.

There is no efficient way of summarizing the 59 detailed good practices in Appendix 2: the reader can only appreciate them by reading them. It is recommended that one process, e.g. Decision, is selected first and examined in detail. The good practices should then be checked in turn with each inspector performing the job to find out whether they are actually met. Again, the question is not whether a practice is included in the operating procedures, but whether it is followed for all engine borescope inspections by all inspectors. The good practices in Appendix 2 can even be separated and used as individual check items. These can the be sorted into, for example, those which are currently fully implemented, those which can be undertaken immediately, and those which will take longer to implement.

7.2 Human Factors Control Mechanisms

Some issues, and their resulting good practices, are not simple prescriptions for action, but are pervasive throughout the borescope inspection system. Note that this report does not go into depth on the background of each control mechanism, as background material is readily available on each. *The Human Factors Guide for Aviation Maintenance 3.0*[42] is one readily accessible source of more information. This is available at the HFAMI web site: http://hfskyway.faa.gov. An additional more general source is the ATA Spec 113 Human Factors Programs,[43] available on the ATA's web site: http://www.air-transport.org.

7.2.1 Borescope Physical Design

Borescopes are available, and used, in a wide variety of designs and from a variety of suppliers. They are primarily purchased because of features required for the tasks to be performed, with durability and cost as major considerations. Using our classification system from 4.2, many hundreds of feature combinations could be available. In practice, some characteristics go together. For example, most borsecope systems with computer-displayed images would be expected to have computer file capture of the resulting images. Once a computer system is included, features requiring a computer can be added easily.

There are, however, a number of human factors issues where the design of the borescope system itself can have a large impact on inspection performance. First there is the design of the borescope guidance system. For a rigid borescope, guidance requirements are minimal and naturalistic. The tip end must be inserted into the access opening and guided into position like many more familiar objects, e.g. dipsticks in cars or pencils into sharpeners. For the initial entry, it has been found that the longer the shaft of any stick-like object, the more difficult the task of insertion and control (Baird, Hoffmann and Drury, in press)[44]. For flexible borescopes the issues are much closer to those raised under **Access** in 4.2.1, i.e. guidance of a "vehicle" along a "path" with lateral restrictions and often many turning points. Because the display may be remote from the control end of the borescope (unless there is direct optical viewing), there is often a non-intuitive relationship between the control actions and the display movement. In 4.2.1 we introduced the concept of controllability to quantify the naturalness of control for a given set of control actions and display movements. Remember that we have all learned a very strong set of movement expectations, e.g. moving a control left (or counter clockwise) to cause a vehicle to turn left. With a borescope we work in three dimensions, making it more analogous to flying an aircraft than driving a truck. Of the dozens of aircraft primary control systems tried by aviation pioneers (e.g. Gibbs-Smith, 1965),[45] only one has stuck as natural: a joystick or yoke with up for climb, etc. As far a possible, designers and equipment purchasers should capitalize on such direction-of-movement population stereotypes to simplify borescope path control. The result will be less reversal errors, and less resultant damage to engine structure or borescope tip. People can be trained to control almost any system, no matter how non-intuitive, but when they are concentrating on other things, such as navigation through to the point of inspection, they will make many reversal errors. Any child who has tried to ride a bicycle with crossed hands can attest to this!

One particular problem for guidance is when the view through the tip is not straight ahead. Many tips have side view, or even retro view, so that the display tells the inspector where he/she is passing or has been. This is analogous to driving or flying using only the side or rear windows. There is room for some experimentation in displays and their associated control to find reliable ways to perform such tasks.

With guidance to the inspection point a function of the controllability, the action of stopping at the desired point is largely a matter of display design, as all borescopes move forward in a natural manner when pushed further into the inspection port. If a job is performed often enough, a borescope probe of exact length can be dedicated to that job removing the stopping task and its possible errors from the inspector. Alternatively, an adjustable stop ring can be added to the borescope shaft, with labels for each specific task. In general, though, stopping without error is a matter of control or judgment, and the display becomes critical. Unless the current position of the borescope tip and the structure surrounding it are in full view, it may not be possible to stop at the correct point. Again, retro or side viewing makes control more difficult.

For viewing, the image should have a brightness and contrast sufficient for the task, bearing in mind that the eyes adapt to brighter areas more rapidly than darker ones. Thus, performance on a display of a given brightness may well be better under hangar illumination than under sunlight, as the eyes will be better adapted to the image luminance, even for direct optical viewing. Contrast should always be high, particularly between indication and background, for best performance in inspection. This is largely a matter of lighting system design, as colors and finishes of the structure are not readily changeable. The lighting applied, typically through the borescope, should provide good "modeling" of structure and defect. In practice, if the illumination comes from the direction of the borescope itself, much of this modeling will be lost and the lighting will be "flat". It is also important to provide even illumination suited to the borescope's field of view. A hot-spot in the visual field will cause inconsistent inspection, as well as making movement control more difficult by obscuring landmarks. The eye has a marvelous range of sensitivity, so that these considerations are more strongly applied when the display is on a video monitor or computer screen. Both of these displays have inherently less luminance range than the eye.

The physical fit between a display and the inspector are equally important. For direct optical viewing, the workplace layout will determine the gross body posture that must be adopted for inspection. The inspector's eye must be within the viewing system exit pupil, and at a distance within the system's eye relief. Better optical systems allow viewing of the complete image even with the eye some distance from the eyepiece. This "high eyepoint" design has found favor among users of other optical equipment such as telescopes, microscopes and professional cameras as it allows for more flexibility of body position to perform the task. Posture itself needs to be thought out in advance. There are some tasks, for example, that are quite awkward to perform with the engine on-wing, although the seam tasks may be relatively easy in an engine shop with easily adjustable engine hoists and stands. Any poor posture will have the twin effects of adversely affecting the inspector's physical well-being and biasing the inspector towards hurrying to complete a physically difficult task to find postural relief. Although inspectors are most conscientious in their duties, working in constrained spaces and bad postures does exert a pressure to complete the job and relieve the affected muscles.

7.2.2 Documentation Design and Use

Much material is now available on better design of documentation for aircraft maintenance and inspection, for example, the Documentation Design Aid (DDA) produced for the FAA/AAM and found at the website http:// hfskyway.faa.gov. This material has been extensively tested with AMTs and inspectors and found to give measurable reductions in comprehension errors (e.g. Drury and Sarac, 1997).46 Given that the workcard designer knows what needs to be told to the inspector, then the layout and formatting of this information to give maximum performance can be done using job aids such as the DDA. For borescope inspection, however, there are additional considerations.

First, the borescope inspector needs to have direct access to definitions of all possible defect types in the task at hand. Many of the defect types may be well-known and expected by the inspector, but some may not. These are the ones where serious errors may occur due to unfamiliarity. Medical general practitioners face the same problem of knowing the common diseases but needing job aids to remind them of the rare, but still possible, diseases they should also check for. Given a list of possible defects, the inspector then needs information on where they are likely to occur, and what they look like. Again, some of this information is well-known to the inspector, but in fact the inspector's recent experience may cause him/her to apply a biased knowledge to the task. For example, if there has been a run of blades with corners burnt through but no recent blade root cracks, the inspector with the best of intentions to "cover the whole blade" may concentrate on the tips rather than the roots, hence missing potentially-dangerous defects. Also on the topic of defects, there needs to be a consistent terminology for defect types so that they can be classified without error. If a defect is misclassified, then the wrong standards may be applied (e.g. for allowable crack length) leading to an inspection error. Names may differ between the engine manufacturer's documentation, the borescope training documentation and local hangar usage. Consistency needs to be specified and enforced, even if it means changing names on drawings and in legacy workcards. Finally, exact standards need to be specified for each defect in each position. For example, blade tip problems may have greater allowances in some engine stages than others. Only when the set of all documents the inspector may use are consistent will they be used correctly. The same layout of standards can be maintained across engine stages, across engine types and even across engine manufacturers. This takes effort, but so do other less-fruitful error-proofing interventions.

7.2.3 Automation and Borescope Use

In all forms of inspection, automation has been proceeding rapidly, and increasingly automated systems have found favor with managers and inspectors. The use of computer technology has accelerated this trend, so that the catalogs of major borescope manufacturers now contain systems with many automated features. We now have data capture by the computer direct from CCD chips at the tip end of the borescope. Both analog and digital signals are used by different manufacturers, but the end result is that image data can be manipulated, stored and dispatched (via EMAIL or even the Internet) easily and rapidly.

While automation can, and has, improved productivity, there are pitfalls to be avoided if this approach is to yield more reliable inspection. There are also exciting opportunities for enhancement of the inspection process if the human is treated as an explicit part of the system, rather than as the entity given those tasks currently not able to be automated. The dangers of human-blind automation have been well-documented from domains as diverse as industrial process control rooms to aircraft cockpits (Bainbridge, 1990;47 Sheridan, 1976,48 Wickens and Hollands, 200049). Alternatively, the benefits of well-designed automation have been clearly measured in aviation maintenance, from computer-based workcards (Drury, Patel and Prabhu, 200050) to a laptop-based OASIS system to aid FAA inspectors in their job (Hastings, Merriken and Johnson, 200051). This section of the report considers the current automation scene in borescope inspection.

The first essential of automation is that the parts of the job given to automation and to people must be appropriate to their different capabilities and needs. This is termed Allocation of Function, and has the greatest impact on subsequent system performance. If the functions are allocated inappropriately, no amount of interface design can produce the optimum system. Computers are excellent at making rapid and consistent measurements, following complex decision rules, performing calculations (including image enhancement) and carrying out lengthy but repetitive sequences of operations. In a borescope context, this implies allocating to the computer necessary measurement and calibration calculations, deciding on whether complex acceptance / rejection criteria are met, enhancing displayed images in real time and automatically transferring files over an Internet link. Human inspectors, however are good at judgment tasks involving weighing of qualitative evidence, understanding the implications of a situation, devising alternate procedures to meet novel situations, and varying their task strategy in light of changed conditions. Thus for borescope inspection, suitable functions for the human inspector would be deciding whether or not to remove an engine that could legally be flown another leg despite defects, realizing that blade tips with a machined look imply a missing shroud, or changing the scanning pattern of each blade based on new evidence of root cracking. [Note: there are more complex treatments of Allocation of Function, e.g. McCarthy, Fallon and Bannon, 2000,52 but the issue for designers remains to allow both human and computer parts of the system to function together to best advantage.]

Having decided on the appropriate human and machine functions, the next consideration is interface design. Some aspects have already been covered, such as control / display direction of movement stereotypes, but others are specific to human computer interaction, HCI. Where the interface is computer mediated, errors can arise from non-intuitive labels on menu choices, from buttons that change their function under different modes of operation, requirement to push a control button multiple times to move of focus, and even poor choice of icons or contrast on the display. Because all borescope automation is unique to this field, the software is usually custom written. Thus, a single program may use conventions that make internal sense, but which can conflict with other programs the inspector may use, or even with current computer stereotypes, e.g. the functions listed under "File" in Windows interfaces. There are many excellent books and guides on HCI, e.g. Helander, Landauer and Prabhu (1997),53 or Liu's chapter in the *Handbook of Human Factors and Ergonomics* (Salvendy, 1997)54. With custom-designed software there is more reason rather than less to follow such guidelines. The danger of not following them is that proliferating computer systems will not be compatible to the inspector, despite compatibility of such hardware functions as file naming and image formats. For example, one borescope program for which I attended training had two functions labeled "hold" and "freeze frame" that were confusing in notation to trainees. As with direction-of-motion stereotypes, people can be trained to do almost anything, but the training (even good training) will break down under stress or distraction. If the correct choice is not the natural choice, people will make more errors at the very time we need them to be error-free.

One aspect of computer use in borescope tasks deserving attention is the measurement system. Trainees learn to use these rather novel systems both by following a set of on-screen procedures and by developing an understanding of the physics involved. Again, some of the terms are not obvious: "distance" and "depth" can be confused, and the latter even confused with depth of an indication. Trainees are given rules "keep line to left of display" but only gradually learn that this means choosing as high a magnification as practical to minimize error. The concept of skill- based, rule-based and knowledge-based behavior has been introduces earlier (4.2) and applies very well here. Inspectors need rules to ease the cognitive load of a complex task, but the also need to be able to function in a knowledge based mode when unusual circumstances apply.

Finally, as part of the observations, one system that automated engine rotation was studied. This system used a small custom-designed display to which the ideas from HCI could be applied to ensure compatibility with computer use stereotypes. [Note: I did not perform a detailed human factors analysis of this system.] However, one aspect of automation that does need to be discussed is the ability given by that system to pre-program blade rotation. The system could be programmed to either:

- Move to the next blade on inspector command
- Move to the next blade after a specified time interval
- Rotate engine slowly and continuously

The discussion earlier of visual search (4.2.1) showed that the time taken to locate a defect if it is present was an exponential function. One characteristic of such a function is the extreme variability from blade to blade in the time required to locate a defect. Even more variability is added when it is realized that very few blades will contain defects, so that for most, a decision must be made as to when to stop searching this blade and move to the next. This time, in many experiments, has been found to be two to three times the mean search time. Overall then, the time per blade is highly variable even for a consistent level of performance. Any attempt to pre-define a "correct" time for each blade will produce cases where the inspector has completed searching and must wait until the blade moves as well as cases where the inspector will not have finished inspecting the blade before it moves on. The former is mildly frustrating, but the latter has serious implications for coverage and hence missed defects. None of this is the fault of the automation, but of its use. It is mentally simpler to pre-set a time per blade, either as a time for which the blade remains stationary or for which it is visible under continuous movement. Inspectors express this as "finding a rhythm" for their task. But this is only an average time, not the same fixed time per blade. The film *Modern Times* gave dramatized versions of working on an externally paced assembly line, but the detrimental effect on inspection performance has been similar in other inspection studies in manufacturing (e.g. Drury, 198555). When automation is provided, training is still required to use it in an appropriate manner.

7.2.4 Automation and Final Decision

All decisions regarding inspection outcomes for engine blades or deep structure have high costs attached to their outcomes. Many of these decisions must be made quite rapidly, e.g. at an overnight inspection at a remote airport. When the decision is obvious, e.g. a broken blade well beyond acceptable limits or a defect-free engine, the inspector can make the correct decision with some confidence. However, when there are marginal defects, or sets of defects not covered by standards, or novel indications, the inspector is typically encouraged to seek second opinions from engineers and managers. This can be a difficult process at remote sites or during night shifts, when these second opinions may not be easily available. Even in an engine repair shop inspectors often have to seek back-up authority before proceeding with non-scheduled disassembly of engines.

In both cases, a major advantage of automation and modern communication systems is that data can be shared quickly and easily between different sites. Photographic images could always be transported to the appropriate central base, or mare recently faxed there. But this led to delays or to degraded images, with the latter being even more difficult for the receiver to interpret than for the original inspector. With video image capture and computer image capture now available, plus internal EMAIL and external Internet links, it has become possible for the inspector and the engineers/ managers to work together on the same image. Thus engineers can bring the latest technical information to bear, while discussing the image and how it was obtained with the inspector on the spot. Image enhancement can be used, and its validity verified on site. Managers can be actively involved, as most have come from technical backgrounds, or they can leave the discussion to the engineer and inspector and confirm a final decision based on documented and interpreted evidence.

A potential danger is that the decision is more easily "kicked upstairs", either by defined procedure or by inspectors seeking coverage for decisions that should be within their authority. Only intelligent use of the potentialities opened up by these technical advances can help keep decision-making where it is best performed.

8.0 RESEARCH NEEDS

From this work arise some clear needs for research and / or development. Some are best addressed at a national level (e.g. FAA or military), such as providing PoD data for borescope inspection. Controllability of the borescope can be addressed by individual manufacturers as it will measurably improve human performance, although again a national research project is feasible. The issue of use of HCI and other Human Factors techniques in design of automated borescope systems would be of interest to manufacturers, although trade organizations could also sponsor such activity.

The overwhelming research need in borescope inspection is for quantitative reliability data. Exactly what type of indication of what size can be detected with what probability? Merely to say that a specific borescope "…will allow the detection of defects as small as 0.xxx inches" is not a quantitative evaluation of inspection reliability. Reliability is not a simple question to answer experimentally because of the wide variety of borescope configurations, possible and actual. Any PoD data will need to be collected for specific indications (cracks, blade defects) under conditions specified by the combinations of parameters in the classification scheme given in Section 6.3. Even with just one example of each combination, that would take 112 combinations, beyond which are variables of magnification, field of view, lighting, and inspector differences. Clearly such a massive effort would not be useful, as most of the combinations may never occur. But systematic evaluation using a planned sequence of studies would allow planners to better specify the most appropriate borescope configuration, and allow inspectors to understand the capabilities and limitations of their equipment.

Issues of controllability of the borescope have been raised throughout this report, and some systematic work is needed to quantify the benefits and costs of different configurations of control system. We know from human factors data that more natural control systems are more controllable, and that this will result in reduced errors and task times. However, the optimal relationships are simple to determine experimentally, using a methodology based on path control tasks (e.g. Drury, 1971)23. A short research program could measure the effectiveness of a number of different control systems so that designers could specify one of a few control / display systems with some degree of certainty. In more need of experimental evaluation are control systems with non-forward viewing. There is no literature for guidance on this, but again, experimentation is simple and relatively inexpensive.

More of an application need than a research need is just to apply human factors consideration, especially HCI, to the design of increasingly automated borescope systems. We have plenty of design principles, backed up by performance and error data, on which to base computer interface designs. The challenge is to make this available for use by designers so that they can apply the principles with minimum disruption of the design process. An obvious suggestion is the development of suitable guidelines by a team of human factors engineers, designers and users. This should be followed by a before-and-after demonstration of the effectiveness of such a design using good human factors evaluation techniques for measuring performance and error rate as well as user reactions.

9.0 CONCLUSIONS

1. This study has concentrated on the use of borescopes in engine inspection, as this is a critical and frequent activity.

2. There are many varieties of borescope available and in use, but few quantitative measures of inspection reliability using borescopes.

3. The methodology developed earlier for FPI process could be applied well to borescope inspection. Specifically, this involved field observations as the basis for task analysis (HTA), which in turn applied Human Factors knowledge to give good practices.

4. Despite the availability of many good borescope systems and job aids, there is still the potential for errors. Some potential errors are serious (e.g. missed defects) and some less so but still costly (e.g. equipment damage). Most can be controlled by one of the mechanisms indicated in the good practices (Appendix 2).

5. Broad control strategies center around the design of the borescope system itself, the potentials and pitfalls of automation, and the design of better work documentation.

6. There are research needs in the areas of generating probability of detection data for borescope inspection, error-reducing guidance mechanisms, and improved lighting.

7. The methodology used here can be applied to other aspects of engine and airframe inspection beyond borescope use of inspecting engine components.

10.0 ACKNOWLEDGEMENT

The author would like to acknowledge FAA staff, borescope manufacturers' representatives, and our airline partners for providing data and facilities that made this report possible.

11.0 REFERENCES

[Note: there are many other references on human factors in aviation maintenance and inspection available at the www site http://hfskyway.faa.gov, generated by the FAA's Office of Aviation Medicine over the past decade. They are not specifically quoted here so as to keep the focus on works directly related to borescope inspection.]

1. Drury, C. G. (1999). Human Factors Good Practices in Fluorescent Penetrant Inspection. Human Factors in Aviation Maintenance - Phase Nine, Progress Report, FAA/Human Factors in Aviation Maintenance, via http://hfskyway.faa.gov.

2. National Transportation Safety Board (1998). National Transportation Safety Board Report #N75B/AAR-98/01.

3. National Transportation Safety Board (1990). National Transportation Safety Board Report #NTSB/AAR-90/06.

4. Federal Aviation Administration (1994). Visual Inspection for Aircraft, Draft Advisory Circular AC 43-XX.

5. Federal Aviation Administration (1996). Nondestructive Inspection for Aircraft, Draft Advisory Circular AC43-ND.

6. Rummel, W. D., Hardy, G. L. and Cooper, T. D. (1989). Applications of NDE Reliability to Systems. Metals Handbook. 17, 674-688.

7. Quan, H. R. C. and Scott, I. G. (1977). Operator Performance and Reliability in NDI. In R. S. Sharp (ed.), Research Techniques in Nondestructive Testing. Chapter 10, London: Academic Press. III, 323-354.

8. Federal Aviation Administration (199x). Visual Inspection, Draft Advisory Circular AC-43-13 1B.

9. NDE Capabilities Data Book (1997). Nondestructive Testing Information Analysis Center.

10. Rummel, W. D. (1998). Probability of Detection as a quantitative measure of nondestructive testing end-to-end process capabilities. Materials Evaluation, 56, 29-35

11. Hovey, P. W. and Berens, A. P. (1988). Statistical evaluation of NDE reliability in the aerospace industry. In D.O. Thompson and D. E. Chimenti (eds), Review of progress in Quantitative Nondestructive Evaluation, Plenum Press, Vol 7B, 1761-1768

12. Panhuise, V. E. (1989). Quantitative Nondestructive Evaluation - Introduction. Metals Handbook, 17, 663-665.

13. Drury, C. G. (1992). Inspection Performance. In G. Salvendy (ed.), Handbook of Industrial Engineering. New York: John Wiley & Sons, 2282-2314.

14. Yang, J. N. and. Donath, R. C. (1983). Improving NDE capability through multiple inspection with application to gas turbine engine disks. Wright-Patterson Air Force Base, OH 45433, Materials Laboratory, Air Force Wright Aeronautical Laboratories.

15. Drury, C. G. and Prabhu, P. V. (1994). Human factors in test and inspection. In G. Salvendy and W. Karwowski (eds.), Design of Work and Development of Personnel in Advanced Manufacturing. New York: John Wiley and Sons, Inc., 355-402.

16. Harris, D. H. and Chaney, F. B. (1969). Human Factors in Quality Assurance. New York, John Wiley and Sons.

17. Drury, C. G. and Fox, J. G. (1975). Human Reliability in Quality Control. London: Taylor & Francis, Ltd.

18. Rasmussen, J. (1983). Skills, rules, knowledge: signals, signs and symbols and other distinctions in human performance models. IEEE Transactions: Systems, Man and Cybernetics, SMC-13 (3), 257-267.

19. McReur, D. T. (1980). Human dynamics in man-machine systems. Automatica, 16(3), 237-253.

20. Barron, S. (1983). An optimal control model analysis of data from a simulated hover task. Proceedings of 18th Annual Conference on Manual Control, Dayton, OH, 186-206.

21. Wickens, C., Mavor, A.S. and McGee, J. P (1996). Right to the Future, Human Factors in Air Traffic Control, Panel on HF in Air Traffic Control Automation, Washington, D.C.: National Academy Press.

22. Salvendy, G. (1998). Handbook of Human Factors. New York: John Wiley and Sons.

23. Drury, C. G. (l971). Movements with Lateral Constraint. Ergonomics, l4.2, 293?305

24. Drury, C. G. (1985). Influence of Restricted Space on Manual Materials Handling. Ergonomics, 28.l, l67?l75.

25. Drury, C.G., Montazer, M.A. and Karwan, M.H. (1987). Self?paced Path Control as an Optimization Task, IEEE Transactions, SMC?17.3, 455?464.

26. DeFazio, K., Wittman, D., and Drury, C.G. (1992). Effective Vehicle Width in Self-Paced Tracking. Applied Ergonomics, 23(6), 382-386.

27. Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. Journal of Experimental Psychology, 47, 381-391.

28. Drury, C.G., and E.R. Hoffman. (1992). A Model for Movement Times on Data Entry Keyboards. Ergonomics, 35(2), 129-147.

29. Eriksen, C. W. (1990). Attentional search of the visual field. In D. Brogan (ed), Visual Search, London: Taylor & Francis, 3-19.

30. Drury, C. G., Prabhu, P. and Gramopadhye, A. (1990). Task analysis of aircraft inspection activities: methods and findings. In Proceedings of the Human Factors Society 34th Annual Conference, Human Factors and Ergonomics Society, 1181-1185.

31. Wang, M.-J. J., Lin, S.-C. and Drury, C. G. (1997). Training for strategy in visual search. International Journal of Industrial Engineering, 101-108.

32. Gramopadhye, A. K., Drury, C. G. and Sharit, J. (1997). Feedback strategies for visual search in airframe structural inspection. Int. Journal of Industrial Ergonomics, 19(5), 333-344.

33. McNichol, D. (1972). A Primer of Signal Detection Theory, Allen and Unwin.

34. Drury, C. G. and Addison, J. L. (1973). An Industrial Study of the Effects of Feedback and Fault Density on Inspection Performance. Ergonomics, l6, l59-l69.

35. Chapman, D. E., and Sinclair, M. A. (1975). Ergonomics in inspection tasks in the food industry. In C. G. Drury and J. G. Fox (eds.), Human Reliability in Quality Control. London: Taylor and Francis, 231-252.

36. Spencer, F. and Schurman, D. (1995). Reliability Assessment at Airline Inspection Facilities. Volume III: Results of an Eddy Current Inspection Reliability Experiment, DOT/FAA/CT-92/12. Atlantic City: FAA Technical Center.

37. Murgatroyd, R. A., Worrall, G. M. and Waites, C. (1994). A Study of the Human Factors Influencing the Reliability of Aircraft Inspection, AEA/TSD/0173. Risley, AEA Technology.

38. American Society of Nondestructive Testing (19xx). Part 2: Optically Aided Visual Testing of Aircraft Structures, Handbook of Nondestructive Investigation, volume on Visual Inspection, 292-301.

39. Lorenz, P.G. (1990). 4-20

40. Drury, C. G., Paramore, B., Van Cott, H. P., Grey, S. M. and Corlett, E. M. (1987). Task analysis, Chapter 3.4, In G. Salvendy (ed.), Handbook of Human Factors, New York: John Wiley and Sons, 370?401.

41. Kirwan, B. and Ainsworth, C. K. (1992). A Guide to Task Analysis. London: Taylor & Francis.

42. Federal Aviation Administration/Office of Aviation Medicine (1995). The Human Factors Guide for Aviation Maintenance 3.0, Washington, DC.

43. Air Transport Administration (19xx). Human Factors Program, ATA Spec 113.

44. Baird K. M., Hoffmann, E. R. and Drury, C. G. (2000 in press). The Effects of Probe Length on Fitts' Law. Applied Ergonomics.

45. Gibbs-Smith, C. H., (1965).The invention of the aeroplane 1799-1909, London, Faber and Faber, Appendix VI, 308-318

46. Drury, C. G. and Sarac, A. (1997). A design aid for improved documentation in aircraft maintenance: a precursor to training. Proceedings of the 41st Annual Human Factors and Ergonomics Society Meeting, Albuquerque, NM, 1158-1162.

47. Bainbridge, L. (1983). Ironies of Automation. Automatica, 19(6), 775-779

48. Sheridan, T. B. (1992). Social implications of telerobotics, automation, and supervisory control. In Telerobotics, Automation, and Human Supervisory Control, Cambridge: The MIT Press, 356-360.

49. Wickens, C. D. and Hollands, J. G., (2000). Engineering Psychology and Human Performance. Upper Saddle River NJ, Prentice Hall

50. Drury, C. G., Patel, S. C. and Prabhu, P. V. (2000). Relative advantage of portable computer-based workcards for aircraft inspection. International Journal of Industrial Ergonomics. The Netherlands: Elsevier, 26(2), 163-176.

51. Hastings, P. M, Merriken, M. and Johnson, W. B. (2000). An analysis of the costs and benefits of a system for FAA safety inspections, International Journal of Industrial Ergonomics., 26(2), 231-248.

52. McCarthy, J. C., Fallon, E. and Bannon, L. (2000). Dialogues on function allocation. Int. J. Human-Computer Studies, 52, 191-201.

53. Helander, M. G., Landauer, T. K., and Prabhu, P. V. (1997) Handbook of Human Computer Interaction, Amsterdam, North Holland

54. Liu, (1987). Software-User Interface Design, Chapter 51. In G. Salvendy (ed.), Handbook of Industrial Engineering, New York: J. Wiley & Sons.

55. Drury, C. G. (1985). Stress and Quality Control Inspection. In C.L. Cooper and M.J. Smith (eds.) Chapter 7, Job Stress and Blue Collar Work. Chichester, UK: J. Wiley and Sons.

12.0 ACRONYMS

AAM FAA's Office of Aviation Medicine

AC Advisory circular

CASR Center for Aviation Systems Reliability

CTSB Canadian Transportation Safety Board

FAA Federal Aviation Administration

FOV Field of View

FPI Fluorescent Penetrant Inspection

HCI Human / Computer Interaction

HTA Hierarchical Task Analysis

NAD Non-Aqueous Wet Developer

NTSB National Transportation Safety Board

NDI Nondestructive Inspection

NDE Nondestructive Evaluation

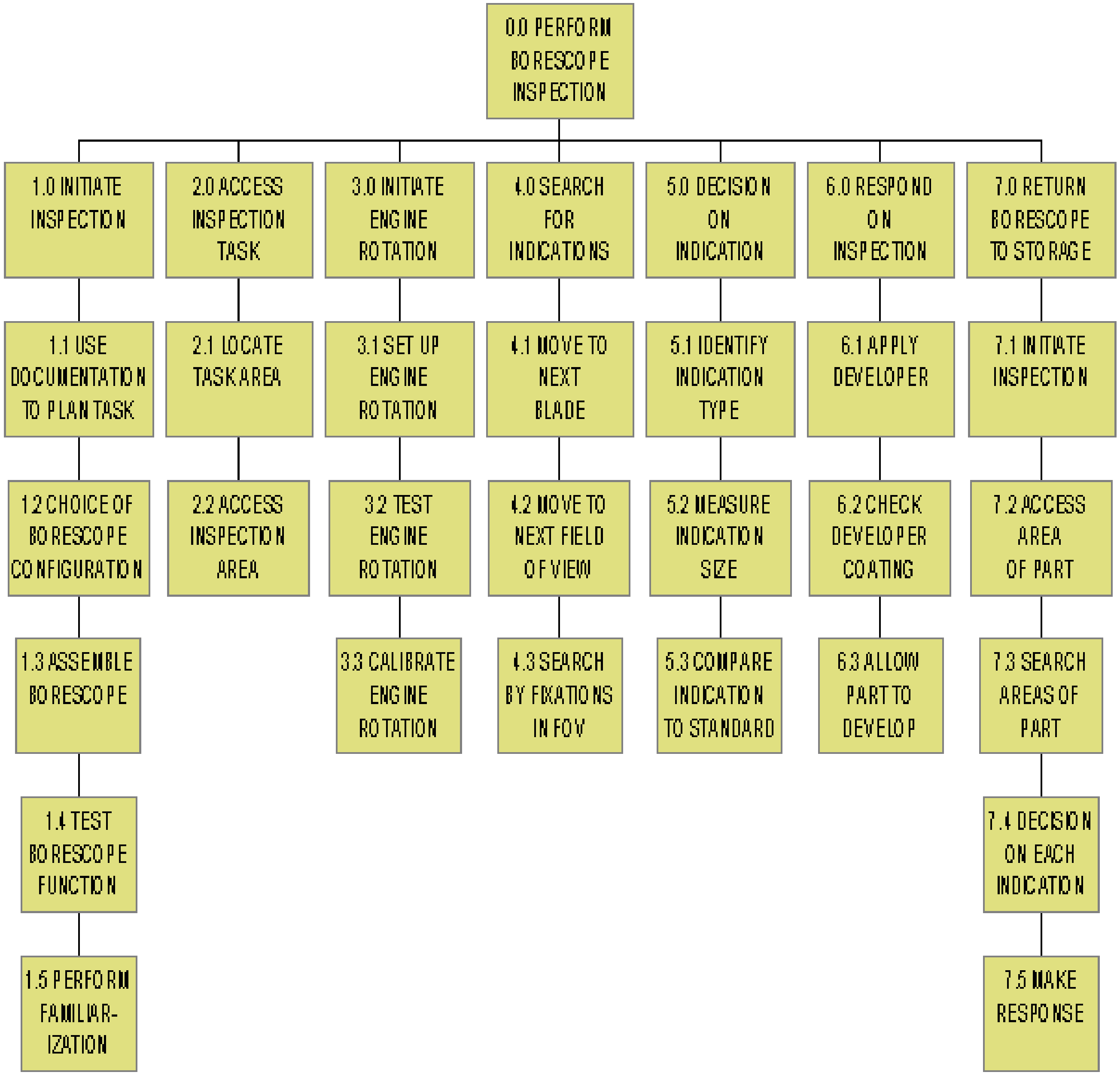
PoD Probability of Detection

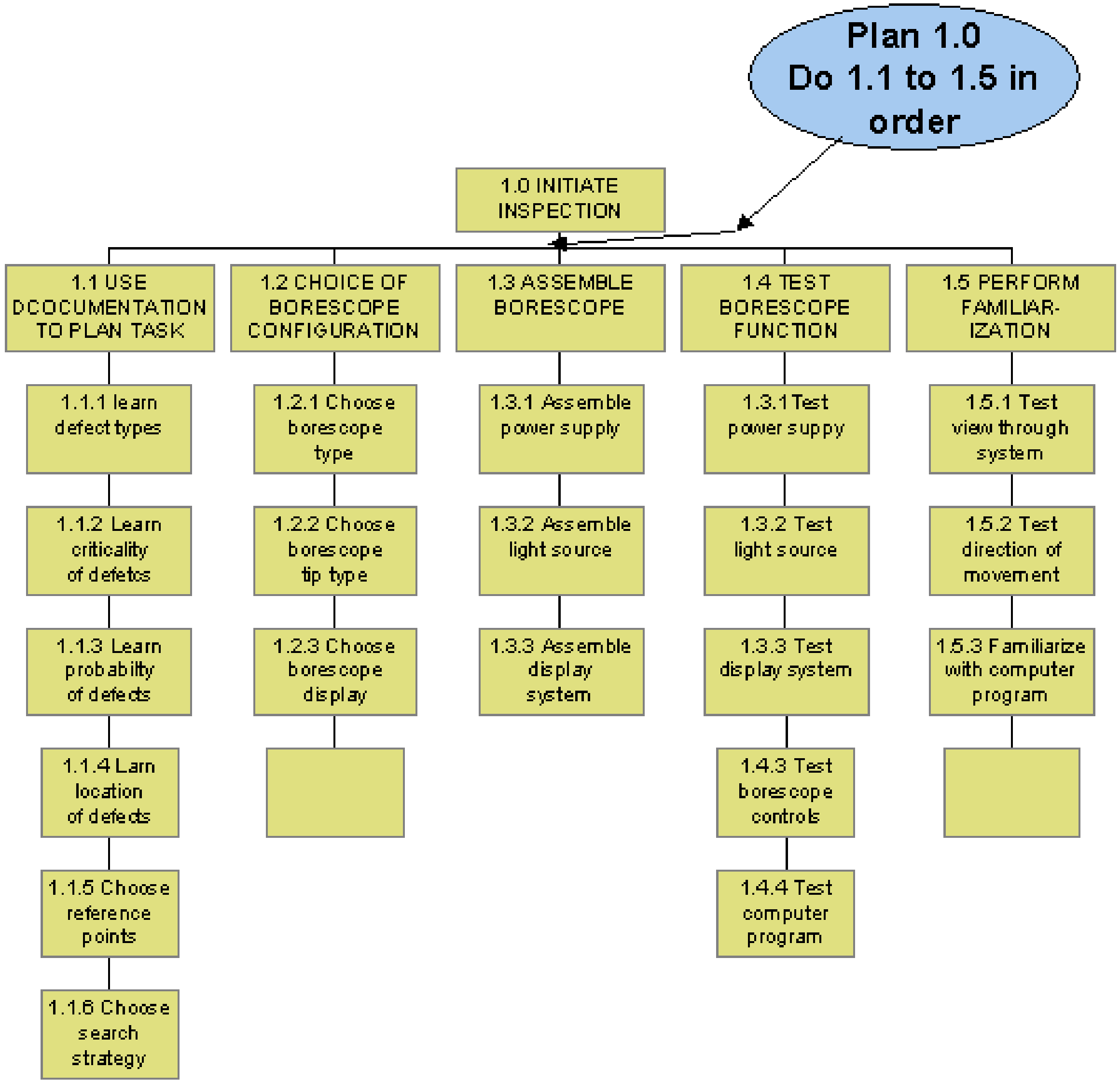
ROC Relative Operating Characteristics

SNL/AANC Sandia National Laboratories

APPENDIX 1 -TASK DESCRIPTION AND TASK ANALYSIS OF EACH PROCESS IN BORESCOPE INSEPCTION

The overall process is presented first as a top-level key (same as Figure 1). Next, each of the seven processes is presented in detail as an HTA diagram. Finally, each process is presented in the most detailed level as a Task Analysis table.


0.0 PERFORM BORESCOPE INSPECTION
1.0 INITIATE INSPECTION
2.0 ACCESS INSPECTION TASK
3.0 INITIATE ENGINE ROTATION
4.0 SEARCH FOR INDICATIONS
5.0 DECISION ON INDICATION
6.0 RESPOND ON INSPECTION
7.0 RETURN BORESCOPE TO STORAGE
1.1 USE DOCUMENTATION TO PLAN TASK
2.1 LOCATE TASK AREA
3.1 SET UP ENGINE ROTATION
4.1 MOVE TO NEXT BLADE
5.1 IDENTIFY INDICATION TYPE
6.1 APPLY DEVELOPER
7.1 INITIATE INSPECTION
1.2 CHOICE OF BORESCOPE CONFIGURATION
2.2 ACCESS INSPECTION AREA
3.2 TEST ENGINE ROTATION
4.2 MOVE TO NEXT FIELD OF VIEW
5.2 MEASURE INDICATION SIZE
6.2 CHECK DEVELOPER COATING
7.2 ACCESS AREA OF PART
1.3 ASSEMBLE BORESCOPE
3.3 CALIBRATE ENGINE ROTATION
4.3 SEARCH BY FIXATIONS IN FOV
5.3 COMPARE INDICATION TO STANDARD
6.3 ALLOW PART TO DEVELOP
7.3 SEARCH AREAS OF PART
1.4 TEST BORESCOPE FUNCTION
7.4 DECISION ON EACH INDICATION
1.5 PERFORM FAMILIAR-IZATION
7.5 MAKE RESPONSE



1.0 Initiate Inspection

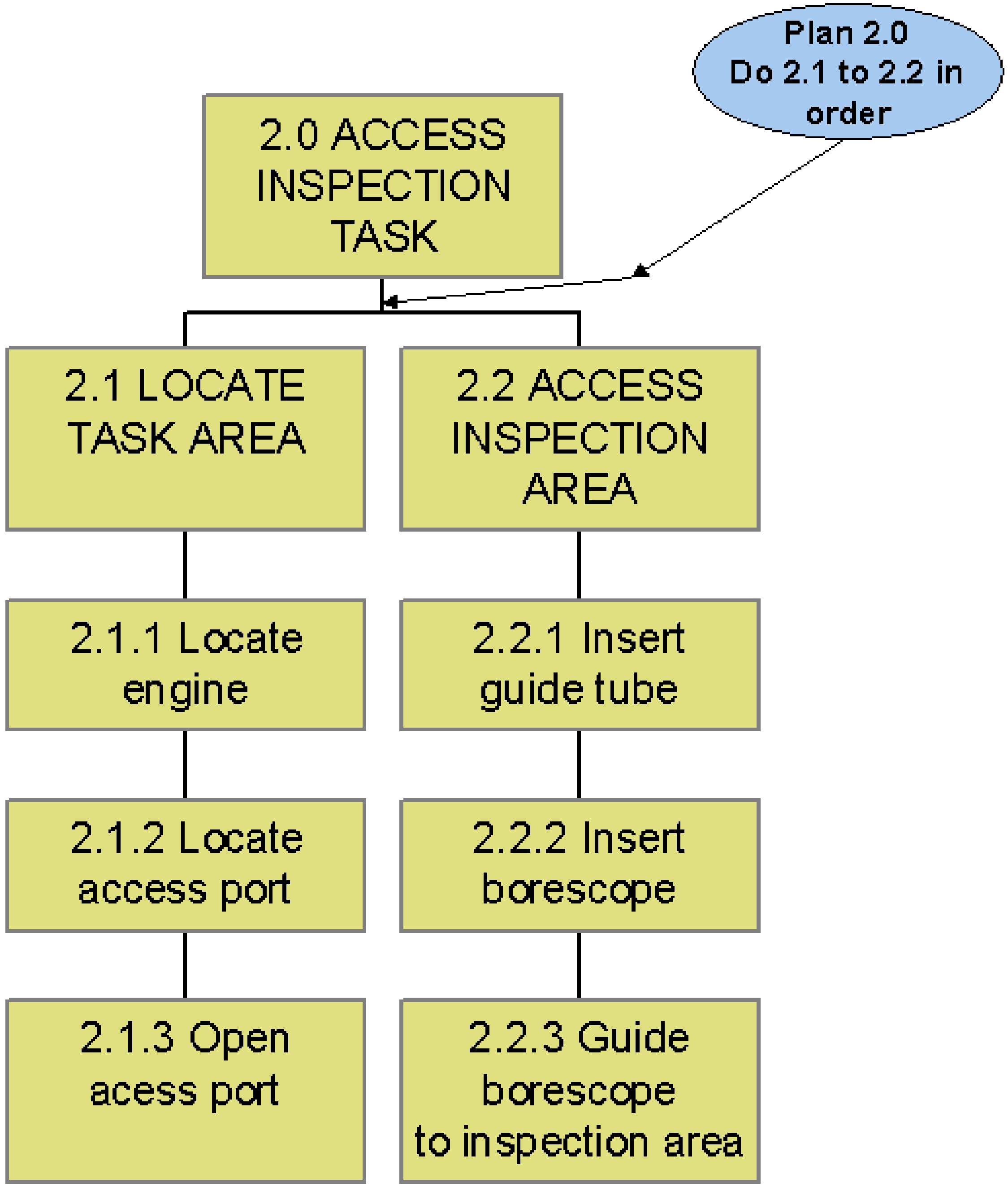
	Task Description	Task Analysis
1.1 Use documentation to plan task	1.1.1 Read documentation on task, e.g. workcard	Is workcard available and current? Is workcard self-contained or does it require access to manuals? Is workcard well human-engineered for layout, content, figures, ease of handling?

	1.1.2 Read documentation on borescope	Is borescope documentation required or is workcard self-contained? Is borescope documentation available and current? Is workcard well human-engineered for layout, content, figures, ease of handling?
	1.1.3 Plan task for borescope setup and mental model of area to be inspected	Is there clear overview of whole task on workcard? Are the diagrams of the area to be inspected and the access path designed to allow for an accurate mental model of the structure? Does inspector have an accurate mental model of the structure where the task will be performed?
	1.1.4 Learn defects: types, criticality, probability, location, standards	Are all possible defects listed? For each defect type are criticality, probability and location listed? Are standards available in a form directly usable during borescope inspection?
	1.1.5 Choose search strategy and starting point	Is starting point specified in workcard? Is strategy (eg. Front of all blades in CW order, then backs) specified in workcard? Does strategy specified fit the task from the inspectors viewpoint?
1.2 Choice of borescope configuration	1.2.1 Read borescope configuration instructions on workcard 1.2.2 Choose borescope type, tip and display	Are configuration instructions complete and unambiguous? Do configuration instructions allow sufficient flexibility for all circumstances? Does inspector have training, skill and authority to make correct choices?
1.3 Assemble borescope	1.3.1 Collect borescope kit	Is borescope kit available and access correctly controlled?
	1.3.2 Check kit for contents	Is kit complete for the task to be performed?
	1.3.3 Check kit and contents for calibration dates	Are calibration dates valid for current use? Is it easy to locate and read calibration information?

1.3 Assemble borescope continued	1.3.4 Assemble parts of borescope	Do parts fit together in only the correct configuration? Is there sufficient workspace to assemble without losing/damaging parts? Is there sufficient lighting and magnification available to perform assembly without error? Can parts be assembled without damaging delicate items such as fiberoptic cable or tip? Can tip be assembled without dropping it? When tip bayonet is performed correctly is there obvious feedback, e.g. click?
1.4 Test borescope function	1.4.1 Read test procedure	Is test procedure included in workcard?
	1.4.2 Follow test procedure	Is test procedure well designed and in an order appropriate to be actual used in the environment? Does test procedure include feedback for each step in a form appropriate to the inspector?
	1.4.3 If test procedure fails, follow recovery procedure	Have all forms of test failure been given a recovery procedure in workcard? Are there clear diagnostic procedures for each failure that ensure a specified outcome? Do inspectors have short-cuts, heuristics or informal recovery procedures to allow task to continue despite failure?
1.5 Perform familiarization	1.5.1 Decide if familiarization required	Does inspector have clear indication that familiarization with the borescope is needed? Is time available for familiarization? Is there implied pressure not to perform familiarization from time pressures and/or professional peer pressure?
	1.5.2 Perform familiarization	Does workplace layout allow inspector to become familiar with path control, display viewing and menu functions?

	1.5.3 Test field of view, movements and computer program	Does field of view produce natural perspective? Do movements of controls move view in anticipated directions? Does computer program have labels and procedures intuitive to inspector?

Errors/Variances: 1.0 Initiate Inspection
Documentation not available
Documentation no self-contained
Documentation not well-human-engineered
Inspector makes wrong choice of borescope configuration
Borescope mis-assembled
Borescope damaged during assembly
Borescope tip dropped or lost
Borescope calibration out of date
Borescope test fails
Failure procedure incorrect
Familiarization not performed



2.0 Access Inspection Task

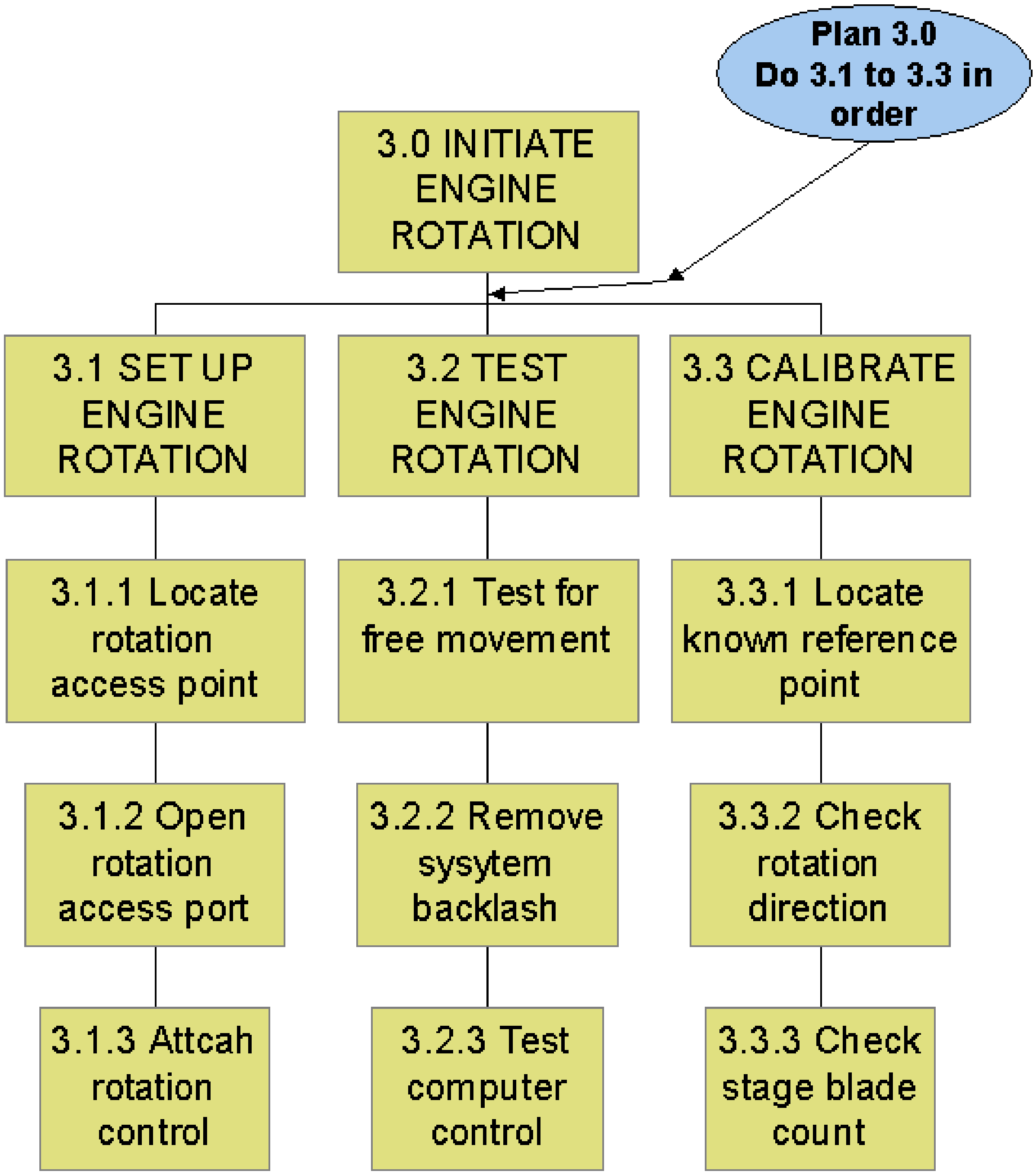
	Task Description	Task Analysis

2.1 Locate task area	2.1.1 Locate correct engine	Is engine numbering system compatible for all aircraft types?
	2.1.2 Locate correct entry port	Does documentation view correspond to inspector's view? Is there visual confirmation that correct port has been selected?
	2.1.3 Locate access equipment	Is required equipment (e.g. ladders, stands, tables) specified in workcard? Is required equipment available for use? Do inspectors select substitute equipment if correct equipment not available?
2.2 Transport borescope to inspection area	2.2.1 Transport borescope to inspection area	Does borescope have to be disassembled for transport? If borescope transported assembled, does borescope retain configuration and calibration when transported? If disassembly and reassembly is required, does borescope retain configuration and calibration when transported?
2.3 Access inspection area	2.3.1 Set up access equipment	Is access equipment safe for this task? Is access equipment adequate for task performance, e.g. tables/stands for holding equipment and accessories?
	2.3.2 Open access entry part (may be AMT task)	Is opening error proof ? Can parts such as fasteners get lost or get into engine?
	2.3.3 Set up borescope at inspection site	Are stands/tables adequate to hold and use borescope equipment and accessories? Can inspector view display while manipulating borescope? Is eye relief distance adequate for direct optical viewing? If two-person task, can manipulation and display personnel communicate adequately? Is display under optimum illumination conditions, e.g. Visible with high contrast and no glare?

	2.3.4 Insert borescope into access port	Does opening to borescope path in documentation correspond with inspector's view? Is there adequate clearance for borescope tip to be inserted into path opening?
2.3 Access inspection area continued	2.3.5 Guide borescope to inspection point	Does inspector have correct mental model of path? Are intermediate points on path visible as confirmation? Are intermediate points shown from inspector's viewpoint in documentation? Are direction choice points visible? Are direction choice points recognizable to inspector? Do directions on display correspond with inspector's mental model of path? Does control system for direction conform to direction of motion stereotypes? Can inspector maneuver tip safely at each choice point? Can inspector judge and control safe speed of borescope insertion?
	2.3.6 Stop borescope at inspection point	Does view of inspection point in documentation correspond to inspector's view on display? Can inspector recognize inspection point from documentation? Is stopping point adequately defined in documentation? Can inspector stop within tolerance limits of inspection point? Does borescope tip remain at inspection point unless consciously moved during inspection?

Errors/Variances: 2.0 Access Inspection Task

Wrong choice of engine/access port
Missing access equipment
Inadequate access equipment
Borescope damaged in transport
Borescope configuration or calibration changed in transport
Inadequate support for equipment
Poor posture for simultaneous manipulation and viewing
Wrong direction of motion stereotypes for direction control
Misperception of routing taken by borescope to inspection point
Inadequate clearances on path to inspection point
Wrong inspection point chosen
Insertion stops outside tolerance of specified inspection point

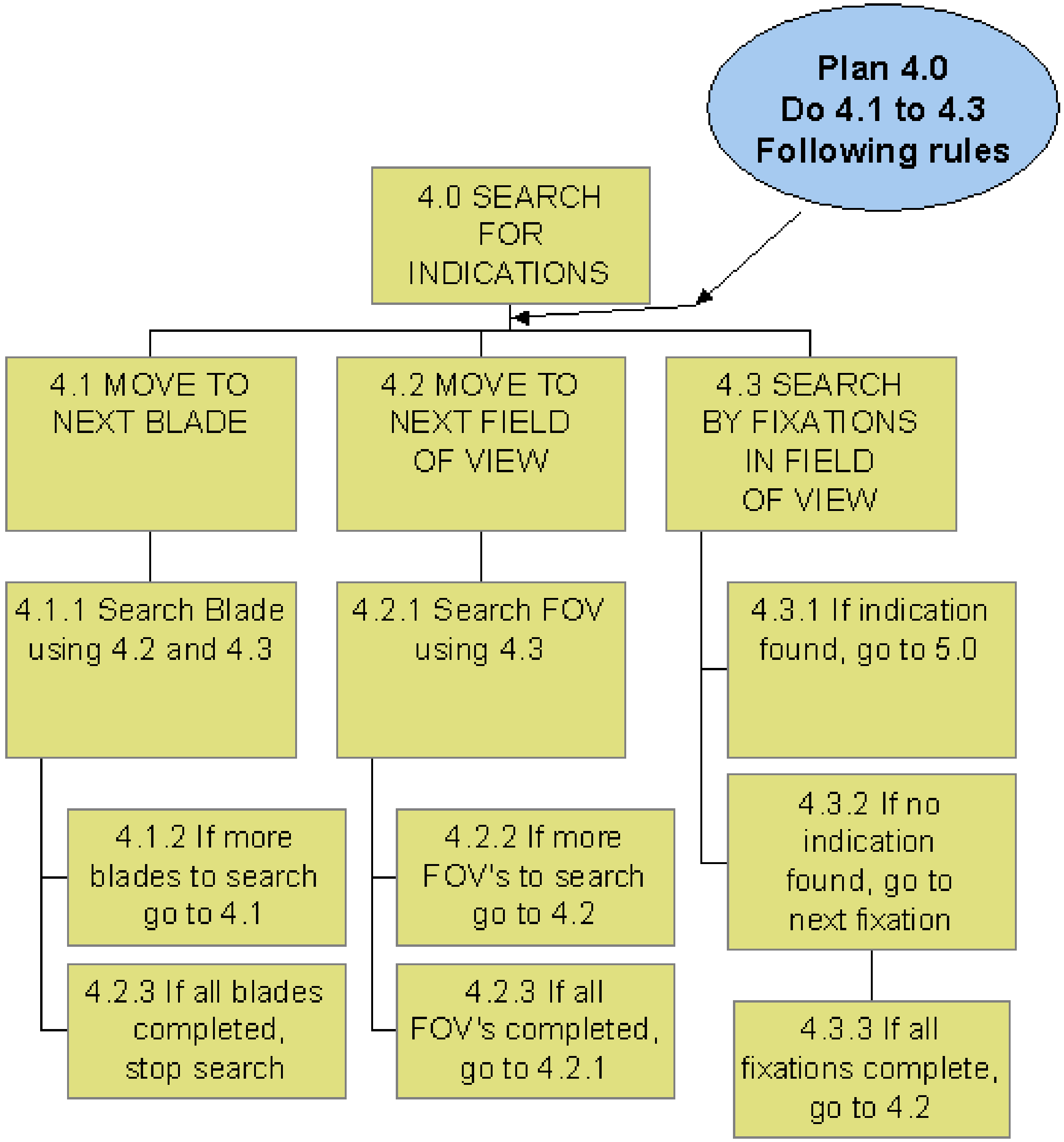

Plan 3.0
Do 3.1 to 3.3 in order
3.0 INITIATE ENGINE ROTATION
3.1 SET UP ENGINE ROTATION
3.2 TEST ENGINE ROTATION
3.3 CALIBRATE ENGINE ROTATION
3.1.1 Locate rotation access point
3.2.1 Test for free movement
3.3.1 Locate known reference point
3.1.2 Open rotation access port
3.2.2 Remove sysytem backlash
3.3.2 Check rotation direction
3.1.3 Attcah rotation control
3.2.3 Test computer control
3.3.3 Check stage blade count

3.0 Initiate Engine Rotation

	Task Description	Task Analysis
3.1 Set up engine rotation	3.1.1 Locate equipment for engine rotation	Is equipment choice (manual vs. automated) specified in workcard? Is equipment available? Are substitutions allowed?
	3.1.2 Locate access for engine rotation equipment	Is access panel clearly specified? Is access panel accessible and easily removable?
	3.1.3 Assemble engine rotation equipment	Can parts be assembled only in correct configuration? Are instructions for assembly in workcard? Are instructions well human engineered? Do parts assemble easily: Is it possible to check each assembly before the assembly is complete?
	3.1.4 Computer set up	Are instructions for setting computerized rotation included in wordcard? Does computer interface comply with human/ computer interaction (HCI) principles? Do control movements correspond to engine movements using population stereotypes? Do engine parameters have to be set manually or is menu choice available?
3.2 Test engine rotation	3.2.1 Test for free movement	Does movement to rotate engine move borescope display in correct sense? Can rotation be accomplished while viewing borescope display? Can errors in installing engine rotation device be detected during rotation test?
	3.2.2 Remove system backlash	Can backlash be removed in a straightforward manner?

	3.2.3 Test computer control	Can engine rotation commands be verified on the borescope display? Does inspector have to alternate between borescope display and rotation computer display to test?
3.3 Calibrate engine rotation	3.3.1 Locate known reference point	Does inspector have choice of reference point (relative reference)? Or is known blade pre-specified (absolute reference)? If absolute reference, can location of reference point be performed easily using borescope display?
	3.3.2 Check rotation direction	Does direction of rotation correspond between rotation control and borescope display?
	3.3.3 Check stage blade count	Is blade count readily available on workcard? Does blade count differ between two stages inspected from same borescope location?

Errors/Variances: 3.0 Initiate Engine Rotation
Rotation equipment not available
Error in assembling rotation equipment
Error in computer set-up
Wrong direction-of-motion stereotypes between rotation controls and borescope display
Poor human-computer interaction design of automated rotation equipment
Wrong or inconsistent reference point chosen
Blades not counted correctly



4.0 Search for Indications

	Task Description	Task Analysis

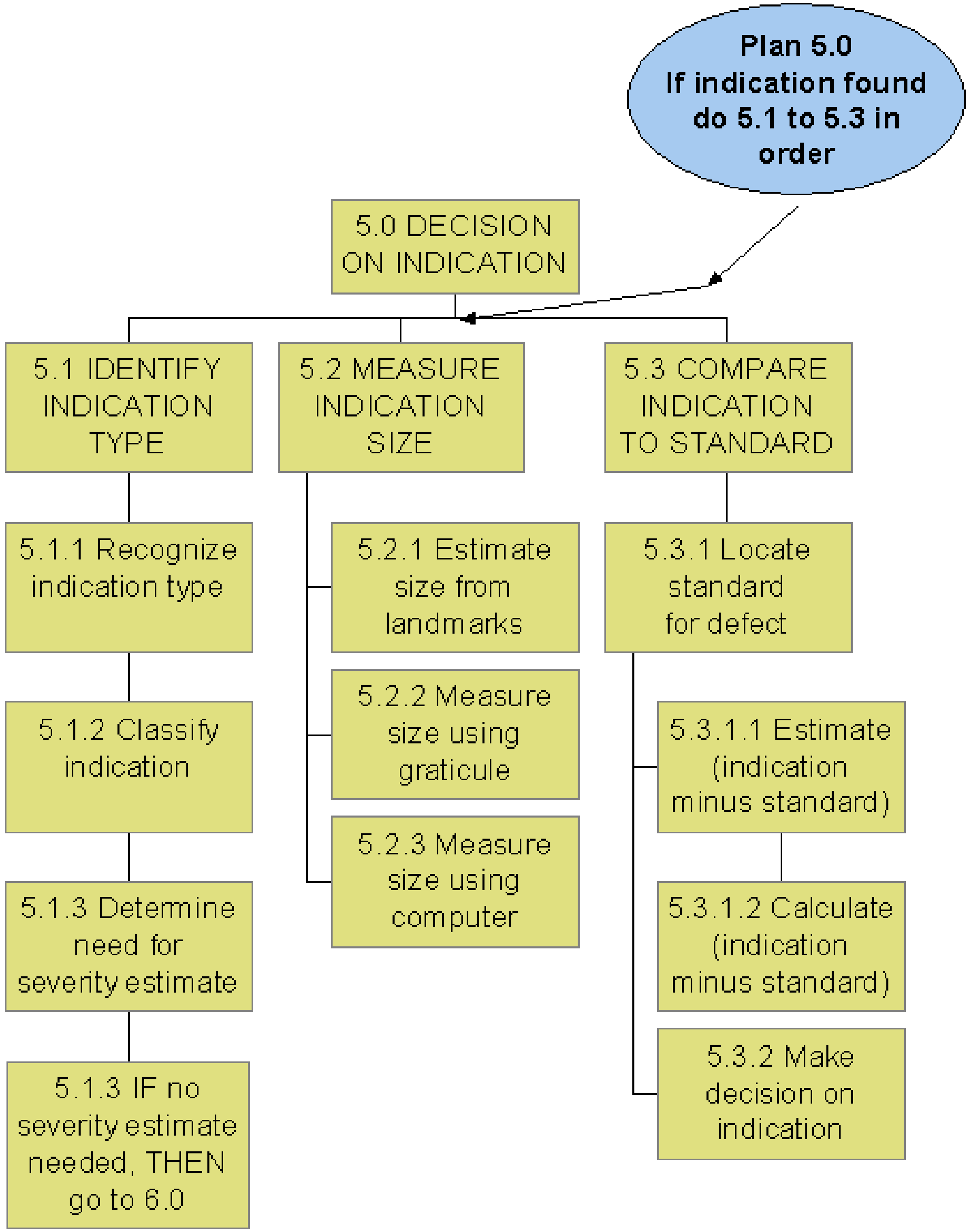
4.1 Move to next blade	4.1.1 Search blade using 4.2 and 4.3	Can engine be rotated easily between blades? Can engine be stopped so that blade is in exact position for inspection? How is blade count maintained for manual and automated engine rotation? Are there multiple possible blade types with different visual characteristics? Does inspector know these different blade types and their possibly different characteristics for defect location, probability, severity? Does automated engine rotation proceed continuously or in discrete movements? Is sufficient time allowed for reliable search for whole blade?
	4.1.2 If more blades to search, go to 4.1	
	4.2.3 If all blades completed, stop search	
4.2 Move to next field of view (FOV)	4.2.1 Search FOV using 4.3	Is FOV movement needed to cover whole inspectable area of blade at adequate magnification? If FOV movement is needed, does FOV move in a direction compatible with borescope controls? Can inspector maintain situational awareness as FOV moves? What is scan path followed by inspector? Does scan path cover complete area?
	4.2.2 If more FOVs to search, go to 4.2	
	4.2.3 If all FOVs completed, go to 4.2.1	

4.3 Search by fixations in FOV	4.3.1 Move fixation to next location	Does eye scan path across FOV cover whole FOV? Are fixations close enough together to detect indication if it is in the fixation? Is fixation time sufficient to detect a target? Is inspector expecting all possible indications each time search is performed? Are some indications expected in particular parts of the structure? Do inspector's expectations correspond to reality for this task? Does inspector return to area where possible indication perceived? Does inspector have high peripheral visual acuity? Is contrast between indication and background high? Is indication visible to inspector if an direct line of sight (Fovea)?
4.3 Search by fixations in FOV continued	4.3.2 If indication found, go to 5.0	Is there a clear protocol for what is an indication? Is there a clear protocol for remembering how much of search was completed before going to decision?
	4.3.3 If all fixations complete, go to 4.2	Does inspector remember whether fixations are complete? Is the policy to scan whole FOV once before stopping? Does inspector try to continue fixations for search while moving FOV?
	4.3.4 If no indication go to next fixation 4.3.1	

Errors/Variances: 4.0 Search for Indications

Blade movement does not meet population stereotypes
Blade movement too rapid for reliable search
Blade count lost
Field of view movement does not meet population stereotypes
Loss of situational awareness by blade or FOV or fixation
Incomplete search coverage by blade, FOV or fixation
Fixation movement too far to ensure reliable inspection
Loss of SA and coverage when finding indication stops search process

5.0 Decision on Indication


Plan 5.0
If indication found do 5.1 to 5.3 in order
5.0 DECISION ON INDICATION
5.1 IDENTIFY INDICATION TYPE
5.2 MEASURE INDICATION SIZE
5.3 COMPARE INDICATION TO STANDARD
5.1.1 Recognize indication type
5.1.2 Classify indication
5.1.3 Determine need for severity estimate
5.1.3 IF no severity estimate needed, THEN go to 6.0
5.2.1 Estimate size from landmarks
5.2.2 Measure size using graticule
5.2.3 Measure size using computer
5.3.1 Locate standard for defect
5.3.1.1 Estimate (indication minus standard)
5.3.1.2 Calculate (indication minus standard)
5.3.2 Make decision on indication

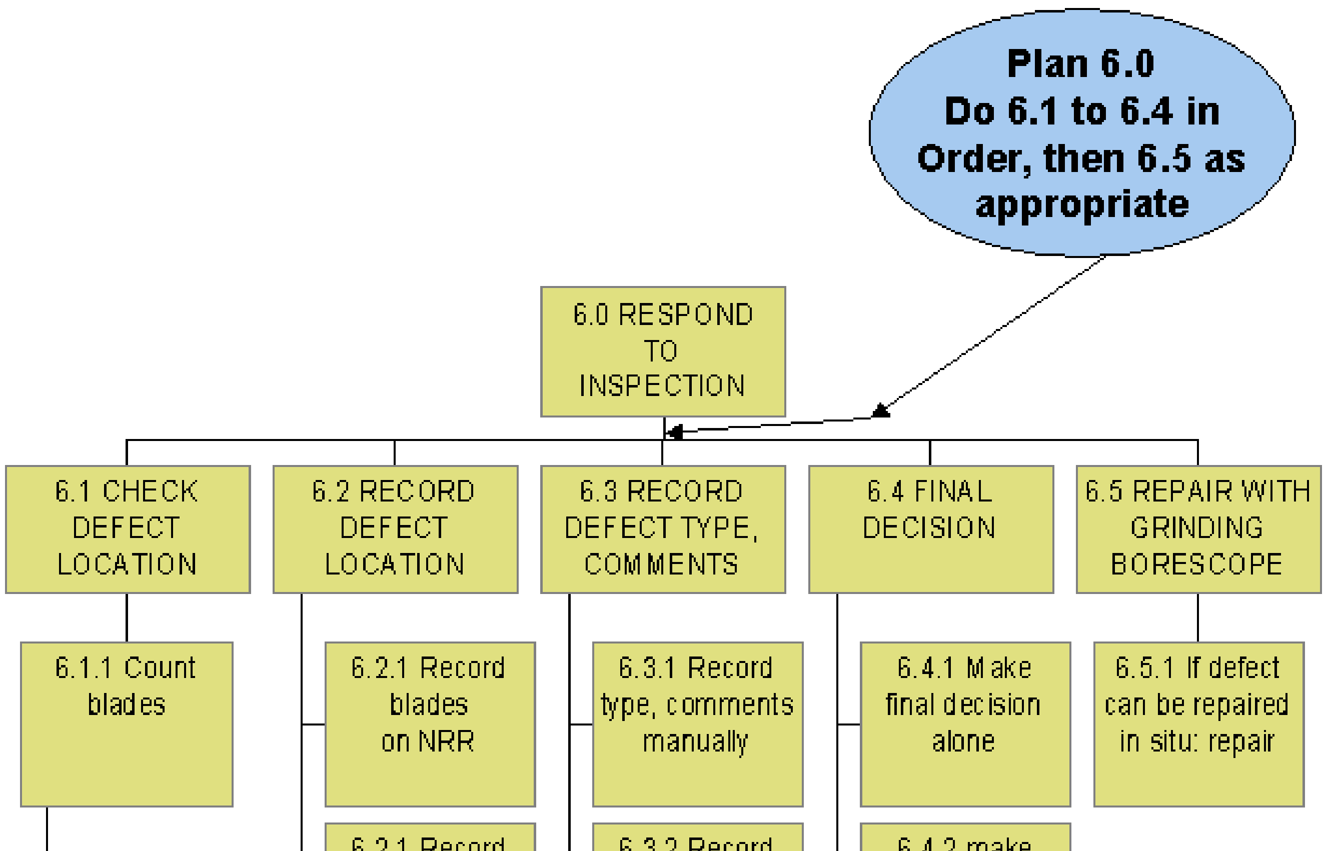
5.0 Decision on Indication

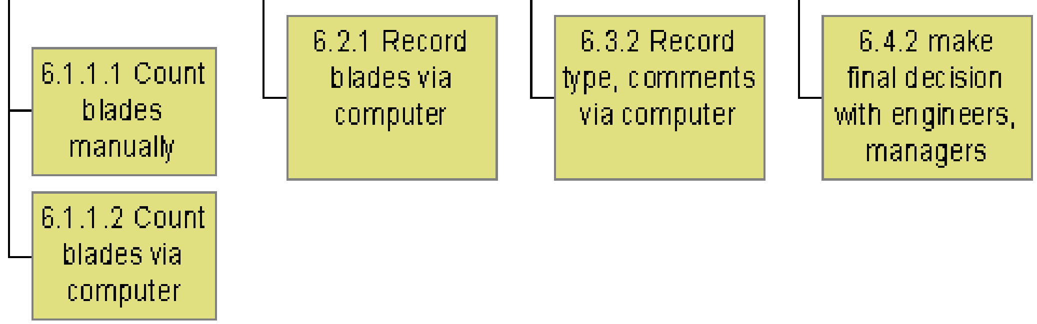
	Task Description	Task Analysis
5.1 Identify Indication Type	5.1.1 Recognize indication type	Does inspector have comprehensive list of possible indication types? Are some indication types under special scrutiny on <u>this</u> inspection? Does inspector have wide enough experience to be familiar with all indication types? Does borescope image of indication correspond to prototypical indications in workcard? Is lighting of correct quality and quantity to ensure adequate recognition of indication?
	5.1.2 Classify indication	Are the correct terms for each indication type listed prominently in workcard? Are there local terms used by inspectors in place of official indication terms?
	5.1.3 Determine need for severity estimate	Does this class of indication need an estimate of size or severity or is any severity level rejectable?
	5.1.4 If no severity estimate needed, go to 6.0	
5.2 Measure indication size	5.2.1 Estimate indication size from landmark	Are correct landmarks identified in workcard? Can inspector locate and recognize correct landmarks (e.g. structure, fasteners)? Are landmarks visible in same FOV as indication? Is there distance parallax between indication and landmark? Is there angular difference between indication and landmark? Does landmark correspond closely in size to indication? If not, can inspector make accurate judgments of relative magnitude between indication and landmarks?

		Does inspector have to remember size / severity or can it be entered immediately onto workcard?
	5.2.2 Measure size using graticule	Can graticule be aligned with critical dimension(s) of indication? Does alignment task involve correct direction-of-movement stereotypes between graticule control and borescope image? Is there distance parallax between indication and graticule? Is there angular difference between indication and graticule? Is numbering on graticule in a left-to-right direction? Are units on graticule the same as units specified in workcard for this indication? Does inspector have to remember graticule reading or can it be entered immediately onto workcard?
5.2 Measure indication size continued	5.2.3 Measure size using computer	Does workcard include detailed instructions for size measurement? Has inspector practiced size measurement enough to be familiar with this technique on engine? Does inspector understand the physical principles on which the measurement system is based? Is the computer program for size measurement designed using principles of HCI? Does measuring line move with the correct direction-of-movement stereotype? Is the line easily visible (high contrast) against the indication and its background? Is there angular difference between indication and measurement system? If so, does inspector know how to correct for angular differences?

		Can the inspector reliably estimate the center of the projected line?

Errors/Variances: Decision on Indication
List of all possible indication types not available.
Inspector does not recognize indication type correctly.
Inspector uses wrong term to classify indication.
Measurement of indication size inaccurate.
Failure to record measurement size accurately.





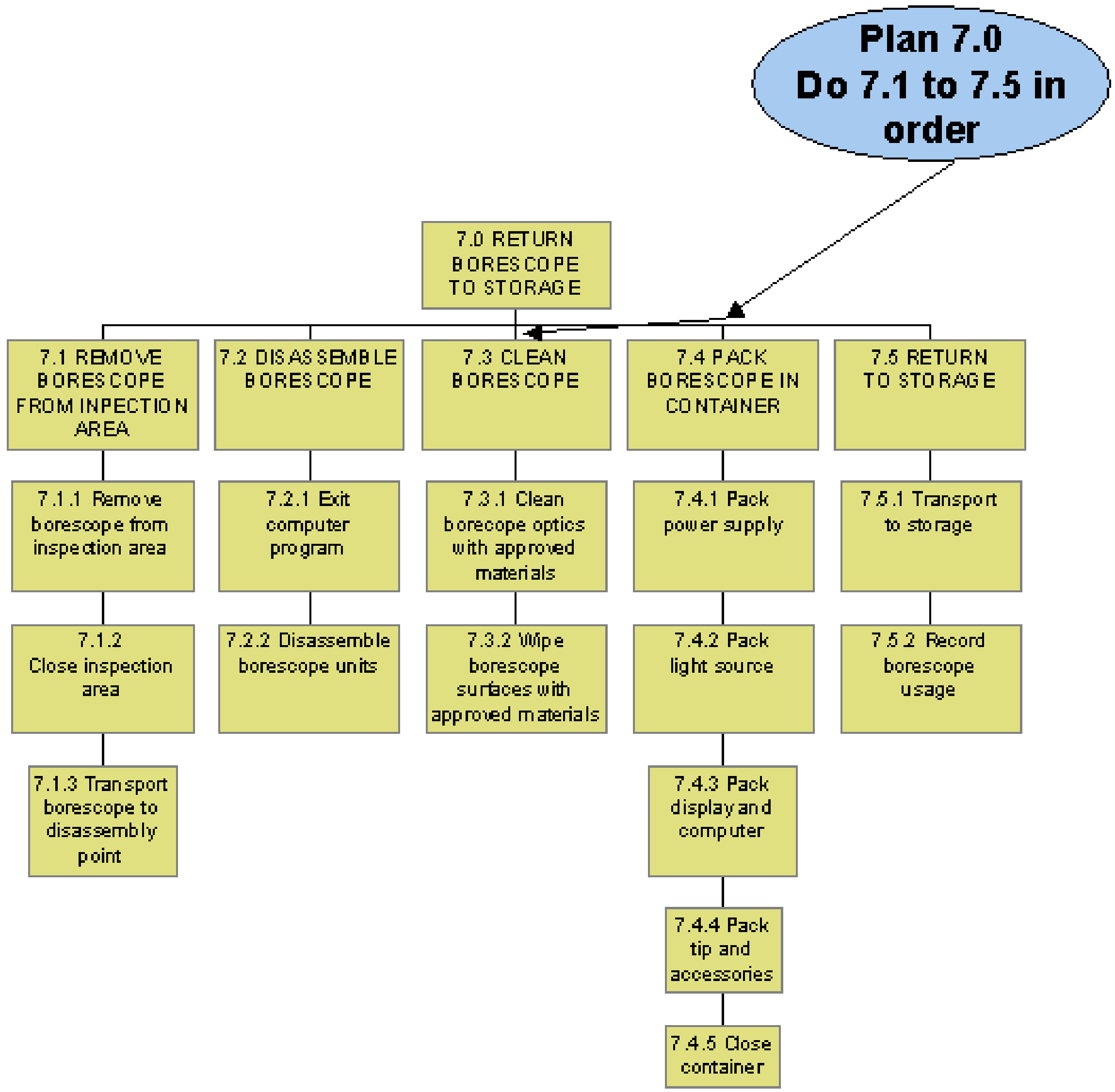
6.0 Respond on Inspection

	Task Description	Task Analysis
6.1 Check Defect Location	6.1.1 Count Blades for defect 6.1.1.1 Manual Blade count: Start from blade with defect, count from known reference mark 6.1.1.2 Computer blade count: use computer interface to note current blade count.	Has known reference mark been determined correctly? Does human inspector count blades correctly? Can each blade be viewed unambiguously as it passes the counting point? Does the computer interface show blade count in its normal inspection mode?
6.2 Record Defect location	6.2.1 Record on work card 6.2.2 Record via computer	Should a workcard or an NRR be used for recording? Is workcard/NRR conveniently located with respect to the inspection site? Is there enough room on workcard /NRR to allow writing all defect locations? Is computer conveniently located with respect to the inspection site? Is computer program in correct mode for recording? Does computer program allow room for all defects to be recorded?

6.3 Record Defect type and comments	6.3.1 Record Defect Type	Are defect types classified unambiguously? Is there a checklist of proper defect types?
	6.3.2 Record defect comments	Is there room for comments on the workcard / NRR / computer program? Are inspectors encouraged to write sufficient comments for later use of data?
6.4 Final Decision	6.4.1 Make final decision alone	Was (indication minus standard) clearly beyond acceptance limit? Is there a clear record of the findings to back up the decision? Does inspector have to weigh consequences of lone decision, e.g. costs, schedule delays? Will managers typically stand by inspector in lone decision?
	6.4.2 Make final decision with engineers, managers	Does the procedure call for others to share the decision? Can engineers / managers be contacted with minimal delay? What happens if correct engineers / managers are not available for contact?
6.4 Final Decision continued		Do engineers / managers display resentment at being contacted? Can facts be transmitted rapidly to engineers, managers, e.g. by engine, using documents / fax, sending computer files? Do engineers / managers respect inspector's skills and decisions in coming to final decision? If inspector is overruled, what are consequences for future inspector performance?
6.5 Repair with grinding borescope	6.5.1 IF defect can be repaired *in situ*, THEN repair	Repair systems not considered in this report

Errors/Variances: 6.0 Respond to Inspection
Defect location not recorded
Defect type not recorded

Defect comments not recorded.
Defect location incorrectly recorded
Defect type incorrectly recorded
Defect comments incorrectly recorded.



7.0 Return Borescope to Storage

	Task Description	Task Analysis

7.1 Remove borescope from inspection area	7.1.1 Remove borescope from inspection area	Can inspector remove borescope from engine without damage to structure or borescope?
	7.1.2 Close inspection area and remove access equipment (may be performed by other personnel)	Are all parts needed for closure of access port available easily? Is correct closure of access port easily confirmed visually? Is correct location for access equipment known and available? Do personnel use "work arounds" (informal and unsanctioned procedures) if location not available?
	7.1.3 (If required) Transport borescope to disassemble point	Can borescope be transported without damage?
7.2 Disassemble borescope	7.2.1 Exit computer program (if required)	Is exit procedure specified in workcard or on-screen? Does exit automatically save results, or prompt for saving? Does exiting from computer program automatically turn off power to parts of borescope system?
	7.2. Disassemble borescope units	Is a clean and convenient place available for disassembly? Is borescope power supply disconnected first? Is light source cool enough to preclude injury to inspector and damage to light source when disassembled? Do all parts of borescope and display disconnect easily? As small parts (e.g. tips) easy to damage or lose?

7.3 Clean borescope	7.3.1 Clean borescope optics with approved materials	Are correct cleaning materials (cloths, solvents) available at workplace? Does inspector have training in correct cleaning procedures? Do inspectors have local work-arounds (informal and unsanctioned procedures) using easily-available materials? Can cleaning be accomplished without optical damage?
	7.3.2 Wipe borescope surfaces with approved materials	Is there a clear difference between materials approved for optical cleaning and those approved for external wipe-down of borescope surfaces? Does wiping clean sufficiently? Do solvents dry in time for borescope packing (7.4)?
7.4. Pack borescope in container	7.4.1 Pack power supply	Does power supply fit container in only the correct orientation? Does power supply load easily in correct orientation? Is power supply cool enough to pack?
7.4. Pack borescope in container continued	7.4.2 Pack light source	Does light source fit container in only the correct orientation? Does light source load easily in correct orientation? Is light source cool enough to pack?
	7.4.3 Pack display and computer	Do display and computer fit container in only the correct orientation? Do display and computer load easily in correct orientation? Are display and computer cool enough to pack?

	7.4.4 Pack tip and accessories	Is there a designed place for all current accessories in container? If not, will current accessories fit into other plan in container? Do tip and accessories fit container in only the correct orientation? Do tip and accessories load easily in correct orientation? Are tip and accessories cool enough to pack?
	7.4.5 Close container	Is there simple visual indication that all parts were packed correctly? Can container be closed without damage to borescope parts?
7.5 Return to storage	7.5.1 Transport to storage	Is container weight safety transportable? Does container have well-designed handling aids, e.g. Handles, wheels? Is there correct storage place for borescope system? Is correct storage place available? Do inspectors have "work arounds" (informal and unsanctioned procedures) if storage place not available?
	7.5.2 Record borescope usage	Is there a procedure for signing borescope back into storage? Is procedure always followed? What happens if borescope is needed immediately on another job? Does it get signed in and out correctly?

Errors/Variances: Return Borecsope to Storage
Borescope damaged while removing from engine
Inspection access port not correctly closed
Computer data not saved

Borescope damage during disassembly
Borescope damage during cleaning
Parts packed into container while still too hot
Tip damaged/lost
Parts damaged when container closed
Borescope not signed back into storage

APPENDIX 2 - HUMAN FACTORS BEST PRACTICES FOR EACH PROCESS IN BORESCOPE INSPECTION

Process	Good Practice	Why?
1. Initiate	Design documentation to be self-contained	1. If multiple sources must be accessed, e.g. workcard, borescope manual, this increases the probability that the inspector will rely on memory, thus increasing errors.
1. Initiate	Design documentation to follow validated guidelines, e.g. Documentation Design Aid (DDA).	1. Well-designed documentation has been proven to decrease comprehension errors 2. Application of validated guidelines ensures consistency across different inspection tasks, reducing errors.
1. Initiate	Include borescope set-up and testing in inspection documentation	1. Errors are less likely if inspector is not tempted to work without hard-to-locate information
1. Initiate	Use documentation and training to help inspector form an appropriate mental model of the inspection task. E.g. provide diagrams showing the path to be followed from multiple angles. E.g. Link new training and retraining directly to the documentation	1. The inspector should have an appropriate mental model of the path to be followed by the borescope through the structure. This will allow the inspector to plan the task ahead, so that the task proceeds without surprises. 2. Inspectors will make less control errors in guiding the borescope is they can visualize its path.

1. Initiate	Define defect types, critical sizes and potential locations early in the documentation.	1. With good information on defects, inspectors can better plan their inspection task strategy. 2. If inspectors know the likely position and size of defects, they can better plan where to position the borescope for search, reducing the chance of missing defects.
1. Initiate	Design borescope for ease of assembly as well as functionality. E.g. Parts should assemble in only the correct way E.g. Color coding for very small components where part and serial numbers are difficult to read. E.g. Visual check that borescope kit is complete before it is transported to the inspection sit or assembled.	1. If parts can be assembled incorrectly, at some time they will be, resulting in improper set-up for inspection or damage to borescope 2. Borescope tips are small and their designation is not easy to see, often being engraved or stamped on to the tip. Errors are likely in choice of tip if the designation is misread. 3. If the borescope packaging has a space for each component, then missing components can be seen very easily, and remedial action taken before the assembly begins. This prevents memory errors if assembly is interrupted to locate missing parts.
1. Initiate	Provide clear feedback of correct assembly during borescope testing.	1. Any problems with the borescope or its assembly should be highlighted during the test of the assembled system. This will prevent assembly errors from propagating to inspection errors.
1. Initiate	Provide an off-line fixture so that inspector can regain familiarity with borescope. E.g. provide a fixture with an inspection access hole and a moderately complex internal route. E.g. in off-line fixture, key different visible surfaces and points using numbers or colors.	1. Borescopes may have non-intuitive control / display relationships, so that practice with movement of borescope under benign conditions can prevent engine or tip damage in subsequent use. A custom fixture for which the inspector has a good mental model will encourage such practice. 2. If surfaces and points are easy to recognize, inspector can practice movement and stopping while maintaining situation awareness easily.

2. Access	Specify correct access equipment in work documentation	1. If correct equipment is not specified, inspectors will be tempted to find an alternate "work arounds" (informal and unsanctioned procedures) so as not to delay the task. This can lead to poor working conditions and hence increased errors.
2. Access	Provide access equipment to facilitate one-person or two-person use E.g. support equipment for a single-person task should allow the inspector to stand or sit comfortably and safely while reaching the borescope controls and viewing the display. E.g. for a two-person task the support equipment must facilitate rapid and accurate communication of instructions and feedback.	1. Sub-optimal equipment leads to poor working postures and / or frequent body movements. Both can increase inspection errors. 2. If a two-person team cannot coordinate effectively, then delays and frustration will result. Under unfavorable conditions, poor physical coordination can lead to communication errors, and hence inspection errors.
2. Access	Design borescope system for ease of transport both in case and partially-assembled. E.g. Wheeled trolley or cart for transport of the system to inspection site after assembly and test	1. If borescope system needs to be assembled, tested and familiarized, this may be more reliably performed away from the aircraft or engine. If the inspector has to disassemble for transport to the access site and re-assemble, then damage or errors may occur. If the borescope system can be transported assembled, this must not lead to alternate damage events.
2. Access	Design access ports to reduce possibility of incorrect closure after inspection. E.g. fasteners that remain attached to the closure, tagging or red-flagging system, documentation procedure to show that port was opened and must be closed before return to service.	1. A common error in maintenance is failure to close after work is completed. Any interventions to reduce this possibility will reduce the error of failure to close.

2. Access	Design access ports large enough to manipulate borescope into correct starting position	1. Size of opening affects the ease of borescope insertion (see section X.4.2.1). If initial access is easier, errors and tip damage will be reduced
2. Access	Install or specify path guide tube when borescope path has difficult choice or control points.	1. If the path requires careful control, and particularly if a reverse-viewing tip is used, then movement errors and tip damage can occur. A custom guide tube can be inserted more easily and with minimal chance of damage. Then the borescope can have positive guidance throughout its path.
2. Access	Design borescope controls for correct direction of movement stereotypes (see section X.5.2.1).	1. Direction of movement stereotypes define preferred and error-free relationships between control movement and display movements. Controls should move in the same sense as the apparent viewpoint on the display, e.g. up gives up, left gives left. Suitable controls for pitch and yaw movement can be separate (two levers / slides) or integrated (joystick). 2. Where the tip shows a lateral or reversed view, the control will be more difficult so that more care must be taken to avoid tip damage or misdirection of borescope resulting in a wrong final location.
2. Access	Design borescope display system for correct orientation of FOV on display	1. Many borescope have a fixed relationship between vertical on the display and vertical at the borescope tip. Unless this is maintained, it is easy to lose situation awareness in borescope guidance along complex paths. Ensure that the borescope does have a fixed and obvious vertical.

2. Access	Design borescope direct viewing display to provide eye relief	1. High eye relief reduces the need to a rigidly fixed body posture for direct viewing. This in turn reduces the need for inspector movements required to provide relief from muscular fatigue. Such movements can result in incomplete search and hence missed defects
3. Engine Rotation	Design manual engine rotation equipment for easy of assembly and check. E.g. When engine rotation equipment is attached to engine, the parts should fit together in only one way E.g. Documentation should match assembly sequence with diagrams. E.g. Mating surfaces of parts can be color coded for simple, reliable assembly E.g. Errors in assembly should be simply detectable visually	1. Rotation equipment design that is not straightforward and easily checked will result eventually in assembly errors. Because parts are being interfaced with the engine, engine damage as well as rotation equipment damage can be the result.
3. Engine Rotation	Design manual engine rotation equipment for ease of use E.g. Direction of movement stereotypes E.g. Access from borescope working point	1. If direction of motion stereotypes are not met, then errors will occur in blade movement. These can cause wrong blade count, double inspection of blades, or even missed blades during inspection. 2. For a one-person inspection, rotating the engine should be possible from the borescope inspection point, or unnecessary movements / poor posture will result. This in turn causes inspector movements to provide relief from muscular fatigue. Such movements can result in incomplete search and hence missed defects
3. Engine Rotation	Design automated engine rotation equipment for easy of assembly and test.	1. Rotation equipment design that is not straightforward and easily checked will result eventually in assembly errors. Because parts are being interfaced with the engine, engine damage as well as rotation equipment damage can be the result.

3. Engine Rotation	Design automated engine rotation system displays and controls in accordance with Human – Computer Interaction (HCI) guidelines. The computer program and the physical interface are unlikely to be standard, e.g. Windows or Unix, but they must be designed to meet the expectations of an increasingly computer-literate workforce.	1. Any incompatibilities between the program used and common programs also used by inspectors will result in control or decision errors. These can arise from menu design, unusual naming conventions for functions or files, screen layout, and unusual key layout. Control and decision errors can result in equipment or engine damage, as well as unnoticed missing of blades during subsequent search.
3. Engine Rotation	Ensure that any reference points on the blades are well documented and easy to locate visually.	1. With both manual and automated systems, any inspection results must be communicated by blade number or location. Unless the starting point is well-defined, accurate blade counting is unlikely.
4. Search	Allow enough time for inspection of each blade	1. As shown in section 4.2.1, the time devoted to a search task determines the probability of detection of an indication. It is important for the inspector to allow enough time to complete FOV movement and eye scan on each blade. When the inspector finds an indication, additional time will be needed for subsequent decision processes. If the indication turns out to be acceptable under the standards, then the remainder of that blade must be searched just as diligently if missed indications are to be avoided.
4. Search	Ensure that blade rotation system is self-paced by the inspector	1. As noted in section 4.2.1, there is no best fixed time for blade inspection: the search process is inherently variable in its completion time. Any externally imposed fixed time per blade (e.g. by programming automated engine rotation) will result is some blades being under-searched while for others the inspector will have to wait for the rotation to take place. These effects have been shown to cause increased errors in other search and inspection tasks.

4. Search	Inspector should take short breaks from continuous borescope inspection every 20-30 minutes	1. Extended time-on-task in repetitive inspection tasks causes loss of vigilance (Section 4.2.1), which leads to reduced responding by the inspector. Indications are missed more frequently as time on task increases. A good practical time limit is 20-30 minutes. Time away from search need not be long, and can be spent on other non-visually-intensive tasks.
4. Search	Ensure that magnification of borescope system in inspection position is sufficient to detect limiting indications.	1. The effective magnification of the borescope inspection system depends upon the power of the optical elements and the distance between the tip and the surface being inspected. If the tip is too far from he surface, indications will not be detectable during search. Choose a system magnification and tip-to-surface distance that ensures detection. This may mean moving the tip closer to the surface, thus decreasing the FOV and increasing the time spent on each blade. The cost of time is trivial compared to the cost of missing a critical defect.
4. Search	Provide lighting that maximizes contrast between indication(s) and background.	1. The better the target / background contrast, the higher the probability of detection. Contrast is a function of the inherent brightness and color difference between target and background as well as the modeling effect produced by the lighting system. Lighting inside an engine mainly comes from the illumination provided by the borescope system, which is often directed along the borescope line of sight. This reduces any modeling effect, potentially reducing target background contrast, so that lighting must be carefully designed to enhance contrast in other ways.

4. Search	Provide lighting that does not give hot spot in field of view	1. Hot spots occur where the lighting is not even across the FOV. This may be inevitable as light source to surface distance changes, but should be minimized by good lighting design. If a hot spot occurs, it can cause the eye to reduce pupil diameter, which in turn limits the eye's ability to see shadow detail. This effect can cause missed indications.
4. Search	Use a consistent and systematic blade rotation direction	1. A good search strategy ensures complete coverage, preventing missed areas of inspection. 2. A consistent strategy will be better remembered from blade to blade and engine to engine, reducing memory errors.
4. Search	Use a consistent and systematic FOV scan path	1. A good search strategy ensures complete coverage, preventing missed areas of inspection. 2. A consistent strategy will be better remembered from blade to blade and engine to engine, reducing memory errors.
4. Search	Use a consistent and systematic eye scan around each FOV	1. A good search strategy ensures complete coverage, preventing missed areas of inspection. 2. A consistent strategy will be better remembered from blade to blade and engine to engine, reducing memory errors.
4. Search	Do not overlap eye scanning and FOV or blade movement.	1. It is tempting to save inspection time by continuing eye scans while the FOV or blade are being moved. There is no adverse effect if this time is used for re-checking areas already searched. But search performance decreases rapidly when the eyes or FOV or blade are in motion, leading to decreased probability of detection if the area is being searched for the first time, rather than being re-checked.

4. Search	Provide memory aids for the set of defects being searched for.	1. Search performance deteriorates as the number of different indication types searched for is increased. Inspectors need a simple visual reminder of the possible defect types. A single-page laminated sheet can provide a one-page visual summary of defect types, readily available to inspectors whenever they take a break from the borescope task.
4. Search	Provide training on the range of defects possible, their expected locations and expected probabilities to guide search.	1. If inspectors know what defects to look for, how often to expect each defect, and where defects are likely to be located, they will have increased probability of detection. 2. If inspector rely on these feed-forward data, they will miss defects of unexpected types, in unexpected locations, or unusual defects. Training and documentation should emphasize both the expected outcome of inspection and the potential existence of unusual conditions.
4. Search	When an indication is found, or the inspector is interrupted, ensure that inspector can return to exact point where search stopped.	1. Loss of situation awareness during blade rotation and after interruptions can lead to missed blades or missed areas on a blade. With visual inspection it is possible to mark the current point in the search, e.g. with a pen or attached marker. For borescope inspection this is not possible, but a means of locking the system when an interruption occurs will lead the inspector back to at least the current FOV.

5. Decision	Ensure that inspector's experience with all defect types is broad enough to recognize them when they do not exactly match the prototypes illustrated	1. In recognition of a defect, inspectors use their experience and any guidance from the documentation. Illustrations show typical versions of a defect that may be different in appearance from the indication seen on the engine. Inspectors' experience should allow them to generalize reliably to any valid example of that defect type. In this way, defects will be correctly recognized and classified so that the correct standards are used for a decision. 2. Training programs need to assist the inspector in gaining such wide-ranging examples of each defect type. They should use multiple, realistic indications of each defect type to ensure reliable recognition.
5. Decision	Design lighting system to assist in defect recognition E.g. provide alternate lighting systems for search and decision.	1. The ideal lighting for recognition and classification may not be the ideal for visual search. Search requires contrast between indication and background, while recognition requires emphasizing the unique visual features of each defect type.
5. Decision	Use consistent names for all defect types	1. Unless indications are correctly classified, the wrong standards can be applied. This can cause true defects not to be reported, and false alarms to disrupt operations unnecessarily.
5. Decision	Provide clear protocol for identifying landmarks used to judge defect size	1. If indication size is to be judged by reference to landmarks (not the most reliable system), then ensure that they are applied correctly. Providing a protocol in the documentation can assist the inspector in size estimation, reducing decision errors.

5. Decision	Ensure that landmarks can be used reliably for size estimation of indication E.g. Landmarks appear in same FOV as indication E.g. Landmark and indication are not separated causing parallax E.g. Indication and landmark have no angular foreshortening	1. Landmarks must appear in the same field of view to allow direct size comparison. Memory of size between FOV's is not reliable. 2. Parallax and angular foreshortening can change apparent size relationships between indication and landmark. There are protocols for dealing with both, but if the indication and the landmark are in the same plane such protocols, and any associated errors, are eliminated.
5. Decision	If graticule used to measure indication size, ensure that it can be used with minimal error E.g. Graticule and indication are not separated causing parallax E.g. Indication and graticule have no angular foreshortening	1. Parallax and angular foreshortening can change apparent size relationships between indication and graticule scale. There are protocols for dealing with both, but if the indication and the landmark are in the same plane such protocols, and any associated errors, are eliminated.
5. Decision	If a computer is used to measure indication size, ensure that errors are minimized E. g. Inspector understands principle and practice of measurement E. g. Good HCI practice is followed in designing the computer interface E. g. Direction of motion stereotypes are followed for control movements	1. Computer-assisted indication measurement uses a number of techniques such as range-finding. While a protocol may give adequate performance, any such rule-based behavior will be less robust to novel circumstances than the knowledge-based behavior that comes from understanding the principles of operation. Good understanding will reduce errors in such novel circumstances. 2. The human/computer interface design must support the inspector if errors of measurement are to be minimized. Use good HCI practices in menu design, function labeling, error recovery and mental model formation.

		3. Computer-mediated movement control is in as much need of following population direction-of-motion stereotypes as direct manipulation of mechanical controls. Good use of stereotypes will avoid damage to the engine or the borescope tip during measurement.
6. Respond	Provide a simple and reliable blade counting system	1. If the blade count is off, then any subsequent actions will be misplaced. People, inspector included, do not have sufficient reliability at maintaining counts in the face of other activities and interruptions. Machines, both mechanical and electronic, are potentially much more reliable in this.
6. Respond	Have a clear policy on what action to take when an indication does not meet defect reporting criteria,	1. Although the general wisdom among inspectors is to avoid writing down anything that does not have to be recorded, this can reduce overall inspection effectiveness by requiring subsequent searches to be successful. If ways can be found to record indication that do not yet meet defect criteria, then these can be tracked in subsequent inspections without having to search for them. Search unreliability is one of the major causes of missed defects in inspection.
6. Respond	Design a reporting system for defects that minimizes interruption of search process E.g. Use of electronic markers in computer assisted engine rotation, so that only a single button push is required and inspector can return to all marked locations after search is complete.	1. Interruptions of the search process give the possibility of memory failure, hence re-starting the search in the wrong place, resulting in incomplete coverage and missed defects. Recording of findings is an interruption of search, so that keeping recording as rapid and easy as possible minimizes the chance of poor coverage.
6. Respond	Reporting system should have sufficient space to describe defect type, location, severity and comments.	1. Inspectors have a tendency to be terse in their reporting, yet subsequent checking and repair depend on clear indications of defect type, location and severity. Consider the use of audio recording to amplify the information recorded on the workcard or NRR.

6. Respond	Provide a standard list of defect names and ensure that these names are used in defect reports.	2. Unless defect names are consistent, errors of severity judgment and even repair can arise. One technique is to use barcodes in the recording system for all defect types.
6. Respond	Have clear and enforced policy on when inspectors can make decisions alone and when others are needed to help the decision making.	1. Inspectors either make decisions on engine return to service / repair alone or with colleagues (engineers, managers). The requirements for choosing which decision mechanism is appropriate should be clearly communicated to the inspector and others. If not, there will be recriminations and loss of mutual trust when the decision made turned out to be incorrect.
6. Respond	If inspector makes decisions alone, consider the consequences if their decisions are later countermanded.	1. Inspectors, like all other people, need timely and correct feedback in their jobs if they are to make regular decisions effectively. They take feedback seriously, and will respond with changes in their own decision criteria. If a decision to change an engine is countermanded, inspectors will tend (despite instructions and management assurances) to be more certain before calling for changing engines in future. Conversely, a decision to sign-off an engine, if countermanded, may lead to tightened standards. If inspectors make the wrong decision, they need to be informed, but the effects of this feedback need to be considered.
6. Respond	Provide a means for rapid and effective sharing of information with other decision makers. E.g. Provide raw borescope images E.g. Provide two-way real time communications.	1. For the best possible shared decision making, there needs to be sharing of information. Modern video and computer based systems allow remote decision makers access to both the raw data, such as the borescope image, and two-way communications about the data and its implications. Two-way communications mean that remote decision makers can ask for new views or different lighting and receive the results rapidly. All of these enhancements can lead to more reliable

		decisions.
7. Return to storage	Design borescope system for ease of transport both in case and partially-assembled. E.g. Wheeled trolley or cart for transport of the system to inspection site after assembly and test	1. If the inspector has to disassemble for transport from the access site the workspace may not be ideal, so that damage, loss of small parts or errors may occur. If the borescope system can be transported assembled, this must not lead to alternate damage events.
7. Return to storage	Design access ports to reduce possibility of incorrect closure after inspection. E.g. fasteners that remain attached to the closure, tagging or red-flagging system, documentation procedure to show that port was opened and must be closed before return to service.	1. A common error in maintenance is failure to close after work is completed. Any interventions to reduce this possibility will reduce the error of failure to close. 2. Ensure that procedures for close-up are adhered to, despite interruptions and time pressures, to prevent loss of closure errors.
7. Return to storage	Design borescope system for reliable disassembly.	1. Disassembly may be performed under more time pressure than assembly, when for example the engine needs to be removed, or the aircraft is nearing it due time for departure. Design for rapid and reliable disassembly can reduce the chances of errors of leaving parts in or around the engine, or failure to disassemble completely.
7. Return to storage	Provide well-marked cleaning materials for cleaning optics and borescope surfaces.	1. Different materials, e.g. cloths or solvents, may be needed to cleaning optical surfaces and working surfaces of borescopes. Materials need to be easily available and clearly marked if unauthorized substitutions are to be avoided. Relying on manufacturers labels is not enough. Labels specific to borescope inspection can easily be printed and added, ensuring that the borescope is both cleaned and not damaged.

7. Return to storage	Design borescope storage system so that all parts have a place to fit, even parts added to system later.	1. Borescope systems are inherently modular, so that new components are often added during the life of the system. Ensure that the storage container can accommodate these additions, otherwise they will become separated and even lost. The cost of new storage containers is low compared to loss of expensive borescopes and components.
7. Return to storage	Have written standards for maximum borescope temperature for packing, and means to measure the temperature.	1. If the borescope parts that get hot during use cannot be packed hot, then provide simple tests so that the inspector can determine whether or not parts are ready to be packed. Direct judgment of temperature ("too hot for hand to rest on for more than 10 sec") are rapid, if they are sufficiently precise to prevent damage. Otherwise, tape a color temperature strip to each component that has a critical temperature requirement.
7. Return to storage	Design borescope storage system so that container can be closed without damage to the system	1. As components are added to a borescope system, the case can become ever more difficult to close. Even new systems in custom cases can have errant light guides or cords that can be damaged easily if the case is closed without care. If closed damage can arise, then it is only matter of time before it will arise in every day use.
7. Return to storage	Ensure safe storage for borescope system	1. The carrying system for the borescope may be heavy or awkward to store. If it weighs more than about 25 lb, then is should be stored at ground level, or at about 3 ft above the ground to prevent either injury to the inspector of dropping damage to the borescope.

7. Return to storage	Provide reliable sign-in / sign out procedure for borescope system.	1. The signing in and out of a borescope should be as painless as possible or it will be violated sooner or later. The inspector may be under time pressure to start the inspection, or another inspector may be waiting for the borescope. Under such challenges, the simplicity of the procedures will determine their reliability.