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DOT/FAA/AM-93/5

Office of Aviation Medicine
Washington, D.C. 20591

Human Factors in Aviation Maintenance – Phase Two Progress Report

Galaxy Scientific Corporation
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Office of Aviation Medicine
Federal Aviation Administration
Washington, DC 20591

April 1993

Final Report

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U.S. Department
of Transportation
**Federal Aviation
Administration**

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AM-93/5		

4. Title and Subtitle	5. Report Date
Human Factors in Aviation Maintenance – Phase Two Progress Report	April 1993
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Galaxy Scientific Corporation	
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Galaxy Scientific Corporation 2500 English Creek Avenue Suite 1100 Pleasantville, NJ 08323	
	11. Contract or Grant No.
12. Sponsoring Agency name and Address	13. Type of Report and Period Covered
Office of Aviation Medicine Federal Aviation Administration 800 Independence Avenue, S.W. Washington, DC 20591	Interim February 1991- February 1992
	14. Sponsoring Agency Code

15. Supplemental Notes

16. Abstract

In this second phase of research on Human Factors in Aviation Maintenance, the emphasis has evolved from problem definition to development of demonstrations and prototypes. These demonstrations include a computer-based training simulation for troubleshooting an airliner environmental control system and a software system to store and display documents. The report describes laboratory and workplace evaluations of workcards, lighting, experimental systems for inspection training, and the initial effects of communication training for maintenance workers. A chapter of the *Human Factors Guide for Aircraft Maintenance* is described.

17. Key Words	18. Distribution Statement
Human factors, maintenance, task analysis, computer-based instruction, simulation, hypermedia	Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	199	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Acknowledgments

The Aviation Maintenance Human Factors research team is directed by Dr. William T. Shepherd and Ms. Jean Watson of the Office of Aviation Medicine.

Galaxy Scientific Corporation is the prime contractor. Galaxy Scientific is technically responsible for Chapters One through Four. Chapter Five was prepared by the Department of Industrial Engineering at the University of Buffalo. BioTechnology, Inc. prepared Chapter Six and worked with Galaxy Scientific to conduct the Human Factors in Aircraft Maintenance workshops. Chapter Seven was prepared by Socio-Technical Systems, Inc. The total report was edited by Ms. Suzanne Morgan of Galaxy Scientific Corporation.

The pragmatic nature of this research is attributable to many FAA, airline, manufacturer, and vendor personnel who provided advice to the research team.

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List of Abbreviations

ABC ..... Artifact-Based Collaboration
AIMES .... Avionics Integrated Maintenance Expert System
AMMS .... Automated Maintenance Management System
AMT ..... Aviation Maintenance Technician
ATA ..... Air Transport Authority
ATC ...... Air Traffic Control
BITE ..... Built-In Test Equipment
CAA ..... Civil Aeronautics Authority
CBT ...... Computer-Based Training
CDI ...... Compact Disc-Interactive
CD-ROM .. Compact Disc-Read Only Memory
CMAQ .... Cockpit Management Attitudes Questionnaire
CRM ..... Crew Resource Management
CRM/TOQ . Crew Resource Management / Technical Operations Questionnaire
ECS ...... Environmental Control System
EFT ...... Embedded Figures Test
EICAS .... Engine Indicating Crew .... Alerting System
EPRI ..... Electric Power Research Institute
ETR ...... Estimated Time for Return
FAA ...... Federal Aviation Administration
FAR ..... Federal Aviation Regulation
FIM ...... Fault Isolation Manual
HFAMR ... Human Factors in Aviation Maintenance Research
HIS ...... Hypermedia Information System
HRA ..... Human Reliability Assessment
IDSS ..... Integrated Diagnostic Support System
IECMS .... In-flight Engine Condition Monitoring System
IES ...... Illuminating Engineering Society
ITS ...... Intelligent Tutoring System
JAA ...... Joint Airworthiness Authority
JTA ...... Job/Task Analysis
MANOVA . Multivariate Analysis of Variance
MAX ..... Maintenance Administrative Expert
MECAMS .. Mobile Enhanced Comprehensive Asset Management System
MFFT .... Matching Familiar Figures Test
MGT ..... Management
MMS ..... Maintenance Management System
NDI ...... Non-Destructive Inspection
NRR ..... Non-Routine Repair
ops .... Operations
OAM ..... Office of Aviation Medicine
PDS ...... Process Diagnosis System
PMAT .... Portable Maintenance Access Terminal
PRA ...... Probabilistic Risk Assessment
PRS ...... Plant Radiological Status
PSF ...... Performance Shaping Factor
RDS .... . Remote Diagnostic System
ROC ..... Receiver Operating Characteristics
SAOC .... Speed/Accuracy Operating Characteristics
SATO .... Speed/Accuracy Tradeoff
SDT ...... Signal Detection Theory
SPSS ..... Statistical Package for the Social Sciences
SRK ...... Skill-Rule-Knowledge
SRM ..... Structural Repair Manual
TOPAS .... Testing Operations Provisioning Administration System

Chapter One
Executive Summary

1.0 SUMMARY

This report details the second phase of the Office of Aviation Medicine (AAM) research program on Human Factors in Aviation Maintenance. This on-going research program enhances human performance in the aviation maintenance system to ensure continuing flight safety and operational efficiency. The research program, as reported in the Phase I report (Shepherd, et al., 1991) was initially planned to have 4 steps, with feedback mechanisms as shown in **Figure 1.1**. Phase I focused on preliminary investigation and problem definition of human performance in airline maintenance environments This Phase II report describes research that centers on the development of hardware and software prototypes with potential to enhance human performance in aircraft maintenance. (In this report the activities subsumed under "inspection" are considered to be part of "aircraft maintenance").

The research reported here has been conducted by a multi-disciplinary team of scientists and engineers from industry and academia. The research team has worked in very close cooperation with the international aviation industry, mostly with US airlines and aviation manufacturers.

This report includes seven chapters and can be considered as an edited volume in that each chapter is written to stand alone as the work of each research group.

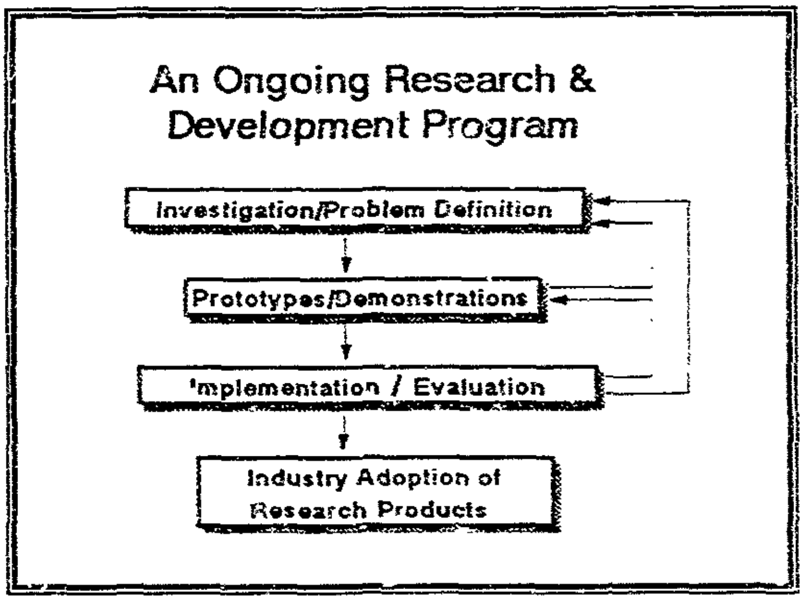

Figure 1.1 The Research Program

1.1 CONTINUING RATIONALE

Shepherd et al. (1991) and Shepherd & Johnson (1991), offered an extensive description of the rationale for the research program. These reports described the complexity of the total aviation maintenance system and the role of the human within the system. Increased maintenance workload, caused in part by an increased level of air carrier operations, is one reason to focus on improving aviation maintenance technician (AMT) performance. The challenge of providing continuing air worthiness of the aging fleet while developing knowledge and skills for maintaining new technology aircraft places a burden on airline maintenance organizations.

Phase I research investigated methods for enhancing human performance in aircraft maintenance. There are ample reasons for continuing these investigations. For example, operations will continue to increase. Airlines will fly more hours with the same fleet sizes. Thus, there will be less time for maintenance and greater stress on the fleet. Therefore, enhancing human performance in maintenance continues to be an important priority.

Resources are finite. Airlines, during 1991-92, have not been profitable. Since the Phase I report was published, major air carriers such as Pan Am and regional carriers such as Midway Airlines have gone out of business. Other carriers have suffered record financial losses and face uncertain futures. Airlines recognize the criticality of cost control in every aspect of their operation. However, cost control cannot jeopardize safety. This research program recognizes that the enhancement of human performance in maintenance is critical to the safety and efficiency of air carrier operations.

1.1.1 Integration of Human Factors Research Efforts

Research to enhance human performance in aircraft maintenance can focus on several dimensions, such as the human, the tools, the work place, work procedures, and management philosophies. The research must be useful to maintenance practitioners as well as to the human factors research community. This report, therefore, has practical as well as scientific value.

1.2 ADVANCED TECHNOLOGY TRAINING (Chapter Two)

Advanced technology training combines artificial intelligence technology with conventional computer-based training. The technology was described extensively in the Phase I report (Shepherd, et al., 1991) and elsewhere (Johnson & Norton, 1991 and Johnson & Norton, in press).

This chapter describes the continuing effort that has converted a Phase I training prototype to a fully operational advanced technology training system for the Boeing 767-300 environmental control system (ECS). The system is simulation-based in that it permits the user to access and operate all panels, controls, and built-in-test equipment of the ECS. **Figure 1.2** shows the human-computer interface for the ECS.

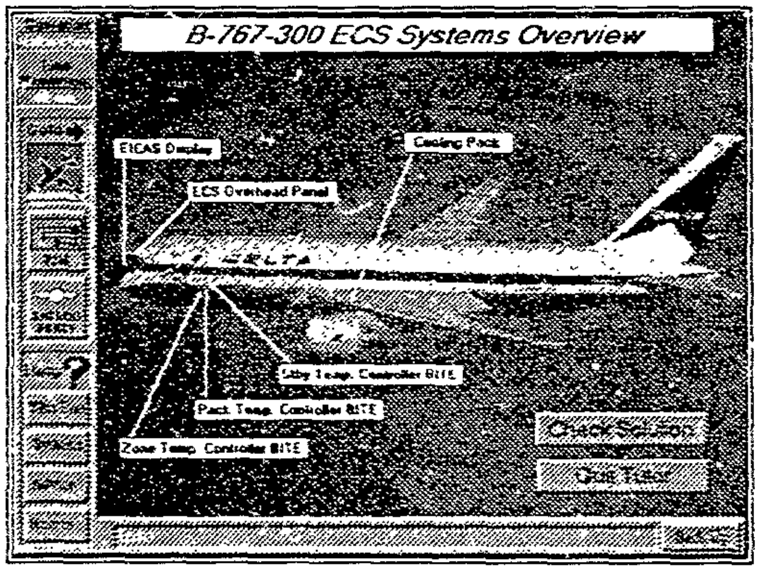

Figure 1.2 Environmental Control System Tutor

The ECS trainer is unique not only because of the simulation but also because of the robust software used for modeling student performance and providing feedback, explanation, and remediation. These modeling features are described in Chapter Two.

In addition to providing simulation, the ECS Tutor provides on-line access to the training manual for the ECS. The software makes it easy for the student to use the manual during training. This research is preparing for development of an integrated information system which can provide not only training but also real-time job aiding and maintenance documentation. Research related to the concept of on-line documentation is also described in Chapter Four.

The chapter also describes the process of formative evaluation that took place as the training systems underwent many iterations with software engineers and training professionals at Delta Air Lines and at Clayton State College. A substantive training effectiveness evaluation will be conducted at Delta.

Finally, as advanced technology training systems become more commonplace, it is likely that they can be used for AMT certification. Therefore, this chapter also reports on the research implications of the pending changes to Federal Aviation Regulation (FAR) Parts 65 and 147.

1.3 ADVANCED TECHNOLOGY MAINTENANCE JOB AIDS (Chapter Three)

This chapter addresses existing approaches to job aiding in maintenance, the drawbacks to such approaches, the prospects for using emerging technologies to develop maintenance job aiding systems, and the impact of emerging technologies on human performance. There were two major themes to the research: 1) many previous attempts at building maintenance job aids consisted of trying to replace human expertise with machine expertise; and, 2) problems with such approaches have led to a reconsideration of the skills and abilities of human operators and ways to capitalize on them.

Accordingly, the chapter calls for a 'cooperative system' approach to designing such systems; a cooperative system is one in which a human and a computer are actively involved in the problem solving process. The chapter presents a study which used this approach in developing a job aid. Some of the results of the study that are relevant to designing maintenance job aids and integrated information systems (Johnson & Norton, 1992 a & b) are also presented. Finally, a research and development plan for building a maintenance job aid for aircraft maintenance is discussed.

1.3.1 Human Performance Implications of Artificial Intelligence Approaches

The bulk of the job aiding systems encountered in a literature review used artificial intelligence and expert systems techniques. While artificial intelligence techniques can provide a computer with powerful problem solving abilities, job aiding systems which rely solely on such techniques often meet with limited operational success. One of the reasons for such limited success is that the computer is supposed to embody the knowledge and abilities of a human expert, when, in fact, such systems are necessarily incomplete. Because builders of expert systems cannot capture all of the human expert's knowledge about a task, such systems often draw erroneous conclusions. Therefore, the operator must have enough expertise to realize that the computer is wrong; the problem is that the operator will not develop such expertise unless he/she is actively involved in the problem solving process. However, these problems do not exclude artificial intelligence techniques from use in operational job aids. Rather, the question is one of emphasis: instead of using artificial intelligence techniques as the foundation for a job aid, they should be used in conjunction with other methods of performance aiding (e.g., representation aiding).

1.3.2 Human Performance with a Cooperative System

A research study (Layton, 1992) which investigated human performance with three forms of a cooperative system provided some interesting insights into how such systems affect human behavior. This system was designed to assist commercial airline pilots and dispatchers in enroute flight planning. (**Figure 1.3** depicts a portion of the system displays and controls.) This research has provided some interesting insights into the ways in which job aiding tools affect human performance.

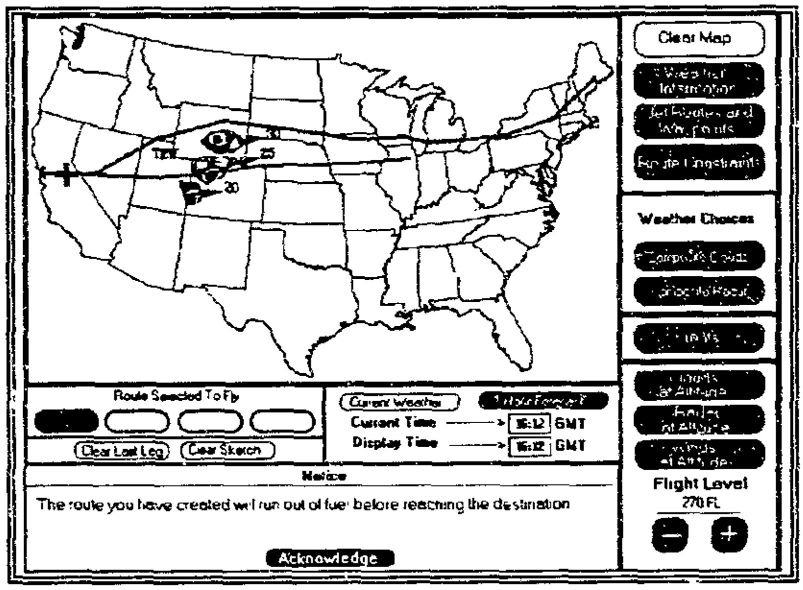

Figure 1.3 Enroute flight planning cooperative system

1.3.3 Research and Development Plan

A three-phase plan for developing an aviation safety inspector job aid using cooperative system techniques was developed. Initial interactions with the Flight Standards Service suggest that the job aid will assist inspectors in researching operator information and documenting inspection activities. The system will link inspection forms so that information that is entered into one form will automatically be entered into the other forms being used. The system will also provide the ability to search for information using on-line documentation. Such documentation may include the federal aviation regulations, advisory circulars, airworthiness directives, FAA policies, and operator-specific information. The system will have a cellular modem capability so that it can connect to the Flight Standards mainframe system and will likely use a CD ROM to store much of the on-line documentation.

1.4 DIGITAL DOCUMENTATION (Chapter Four)

Maintenance personnel are often overwhelmed with the amount of technical documentation necessary to accomplish a given task. The information comes from a variety of sources including company and manufacturer's manuals, and government documents, like advisory circulars or regulations. Currently most maintenance documentation exists as hard copy or microfiche. The task of keeping these databases current is very time consuming and expensive.

This research task, called the Hypermedia Information System, (HIS) shown in **Figure 1.4**, studies advanced technology software and hardware techniques for information storage and retrieval. The primary products of this research will be techniques for the development and use of large information sources on small portable computer systems.

The term "hypermedia" refers to a combination of text, graphics, animation, audio, and video to convey information. Such information bases are designed to be accessed easily, usually in a non-linear fashion. This hypermedia research will make it possible for a technician to access a manual for all media and information to complete a job. The research fosters co-development of integrated information systems (Johnson & Norton 1992, a & b) that provide training, job-aiding, and on-line documentation.

A by-product of the research is the development of a hypermedia information system for all technical publications from the Aviation Medicine Human Factors in Aviation Maintenance research program. Ultimately this digital source of information will be published on a CD-ROM (Compact Disc-Read Only Memory).

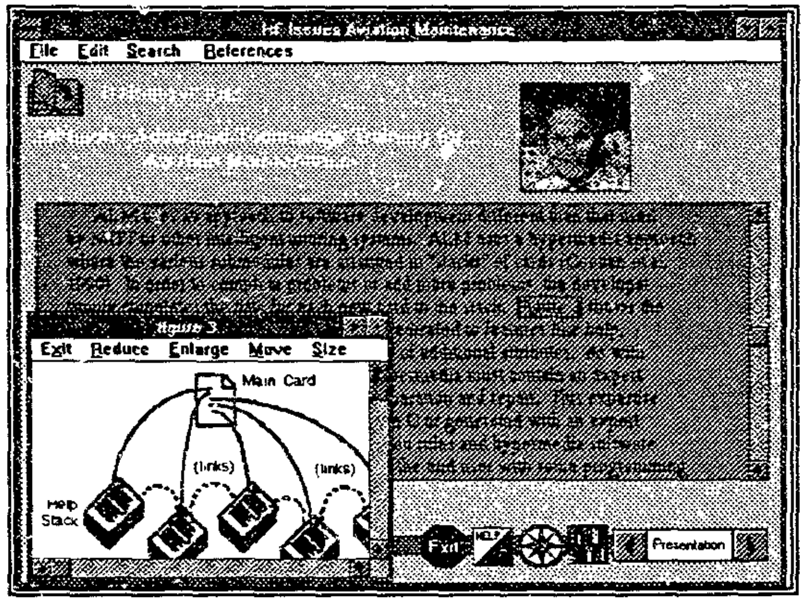

Figure 1.4 Hypermedia Information System

The proceedings of one of the first six conferences on aviation maintenance human factors has already been prepared for distribution as a digital document. The seventh conference will be the first time that the meeting proceedings will be distributed in digital format at the meeting. The software developed through this research effort has facilitated the timely publication of such digital documentation.

1.5 HUMAN RELIABILITY IN AIRCRAFT INSPECTION (Chapter Five)

The research related to improving human reliability in aircraft inspection built upon the solid task analytic foundation derived under Phase I. The chapter describes two studies: one study related to the re-design of workcards for inspection and the other a study of the lighting environment for inspection. Both studies offer practical human factors guidelines applicable to these topics. The chapter also describes a plan to consider human-computer interface issues applicable to computer-based maintenance aids.

This chapter also describes a series of laboratory experiments that evaluate the effects of time pressure on inspection and the improvement of training techniques for visual inspection. The chapter describes a study of the classification of human error in inspection. The classification is particularly valuable in its review of many scientific studies of human error. These studies form the basis for the team's development and presentation of system models of human error in inspection. These models provide the means to understand, predict, report and manage inspection errors.

Inspection is information processing. The chapter reports research on the design of information flow in the inspection environment. The research helps to determine what, when, and how to present information to the inspector. Experimental results are presented regarding optimal methods of information presentation in inspection tasks.

Chapter Five also describes a joint study of inspection practices in the UK and USA. The comparative study observed that management structures of maintenance and inspection are more closely intermeshed in the UK than in the US. Other differences and rationales are reported.

1.6 GUIDELINES FOR HUMAN FACTORS IN MAINTENANCE (Chapter Six)

Human Factors principles are often derived in laboratory studies of procedures, equipment, effects of time, temperature, lighting and other variables. Much of the information derived from these studies is reported for scientists, psychologists, and engineers for academic applications. This task is reviewing the human factors literature from a wide variety of parallel and similar areas to aircraft maintenance. All of the research results from the Aviation Medicine Aircraft Maintenance Human Factors program will be combined with this information base to produce a Human Factors Guide for Aircraft Maintenance. This guide promises to be useful to airline maintenance management system designers, FAA oversight personnel, and others as they strive to improve human performance in the maintenance system. Chapter Six offers an example chapter from the Human Factors Guide.

1.7 CREW RESOURCE MANAGEMENT FOR MAINTENANCE: EVALUATION OF A TRAINING PROGRAM (Chapter Seven)

Phase I (Shepherd, et al., 1991) reported on management-worker communications in the aviation maintenance environment. Phase II research has shifted focus to the effects of crew resource management (CRM) training in an airline maintenance environment. The research has concentrated on communication among maintenance crews. The researcher participated in the evaluation of the effectiveness of a particular airline's CRM training for maintenance personnel and in the post-training performance effects on maintenance managers and technicians.

The CRM course acceptance has been very high. In fact maintenance crews have demonstrated greater acceptance of the CRM principles than have flight crews. The research indicates that relevant attitudes about CRM improved immediately after training. Course attendees have reported that the CRM principles have caused them to be more actively involved in all maintenance decision making.

The CRM evaluation research is valuable in that it has created instruments and criteria to measure post-training maintenance performance. These measures will be helpful to assess the training and cost effectiveness of such human performance enhancement courses.

1.8 CONTINUED COMMUNICATION

The seven workshops that have been conducted to date under the Aviation Medicine research program have facilitated communication between researchers and industry. The immediate application of some of the research activities described above will allow the industry to increase reliability and lower costs. The Office of Aviation Medicine (AAM) intends to continue sponsorship of the workshops throughout the duration of the research program.

The participation and cooperation of the airline industry has been instrumental to the AAM research program. Air carriers, manufacturers, and schools have been extremely cooperative and helpful. This cooperation is gratefully acknowledged.

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Chapter Two
Advanced Technology Training for Aviation Maintenance

2.0 INTRODUCTION

As technology advances, the job of the aircraft maintenance technician (AMT) becomes increasingly difficult. The AMT must deal with new technology (digital components, composite materials, etc.) as well as an aging aircraft fleet. Concurrently, the AMT work force dwindles (Shepherd, et al., 1991). Therefore, maintenance training must respond to these challenges by increasing the effectiveness of the current work force. This chapter outlines how the Office of Aviation Medicine (AAM) uses advanced technology training to address these issues.

2.1 RESEARCH PHASES

The advanced technology training research began in January of 1990. This earlier phase of the work assessed the status of training technology for maintenance technicians. Based upon this assessment, the AAM built a prototype intelligent tutoring system (ITS) for the Environmental Control System (ECS) (Shepherd, et al., 1991). See (Polson and Richardson, 1988) for more information on ITS.

The current phase of the research expands this prototype to be an operational tutoring system for the ECS. In order to provide a measure of the effectiveness of the Tutor, this phase also designs an evaluation of the tutor. Finally, as advanced technology training systems become more commonplace, it is likely that they can be used for AMT certification. Therefore, this phase also reports on the research implications of the mechanic certification rules changes to Federal Aviation Regulation (FAR) Parts 65 and 147.

It is important that the Tutor be an effective training tool. Despite formative evaluation of the Tutor throughout the second phase, a formal evaluation will be conducted during the third phase. This will evaluate the Tutor for user acceptance, training effectiveness, and cost effectiveness. In addition, the third phase of the project will investigate the use of advanced technology training for psychomotor activities.

2.2 ADVANCED TECHNOLOGY TRAINING TUTOR

The Advanced Technology Training research developed an operational tutoring system for the ECS of the Boeing 767-300, as shown in **Figure 2.1**. This section describes the features of the Tutor, the design of the Tutor, and the lessons learned while developing the operational Tutor.

2.2.1 Description of the ECS Tutor

In the ECS Tutor, the student interacts with panels, controls, test equipment, manuals, and displays. These graphics are meant to simulate the "look and feel" of the real ECS components. A simulation of the ECS responds to the student's actions by updating the appropriate data values on the Engine Indicating Crew Alerting System (EICAS) display and the Overhead Panel, as shown in **Figure 2.2** and **Figure 2.3**, respectively.

The system operates in two distinct modes: Normal Operation and Malfunction. During normal operation, the ECS simulation lets the student see the proper operation of the system. During a malfunction, the ECS

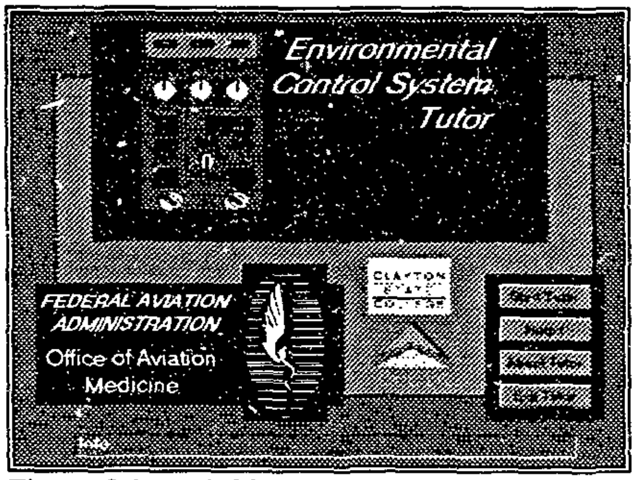

Figure 2.1 ECS Overview Screen

will exhibit the symptoms associated with the current malfunction. The student controls whether the system operates in normal mode or malfunction mode.

Regardless of the mode, the student's interaction with the system is similar. In both modes, the student has access to all of the tools needed to operate the ECS. The student interacts with control panels, information displays, built-in test equipment, component information, etc. However, malfunction mode is unique in several respects.

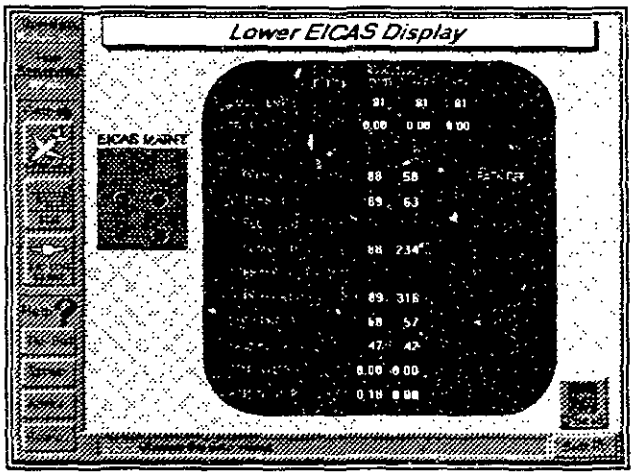

Figure 2.2 EICAS Display

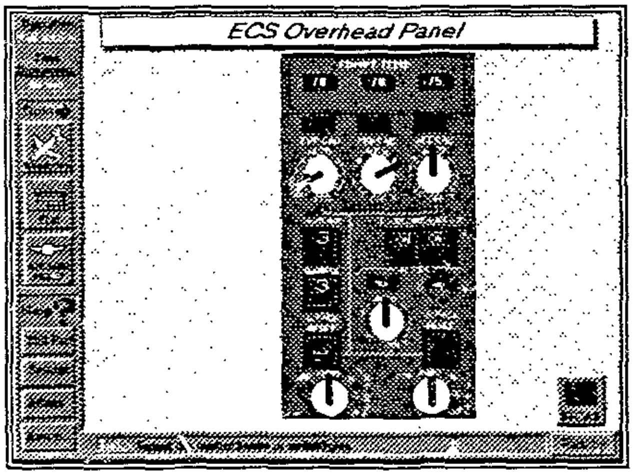

Figure 2.3 Overhead Panel

As a malfunction begins, the student sees a description of the problem, with the accompanying fault code. After seeing the description, the student may order replacement parts to be delivered to the plane. If the students does not order a part that they need, when they go to replace the part they must wait for the part to arrive. The Tutor simulates this wait by removing 15 minutes from the time that remains.

During a malfunction, the student has access to the Fault Isolation Manual (FIM), shown in **Figure 2.4**. The FIM is the fault tree that the AMT follows while troubleshooting. It outlines the tests and procedures that should be performed while diagnosing a failure. While troubleshooting from the FIM, the student must perform the tests in the order prescribed by the FIM.

Even though the FIM is the recommended method of troubleshooting, the ECS Tutor supports a more flexible way to troubleshoot. The Tutor provides a schematic of the cooling pack from which the student may troubleshoot. The student selects a component (in any order) from the schematic and then chooses whether to Inspect, Test, or Replace the component.

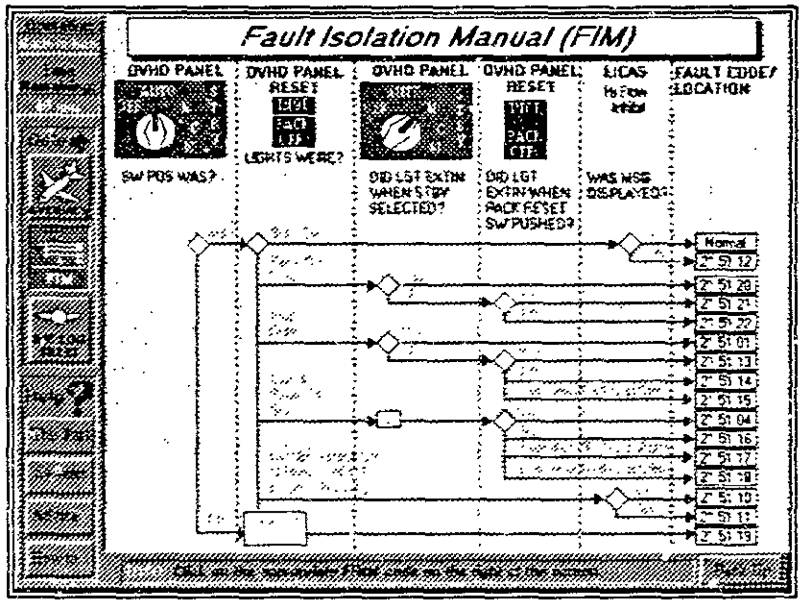

Figure 2.4 Fault Isolation Manual Display

In both the FIM and the cooling pack schematic, the Tutor records the student's actions. At any time, the student may ask for advice on how to troubleshoot the current malfunction. The tutor compares the student's actions with the actions of an expert. The Tutor suggests the appropriate next step to the student.

When the student replaces a faulty component, the Tutor updates the simulation to reflect proper operation. However, just as on the flight line, the student must verify that the replacement was effective. When the students are confident of success, they can have the Tutor check their solution.

2.2.2 Design of the ECS Tutor

During the design of the ECS Tutor, several separate design issues were addressed. These issues include interface design, instructional design, and simulation design. This section also describes the tools used to implement this design.

2.2.2.1 Interface Design

The design of the ECS Tutor ensures that the majority of relevant troubleshooting information is only one mouse click away from the primary display, shown in **Figure 2.5**. From this Overview display students may access the displays, controls, and components that they need to troubleshoot a malfunction.

Every troubleshooting screen in the Tutor adheres to a standard format, which consists of a grey border on the edge of the screen. The border contains functions that are useful for all troubleshooting screens. The left-hand border consists of three different areas - the Status area, the Navigation (or "Go To") area, and the Help Area. The bottom border contains a Message Area.

The top-most portion of the border is the Status area. This area notifies the student of the current operating mode - "Normal" or "Malfunction". During a Malfunction, this area also indicates the amount of time that remains for troubleshooting. The center portion of the border is the Navigation area. These three buttons allow the student to immediately go to one of three commonly used screens - the Overview Screen, the Fault Isolation Manual, or the Aircraft Log Sheet.

The lower portion of the border is the Help area. This area assists the student in four different ways:

- How to use the current screen
- Information about mechanical, electrical, pneumatic concepts
- How to navigate through the system
- What to do next - advice during troubleshooting

Finally, the border that runs along the bottom of the screen is the Message area. As the student moves the cursor across selectable regions, the Message area shows additional information about that selectable region. For example, the Overview display contains a button labeled "Check Solution". When the cursor enters this button, the Message area will read "Info: Click this button when you think you have solved the problem."

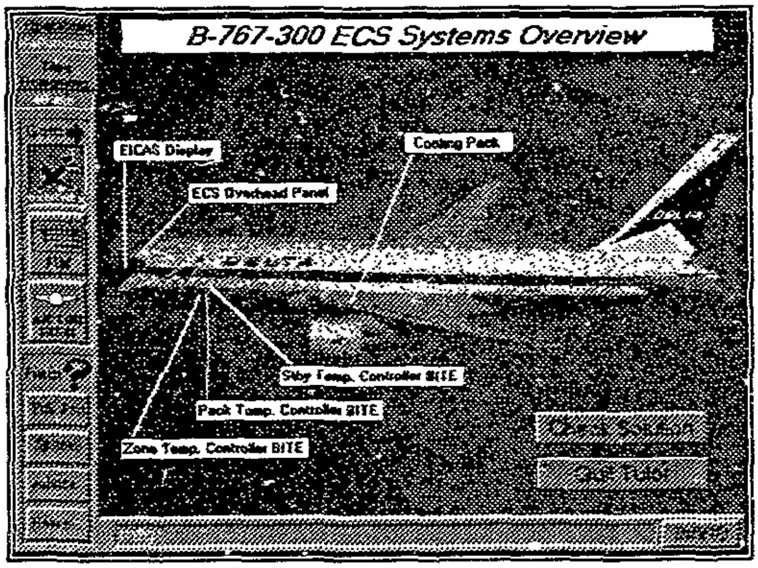

Figure 2.5 ECS Overview Display

2.2.2.2 Instructional Design

The instructional design of the ECS Tutor was improved in two ways. First, a lesson orientation provides more context for each of the malfunctions. Also, the "over-the-shoulder" advice helps students who are not making progress toward a solution. The following sections describe each in more detail.

2.2.2.2.1 Lesson Orientation

The instructional design for the ECS Tutor centers around the idea of a lesson, where a lesson is a logical collection of malfunctions. Since the Fault Isolation Manual (FIM) is driven by symptoms, the ECS Tutor assembles lessons according to the symptoms for each malfunction (e.g. PACK OFF/INOP lights) . As the Tutor presents each lesson, it provides the student with information similar to that shown in **Figure 2.6.**

The Background Information section describes the bases for the indicator lights. This section gives the common causes for the symptom. The Systems section gives a list of systems that relate to the indicator light. The user may choose one of these items to get more detailed information about a specific system. The Objects section provides a list of components that may be useful in solving the current malfunction. The user may choose one of these items to get more information about that component.

After completing a lesson, the Tutor reviews the student's performance from the previous lesson. If the Tutor detects any deficiencies, it will provide material that will help the student overcome the deficiencies.

2.2.2.2.2 Over-the-Shoulder Advice

Another addition to the ECS Tutor makes the advice that the student receives "smarter". In the Prototype, the student received advice only on demand. In the Phase Two Tutor, the system monitors the student's progress toward a solution and offers help to the student if the student does not appear to be making satisfactory progress. The student may choose to see this "over-the-shoulder" advice or ignore it.

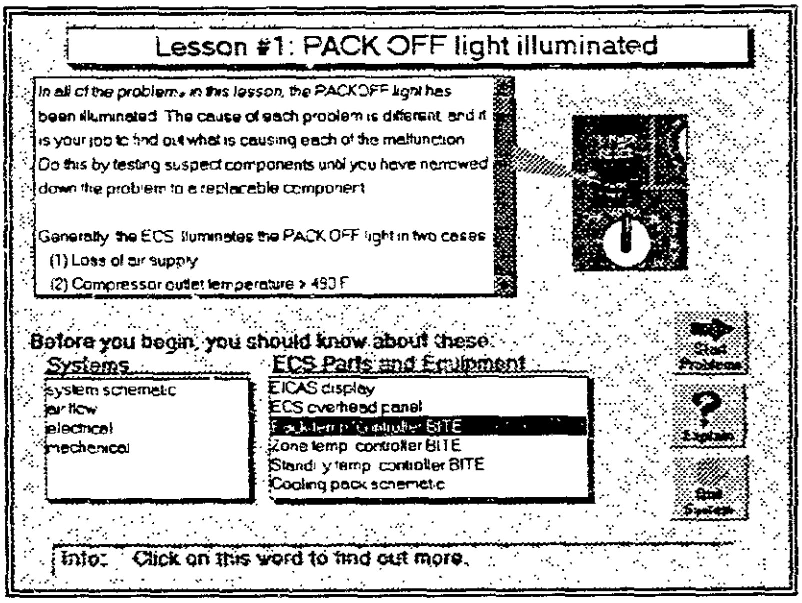

Figure 2.6 Lesson Overview Screen

2.2.2.3 Simulation Design

The simulation provides realistic responses to a student's actions. For example, the ECS adjusts output temperature of the cooling pack when the student alters the desired zone's temperature. The new data values appear on the Overhead Panel and the EICAS display. The way in which the simulation accomplishes this temperature change should be transparent to the student.

In Phase One, the prototype "simulation" consisted of a table of data values for certain predefined conditions. The data shown to the student was updated according to this table. This approach was adequate for the prototype because of the limited scope of the prototype. However, due to the expanded number of potential malfunctions, the Phase Two operational tutor needed a more robust simulation of the ECS environment.

Phase Two's simulation contains a model of individual components. The simulation acts upon each component's inputs to produce that component's outputs. This approach allows a malfunction to propagate through the system. For example, if a valve fails, it will affect its outputs (such as air flow). The component that is downstream from the valve will receive unsatisfactory air flow and produce an erroneous output. The next component will receive this as its input, and the fault will continue to propagate.

The simulation will act upon inputs to produce outputs, whether those inputs are good or bad. This design allows for the same simulation to be used in both normal operation as well as during malfunctions.

2.2.2.4 Development Tools

The ECS Tutor uses a variety of software tools. The Tutor uses different tools to create the interface, the simulation, and the graphics, as described below.

The <u>interface</u> was developed using Asymetrix *Toolbook*. *Toolbook* supports quick and easy interface development in the Microsoft Windows environment.

The Prototype simulation also used *Toolbook*. However, as the simulation matured, it migrated from *Toolbook* to the "C" programming language. "C" provided greater speed and more flexibility than *Toolbook*.

The graphics used in the operational tutor combine many different graphics creation techniques. Some graphics were custom-designed using graphics packages, while others were scanned from existing training documentation. The Tutor also used photographs taken with a digital camera and stored as graphics files. As the training display hardware advances, digital photographs will become crisper and more realistic.

2.2.3 Lessons Learned from the Development of the Tutor

As the Tutor progressed from the Prototype to the complete, operational system, formative evaluations highlighted several different areas that needed to be addressed: advice, instructional motivation, and student confidence with the interface. A description of each area follows.

2.2.3.1 Advice

When the Prototype gave advice to the student, the advice told the student what procedure to perform next. It followed the FIM exactly. However, it did not provide enough motivation as to why to perform a certain procedure. The current tutor enhances the advice to help answer the question "Why perform this procedure instead of a different procedure ?" With this extra information, the student learns the logic behind the FIM, instead of blindly following procedures.

2.2.3.2 Instructional Motivation

The Prototype emphasized troubleshooting, but lacked instructional focus. During this phase, the Tutor adds more emphasis to instructional issues. As described above in **Section 2.2.2.2**, each lesson contains background information, system information, component information. Much of this information was available for the Prototype, but the student had to search for it. The Tutor now presents the information to the student in a more directed manner. This method reinforces to the student which pieces of information are important under different circumstances.

2.2.3.3 Student Confidence with the Interface

As students used the system, especially for the first time, they were hesitant to click on buttons with the mouse because they weren't sure what would happen. To allay some their indecision, the Tutor now contains the Message area. Anytime the cursor enters a selectable region, a short descriptive message appears in the Message area that describes the function of the selectable region. As training developers, we must be mindful to provide as much reassurance to the student as possible.

2.3 EVALUATION PLAN

If Advanced Technology Training is to become commonplace, it must be accepted by the user population. Also, if it is acceptable to the AMT's it must also prove to be an effective training tool. This section outlines a plan to evaluate the ECS Tutor for user acceptance, cost effectiveness, training effectiveness.

2.3.1 User Acceptance Testing

User acceptance testing will be conducted in the following different user populations:

- Delta Air Lines instructors
- Delta Air Lines students
- Clayton State College Airframe & Powerplant (A&P) students

This testing will use questionnaires and interviews to gather data. The ECS Tutor will be modified as necessary to accommodate problems areas that the test identifies.

2.3.2 Training Effectiveness Study

The training effectiveness study will test the following hypothesis:

> A combination of conventional, classroom teaching and the ECS tutor is more effective than conventional, classroom teaching.

This experiment uses both a control group and an experimental group (from the Delta Air Lines student population). Both groups will receive the normal 4 to 5 hour ECS classroom training segment. The control group will receive an additional classroom session on ECS troubleshooting. The experimental group will receive the lesson on ECS troubleshooting via the ECS Tutor. After the troubleshooting session, each group will take an exit exam which will measure their ECS proficiency. The scores on the exit exam will be used as the basis of comparison. **Figure 2.7** summarizes the experiment.

2.3.3 Cost Effectiveness Study

A cost effectiveness study will measure the effectiveness of the ECS Tutor along several dimensions. Among these are both development costs and delivery costs.

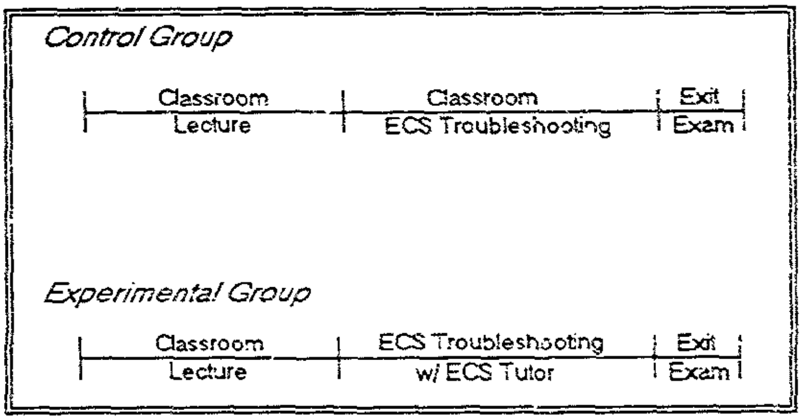

Figure 2.7 Evaluation Plan

2.4 PART 147 & PART 65 RULE CHANGES AND HUMAN FACTORS IMPLICATIONS

2.4.1 Part 147 - Aviation Maintenance Schools

From 1989 through 1991 there has been a rule change in the making for FAR Part 147 - Aviation Maintenance Technician Schools. After extensive public hearings, the rule changes are completed and will be published in 1992. The changes in the approved curricula were designed to be more responsive to the needs of today's aviation industry. For example, skill and knowledge requirements for gas turbine engines have been increased while requirements related to fabric covered aircraft have been lessened.

A second significant change in FAA philosophy regards educational media. The new rule permits the substitution of advanced technology training systems (like computer-based training, CBT) for classroom and laboratory instruction. This change in the rule is likely to foster an explosion of CBT for aviation maintenance training. The FAA should monitor the quality of such CBT to ensure that content and the delivery methods are appropriately applied.

The changes to Part 147 are not significant in number. However, the recognition of the potential for computer-based training is a very positive step in helping the schools to train for modern aircraft systems.

2.4.2 Part 65 Certification: Airmen Other than Flight Crewmembers

The public hearings and Aviation Rulemaking Advisory Committees are currently working with the FAA to consider changes to Part 65. The changes that are being considered address such issues as experience requirements, training and proficiency requirements, and issues related to issuances of certification of personnel for repair facilities outside of the United States.

2.4.3 Job/Task Analysis

All who have been involved in Part 147 and Part 65 agree that there is a dire need for a new Job/Task Analysis (JTA) for the Aviation Maintenance Occupation. Such a JTA has not been done since 1969. The activity related to this rule change is prompting the appropriate funding for the AMT JTA.

2.5 SUMMARY

This research shows that Advanced Technology Training can be applied to the Aviation Maintenance community. This particular system concentrated on the ECS because of the generic nature of the ECS system (i.e., ECS principles are similar from aircraft to aircraft). However, this same approach is applicable in all other aviation maintenance areas. Up to this point, the Advanced Technology Training has concentrated on the mental aspects of training (logical troubleshooting). As this work continues, the research will attempt to combine the logical troubleshooting techniques with the psychomotor skills required to maintain the aircraft.

2.6 ACKNOWLEDGEMENTS

This research would not be possible without the cooperation of the aviation industry. Delta Air Lines and Clayton State College have enthusiastically offered their time and ideas to make the final product a success. The authors thank Rick Spavelko, Gary Drake, and Bruce Gindlesperger of Delta Air Lines and Jack Moore of Clayton State College for their cooperation and support.

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Chapter Three
Emerging Technologies for Maintenance Job Aids

3.0 INTRODUCTION

Maintenance is fast becoming one of the most frequent application areas for job aiding. Maintenance job aids range from automatic preventive maintenance schedulers, to systems that monitor equipment status and recommend maintenance based on trends in equipment behavior, to systems that aid in fault diagnosis and repair. Application domains range from production equipment (e.g., clutch assembly machines), to process equipment (e.g., turbine generators), to high technology specialized equipment (e.g., fighter aircraft). There is a range of methodologies employed, as well, including algorithmic approaches for the preventive maintenance schedulers to expert systems for fault diagnosis and repair. The technologies employed encompass a range from VAX mini computers to desktop microcomputers linked to video disks. This chapter addresses extant approaches to job aiding in maintenance, the prospects for using emerging technologies for such systems, and the impact of emerging technologies on human performance, particularly in aviation maintenance applications. This section also calls for a new design philosophy in building job aids. A study which used this philosophy and compared three different levels of aiding on a task is also discussed. Some of the results of the study and their applicability to maintenance job aids are presented.

This chapter is similar to a previous review of job aids (see Chapter 5 of Shepherd, et al., 1991), in that many of the systems encountered were concerned with technological developments, rather than performance achievements. Whereas that previous work identified some of the difficulties with introducing advanced technology job aids into an operational environment, this discussion addresses some of the fundamental problems with past approaches to job aids and presents a design philosophy which capitalizes on the skills and abilities of the operator in order to produce a combined human-computer system that attains increased performance.

3.1 SURVEY OF MAINTENANCE JOB AIDS

A survey of academic, industrial, and popular literature revealed a wide variety of approaches to building maintenance job aids (see Appendix). These differing approaches include both hardware and methodological considerations, ranging from stand-alone, automatic scheduling systems to portable, interactive troubleshooting systems. The hardware aspects are addressed first, followed by a discussion of some of the different methods used.

3.1.1 Hardware Employed

The following systems exemplify different hardware approaches used for maintenance job aids. These systems are presented in order of increasing sophistication.

Folley and Hritz (1987) describe an expert system that assists in troubleshooting clutch assembly machines on a production line. Fault lamps above the machine stations indicate which stations are malfunctioning. A technician takes a maintenance cart to the malfunctioning station. The cart carries a two-button control and a monitor and the technician connects these to a junction box at the station. This junction box links the monitor and control to a remote computer and video disk player. The technician uses the control to move through a menu system to specify the faulty station. The computer then specifies the tests to be performed, along with graphic displays of the equipment, and the technician enters the results of the tests. In this way, the computer guides the technician through troubleshooting and repairing the malfunctioning equipment.

A similar system developed by the Electric Power Research Institute (EPRI) also uses a video disk player for displaying maintenance information and procedures for gas-turbine power plants. This system uses a dual processor computer system. One processor manages an expert system, while another controls a video disk player. The EPRI system also uses voice recognition and synthesis for input and output, respectively.

General Motors developed an expert system to assist in vibration analysis of production machinery (cf. "GM unveils 'Charley'..."). Named after a retiring technician with many years of experience, 'Charley' was intended to help less experienced technicians locate parts that needed repair in production equipment with rotating components. Charley stores a signature file for each properly operating piece of equipment; technicians record the vibration signature of a problematic piece of equipment with a special data recorder and then connect the recorder to a Sun workstation. Charley compares the newly recorded signature with the database and begins diagnosing the problem. Charley guides interactions, may ask the technician for additional information, and explains its troubleshooting strategies. Charley can also be used as a consultant and allow a technician to explore 'what if' questions. Finally, Charley is also used to train new technicians. The emphasis of the system is on preventive maintenance, rather than repair of failed equipment.

McDonnell Douglas developed the 'Avionics Integrated Maintenance Expert System' (AIMES) for use on F/A-18 fighter aircraft (cf. "McDonnell Douglas flight tests..."). AIMES is a self-contained on-board box which contains a microprocessor and records flight avionics data on a cassette for later analysis. Production rules detect and isolate avionic failures at the electronic card level. AIMES generates queries and tests based on data and concludes whether a fault is present. If there is a fault, AIMES supplies the fault data, the card name, and the reasoning that led to the fault isolation conclusion.

The telecommunications industry is a large user of advanced technology maintenance aids, particularly in network switch and cable analysis (cf. "Expert system from AT&T..."). The 'Automated Cable Expertise' system runs automatically each night to detect trouble spots in cables. Upon identifying a problem, it reports the repair history of the area and suggests corrective action.

3.1.2 Methods Employed

The following systems exemplify the range of methodologies employed in maintenance job aids. These systems are presented in order of increasing sophistication.

Berthouex, Lai, and Darjatmoko (1989) discuss a system for determining daily operations for a wastewater treatment plant. This system is billed as an 'expert system', although it was developed using standard spreadsheet (Lotus 1-2-3) and database software (d-Base III), rather than one of the many production system shells. (Expert systems have historically been written using production rules (if-then clauses) in one of many languages specifically designed for that purpose, for example OPS5 or LISP. Popularization of the term 'expert system' has led to decreasing precision of use of it.)

'Process Diagnosis System' (PDS) was developed by the Westinghouse Research and Development Center and Carnegie Mellon University for maintenance of steam generators. PDS is a condition monitoring system for preventive maintenance in order to alleviate both breakdown maintenance and unnecessary maintenance. The system is designed to detect deterioration early and predict the duration of safe operation. PDS also recommends specific preventive maintenance for regularly scheduled down times.

Vanpelt and Ashe (1989) describe the 'Plant Radiological Status' (PRS) system for nuclear power plants. The PRS system presents a three dimensional model of the power station and equipment so that maintenance teams may plan maintenance tasks in advance. The PRS system facilitates access to and interpretation of radiological conditions by identifying hotspots and contaminated areas, as well as identifying obstructions and available workspace. The goals of the PRS system are to reduce maintenance time and radiation exposure.

Several systems for supporting operations and maintenance were reviewed by Bretz (1990). One of the systems was developed by Chubu Electric Power Company and Mitsubishi Heavy Industries, Ltd. in Japan. This comprehensive expert system assists in power plant boiler failure analysis and maintenance planning. The failure diagnosis reports the most probable causes for failure, guidelines for inspection, the items to be investigated, repair methods, and suggested preventive maintenance. The maintenance planning subsystem automatically prepares daily repair schedules, a work estimation plan, and work specifications.

The distinction is sometimes made between 'deep' and 'shallow' knowledge in expert systems. The knowledge typically represented in production systems is considered shallow knowledge because it contains only antecedent-consequent relationships without any information as to why one thing follows from the other. Deep knowledge, on the other hand, captures the functional and causal relationships between the components of the object or system being model. Atwood, Brooks, and Radlinski (1986) call 'causal models,' which use components functions as the basis for their reasoning, the next generation of expert systems. Clancy (1987) describes a system for diagnosing switch mode power supplies which uses a model of the component level of the electronics for its diagnosis. Whereas one can test for signal presence at the module level of the electronics, the component level is concerned with the way in which a signal changes as it passes through the components. Finally, a system developed for Britain's Central Electricity Governing Board uses a model of the cause and effect relationships inherent in turbine generators for diagnosis and maintenance (see "Expert system probes..."). This expert system monitors and analyzes the vibration patterns of the equipment in its analysis.

The most sophisticated system encountered in the survey is the 'Testing Operations Provisioning Administration System' (TOPAS) developed by AT&T. Clancy (1987) describes TOPAS as a real-time, distributed, multi-tasking expert system for switched circuit maintenance. TOPAS performs trouble analysis, localization, and referral of network troubles. Clancy claims that TOPAS "does network maintenance without human intervention or consultation" (p. 103). If this is true, then TOPAS is not really a job aid, because it performs the job itself.

3.2 THE USE OF ARTIFICIAL INTELLIGENCE IN JOB AIDS

The methods and design philosophies used in building job performance aids vary with the designer(s). While some of the systems surveyed placed the technician in charge of the troubleshooting and maintenance, the majority of the approaches relied on artificial intelligence. The following describes various artificial intelligence approaches and their impact on human performance.

3.2.1 Expert Systems

Expert systems typically have three components: a rule base, a knowledge base, and an inference engine. The rule base contains the problem solving strategies of an expert in the domain for which the system was developed. The rule base is made up of production rules (if-then clauses). The knowledge base contains the history and the current data of the object under consideration (this object may be anything from an aircraft engine to a medical patient). The inference engine is responsible for determining what rules get activated and when the system has solved the problem or is at an impasse. Expert systems are typically written in a programming language specifically designed for such use, such as LISP or OPS5.

Typically, the human expert is not the person who builds the expert system, rather he/she interacts with a 'knowledge engineer' who is responsible for extracting the expert's expertise. One difficulty with expert systems has frequently been referred to as the 'knowledge engineering bottleneck'; it can be difficult to access and program the knowledge of the expert into the expert system. For instance, the expert may not even be aware of what he/she does to solve a particular problem. Furthermore, it is impossible to guarantee that the rule base contains all of the knowledge of the expert.

3.2.2 Knowledge-Based Systems

Knowledge-based systems place less emphasis on production rules as a way of representing knowledge, and more emphasis on using a large database of information. This database may consist of information such as vibration patterns of equipment, as in Charley discussed above, or it may consist of typical hardware configurations, for instance. The point of knowledge-based systems is that they rely on a large body of readily-available information for the bulk of their processing.

3.2.3 Model-Based Systems

Model-based systems are an attempt to produce more robust problem solving systems by relying on 'deep' representations of a domain. The models depend on a description of the functionality and relationships of the components that make up the domain. Model-based systems are concerned with not only how a component functions, but why it functions that way. Developers of model-based systems believe that these systems will be able to solve novel problems, whereas expert systems can only solve problems with which an expert is familiar.

3.3 HUMAN PERFORMANCE IMPLICATIONS OF ARTIFICIAL INTELLIGENCE APPROACHES

The human performance implications of using an artificial intelligence-based problem solver are many. All of these systems revolve around the 'machine expert' paradigm, in which the computer controls all problem-solving activities. One problem with the machine expert paradigm is that because computers do not have access to the 'world', they must rely on a person to supply all relevant data about the world. Thus, the machine expert directs tests to be run and requests the results of those tests. Based on these data, the computer requests more information or reaches a conclusion, and that conclusion may be erroneous. In the words of one cognitive engineering researcher, the human is reduced to a "data gatherer and solution filter" for the machine.

One problem associated with this lack of environmental access is that the person may have knowledge that the computer does not. Since the computer directs the problem solving, it may never ask for information that may be critical to successfully solving the problem. Furthermore, there is usually no provision for the operator to volunteer such information. The person may even have different goals than the machine or may not know what the machine's goals are when it is attempting to solve a particular problem. Additional difficulties arise when the human operator accidentally enters the wrong data or when he/she misinterprets a request from the computer. Suchman (1987) discusses the problems of human machine communication at length.

Probably the biggest problem associated with expert systems is that they are brittle. As mentioned above, expert systems can only solve problems that the human expert has seen or remembers to discuss with the knowledge engineer. People (either experts or expert system designers) simply cannot anticipate all of the environmental variability encountered in the world. This leads to the tragic irony of such systems: expert systems are most needed when a problem is difficult, and that is precisely when the expert systems fail. The upshot is that the human operator is left to solve a difficult problem without the benefit of having developed expertise through solving other problems, because those were handled by the expert system!

All of these problems and more arose in a study by Roth, Bennett, and Woods (1987), in which the authors observed technicians using an expert system to troubleshoot an electro-mechanical device. One of the major findings of the study was that only those technicians who were actively involved in the problem solving process and performed activities beyond those requested by the expert system were able to complete the tasks. The technicians who passively performed only those activities requested by the expert system were unable to reach solutions on any but the most trivial tasks.

The above should not be interpreted as a condemnation of all uses of artificial intelligence techniques, however. Indeed, artificial intelligence has greatly advanced our understanding of the capabilities, as well as the limitations, of computational tools. Prudent use of such techniques can greatly enhance the ability of a cognitive engineer to provide operators with powerful problem solving tools.

3.4 EMERGING TECHNOLOGIES

Continued advances in hardware and software technologies will further increase the cognitive engineer's design repertoire. Indeed, there are many emerging technologies that could be profitably used in maintenance job aids. Advances in computer hardware, display hardware, and object modeling all have great potential to improve job aiding capabilities. Each of these is discussed below.

3.4.1 Advances in Computer Hardware

As computer hardware has become smaller and more powerful, there has been a progression to smaller, more portable job aids. Whereas earlier job aids ran on minicomputers, then workstations and personal computers, newer job aids are being designed using laptops. There is no reason to believe that the laptop computer is the smallest, lightest computer that will be developed, however. Indeed, the NCR NotePad has recently been introduced. This computer is pen-based; that is, all input is performed via a pen stylus, rather than through a keyboard or mouse. The NotePad is light enough that it can be easily held in one hand, which greatly facilitates taking it to the maintenance site. The NotePad is relatively quick, it has reasonably large storage capacity, and it has limited handwriting recognition abilities.

An aviation industry working group is currently defining the standards for a 'Portable Maintenance Access Terminal' (PMAT) for use in commercial aviation. As currently conceived, the PMAT would connect to the 'Onboard Maintenance Systems' of current aircraft and would be used for troubleshooting. Because the emphasis is on portability, it is likely that something similar to the NotePad or a standard laptop computer will be specified.

Another emerging hardware technology is the use of 'built-in test equipment' (BITE) in engineered systems, no doubt due in part to the widespread use of microprocessors. BITE likely does not eliminate the maintenance technician, however, because it may be difficult to implement such equipment in mechanical systems or in very complex systems. Indeed, BITE may introduce additional problems for maintenance people because there is a lack of standardization on how BITE should operate; thus, there may be confusion when dealing with similar, but different, BITE. Further complications may arise due to issues of granularity in BITE; BITE may simply indicate that a piece of equipment is not functioning properly, without indicating the specific nature of the malfunction or without indicating which component must be repaired or replaced. Another issue is: What happens when the BITE malfunctions?

3.4.2 Advances in Display Hardware

One of the surveyed systems used a personal computer to control a slide projector for displaying maintenance graphics. Several of the systems used a computer-controlled video disk for such displays. With the advent of digital cameras and compact disc-interactive (CDI) technology, systems with higher fidelity and portability can be achieved. Appropriately designed CDI systems could store many views of the object(s) being serviced, as well as maintenance procedures and information. Indeed, what graphics were displayed would depend on the fault manifestations. Furthermore, well-designed CDI systems would allow the technician to troubleshoot by hypothesizing a failed component and watching how a simulation of the system performed. Similarly, the technician could replace a component in the simulation and see the results. In this manner, the technician could develop expertise more quickly than learning on-the-job (because the technician would have control over what aspects he was learning, rather than relying on whatever malfunction happened to occur).

3.4.3 Advances in Object Modeling

An extension of the three-dimensional model discussed above is virtual reality. Virtual reality has received a lot of attention as a result of the Defense Advanced Research Project Agency's development of the 'Pilot's Associate Program' and consists of replacing an operator's view of the 'real world' with a simulated view of that world. Thus, real world objects are replaced with simulations of those objects. One possible use of virtual reality would be to allow the maintenance technician to 'stand' inside a device, such as an engine, and watch how it functions, both normally and with failed components. The technician could also see the effects of replacing components, similar to the CDI system above, but with the benefit of observing the effects more directly. As with CDI, the technician need not replace the actual system *components, but may replace components in the simulation of that system. The uses of virtual reality* appear to be limited only by the job aid designer's imagination.

3.5 HUMAN PERFORMANCE IMPLICATIONS OF EMERGING TECHNOLOGIES

While many past approaches to job performance aids sought to replace human expertise with machine expertise, there is a growing appreciation for the importance of human skill. The machine expert paradigm sought to overcome human information processing 'limitations' with a computer prosthesis. However, even computers are limited resource processors. A more enlightened approach is to view computers as tools to amplify human capabilities, not overcome limitations. In this sense, computers can be seen to be like other tools, such as telescopes or automobiles: they are instruments which provide additional resources for achieving our needs and desires. Woods and Roth (1988) discussed the above issues and addressed many more cognitive engineering issues inherent to developing systems that have powerful computational abilities.

Technology is not a panacea; each new technology brings with it significant drawbacks, as well as benefits. The challenge to designers is to use emerging technologies to build cooperative systems, in which both the human and the computer are actively involved in the problem solving process. Humans can no longer be regarded as passive 'users' of technology, but as competent domain practitioners with knowledge and abilities which are difficult to replace. The following section discusses a study which addressed just such issues.

3.6 A STUDY OF HUMAN PERFORMANCE WITH A COOPERATIVE SYSTEM

A study which addressed some of the human performance issues discussed above was carried out as part of the author's graduate program (Layton, 1992). This study compared three different levels of computer support on the basis of their effects on human performance. Although the domain for which the systems were developed was enroute flight planning, the general principles behind the alternative designs can be applied to developing aviation maintenance aids, as well. The following is a discussion of enroute flight planning, the design concepts behind the three levels of computer support, the method employed for comparing the various systems, the general outcomes of the study, and the implications of those outcomes for developing aircraft maintenance job aids.

3.6.1 Enroute Flight Planning

Enroute flight planning consists of modifying the flight plan of an airborne aircraft in response to changes in the capabilities of the aircraft, to crew or passenger emergencies, to changes in weather conditions, and/or to problems at the destination airport. The study focused on flight plan adaptation in response to changes in weather conditions. From a pilot's perspective, the components important to enroute flight planning include the airplane, possible flight routes, weather conditions, and airline company dispatchers. The pilot is concerned with getting from a given origin to a given destination on time, with a minimum of fuel consumed, while maintaining flight safety. He/she must consider what routes to take (these routes consist of waypoints, or navigational points, and jet routes, the so-called "highways in the sky"), what altitudes to fly, what weather to avoid, and the ever-changing capabilities of the aircraft (eg. the weight of the plane decreases with fuel consumption; the lighter the plane, the higher it can fly, within limits).

The initial flight plan is rarely followed exactly, due to unforeseen events occurring while enroute. Indeed, minor changes in flight plans are frequently made and major changes are fairly common. These amendments to the original result from the dynamic, unpredictable nature of the 'world' in which the plans are carried out. Weather patterns do not always develop as predicted, resulting in unexpected areas of turbulence, less favorable winds, or storms that must be avoided. Air traffic congestion may delay take-off or restrict the plane to lower-than-planned altitudes. Airport or runway closures can cause major disruptions, not just for one aircraft, but for everyone planning on landing at that airport. Mechanical failures, medical emergencies, or other critical problems may delay take-off or may force an airborne plane to divert to a nearby airport.

Furthermore, there are several constraints on the flight plans that can be developed. Planes must maintain a certain separation distance between each other and between thunderstorm cells, as specified in the Federal Air Regulations. Planes must fly along the jet routes. They are also limited to certain altitudes. Over the continental United States, for example, 33,000 feet is an 'eastbound only' altitude. There are also physical limitations: the plane can't fly if it is out of fuel and it can't land at an airport with runways that are too short. Some of these constraints are actually 'soft', in that they may be violated in some circumstances. If, for instance, there is no eastbound traffic, Air Traffic Control (ATC) may allow a plane to fly west at an 'eastbound only' altitude. Similarly, ATC may approve a vector that deviates from the jet routes in order to avoid a storm or to save fuel.

3.6.2 System Design Concepts

It is clear that enroute flight planning is a complex activity, but it is not clear how humans deal with these complexities or how one might program a computer to choose the 'optimum' solution to any given problem. For instance, how does one make tradeoffs between fuel conservation, flight safety, and prompt arrival at the destination? Because pilots make such tradeoffs on a routine basis, one goal of the study was to develop a system to support the pilots in making such decisions. There is a heavy emphasis, therefore, on allowing the pilots to explore "what if" types of questions so that they could gain feedback on the impact of a planning decision on flight parameters.

The three levels of computer support corresponded to successively greater flight planning power. Common to all three systems were: 1. a map display which consisted of the continental United States, the aircraft, and flight routes; 2. a representation of a flight log, which included the flight route and altitudes; and, 3. a display of flight parameters. These three items were displayed on two monitors. **Figure 3.1** depicts the map displays and controls, and **Figure 3.2** depicts the flight log display and controls and the flight parameter display. The pilot could elect to display weather data, waypoints, and jet routes on the map display. The lowest level of enroute flight planning support provided the pilot with the ability to sketch proposed flight plans on the map, in accordance with the waypoint and jet route structure. The latter condition required a pilot to sketch routes one waypoint at a time. Once the pilot completed a proposed flight plan, in terms of geographic location, the computer responded with various flight parameters, such as time of arrival and fuel remaining at the destination. The computer also indicated whether the flight was predicted to encounter any turbulence and the severity of that turbulence. The computer also proposed the most fuel efficient vertical flight profile for the proposed route. This form of support encouraged the pilots to propose options and see their effects on flight parameters. This form of support is referred to as the 'sketching only' system.

The next level of computer support incorporated the sketching form of interaction, but also included a method for placing constraints on a desired solution and allowing the computer to propose a solution which satisfied those constraints. For instance, the pilot could place limits on the maximum severity of turbulence and precipitation encountered, and could specify the desired destination. The computer would then perform a search of the data and solution spaces and propose a route that satisfied the pilot's constraints while minimizing fuel consumption. This proposed route would include both the geographic route and the vertical profile, along with its associated flight parameters. This form of flight planning causes the pilot to plan at a more abstract level than the sketching form of interaction, because the pilot is able to think about the characteristics of a desired solution while the computer handles the lower level details of specific routings. Using the sketching tool, the pilot was free to modify the route proposed by the computer and note the impact of such changes on the flight parameters. This second level of planning can be roughly construed to be a form of consultation system because the computer can be asked for its advice on a problem; it is referred to as the 'route constraints and sketching' system.

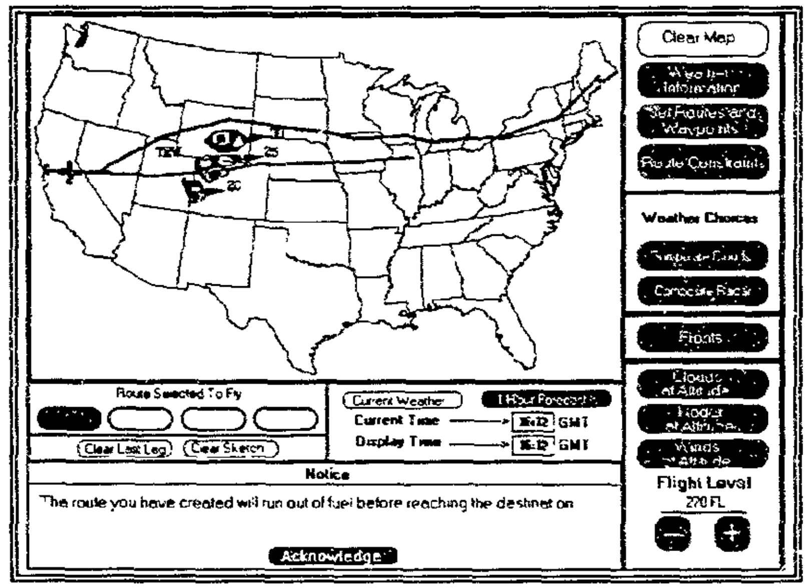

Figure 3.1 Left Monitor Displays and Controls

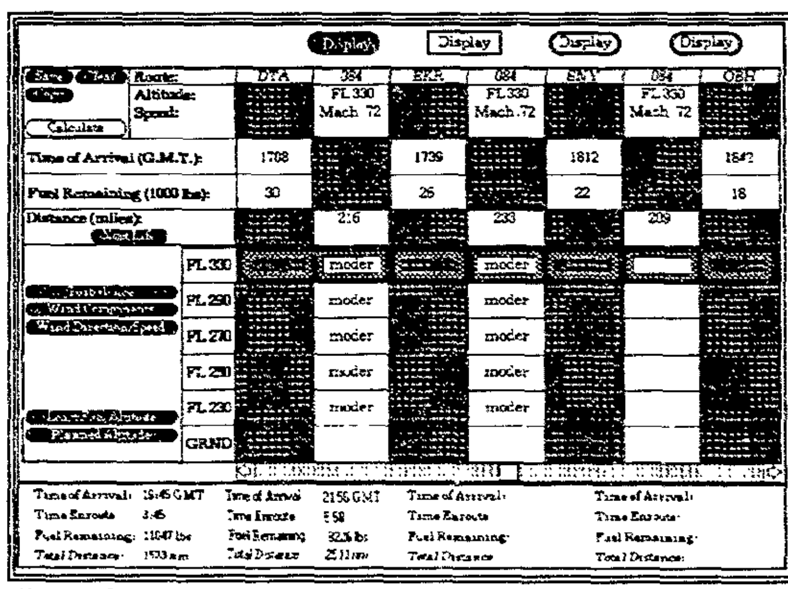

Figure 3.2 Right Monitor Displays and Controls

The highest level of support corresponds to an expert system that automatically solves a problem as soon as it is detected; upon loading the scenario information, the computer would propose a solution which minimized fuel consumption and satisfied the constraints of encountering no turbulence and no precipitation, as well as arriving at the planned destination. As in the previous level of support, the computer would propose both the geographic route and altitude profile, along with the corresponding flight parameters. If desired, the pilot could also request a solution from the computer based on different constraints, and he could sketch his own solutions.

3.6.3 Study Method

Thirty male commercial airline pilots were randomly assigned to one of three treatment conditions, wherein each condition consisted of one of the three forms of computer support described above. There were ten subjects in each condition. Each pilot was trained for approximately one hour on his system prior to solving four enroute flight planning cases. Each case consisted of a planned flight that was disrupted because of a change in weather conditions. The task for the pilot was to decide what to do in each situation. All of the pilots solved the four cases in the same order. It took approximately an hour and a half to solve the four cases.

3.6.4 Study Results

Each of the four cases provided some interesting insights into the influences of computer tools on human behaviors. The overriding results of each of the four cases are discussed below.

3.6.4.1 Case 1 General Results

In the first case, most of the subjects in the 'route constraints and sketching' and the 'automatic route constraints, route constraints, and sketching' conditions chose to fly the computer-suggested route (as expected). However, the 'sketching only' subjects tended to choose routes that were more robust; that is, these subjects put more distance between the aircraft and the storm. These subjects commented that they would like to have more distance from the storm than afforded by a more direct route (such as the one suggested by the computer in the other two treatment conditions). Furthermore, the 'sketching only' subjects were more apt to explore multiple routes and multiple types of routes, than were the subjects in the other two groups. These results suggest that the sketching form of interaction caused the subjects to consider the data more carefully than did the route constraints tool. One reason for this result is that the sketching tool gave the subjects the opportunity to consider the relationships of various route options and the weather at several points and to consider the robustness of those options given the uncertainties associated with weather. The constraints tool, on the other hand, did not encourage such behavior, and, indeed, the subjects using that tool may have been under the impression that the computer was considering the robustness of routes, when in fact it was not. If the sketching tool encouraged more careful examination of the data than did the constraints tool, and this behavior persisted, one could imagine situations wherein the constraints tool could lead to bad decisions.

3.6.4.2 Case 2 General Results

While Case 1 provided evidence for the benefits of tools that make the operator the sole decision maker, Case 2 provided evidence to the contrary. In Case 2, the 'sketching only' subjects had significant difficulty, as a group, in searching the relatively large data and solution spaces. Many of the routes explored by these subjects passed through strong turbulence. Indeed, four of these ten subjects chose deviations that exacted a high fuel consumption cost, either because they could not find a more efficient route around/through the weather or because they did not examine wind data which would have indicated that their chosen route encountered strong head winds. By contrast, the subjects in the 'route constraints and sketching' and 'automatic route constraints, route constraints, and sketching' groups successfully used the computer to rapidly find a fuel efficient deviation that avoided all of the weather. Furthermore, nearly all of the subjects who chose an inefficient deviation later stated that they preferred the more efficient deviation suggested by the computer to the other groups.

3.6.4.3 Case 3 General Results

As noted in the discussion of Case 1, the 'sketching only' subjects chose rather different solutions than did the 'route constraints and sketching' and the 'automatic route constraints, etc.' subjects. Furthermore, it was hypothesized that the 'sketching only' subjects were more involved in the problem solving process than were the subjects in the other two groups. The third case was designed to address the issues related to what happens when the automatic tools suggest questionable solutions: Does the operator recognize that the solution may not be appropriate? Assuming the operator does recognize that the solution is inappropriate, can he readily come up with a better solution?

In Case 3, the computer suggested two different routes in the 'route constraints and sketching' and 'automatic route constraints, etc.' conditions, depending upon the constraints placed on it. One deviation passed between two large thunderstorm cells of a volatile storm, which is a risky practice, at best; this route was suggested on the basis of no turbulence and no precipitation. The other route avoided the bulk of the weather, at the cost of slightly higher fuel consumption and a small amount of turbulence; this route was suggested on the basis of light chop (or greater) turbulence and light (or heavier) precipitation. The trend in this case was for the 'route constraints and sketching' and the 'automatic route constraints, route constraints, and sketching' subjects to choose the first route more frequently than the 'sketching only' subjects. If these subjects had not examined both routes, then it would suggest that these subjects were simply over-reliant on the computer. However, several of the subjects in the 'route constraints and sketching' and 'automatic route constraints, etc.' groups examined both routes before choosing the more risky route; thus, these subjects chose a risky route despite evidence that it may have been a poor choice and that a better option existed. These subjects nearly unanimously changed their minds when later questioned about their decisions.

With few exceptions, the 'sketching only' subjects planned very conservative deviations that completely avoided the weather. However, the 'sketching only' subjects had considerable difficulty in finding acceptable deviations. In fact, one subject chose a deviation that was predicted to cut into his required landing fuel reserves prior to arrival at the destination. Thus, even though the 'sketching only' subjects may have considered the data very carefully, the problem was sufficiently complex that they would have benefitted from some computer assistance.

3.6.4.4 Case 4 General Results

Case 4 provided some interesting results with regard to individual differences and with regard to the influence of computer recommendations. The 'sketching only' and 'route constraints and sketching' subjects were nearly evenly divided between a fuel efficient deviation and a robust deviation. When asked about his decision, one of the 'sketching only' subjects made the comment that the decision depended on the person's role in flying the aircraft at the time: if the captain were flying that leg, he would go one way so that he could look at the storm, but if the first officer were flying that leg, he'd go the other way around so that he could see the storm. Obviously this is an extreme example, but it underscores the role of individual differences in decision making.

Unlike the subjects in the other two groups, the 'automatic route constraints, route constraints, and sketching' subjects, were more likely to choose the computer-suggested, economical route, even when they had explored both routes. Combined with the results of Case 3, this result suggests that the computer exerts a strong influence on decision making when it recommends a solution at the onset of a problem.

3.6.5 Study Conclusions

The goal of the research was not to determine which particular version of an enroute flight planning tool resulted in the best human performance. Rather, one goal was to see how human behaviors were influenced by the tools available. Subjects who had multiple tools available to them (the 'route constraints and sketching' subjects and the 'automatic route constraints, route constraints, and sketching' subjects) were able to use them to develop alternative plans. In fact, there were many instances in which the solution recommended by the computer did not meet the needs of the pilots, so the pilots developed their own plans through sketching. Thus, not only is there a need for tools that allow the operator to go beyond a computer's solution, but there is a need to support individual differences, as well.

The subjects who had only the sketching tool available to them closely examined the available data. As a result, these subjects often planned robust deviations that would not need to be altered if there were further changes in the weather. Where these subjects ran into difficulties, however, was in situations in which there were a lot of potential solutions and there was a large amount of data. In such situations, these subjects had trouble finding appropriate solutions. Indeed, some of these subjects made poor decisions because of these difficulties. The subjects who had some form of computer assistance were able to more efficiently search these spaces, but with some costs.

The tool that automatically suggested a solution to the problem as soon as it was detected did not encourage the subjects to closely examine the data. While this fact did not cause problems in some cases, it clearly did lead to bad decisions in others. Furthermore, the automatic tool's influence on decision making went beyond simple over-reliance to the point where it shifted attention from data which were important to making a good decision.

3.6.6 *Implications for Maintenance Job Aids*

The conclusions outlined above can be readily applied to developing maintenance job aids. For instance, one of the conclusions is that there is a need for tools that allow an operator to go beyond a computer's solution. As discussed above, particularly with regard to Case 3, and as discussed by Roth, Bennett, and Woods (1987) and Suchman (1987), operators frequently have knowledge or information which is not available to the computer, but which is critical to making a good decision. By giving the authority and responsibility for decision making to the operator, and by providing a tool which supports the operators activities (rather than the other way around), the operator is free to explore solutions that may not have been designed into a machine expert.

Another conclusion reached by the above study was that the form of tool that required a person to make a series of decisions (the sketching tool) encouraged the operator to think hard about the problem and to consider the available data at a deeper level, than did the form of tool that encouraged the operator to make a single 'yes' or 'no' decision (the automatic route constraints tool) In this regard, the conclusion supports the notion that designers need to "keep the person in the loop".

However, another conclusion of the above study was that "keeping the person in the loop" did not provide adequate support in some situations. Indeed, in some of the cases (such as Cases 2 and 3) some of the operators were simply unable to find adequate solutions on their own. These operators could have used some help from a computer in exploring solution possibilities. In such situations this is rarely a reflection of human 'limitations', rather it is an indication of the difficulty of the problem. In maintenance, for instance, diagnosing multiple, interacting faults is a difficult problem. One symptom may be characteristic of several faults, or one fault may mask the presence of another. A tool which helps to focus the diagnostician's attention and eliminate false leads would be very beneficial.

Finally, it is important to realize that each person has a different style of decision making: two people who complete the same training course on a given method for dealing with a problem may use slightly different approaches. Such differences are likely to increase with experience as each person learns methods that consistently work for him/her. Indeed, experts often use several different approaches to solving truly difficult problems because each approach has unique limitations as well as unique benefits. For instance, knowledge of thermodynamics may help localize a fault to a heat exchanger, but knowledge of circuits may lead one to test the power supply to the heat exchanger, as well. Thus, tools need to be flexible to support such individual differences, rather than use a single, lockstep approach, as in the case of 'expert' systems. (Note that although some expert systems do incorporate the observable components of such methods, they do not allow the operator direct access to those methods. Because the knowledge and capabilities of such systems are necessarily incomplete, the systems are 'brittle' in the face of difficult problems, as discussed above in **Section 3.4**)

3.7 RESEARCH AND DEVELOPMENT PLAN

The above discussion points to the challenge for cognitive engineers involved in designing maintenance job aids: build systems that capitalize on both human strengths and computer strengths so that task performance is improved. As outlined above, because of relatively recent advances in hardware and software, it is possible to use sophisticated computational techniques (eg. cooperative system techniques) to develop real time, computer-based job aids for a wide range of technical tasks. Furthermore, hardware like the NCR NotePad will make it easier for people without previous computer training to use such job aids. We are working with the Flight Standards Service of the FAA to develop a Portable Performance Support System (PPSS) to aid Aviation Safety Inspectors in their daily activities. The initial focus of this effort is on the tasks performed by Airworthiness (maintenance) Inspectors, particularly the Ramp Inspections task. Inspectors need access to many of the same types of information that maintenance technicians use. Inspectors must also document their activities and the outcomes of those activities. We are taking a three Phase approach to developing a PPSS: Phase I, already underway, will identify a prospective task and perform an information needs analysis for that task; during Phase II we will design and develop a prototype PPSS for the task; and we will create a plan for the development of the prototype into a fully functional system during Phase III. Each of these phases is described more fully below.

3.7.1 Phase I: Problem Definition and Information Needs Analysis for Aviation Safety Inspectors

<u>Goal:</u> Identify a typical task for which a computer-based job aid is an appropriate application and conduct appropriate information needs analysis to define the work environment and information needs for aviation safety personnel.

We are working with the personnel of the Fort Lauderdale Flight Standards District Office (FSDO) to help identify an appropriate task for computer-based job aiding. Such a task should be one which is typical for the personnel, but which may require some experience to attain proficiency. This Phase of the research is an ongoing process continued throughout the life of the project.

The task initially proposed to the Fort Lauderdale FSDO is one of an Airworthiness Inspector performing Ramp Inspections. Ramp Inspections are used to verify aircraft airworthiness just prior to a planned flight. The inspectors walk around the aircraft, identifying problem areas and documenting those problems on a Program Tracking and Reporting Subsystem (PTRS) form (if an aircraft meets safety standards, that information is noted on the same form). The PTRS form is used to document all activities in which inspectors are involved; such activities include accident/incident investigation, airman certification, flight school certification, etc. Inspectors also use paper-based "job aids", which are essentially checklists, to assist them in their activities. Filling out forms and following checklists are the types of activities for which the NotePad was designed. Therefore, such tasks are amenable to transfer to pen-computer technology. Furthermore, the computer allows multiple forms to be linked together such that entries in one form are automatically propagated to all related forms; this approach would eliminate the duplicate entry of data which currently occurs. Finally, PTRS forms are currently recorded in paper format and given to data entry clerks who must interpret the inspector's handwriting and transfer the data to the FSDO's local computer-based database (which feeds into the national PTRS database). The PTRS data collected on a PPSS will be in a format that can be directly transferred into a FSDO's local PTRS database, thus eliminating the intermediate manual data entry step.

Inspectors must also have access to large amounts of information, such as Federal Aviation Regulations, Inspector's Handbooks, Airworthiness Directives, Advisory Circulars, etc. Whereas inspectors must currently retain hard copies of such information or refer to the FAA's mainframe repository, it can become cumbersome to access and track this information. This suggests that a hypermedia on-line documentation system can be beneficial to the inspectors. This system can run off either the NotePad's internal hard drive or an external CD ROM device. Such an on-line documentation will facilitate rapid access to up to date information.

Based on initial conversations with the Flight Standards Service, it appears that a PPSS will:

- Provide inspectors with an integrated, linked form system
- Provide a means to reduce data entry performed by clerks
- Provide on-line documentation, including FARs, handbooks, etc.

3.7.2 Phase II: Design and Development of a Prototype Portable Performance Support System

Goal: Build and demonstrate a prototype Portable Performance Support System to support Aviation Safety Inspectors doing Ramp Inspections.

This phase will involve several iterations of development and demonstration. Rapid prototyping of the PPSS will permit us to demonstrate the system to inspectors for quick feedback about the design and content of the system. We will work closely with the inspectors during this phase to ensure the accuracy of the information and the usability of the PPSS. While these evaluations will primarily involve the airworthiness inspectors, it is extremely helpful to have other inspectors evaluate the PPSS, because they can provide a fresh perspective and would be likely to identify additional areas for improvement.

3.7.3 Phase III: Create a Plan for the Development of the Prototype System into a Fully Operational System

Goal: Create a plan to convert the prototype PPSS into a fully operational system for evaluation and integration into the work environment.

This phase will require a formal review of the prototype PPSS to identify its strengths and weakness. Following this review, a plan will be developed to fully implement the PPSS. The plan will include the design of a study to evaluate the effectiveness of the PPSS in the work environment.

3.8 SUMMARY

Several past approaches to maintenance job aiding were discussed with respect to their impact on human performance. Such approaches have typically used a 'machine expert' to guide technicians through the maintenance process. However, the 'machine expert' paradigm has met with limited success in operational environments because of problems with unanticipated variability in the environment (or 'brittleness'), extra-machine knowledge, and inflexibility. An alternative philosophy to developing systems was presented, cooperative systems, in which both the human and the computer are actively involved in the problem solving process. This philosophy advocates a change in perspective toward computers as tools to assist people in their work, rather than as prostheses to overcome human 'limitations'. The cooperative problem solving paradigm capitalizes on the strengths of humans and computers in order to improve the performance of both. A study which compared different versions of a job aiding system designed with using this philosophy was presented, along with implications for developing maintenance job aids. Finally, a plan for developing a portable performance support system for aviation safety inspectors was presented.

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Chapter 3 Appendix

Annotated References

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Article describes artificial intelligence software that continuously monitors systems, isolates faults, and indicates fault presence, on Boeing B1B bomber. The system is projected to save $260 million in maintenance. Also discusses an F/A-18 on board maintenance processor that creates data files in flight to be later processed by an expert system. See also "AI to help keep..."

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Westinghouse Electric Corp. developed 'Argus', an alarm response advisor. Argus details alarm causes and required responses. The system collects data on-line, diagnoses problems, and makes recommendations.

Computational Systems, Inc. developed an expert system for vibrational analysis of rotating machinery.

Chubu Electric Power Co. and Toshiba Corp. developed a maintenance support expert system for large turbine generators. The system handles complex and time-consuming tasks. A engineer enters a failure into the system and the system responds with other damages that may result from a suspected root cause, it gives standard repair methods and design specifications, and it displays the most likely failure sources.

Chubu Electric Power Co. and Mitsubishi Heavy Industries, Ltd. developed an expert system for boiler failure analysis and maintenance planning. Failure analysis produces the most probable causes, guidelines for inspection, items to be investigated, repair methods, and suggested preventive maintenance. A maintenance planning subsystem automatically prepares daily repair schedules, work estimation plans, and work specifications.

Byrd, T. A., Markland, R. E., & Karwan, K. R. (1991, July-August). Keeping the helicopters flying--using a knowledge-based tank support system to manage maintenance. *Interfaces*, pp. 53-62.

Discusses a knowledge-based system which generates reports for helicopter maintenance. The system tracks helicopters and notifies maintenance staff of which helicopters are nearing regular inspections or special inspections. Reports specify the time-between-overhaul components that will require maintenance soon and give flying schedules prioritized on mission and maintenance needs. The system replaced a cumbersome manual system.

Callahan, P. H. (1988, January-February). Expert systems for AT&T switched network maintenance. *AT&T Technical Journal*, pp. 93-103.

Describes 'Testing Operations Provisioning Administration System' (TOPAS), a real-time, distributed, multi-tasking expert system for switched circuit maintenance. TOPAS performs trouble analysis, fault localization, and referral for network switches. TOPAS is claimed to do maintenance without human intervention or consultation.

Clancy, C. (1987, November). Qualitative reasoning in electronic fault diagnosis. *Electrical Engineering*, pp. 141-145.

Describes an expert system for diagnosing switch mode power supplies by using a functional model.

Computer oversees maintenance. (1992). *American Water Works Association Journal, 84*, 107-108.

Discusses a pc-based preventive maintenance and training system for water mains.

Cue, R. W. & Muir, D. E. (1991). Engine performance monitoring and troubleshooting techniques for the CF-18 aircraft. *Journal of Engineering for Gas Turbines and Power, 113*, 11-19.

Discusses the In-flight Engine Condition Monitoring System (IECMS) as a foundation for 'on-condition' maintenance of fighter aircraft engines. On-condition maintenance actions are undertaken based on actual engine conditions, rather than as preventive maintenance. IECMS monitors and records engine performance parameters, notifies the pilot when caution should be exercised, and records maintenance codes when an operating limit has been exceeded. Data are stored on a removable tape cartridge. The article features several examples of data indicating normal and abnormal operating conditions.

Culp, C. H. (1989). Expert systems in preventive maintenance and diagnostics. *ASHRAE Journal, 31*, 24-27.

Sales article on using expert systems for heating, ventilation, and air conditioning maintenance.

Dallimonti, R. (1987, June 18). Smarter maintenance with expert systems. *Plant Engineering*, pp. 51-56.

An introduction to the prospects of using expert systems for maintenance. Surveys systems from Hughes Aircraft Company, Rockwell International, and Campbell Soup Company.

de Kleer, J. (1990). Using crude probability estimates to guide diagnosis. *Artificial Intelligence, 45*, 381-391.

Extension of 'General Diagnostic Engine' discussion in de Kleer and Williams.

de Kleer, J. & Williams, B. C. (1987). Diagnosing multiple faults. *Artificial Intelligence, 32*, 97-130.

An academic discussion of a 'General Diagnostic Engine' for diagnosing multiple faults. Combines model-based prediction with sequential diagnosis to propose measurements to diagnose faults.

Dobson, R., & Wild, W. (1989, May). Plant's computerized maintenance system improves operations. *Power Engineering*, pp. 30-32.

A Lotus Symphony-based system automatically processes maintenance clearances for power plant.

Dohner, C. V., & Acierno, S. J. (1989, August). Expert systems for gas-turbine powerplants passes first tests. *Power*, pp. 63-64.

Citing the limited amount of troubleshooting and diagnostic information in the manufacturer's maintenance manuals, EPRI developed an expert system for gas-turbine power plants. A portable pc uses voice recognition and synthesis and links to a pc in control room. The control room pc drives a video disk player and a printer.

Doorley, R. (1988, August). Hydraulic troubleshooting using an expert system. *Hydraulics & Pneumatics*, pp. 91-92.

Discusses the 'MindMeld' system for steel mill hydraulic equipment maintenance. MindMeld uses test equipment data and operator information to determine the likely cause of a problem. See also Doorley, (1989).

Doorley, R. B. (1989, June 22). Expert systems probe hydraulic faults. *Machine Design*, pp. 89-92.

More on the 'MindMeld' system for hydraulic equipment troubleshooting in steel mills. The pc-based system focuses on faults that are difficult to locate and which require extensive dismantling of machinery if left unrecognized.

Expert system from AT&T Bell Laboratories is an 'ACE' at telephone cable analysis. (1983, October). *Record*, p. 1.

The 'Automated Cable Expertise' system identifies trouble spots in telephone cable systems. ACE gives repair histories of problematic areas and suggests corrective action. The system is automatic and runs daily.

Expert system guides tube-failure investigations. (1989, August). *Power*, p. 85.

Discusses an expert system for boiler tube failure diagnosis and corrective action (including non-destructive examination, repair, welding, metallurgical tests, references). The system an be used to determine tube failure mechanisms. The system also has a database for tube history, design, inspection, maintenance and it provides context-sensitive information about repair practices. PC-based, linked to a slide projector. See also Smith, (1989, December).

Expert system probes beneath the surface. (1990, January). *Mechanical Engineering*, p. 112.

Britain's Central Electricity Generating Board developed an expert system for monitoring and analyzing vibration patterns of turbine generators. The expert system uses 'deep knowledge' of cause and effect relationships in turbine generators. The goal in developing the system was to transfer initial analysis from specialist staff to engineering/operations staff.

Expert systems to hone jet engine maintenance. (1986, April 21). *Design News*, pp. 36-38.

Describes an expert system to diagnose engine malfunctions and facilitate preventive maintenance by predicting when parts must be replaced. The system switches maintenance from a scheduled replacement basis to an 'as-needed' replacement basis. It uses qualitative and historical maintenance data. The pc-based system was developed by the General Electric R&D Center in conjunction with GE's Aircraft Engine Business Group for the Air Force.

FAA and NASA design program to improve human performance. (1989, May 29). *Aviation Week & Space Technology*, p. 115.

Outlines joint FAA and NASA effort to sponsor human factors research.

Foley, W. L. , & Svinos, J. G. (1989). Expert advisor program for rod pumping. *Journal of Petroleum Technology, 41*, 394-400.

'EXPROD' is an expert adviser program for rod-pumping diagnostics used by Chevron. The program analyzes field data to identify equipment problems and recommend solutions. EXPROD uses statistical pattern recognition in conjunction with diagnostic rules. Some worker expertise is still required to diagnose problems. EXPROD runs on a microcomputer.

Folley, J. D., & Hritz R. J. (1987, April). Embedded AI expert system troubleshoots automated assembly. *Industrial Engineering*, pp. 32-35.

Discusses an expert system to assist technicians in diagnosing a clutch assembly machine. The expert system uses a computer-controlled video disk to indicate what the technician should be doing or looking at.

Fault lamps above stations indicate malfunctioning assembly stations. The technician takes a monitor, a two-button control, and a maintenance cart to the faulty station and plugs into a junction box connected to the computer and video disk player. The technician selects the station or procedure from a menu and the computer specifies tests or actions with graphics. The technician supplies data and the computer specifies the next action.

GM unveils "Charley", an expert machine diagnostic system. (1988, May). *I&CS*, pp. 4-7.

Describes vibration analysis expert system for production machinery with rotating components. Charley helps mechanics: 1. identify parts that need repair; 2. repair or adjust equipment prior to failure; 3. speed up diagnosis; 4. distribute expertise; and 5. avoid fixing functioning equipment. See also Stovicek, (1991).

Gunhold, R., & Zettel, J. (1986). System 12 in-factory testing. *Electrical Communication, 60(2)*, 128-134.

Describes a diagnostic expert system for ITT System 12 printed circuit board assemblies.

Hartenstein, A. (1988, January). Computer system controls all maintenance activities. *Public Works*, p. 60.

The system maintains several types of records and schedules preventive and corrective maintenance. It also issues work orders and monitors progress. It is a database system.

Hill, S. (1990, February). Ask the expert. *Water & Pollution Control*, pp. 12-13.

Concept paper that discusses possibilities of expert systems to design wastewater treatment facilities and control such plants.

Hughes, D. (1988, March 7). Digital develops special applications to meet diverse aerospace needs. *Aviation Week & Space Technology*, pp. 51-53.

Jet fighter uses AI as troubleshooter. (1986, July 21). *Design News*, p. 20.

More on AIMES. See also "McDonnell Douglas..."

Keller, B. C. & Knutilla, T. R. (1990, September). U.S. Army builds an AI diagnostic expert system, by soldiers for soldiers. *Industrial Engineering*, pp. 38-41.

Describes the 'Pulse Radar Intelligent Diagnostic Environment' for troubleshooting the Pulse Acquisition Radar of a Hawk missile system.

King, I. J., Chianese, R. B., & Chow, M. P. (1988, December). Plant diagnostics relies on AI transmissions from remote site. *Power*, pp. 57-60.

Describes a suite of on-line power plant diagnostic systems developed by Westinghouse Electric Corp. Development goals were to maximize availability and efficiency and reduce forced-outage rates of turbine generators. The systems identify worn or damaged components early. 'ChemAID' diagnoses problems in the steam/water cycle; it determines the type, severity, and location of water chemistry problems. ChemAID assists the operator in determining the need for immediate or delayed action. It can also serve as a consultant.

'TurbinAID' diagnoses problems in steam turbines. It diagnoses the condition and thermodynamic performance of turbines and reports current and target performance parameters.

'GenAID' monitors trends for gas-cooled generators.

Kinnucan, P. (1985, November). A maintenance expert that never sleeps. *High Technology*, pp. 48-9.

The 'Intelligent Machine Prognosticator' (IMP) is an expert system for maintenance of an epitaxial reactor (equipment that 'grows' additional silicon crystals on silicon wafers). IMP diagnoses faults and recommends repair procedures. The system was developed because vendor support was difficult to obtain. IMP reportedly reduced repair time by 36%.

Kolcum, E. H. (1989, January 2). Growing flight, maintenance simulator market attracts many competitors. *Aviation Week & Space Technology*, pp. 91-93.

Discusses proposed military expenditures on simulators for maintenance training.

Layton, C. F. (1992). An investigation of the effects of cognitive tools on human adaptive planning in the domain of enroute flight planning. Doctoral dissertation, The Ohio State University, Columbus, OH.

Discusses a study which compared three different levels of computer support for enroute flight planning. The study compared the behaviors of thirty professional airline pilots assigned randomly to each of three treatment conditions (ten subjects per condition, each condition consisted of a different form of computer support). The subjects were trained on system use prior to solving four enroute flight planning scenarios. The focus of the research was not on the principles used to design the enroute flight planning systems, rather it was on what characteristics the designs shared and what characteristics were unique to a particular system. The purpose of the research was to study how these three system designs, as examples of broader classes of planning assistance tools, affected enroute flight planning, as an example of adaptive planning. The goals of this study were to develop a better understanding of the adaptive planning process and to develop recommendations for designing tools to support that process.

Maintenance expert in a briefcase. (1986, April). *High Technology*, p. 9.

'Mentor' is a portable expert system for routine maintenance and diagnosis of air conditioners. Mentor keeps service records of each piece of equipment. The emphasis is on preventive maintenance.

Majstorovic, V. D. (1990, October). Expert systems for diagnosis and maintenance: State of the art. *Computers in Industry*, p. 43-68.

Discussion of typical expert system components and survey of diagnosis and maintenance expert systems. Discusses expert systems for maintenance of flexible manufacturing systems.

McDonnell Douglas flight tests AI maintenance data processor. (1986, February 17). *Aviation Week & Space Technology*, p. 69.

Describes 'Avionics Integrated Maintenance Expert System' (AIMES) for F/A-18. AIMES gathers aircraft data and creates flight files for later analysis. Production rules detect and isolate avionic failures at the electronic card level. Analysis provides fault data, the card name, and the reasoning that led to the fault isolation conclusion. AIMES is a self-contained on board system with a microprocessor and a data storage cassette. AIMES includes BITE. See also "AI to help keep..."

McDowell, J. K., & Davis, J. F. (1991). Managing qualitative simulation in knowledge-based chemical diagnosis. *AIChE Journal, 37*, 569-580.

An academic discussion of an approach for dealing with multiple interacting faults with an expert system.

Melhem, H. G., & Wentworth, J. A. (1990, March). FASTBRID: An expert system for bridge fatigue. *Public Roads*, pp. 109-117.

'Fatigue Assessment of Steel Bridges' is a training aid for bridge inspection and planning remedial actions. It is also an advisory system for evaluation of bridges. The advisory system helps organize fatigue inspection, evaluate inspection results, and determine a course of action.

Miller, D. M., Mellichamp, J. M., & Wang, J. (1990, November). An image enhanced, knowledge based expert system for maintenance trouble shooting. *Computers in Industry*, pp. 187-202.

Describes an expert system for diagnosis of the electrical/hydraulic system of an electric utility vehicle. The vehicle system is difficult to diagnose because faults can be masked by behavior of equipment. The expert system displays a limited number of photographs of a vehicle. The expert system is pc based.

Miller, F. D., Rowland, J. R., & Siegfried, E. M. (1986, January). ACE: An expert system for preventive maintenance operations. *Record*, pp. 20-25.

Discusses the 'Automated Cable Expertise' (ACE) system for telephone cable analysis. ACE is an automatic report generator which runs daily. Seil also "Expert system from AT&T Bell Laboratories...".

Moradian, S., Thompson, E. D., & Jenkins, M. A. (1991, May). New idea in on-line diagnostics improves plant performance. *Power*, pp. 49-51.

Discusses Westinghouse expert systems, particularly GenAID. See also King, Chianese, and Chow (1988, December).

Nelson, B. C., & Smith, T. J. (1990). User interaction with maintenance information: A performance analysis of hypertext versus hardcopy formats. *Proceedings of the Human Factors Society 34th Annual Meeting*, 229-233.

Research paper which discusses experimental results of comparing hypertext versions of maintenance manuals with hardcopy versions of those manuals. Subjects were slower with hypertext than hardcopy, but preferred hypertext. Enhanced versions of manuals (hypertext and hardcopy) improved access to information and comprehension of that information, but subjects did not recognize improvements.

Nordwall, B. D. (1989, June 19). CTA develops new computer system to speed civil aircraft maintenance. *Aviation Week & Space Technology*, pp. 153-157.

Describes the 'Automated Maintenance Management System' (AMMS) and the 'Mobile Enhanced Comprehensive Asset Management System' (MECAMS) developed by CTA, Inc. The AMMS collects inflight information on F/A-18 aircraft engines and stores it on a floppy disk for later analysis by MECAMS. MECAMS runs on a laptop computer connected to a minicomputer, which in turn could be connected via satellite or phone link to a database of troubleshooting and logistics information. MECAMS first identifies periods when engine performance parameters are exceeded, then it assists technicians in troubleshooting and maintaining the engines. CTA indicated that the F/A-18 engine system was a proof of concept and was proposing that the same system could be extended to civil aircraft engines and avionics.

NYNEX cuts costs in 40 offices using expert system. (1990, September). *Industrial Engineering*, pp. 81-82.

'Maintenance Administrator Expert' (MAX) diagnoses problems with residential and small business telephone service. MAX interprets trouble report data in 5-10 sec. as opposed to the 5-10 min. a human requires. MAX dispatches the correct technician and reduces false dispatches. The system reportedly saves $4-6 million/yr. MAX was developed by NYNEX Science and Technology Center and runs on a Sun 3/260.

Pauta, G. (1990, March). Expert system diagnoses transmission-line faults. *Electrical World*, pp. S41-S42.

Describes an automatic expert system that uses a mathematical model of a power transmission system for fault diagnosis. The expert system activates upon failure of the transmission system and produces a prioritized list of possible fault locations and their corresponding failure probabilities.

Ray, A. K. (1991, June). Equipment fault diagnosis--a neural network approach. *Computers in Industry*, pp. 169-177.

Describes a system designed for mechanical equipment diagnosis in the steel industry.

Reason, J. (1987, March). Expert systems promise to cut critical machine downtime. *Power,* pp. 17-24.

Discusses prospects for continuous vibration monitoring systems, leading to automatic diagnostic systems. The article also highlights several expert systems in the power industry. 'Turbomac' is an expert system for diagnosing vibrations in large turbo machinery, particularly power generating facilities.

'GenAid' is an expert system developed by Westinghouse Electric Corp. for diagnosing hydrogen-cooled electric generators. The purpose of GenAid was to avoid catastrophic failure. See also King, Chianese, and Chow (1988, December).

The Central-Hudson Electric & Gas Corp. developed an expert system for scheduling outages. The purpose of the system was to reduce the number of scheduled outages without compromising equipment integrity. The system schedules outages for preventive maintenance at the first sign of trouble.

'Transformer Oil Gas Analyst' is an expert system for detecting and diagnosing signs of impending transformer failure.

General Electric developed an expert system for turbines. The system is portable, links to a video disk display, and uses voice recognition for form fill-in or multiple choice input.

Rodriguez, G., & River, P. (1986, July). A practical approach to expert systems for safety and diagnostics. *InTech,* pp. 53-57.

Describes an expert system for diagnosis of a 400/200 KV hybrid gas insulated substation of the Laguna Verde Nuclear Power Station in Mexico. Engineers and literature provided information to build fault trees to model loss of current to safety-related control boards. System objectives were the timely diagnosis of abnormal events or transients, and analysis of events leading to, and consequences of, an abnormal situation.

Roth, E. M., Bennett, K. B., & Woods, D. D. (1987). Human interaction with an "intelligent" machine. *International Journal of Man-Machine Studies, 27,* 479-525.

Reports a study investigating technicians using an expert system to troubleshoot an electro-mechanical device. The article documents common problems of 'machine expert' problem solving systems. Only technicians who were actively involved in the problem solving process and who performed actions in addition to those requested by the expert system successfully completed the sample tasks. Technicians who responded passively to expert system requests were unable to solve the problems. This study should be read by all those interested in improving human performance through computational support.

Rowan, D. A. (1988, May). AI enhances on-line fault diagnosis. *InTech,* pp. 52-55.

Describes 'Fault Analysis Consultant' (Falcon) for on-line fault diagnosis in a commercial chemical plant. Falcon reasons from first principles and heuristic knowledge. Falcon went on-line in 1988.

Rustace, P. (1988, June 9). Knowledge of an expert compressed on computer. *The Engineer*, p. 44.

Discusses monitoring expert system for gas turbine-driven compressor sets.

Save plant know-how with expert systems. (1987, August). *Electrical World*, pp. 54-55.

Discusses expert system to resolve power plant control room alarms.

Schaaf, J. R. (1985, September). Computerization of sewer maintenance scheduling. *Public Works*, pp. 128-129.

'Computerization of Sewer Maintenance Operations' (COSMO) schedules routine cleaning operations. COSMO also tracks performance, debris severity, and maintenance history and uses this information to set cleaning priorities and schedule sewer cleaning. Database system.

Shifrin, C. A. (1985, October 28). Eastern computer system reduces maintenance layovers, staff levels. *Aviation Week & Space Technology*, pp. 40-45.

Describes a computer system that includes computerized work cards to be filled in by maintenance personnel. The system will also produce hard copies of tasks and checks. The work cards contain detailed instructions, warnings, and notes. The system aids in capacity planning through tracking line slippage, schedule constraints, and manpower limitations.

The article also discusses a parts tracking and scheduling system.

Smith, D. J. (1987, May). Diagnostic analysis leads the way in preventive maintenance. *Power Engineering*, pp. 12-19.

Describes 'Process Diagnosis System' (PDS) developed by Westinghouse R&D Center and Carnegie Mellon University. PDS diagnoses problems with steam generators and provides recommendations and procedures for fixing the problems. PDS is claimed to cut down on 'over-maintenance', but prevent 'breakdown maintenance'. The system monitors the condition of an operational plant and analyzes plant data to detect incipient faults and deterioration. PDS uses this information to diagnose faults and predict the duration of safe operation without maintenance. PDS also recommends preventive maintenance tasks to be performed during scheduled down periods.

Smith, D. J. (1989, January). Artificial intelligence--today's new design and diagnostic tool. *Power Engineering*, pp. 26-30.

Overview of AI applications in maintenance. The article describes the EPRI-developed 'Gas Turbine Expert System' and a Westinghouse-developed system for on-line valve diagnosis

Smith, D. J. (1989, December). Intelligent computer systems enhance power plant operations. *Power Engineering*, pp. 21-26.

Discusses several expert systems in use in the power industry. The 'ESCARTA' system for reducing boiler tube failures has several uses: it permits an engineer to track down a failure mechanism, it provides non-destructive testing procedures, it provides welding procedures, it provides corrective actions for failure repair, and it facilitates training. ESCARTA will show operators the correct procedures for investigating tube failures. It also suggests root causes that could have led to a failure. ESCARTA is pc based.

'Coal Quality Advisor' assesses coal quality. The system helps assess cost and performance aspects of using different coals or coal blends. It is pc based.

'Smart Operator's Aid for Power Plant Optimization' diagnoses causes of heat rate degradation on oil- and gas-fired power plants. The system justifies its diagnosis through logic trees or messages. It also recommends corrective actions.

'TurbinAID', 'GenAID', and 'ChemAID' make up a suite of expert systems for diagnosis of turbine generators. The systems were developed by Westinghouse Electric Corp. See also King, Chianese, and Chow (1988, December).

Stacklin, C. A. (1990, June). Pairing on-line diagnostics with real-time expert systems. *Power*, pp. 55-58.

Concept paper on using expert systems to reduce unscheduled down time. Discusses fault trees, failure modes and effects analyses, and pattern recognition.

Stein, K. J. (1988, March 14). Expert system technology spurs advances in training, maintenance. *Aviation Week & Space Technology*, pp. 229-233.

Discusses emerging expert system technology in maintenance. The Navy Sea System Command's Integrated Diagnostic Support System (IDSS) collects fault-related data and isolates faults. The system continually builds its knowledge base so that it becomes more efficient with use. IDSS will isolate faults to the microchip level by using fault trees. IDSS uses a touch screen, a flat panel display, and an interactive maintenance tutorial on a video disk. IDSS is expected to aid systems designers in building self-diagnostics in new avionics systems.

The article also describes Flex-MATE for use with the USAF modular automatic test equipment.

Stovicek, D. (1991, February). Cloning knowledge. *Automation*, pp. 46-48.

Discusses General Motors' 'Charley' system for vibration analysis of production equipment. Charley is an expert system developed by GM's Advanced Engineering Staff and is named and modeled after a retired vibration analysis expert. Charley contains three modules: 1. a rule-base for vibration analysis, 2. a 'vibration signature' database, which contains the vibration curves of the various pieces of equipment, and, 3. a machine database, which contains historical data on each machine. Charley is used for failure diagnosis, preventive maintenance, and training. Charley can be used to answer 'what if' questions and explains diagnosis strategies. Runs on a Sun computer. See also "GM unveils..."

Suchman, L. A. (1987). *Plans and situated actions: The problem of human machine communication.*

Discusses human action with respect to circumstantial variability and the difficulties in communicating such variability to a machine. Rigid problem solving on the part of the machine and misinterpretations on the part of the human are some of the obstacles to successful human computer interaction discussed.

Sutton, G. (1986, January). Computers join the maintenance team. *WATER Engineering & Management*, pp. 31-33.

'Maintenance Management System' (MMS) for water and wastewater treatment facilities. MMS tracks organization performance, determines resource utilization and work backlog, and makes personnel and resource utilization projections. It also schedules preventive maintenance. MMS is a database system.

Thandasseri, M. (1986). Expert systems application for TXE4A exchanges. *Electrical Communication, 60(2)*, 154-161.

Describes 'Advance Maintenance Facility', an expert system for fault identification. Normally the system controls interactions, but it can be 'controlled' by an operator. Output is corrective action and post-repair tests.

Toms, M., & Patrick, J. (1987). Some components of fault-finding. *Human Factors, 29(5)*, 587-597.

Research paper on human performance in network fault-finding tasks.

Turpin, B. (1986, March 3). Artificial intelligence: Project needs. *Design News*, pp. 104-114.

Discusses expert system developed by Campbell Soup for diagnosing problems with 'cookers'. The system was built to replace a retiring technician with 25 years of experience.

The article also discusses an expert system (Intelligent Machine Prognosticator) developed by Texas Instruments for epitaxial reactor maintenance. See also Kinnucan (1985, November).

Users get expert advice on-site. (1987, March 12). *ENR*, p. 21.

The 'Exstra' expert system troubleshoots mechanical equipment failures in compressors, water pumps, and other rotating equipment. Exstra lists possible conclusions with likelihood ratings. It also explains why it asks particular questions. Exstra is VAX based.

Uttley, A. (1985, October 17). Computer 'expert' helps find faults. *The Engineer*, p. 76.

Describes expert system shell software.

Vanpelt, H. E., & Ashe, K. L. (1989, April). Radiation exposure reduced with computer-aided maintenance. *Power Engineering*, pp. 40-42.

Describes 'Plant Radiological Status' (PRS), a three dimensional computer model of a power generating station and its equipment, developed by Duke Power Co. PRS is claimed to reduce maintenance time and radiation exposure by supporting planning activities. PRS identifies maintenance interference problems (eg. restricted access) and available work space. PRS also facilitates access and interpretation of radiological conditions in the plant; it identifies hot spots and contaminated areas.

Woods, D. D. & Roth, E. M. (1988). Cognitive engineering: Human problem solving with tools. *Human Factors, 30(4)*, 415-430.

Concept paper which describes the fundamental aspects of cognitive engineering. According to the authors, "Cognitive engineering is an applied cognitive science that draws on the knowledge and techniques of cognitive psychology and related disciplines to provide the foundation for principle-driven design of person-machine systems." (p. 415). Like Roth, Bennett, & Woods (1987), this article should be read by all those interested in supporting human performance through computational support.

Yu, C-C., & Lee, C. (1991). Fault diagnosis based on qualitative/quantitative process knowledge. *AIChE Journal, 37*, pp. 617-628.

An academic discussion of an approach for combining qualitative and quantitative reasoning in an expert system through fuzzy logic. Aside: Although fuzzy logic is a technique that is often used in artificial intelligence because it doesn't carry the overhead associated with Bayesian or other probability theory based methods, it also lacks the mathematical rigor of the latter methods.

Chapter Four
The FAA Aviation Maintenance Human Factors Hypermedia System

4.0 INTRODUCTION

The Federal Aviation Administration (FAA) Aviation Maintenance Hypermedia Information System (HIS) is part of the Office of Aviation Medicine (AAM) Human Factors in Aviation Maintenance Research (HFAMR) program. The goal of the HIS project is to create new tools and methods for information access and use and to provide these tools and methods for support of other HFAMR activities (e.g., training and job aiding systems). These tools and methods provide the vital information access component for any computer-based aviation maintenance integrated information system (Johnson and Norton, 1992).

In its present state the HIS provides an environment to create and explore large collections of related information. The HIS provides a simple, yet powerful, way of creating and following associations between related pieces of information. Using the HIS, the user can browse and view information in a variety of ways. This flexible method of information access and utilization is not available to users of conventional text retrieval systems.

Publications and presentations from the HFAMR program are being placed into the HIS for the initial domain. This material includes presentations from the first five Human Factors in Aviation Maintenance Conferences, as well as complete material from the HFAMR Phase I (Shepherd, et al., 1991) and Phase II Progress Reports. The result is an on-line document that employs the latest hypermedia software technology. More importantly, software tools and methods have been constructed that provide the ability to quickly store, locate, and deliver information for a variety of aviation maintenance tasks.

4.1 PRACTICAL ASPECTS OF HYPERMEDIA

The fundamental nature of computer-based hypermedia is to structure information in a fashion that can be quickly and randomly located. Conventional forms of media delivery (e.g., books, television, video, audio tapes, etc.) tend to be linear in nature. The reader of this linear information typically starts at the beginning of a presentation and progresses along a predetermined path (e.g., turning to the next page in a book, or being forced to sit through commercials while watching TV). The reader or viewer of this information often has little choice in determining what information comes next.

Hypermedia, on the other hand, arranges information in a form in which a reader or viewer can "bounce" around between different segments of information (similar to a reader of a mystery book flipping to the end of the story; or a reader of a technical manual first looking up a term in a index, and then going to the correct page in the manual). This idea of associations, or links, between segments of information is a core feature of hypermedia systems. An example of a typical hypermedia system is illustrated in **Figure 4.1.**

For example, a hypermedia version of a car maintenance manual would first present the reader with a diagram of a car. From this diagram, the reader would point to a particular portion of the car (e.g., the engine) and request more information. The hypermedia system would then display a diagram of the engine. The reader would point to an engine component (e.g., the battery) and the hypermedia system would then present a verbal description of the battery and list possible troubleshooting advice dealing with common battery problems.

For the purposes of this paper, the term "hypermedia" is used because the research is not restricting the usage of this system to only text - "hypertext." The scope of this system has been extended to include text, still images, graphical animation, audio, and video - "hypermedia".

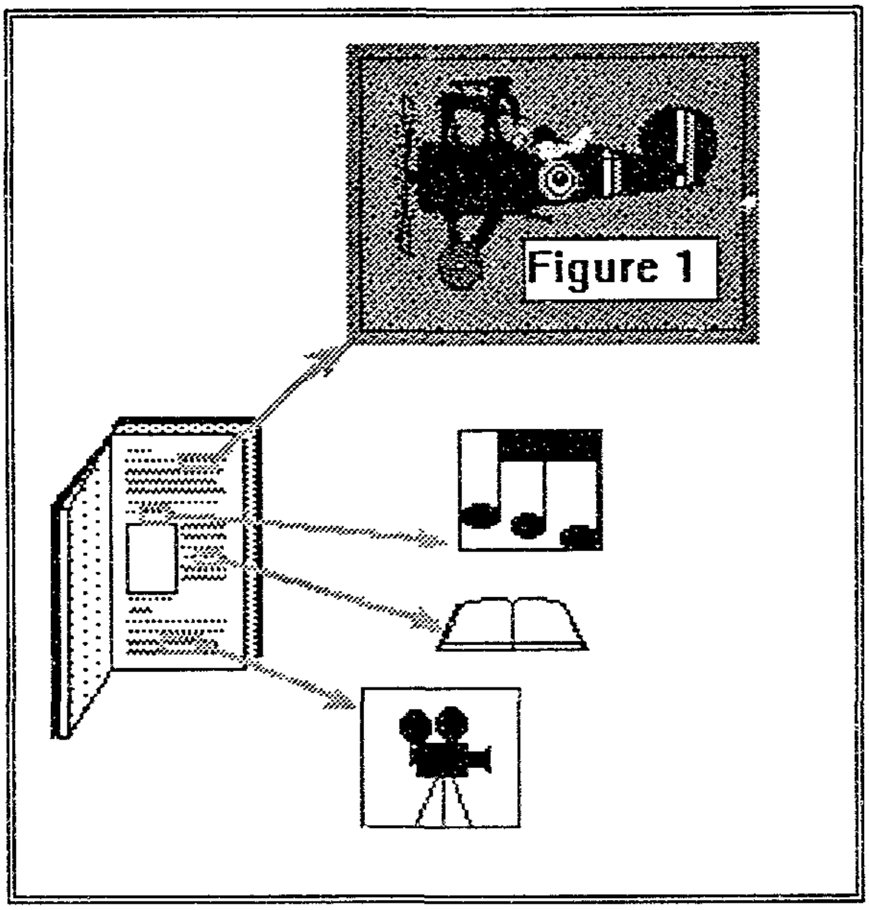

Figure 4.1 A Typical Hypermedia System

One of the advantages of using hypermedia technology is its strong support for easy access to items stored in large collections of information. Typically, structures of large collections of information are complex. This leads to various indexing schemes that are used to aid readers in locating information (e.g., tables of contents and indices for books, Dewey Decimal and Library of Congress indexing for libraries). Even with these schemes however, someone searching for a particular piece of information may still have limited success in locating the desired information. Hypermedia systems extend the indexing of information by providing associations, or links, between particular related pieces of information. The idea is to provide readers with the ability to access a general location in the information base using various indexes and searching schemes. Then the reader can browse the general locations using specific associations to locate the desired information. To support browsing and exploration of information, the presence of anchors (also often called buttons) is employed to signal the reader that related information is available (Duchastel, 1990).

The Intermedia project at Brown University is a very good example of hypermedia technology being implemented for a large information space. Over a thousand pieces, or "nodes," of information are connected by over two thousand links. Intermedia presents the user with a graphical information browser, a set of graphical editors for text, graphics, timelines, animations, and videodisc data, a browser for link information, and the ability to create and traverse links between any two selections in any document in the system (Haan, Kahn, Riley, Coombs, and Meyrowitz, 1992). The Intermedia system illustrates the ease in which information can be placed into hypermedia systems and how that information can immediately benefit other users of the system.

The Artifact-Based Collaboration (ABC) project at the University of North Carolina (Smith and Smith, 1991) is a good example of hypermedia technology being used to support groups of individuals working together to build large, complex structures. ABC has five components that include a graph server, a set of graph browsers, a set of data application programs, a shared window conferencing facility, and real-time video and audio. ABC also demonstrates the ability of hypermedia technology to assimilate new information and to quickly disseminate the information for immediate use.

4.2 THE FAA HYPERMEDIA SYSTEM

The overall goal of the FAA Hypermedia Information System (HIS) development is to study the prospects and problems of creating an electronic document. The project will also determine how these technologies can be used to improve the delivery of information to support aviation maintenance. Although focused on one particular discipline, this development should produce results that help to guide the development of many kinds of future aviation maintenance support applications, hereafter referred to as FAA integrated *information systems.*

4.2.1 Research Phases

The development of the HIS is divided into two phases that will be conducted over a two year period. The work began in July of 1991. The first eight months (Phase I) were dedicated to the prototype design and development. The results of this phase have been:

1) A functional on-line version of the Third FAA meeting on Human Factors Issues in Aircraft Maintenance and Inspection. This version is functionally equivalent to the final version to be implemented in 1992.

2) Specifications to authors of future FAA HF conference papers to aid the incorporation of new information into the HIS.

3) Reusable technology base for indexing and retrieving hypermedia text and graphics.

The second phase is currently under development and is divided into four tasks. The first task focuses on incorporating the remaining four conference proceedings into the HIS and includes the production of a CD-ROM version of the HIS. The second task focuses on enhancement of the Hypermedia technology base. The third task will involve support for the transition of Hypertext technology to FAA integrated information system research. The fourth task will focus on demonstrating and reporting research results to fellow HF team members, the project sponsor, and the HF community.

4.2.2 Features of the Hypermedia Information System

The Hypermedia Information System (HIS) was designed with a variety of features to aid a reader of the document in locating and using the information contained in the system. Most of these features were derived by analyzing the eventual information needs of the readers of the HIS, as well as reviewing state-of-the-art information retrieval and hypermedia systems. These features are discussed in the subsequent sections.

4.2.2.1 Information Browsing

The HIS allows readers to browse through the information contained in the on-line database. That is, the user is allowed to leisurely wander through the information, selecting items of interest and inspecting various topics that pique the interest of the reader. For example, some readers might browse the information looking only at the pictures that may have some relevancy to the topic at hand. Other readers might choose to view only the titles and authors of individual papers, searching for a topic that may have some application to their current task.

The HIS supports this browsing operation in two ways. First, the information is loosely structured in the database, allowing the HIS to present the same information in many different ways. Second, the HIS provides mechanisms to the readers in which they can easily locate additional information related to the current topic. For example, while reading a conference paper stored in the HIS, a reader might come across a reference to a related photograph. The HIS allows the reader to select this reference to view the actual photograph.

This method of linking, or associating, information can easily extend to other objects stored in the HIS. For example, readers can point to references to videos, animations, text, sound, etc. and request to see (or hear) this information. The HIS is able to retrieve these items and display them to the reader. This linking capability allows the reader to freely move about the information contained in the HIS, literally wandering and exploring at will.

The HIS supports linking through the use of buttons and icons (see **Figure 4.2**). Buttons allow the reader to activate certain links, while icons provide some sort of visual clue to the reader as to what the button will do when it is activated. Usually icons are a picture of some object (e.g., a video camera to represent video). However, text can also serve as an icon (e.g., the words FIGURE 62 represent the actual figure). The HIS supports both text and graphics as icons to support the reader in determining when a button is present, and what that button will do when it is activated. The HIS also contains an overview diagram of the information contained in the database (**Figure 4.3**). This overview diagram allows a reader to view the entire HIS database at once. Using the overview diagram, the reader can gain a perspective of how one piece of information is related to other information. Also from the overview, the reader can select any piece of information and go directly to it, without having to browse through the system.

4.2.2.2 Information Searching

Often a reader will come to the HIS with a specific idea of what information is needed. The chances of locating the exact piece of needed information simply by browsing are fairly low, even in relatively small documents. Even if a reader happens to come across one piece of relevant information, there might be additional information that the reader might miss. An even worse scenario is when a reader has a request for information that is not contained in the HIS. The reader might browse indefinitely without finding a relevant piece of information. The reader would not be able to tell if their lack of success was due to their bad luck in browsing or to the fact that the information did not exist at all.

To overcome these problems, the HIS provides a facility for conducting direct searches for information. The HIS contains an index into the information that aids readers by allowing them to search the index, rather than the information for a piece of information. The index contains both the search items and the location of those items in the HIS system. This technique is similar to the uses one might find in the local telephone listings. For example to locate the residence of your friend Timothy Handson, you could use the telephone listings to locate all of the entries for Timothy Handson. Once you have found the correct entry, you are able to get the address of his residence and then go to his home. This directed search method is much more efficient than browsing.

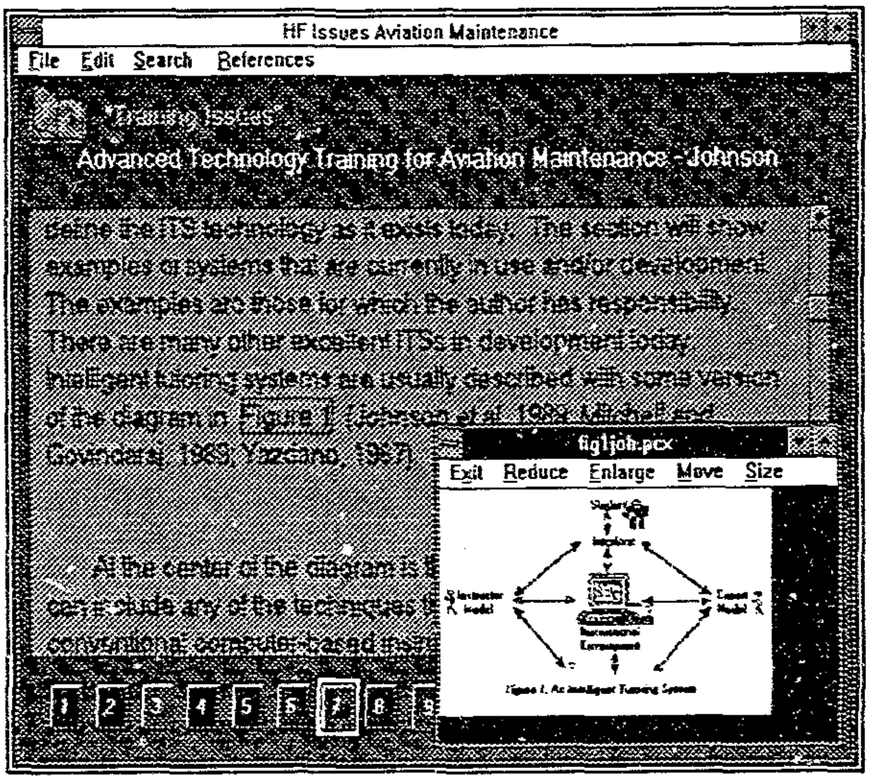

Figure 4.2 Buttons and icons allow readers to access related information

The HIS system works in a fashion to the telephone listing analogy. The HIS system contains many indices indicating exactly what each piece of information is, including what type of information it is (i.e., text, video, graphics, sound), and where it is located (i.e., exactly what conference paper, what paragraph, and what sentence). Readers using the HIS would enter a description of the information that they are looking for, and the HIS uses these indices to tell the reader where this information is located. The reader can directly "jump" to this information, bypassing the entire browsing process.

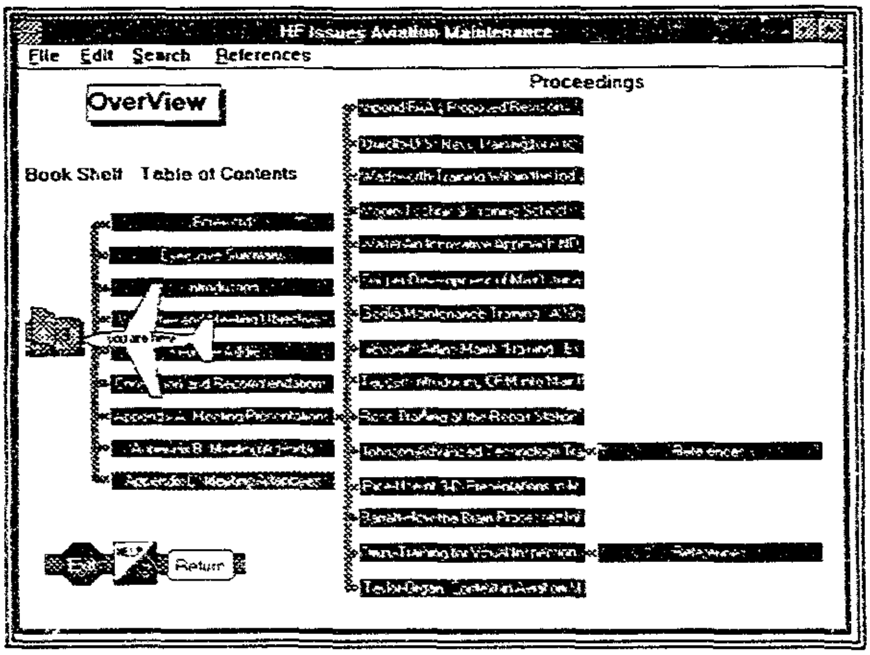

Figure 4.3 The Overview Diagram

In the present HIS system, the reader initiates a search by entering a query, or a description of the desired information, into the system (**Figure 4.4**). This query is made up of individual terms and boolean operators on those terms. For example, search terms could include: Airplane, Human Factors, Helicopter, Navigation, etc. Any word is a valid search term. The reader also uses boolean operators (AND, OR, NOT) to indicate relationships between multiple search terms. For example, a possible query could be Computer AND Training, indicating that reader is looking for a piece of information that is related to both computers and training.

The HIS uses this query to search the indices for related information. In the case of the example query above, the HIS would first look for information related to computers, then look for information related to training, and would then look for pieces of information that were in both of those wsets. The results of this search are then presented back to the reader (see **Figure 4 5**). Often, there are multiple pieces of information that match a readers query (e.g., just as there might be multiple listing for Timothy Handson in the telephone book). In this case, the readers are shown all of these matching pieces of information, and are allowed to browse through those that they feel could be relevant.

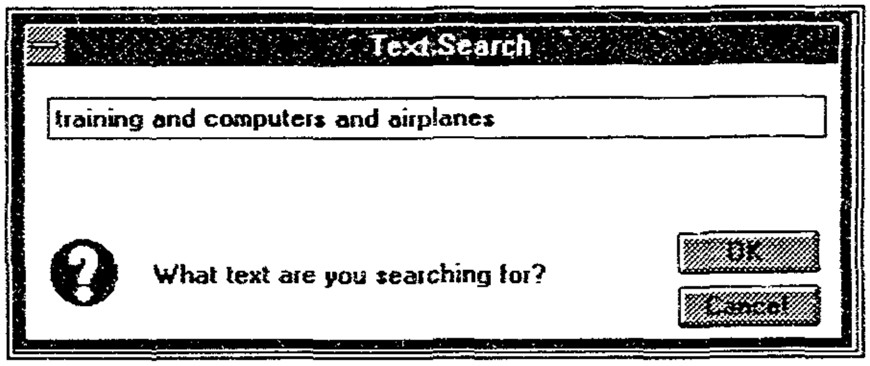

Figure 4.4 Entering Search Terms

4.2.2.3 Search Aiding

When the HIS finds multiple matches to a query, these matches are presented to the reader for review. The HIS also aids the reader in determining which matches are likely to be most relevant to their query by providing relevancy bars along with the query results (see **Figure 4.5**). The magnitude of each relevancy bar indicates the likelihood of that document being most relevant; the longer that bar, the more relevant the document is likely to be to the reader.

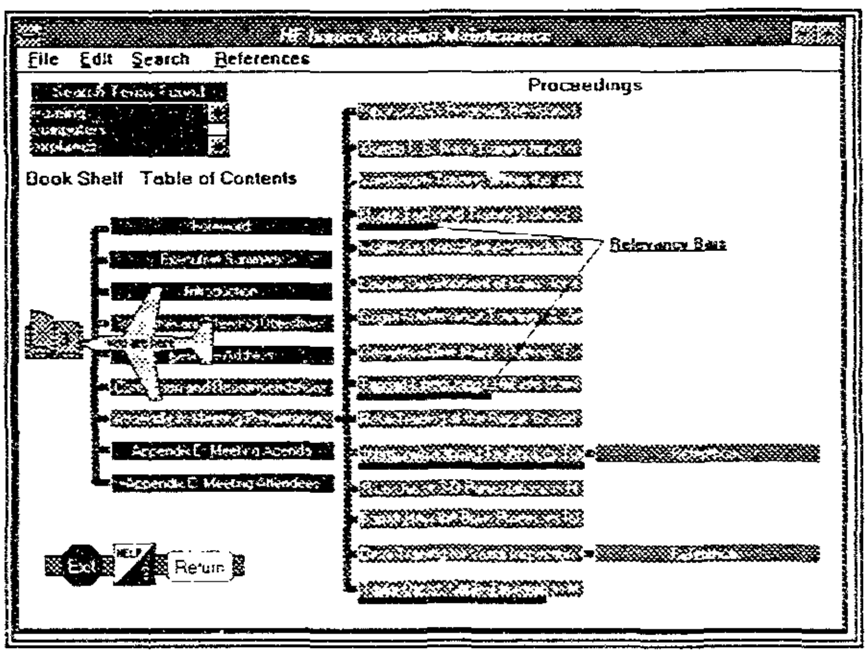

Figure 4.5 Search results are shown on the overview diagram by highlighting matching items

Another search aiding technique is allowing the reader to refine and edit previous queries. Entering a search query is usually not a one-time process. Sometimes a query is too broad, in that too many pieces of information are retrieved for the reader to handle at a time. Sometimes, a query is too narrow, yielding little or no matches to the query. Readers can refine queries either by adding or deleting search terms. The HIS retains previous queries to aid the reader in determining which queries to expand.

The HIS also aids the reader by expanding and refining queries. To be implemented in future versions of the HIS, a term thesaurus will be included to help the reader in locating additional terms that might be relevant to the desired information. These terms can the be used by the reader as part of subsequent queries into the information.

4.2.3 System Architecture

The HIS operates on an IBM PC-compatible desktop platform with 4 Megabytes of system memory, a Microsoft Mouse (or compatible), and Microsoft Windows 3.1. Initial versions of the HIS can run off of the system's hard disk, but future versions will require a CD-ROM reader to use the system, due to the large amount of information contained in the system. The overall software architecture is shown in **Figure 4.6**. The system was constructed using a variety of development tools, including: Microsoft Windows 3.1, Asymetrix Toolbook, Borland C++ Compiler, and Raima Corporation DB_Vista.

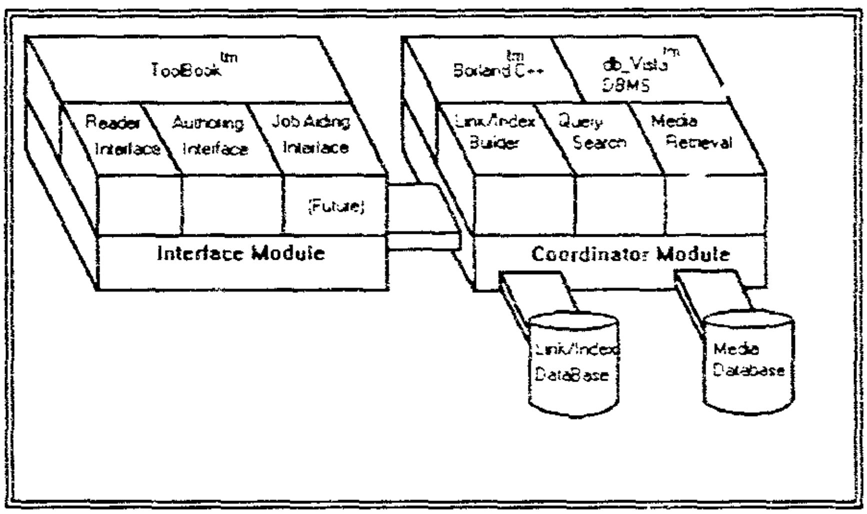

Figure 4.6 The Overall Architecture of HIS

These tools were used to construct two distinct environments. The first environment is the reader interface, which was described in earlier sections. The reader interface allows users of the information to search and browse the information contained in the HIS. The second environment, the author interface, contains tools that allow authors to place information into the HIS. These tools include editors, link builders, indexers, and database manipulation tools. Future versions of the HIS will allow access to these tools from the reader interface, thus allowing readers to store and index information in addition to the material already contained in the HIS.

The HIS contains two distinct databases. The first database, the Media Database, contains the actual information to be retrieved by the user. This material includes graphics, text, and eventually sound, animations, and other multimedia information. The second database, the Link/Index Database, contains information to help the HIS search for and retrieve information. The Link/Index database contains information regarding file location, search term location, document information, graphic information, and link structures.

4.3 CURRENT RESEARCH STATUS AND FUTURE PLANS

Phase I has produced a working prototype of HIS. It includes an on-line version of the 3rd FAA Human Factors in Aviation Maintenance meeting. This prototype is available for distribution. Directions for future research include:

1) Provide one operation for indexing the HIS information. Presently, three distinct operations are required to store this information. By integrating these three steps into a common environment, these three operations can be performed simultaneously.

2) Improve navigational strategies to allow readers to return to information already seen. Similar to the idea of "bookmarks," this strategy will allow readers to quickly mark and return to important information.

3) Improve searching strategies by providing feedback to the users regarding the effectiveness of their searches. Aids such as on-line thesauruses, enhanced search control, and relevancy feedback can be used to improve searching by even the most novice user.

4) Integrate the authoring and reader interfaces. This integration will allow future users of the HIS to incorporate relevant information into the HIS system and will allow them to rapidly associate this information with material already stored in the HIS.

5) Incorporate additional media types such as video, animations, and sound.

The technology provided by this research will be used to support the information retrieval needs across a variety of FAA and airline maintenance software support systems. Already, various training systems have benefitted from incorporating the HIS technology into these systems. Students are now able to quickly access information when it is needed during a training session. Current plans include the incorporation of the HIS technology into the various maintenance job aiding systems as well. Anticipated benefits of this marriage between hypermedia and job aiding include quicker access to information, exposure to material that might have been overlooked using conventional information access systems, and subsequent reduction of maintenance personnel error.

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Chapter Five
Human Reliability in Aircraft Inspection

5.0 INTRODUCTION

This section describes the continuing work on aircraft inspection, whose long-term objective is to enhance system reliability through human factors interventions. It builds upon the Phase I outcomes reported in Shepherd, et al., 1991, and thus does not re-justify human factors applications in this field.

Phase I provided detailed Task Descriptions and Task Analyses of many aircraft inspection activities observed at major carriers in the U.S.A. During Phase II, visits were made to other inspection sites, with coverage of regional airlines, repair centers, and sites in the U.K. (see **Section 5.3.6**). The concentration was on specific aspects of the system, such as Non-Destructive Inspection (NDI), information flow, and training. Although inspection tasks were observed, no additional formal Task Analyses are reported here.

In Phase II, the implications of the data collected earlier have been researched in more detail than was provided in Shepherd, et al., 1991. This has led to a series of studies by the research team, all under the objective of human factors interventions to improve inspection system reliability. These studies can be broadly classified into those with short-term and long-term outcomes. While the former have led to specific, on-going interventions at airline inspection sites, the latter have produced insights and on-going experiments in an off-site setting. One additional activity has been a joint project with the Civil Aeronautics Authority (CAA) in the U.K. to document and evaluate international differences in civil aircraft inspection (Drury and Lock, 1992).

Chapter 3 of Shepherd, et al., 1991 listed a set of short-term and long-term research needs, and this list has provided the guidance for Phase II work. All of these needs were derived from a basic description of the inspection system, and a generic task description of inspection. As these descriptions form the basis of all that follows, an updated system description (from Drury and Lock, 1992) is included here.

5.1 THE INSPECTION SYSTEM: A HUMAN-FACTORS DESCRIPTION

An aircraft structure is designed to be used indefinitely provided that any defects arising over time are repaired correctly. Most structural components do not have a design life, but rely on periodic inspection and repair for their integrity. There are standard systems for ensuring structural safety (e.g., Goranson and Miller, 1989), but the one which most concerns us is that which uses engineering knowledge of defect types and their time histories to specify appropriate inspection intervals. The primary defects are cracks and corrosion (which can interact destructively at times) arising respectively from repeated stretching of the structure from aerodynamic or internal pressure loads, and from weathering or harmful chemicals. Known growth rates of both defect types allow the analyst to choose intervals for inspection at which the defects will be both visible and safe. Typically, more than one such inspection is called for between the visibility level and the safety level to ensure some redundancy in the inspection process. As the inspection system is a human/machine system, continuing airworthiness has been redefined by the design process from a mechanical engineering problem to an ergonomic one. Inspection, like maintenance in general, is regulated by the FAA in the U.S.A., the CAA in the U.K., and equivalent bodies in other countries. However, enforcement can only be of following procedures (e.g., hours of training and record-keeping to show that tasks have been completed), not of the effectiveness of each inspector. Inspection is also a complex socio-technical system (Taylor, 1990), and as such, can be expected to exert stresses on the inspectors and on other organizational players (Drury, 1985).

Maintenance and inspection are scheduled on a regular basis for each aircraft, with the schedule eventually being translated into a set of job cards for the aircraft when it arrives at the maintenance site. Equipment which impedes access is removed (e.g., seats, galleys). The aircraft is cleaned, and access hatches are opened. Next comes a relatively heavy inspection load to determine any problems (cracks, corrosion, loose parts) which will need repair. During inspection, each of these inspection findings is written up as a Non-Routine Repair (NRR) item. After some NRRs are repaired, an inspector must approve or "buy back" these repairs. Thus, the workload of inspectors is very high when an aircraft arrives (often necessitating overtime working), decreases when initial inspection is complete, and slowly increases towards the end of the service (due to buybacks). Much of the inspection is carried out in the night shift, including routine inspections on the flightline, of aircraft between the last flight of the day and first flight of the next.

At a more detailed level, the task of inspection can be broken into a set of subtasks which follow in logical order. **Table 5.1** shows a generic task description based on simpler tasks for industrial inspection tasks (Drury, 1978). For each subtask, **Table 5.1** presents an example from both Visual Inspection and Non-Destructive Inspection (NDI). In a typical inspection schedule, well over 90% of the job cards are for Visual Inspection.

With these seven task steps, the complex problems of error control, design of the information environment, and development of training schemes all become more manageable as specific human factors knowledge can be brought to bear on each task step in turn. The current review of projects shows this structure clearly, both in terms of deriving the needs for rapid interventions, and in developing off-line experiments to investigate the sensitivity of human performance to systems variables.

5.2 SHORT-TERM DEMONSTRATION PROJECTS

Although human factors engineering is becoming known to the aviation maintenance community through the FAA/AAM series of meetings, there is still a need to show straightforward, practical interventions which produce relatively rapid changes. Such demonstration projects can lead to widely disseminated changes, and to a model for how human factors studies can be conducted by airlines themselves. Three projects were chosen by FAA/AAM, of which two were to be pursued during Phase II, with the choice left to the airlines themselves. The three projects were on redesign of hard-copy workcards (job cards), design of the lighting environment for inspection, and redesign of the human interface of typical NDI equipment to follow human factors principles. The first two of these to be taken up by the industry were the workcards and lighting projects, so these are described in some detail in the following sections. Other projects, including the NDI interface design, are to be performed in future years and hence are described briefly.

To our knowledge one aircraft manufacturer and one airline company have started human factors groups in the maintenance/inspection field, but this still leaves many other airlines with a shortage of human factors expertise. Information is available through the proceedings of the FAA/AAM meetings on Human Factors in Aircraft Maintenance and Inspection, but it is often either human factors specialists telling what could be done, or existing industry personnel showing what has been done without formal human factors knowledge. With this background the short-term demonstration projects have been structured to allow human factors specialists and aircraft industry personnel to work together on projects which neither could conveniently perform alone. To this end, the FAA/AAM support has provided human factors expertise, while airline partners have provided facilities and personnel with detailed knowledge of inspection of particular aircraft. The airline partners have also agreed to provide travel to and from the work site. For their cooperation, airline partners get their personnel to understand some aspects of human factors, as well as a response to their specific needs. All partners have agreed to allow dissemination of study methodology and results.

TASK DESCRIPTION	VISUAL EXAMPLE	NDT EXAMPLE
1. Initiate	Get workcard. Read and understand area to be covered.	Get workcard and eddy current equipment. Calibrate.
2. Access	Locate area on aircraft. Get into correct position.	Locate area on aircraft. Position self and equipment.
3. Search	Move eyes across area systematically. Stop if any indication.	Move probe over each rivet head. Stop if any indication.
4. Decision Making	Examine indication against remembered standards, e.g., for dishing or corrosion.	Re-probe while closely watching eddy current trace.
5. Respond	Mark defect. Write up repair sheet or if no defect, return to search.	Mark defect. Write up repair sheet or if no defect, return to search.
6. Repair	Drill out and replace rivet.	Drill out rivet. NDT on rivet hold. Drive out for oversize rivet.
7. Buy-back Inspect	Visually inspect marked area.	Visually inspect marked area.

Table 5.1 Generic Task Description of Incoming Inspection, with Examples from Visual and NDT Inspection

As these are on-going projects, with the first two due for completion in May 1992, only the needs and methodology are presented here.

5.2.1 HUMAN FACTORS IN WORKCARD DESIGN

A major air carrier has agreed to become the partner on the workcard design project, working through maintenance facilities. Although the issue of information flow within the inspection/maintenance system is complex (see **Section 5.3.3**), and high-technology interventions are possible (Johnson, 1990), many airlines have too large an investment in current hardware to consider alternatives beyond hard-copy workcards as the inspectors' primary information. Airlines often have computer-generated workcards, and wish to continue using some version of the same medium, at least in the near-term. Thus, while we are moving towards new generations of computer-based job information aids, there is still an on-going need to apply human factors techniques to existing workcard generation systems.

The workcard controls the inspection workflow by describing to the inspector the location of the work area, the area(s) to be inspected, and the inspection procedure. It is the primary document that inspectors carry during inspection.

The task analyses of aircraft inspection (Drury, Prabhu and Gramopadhye, 1990) suggested that workcards are the main source of on-line feedforward information. However, even within the relatively homogeneous sample of air carriers, there was considerable variability in the design of these documents. Since the "paper document" is currently the prevalent and preferred means by which the inspector has access to the information that is needed on the job, the availability of quality documentation is of critical importance to inspection performance.

Table 5.2 *classifies the various human factors issues which the Task Analysis data showed to be relevant* to documentation design. The workcard, which is a paper document, must be evaluated with these issues in mind. The taxonomy also provides a framework with which to design a new workcard which adheres to human factors principles.

1. Information layering	• Amount of information • Experts versus novices • *Use of cues/indications/checklists*	• Levels of information • Accessibility • *Flexibility of use*
2. Layout of information	• Spatial layout • Grouping of information • Chunking	
3. Presentation of Text	• Visual organization • Visual density • Letter case	• Word spacing • Line spacing • Line length
4. *Presentation of Graphics*	• *Visual organization* • Spatial location w.r.t. text	• *Contrast* • Labeling
5. Language Constraints	• Minimal number of words • Standardized nomenclature • Appropriate abbreviations	• Fixed syntax • Concise wording
6. Physical Implementation	• Completeness of information • Consistency across cards	• Physical accessibility • Accuracy of information

Table 5.2 A Taxonomy of Human Factors Issues in Workcard Design

Since the workcard is the means of communication of command information (both directive and feedforward), it is important to understand the effects of workcard design on the use of its information content by the inspectors. Current research in human factors and cognitive science in the areas of information processing, visual perception, learning, document design and computer display design (e.g., Wright, 1991) provide us theoretical, as well as empirical, guidelines that can be used for the design of more effective workcards. The taxonomy is an attempt to organize these guidelines to provide a framework that can direct the documentation design process.

Table 5.3 presents an analysis of the original Task Analysis data of aircraft inspection, classified using the above taxonomy. The points raised are not in any implied order of importance.

Information Layering	• None of the workcards provided layered information, i.e., the opportunity to access more detailed information on inspector selected points. • Key points were not clearly differentiated. • Little feedforward on problem areas to be expected on this aircraft at this time. • Few workcards provided checklist of probable/possible defects. • Necessary safety precautions not specified. • Task cards did not specify limits on wear, play, etc. for visual inspection to help the human inspector make more consistent judgements. • Cues indicating defects not listed in workcards, e.g. scuffed paint on fairings (of wing) indicates rubbing.
Layout of Information	• Poor legibility in some workcards. • Relevant information spread over multiple pages. • Much information of a legal or general nature occupied prime space at the top of the card. • Column layout, text boxes and other enhancements now available on computer-generated text were not used.
Presentation of Text	• Some cards were in all capitals, a violation of human factors principles. • Font design was not considered for legibility in highly variable lighting conditions. • Quality of printing and copying was not uniformly good.
Presentation of Graphics	• Workcards designed without considering correct location of graphics. • Some graphics were confusing even to experienced inspectors. • Some graphics for accessing the inspection area were ambiguous. • Most graphics were of poor quality. • Color coding was not used, but may need to be considered if it offers worthwhile performance improvements.
Language Constraints	• Procedures were not concisely worded in many workcards • There seems to be no evidence of any conscious design procedure to use fixed syntax, consistent use of phrases or a standardized nomenclature.
Physical Implementation	• Imperfect matching of nomenclature for parts and defects between worksheet and secondary source material. • Inconsistent description of tasks. Some were described very briefly and others in detail. • No tool or aid that ensures that the inspector has covered the entire inspection area. • Drawings on workcard sometimes do not match configuration of the same area on the workcard • Illumination specifications not available/not specified on workcard. • Some workcards do not have figures showing relative location of various parts. • Some workcards did not specify equipment/gauges to be used in the inspection. • Completeness and currency of information is not assured, and not, therefore, trusted by all inspectors. • Physical size and shape of workcards is not always well integrated with other tools the inspector must carry and use.

Table 5.3 Classification of Observations from the Task Analyses of Inspection, Classified by the Taxonomy of Table 5.2

5.2.1.1 A Demonstration Program for Workcard Redesign

With our airline partner, a workcard redesign program is being undertaken as a demonstration of how human factors techniques can improve inspection. Existing workcards for a small number of relatively common maintenance events (an A-check and a C-check) are being analyzed with respect to the issues derived in the taxonomy. Good and poor aspects of the workcard design have been noted, both from analysis of the workcard itself and from analysis of its use by inspectors. From this data collection phase will come a series of design requirements which, if met, will ensure good human factors design.

With airline partner representatives, design solutions will be developed to cover both short-term and long-term changes. Short-term interventions for workcards may include, for example:

1. Changing the presentation format and layout to improve ease of use and legibility.
2. Ensuring that visual material is incorporated into the worksheet.
3. Consistent naming of parts, directions, defects, and indications between all documents used by inspectors.
4. Multi-level workcard systems, useable by inspectors with different levels of immediate familiarity with the worksheet content.
5. A better physical integration between the workcard and the inspector's other documents and tools needed at the worksite.
6. Providing a better spatial integration between the workcard and the inspection tasks around the aircraft.

Each design solution will be implemented and a series of prototype workcards produced. These will be pre-tested by having inspectors use them while providing a verbal protocol of their actions. From this user evaluation will come a refined design.

The final design will be tested against the current design using controlled tests during A-checks and C-checks. Measurements will be taken of inspector verbal protocols, errors/confusions observed, and questionnaire evaluation from both inspectors and supervisors.

The results will be documented as a case-study to show:

a. How other maintenance/inspection operations can improve their workcards.
b. How to apply human factors principles to the improvement of other maintenance/inspection functions.

5.2.2 DESIGNING THE VISUAL ENVIRONMENT FOR INSPECTION

A second major carrier is cooperating with the University at Buffalo team to improve the inspector's visual environment. This project is based at the maintenance facilities operated by the carrier at a single airport. There is a single maintenance hangar, with three aircraft bays, and apron areas outside the hangar and by the gates. The main concentration will be on in-hangar activities, but other sites will also be considered. Having a single hangar makes the demonstration project manageable while still providing a representative application of human factors.

Analysis of aircraft inspection activities has shown that visual inspection dominates other inspection activities (Drury, Prabhu, and Gramopadhye, 1990). Since visual inspection is such an important component, accounting for almost 90% of all inspection activities, it is imperative that the task be performed in the most suitable work environment. From the task analysis of various inspection tasks in **Table 5.1**, it is seen that "visual search" is an important component of the inspection task, and the success of this stage is critical for successful completion of the inspection task. In visual search the inspector must closely examine each area for a list of potential faults. The amount of effort required on the part of the inspector for each area depends upon various factors such as the prior information (from training experience on the workcard) and the suitability of the physical conditions for inspections (lighting, illumination levels, etc.).

Studies in aircraft inspection have shown that poor illumination, glare, and other adverse lighting conditions could be the single most important reason for "eye strain" or visual fatigue. Visual fatigue results in deterioration in the efficiency of human performance during prolonged work. Progressively more effort is required to maintain performance, and eventually performance level decreases despite the extra effort. The purpose of this study is to identify potential sources of improvement in inspection lighting and to suggest modifications so that the task can be performed under improved visual conditions.

From the detailed Task Analyses of numerous inspection activities performed in Phase I, **Table 5.4** gives a list of examples of poor human factors design. Each represents an opportunity for intervention to improve the human/system fit and hence, increase job performance with decreased work stress.

1.	Illumination levels beneath the aircraft varied depending on the location. Measured levels during daylight ranged from 25 ft. candles under wings and fuselage areas on the side of the aircraft facing open hangar doors, to 2-5 ft. candles under the wings and fuselage on the opposite side of the aircraft.
2.	Lighting levels beneath the aircraft were adequate only for gross visual inspection.
3.	Inspectors often used a flashlight as an aid during visual inspection. It should be noted, however, that the type of flashlight used was not consistent among all inspectors even within a single aircraft operator, and varied considerably between carriers.
4.	Often it was found that the overhead lighting used for general illumination was covered with dirt and paint, inhibiting full illumination capability.
5.	Aircraft near the hangar doors were exposed to higher illumination. Illumination ranged from 16 ft. candles to 114 ft. candles.
6.	Lighting conditions were different during the day shift and night shift. During the night shift illumination ranged from 29-33 ft. candles.
7.	Supplemental lighting was often not provided under the aircraft. Measured levels in these areas ranged from a day time high of 42 ft. candles to a night time low of 1.2 ft. candles.
8.	The general lighting level inside the aircraft fuselage averaged between 1.5 t. candles to 3 ft. candles.
9.	Glare from open hangar doors within the inspector's visual field was apparent.
10.	When using supplemental lighting (flashlight, helmet light, portable fluorescent) the illumination on the aircraft surface was increased, but glare was caused when searching inside the aircraft structure.
11.	Portability of supplemental lighting was often poorly designed, and not well integrated into the inspector's kit.

Table 5.4 Observations on Visual Environment of Inspection from Task Analysis Data

In designing lighting systems, the following factors need to be considered:

- Recommended Light Levels for Different Tasks

The recommended illumination depends upon the type of task and whether the visual task is of high or low contrast. The Illuminating Engineering Society (IES, 1984) recommends that surface areas requiring visual inspection be provided with 75-100 ft. candles (800-1050 lux) of illumination. Vision can be improved by increasing the lighting level, but only up to a point, because the law of diminishing return operates (e.g., IES Lighting Handbook, New York, 1984). Increased illumination could also result in increased glare. Older persons are more affected by the glare of reflected light than younger people, and inspectors are often senior personnel within an organization.

- Selection of Light Sources for Color Rendering

In the selection of artificial light sources one of the most important considerations is color rendering, i.e., the degree to which the perceived colors of an object illuminated by various light sources match the perceived colors of the same object when illuminated by a standard light source. Color rendering could be important, because often "change in color" of true sheet metal is used as a clue to indicate corrosion.

- Direct and Indirect Lighting: Glare

The quality of illumination can be improved by reducing glare. Direct glare is caused when a source of light in the visual field is much brighter than the task material at the workplace. Thus, open hangar doors, roof lights, or even reflections off a white object such as the workcard can cause glare from surrounding surfaces. Glare can be reduced by resorting to indirect lighting. Of particular concern is that in inspecting partially-hidden areas (e.g., inside access panels) the lighting used to illuminate the defect may cause glare from surrounding surfaces. Carefully designed combinations of general area lighting, portable area task lighting and localized spotlighting need to be produced.

- Specialized Lighting

During visual inspection of an aircraft structure the inspector is looking for multiple defects, such as corrosion, ripples, hairline cracks, dents, missing rivets, damaged rivets (e.g., "pooched", "dished" rivets), and rivet cracks.

It is possible that not one single lighting system is suitable for detecting all defects. Therefore, the use of a specialized lighting system for each class of defects may be necessary. However, the use of special light systems has one major drawback. It implies that the area must be examined for each class of defects sequentially rather than simultaneously, which could involve time and expense. A typical example is the difference between general illumination and the grazing illumination provided by special purpose lighting. The diffused nature of general illumination tends to wash out the shadows while the surface grazing light relies upon showing shadows to emphasize objects that project above or below the surface. Task visibility for surface topography is distinctly better with grazing light, whereas color changes or corrosion may be better seen under general illumination. An example of surface topography is the inspection of the fuselage for ripples. Ripples are easy to detect using surface-grazing light but general illumination tends to wash them out. However, strong side lighting may mask important color differences.

- Design Requirements for Lighting

Studies of visual search have shown that the speed and accuracy with which the search process can be accomplished is dependent on the conspicuity of the defect, which in turn is dependent on the size of the defect, defect/background contrast, and lighting intensity (see **Section 5.3.3**).

Lighting design has a clear impact upon the final two variables, but it has broader requirements to fulfill as visual inspection involves more than visual search. Lighting should be designed such that the following tasks can all be performed satisfactorily and preferably optimally:

1. Inspection (visual search) of the aircraft fuselage for defects.
2. Reading the workcard/instructions.
3. Movement around the aircraft (using the scaffolding, or equipment, e.g., cherrypicker).

In addition, special purpose lighting should not interfere with any other parallel task in progress. In designing the visual environment, one must consider the minimum lighting requirements for each task and subtask, the type of artificial light sources that can be used to illuminate the work surface, the amount of task lighting that can be provided, and the available methods to minimize glare. These factors must be balanced with implementation and operating costs.

Since inspectors have to move to different areas on the aircraft during a single task and all areas may not be accessible to generalized lighting from a static source, generalized lighting may be augmented from a combination of static portable sources, and then further augmented, if necessary, using flashlights.

It is proposed to use the Task Analyses performed so far and lighting surveys of the inspection work areas to determine the design requirements for lighting in detail. The market will then be surveyed for available solutions (e.g., area lights, flashlights, headlights, stand lights) to choose a small number of promising systems. On-site human factors evaluations of these lighting systems will be performed to determine which, if any, improves visibility of defects or other indications to inspectors, while maintaining portability.

The specific steps to be undertaken for this project are:

1. Site visit and task analysis to determine specific visual requirements and lighting requirements of tasks, and the current visual environment. Luminance and illuminance will be measured throughout the hangar to determine consistency and adequacy. A checklist of visual factors (from Drury, 1990a) will be used to assess the adequacy for the specific tasks performed.

2. Survey market for available solutions to identify promising systems for illumination, diffusion and specialized lighting.

3. On-site human factors evaluation of selected lighting system to demonstrate advantages. This will include performance evaluation (speed, accuracy) as well as operator acceptability and cost.

4. Produce a set of design recommendations which can be used as the basis for future lighting design.

5.2.3 FUTURE SHORT-TERM PROJECTS

The research will continue to focus on long- as well as short- term projects. These short-term, immediate payoff projects will study such topics as using portable computers for development and evaluation of multi-level job cards. Such studies will involve airline and/or manufacturer participation to ensure that research results and by-products can readily be transitioned into aircraft maintenance work environments.

5.3 LONG-TERM RESEARCH PROJECTS

From Phase I came a wealth of Task Analysis data and descriptions of specific inspection and maintenance organizations at many carriers. In addition, information from the FAA/OAM meetings, reports and visits to aircraft manufacturers and specialized equipment suppliers, gave a clear description of the inspection and maintenance system to the human factors engineers involved. The Phase I report (Shepherd, et al., 1991) made a first attempt to merge this data with existing and current concepts in human factors. An obvious need was to perform this integration at a deeper level to guide the long-term human factors needs of the aviation maintenance industry. During Phase II, this step was undertaken; system demands were interpreted in terms of known human capabilities and limitations.

The first fruits of this process were four reports which covered a framework for human reliability in this field, a detailed examination of the information environment, an analysis of the effects of time on inspection (especially the speed/accuracy tradeoff), and a study of the improvement of training for visual inspection. These reports are listed with other publications at the end of this section. The findings of each report are summarized in **Sections 5.3.1** through **5.3.5**, augmented where necessary by off-line experiments. Additionally, a joint venture between the FAA and the CAA on inspection is presented as **Section 5.3.6.**

5.3.1 COMPUTER-BASED INSPECTION EXPERIMENTS

It became apparent that the traditional experimental work in aviation inspection was not always the best way to perform human factors evaluations. Studies of crack detection probabilities (ref) have been large, costly, and complex, but have not addressed many of the human factors issues beyond the psychophysics of NDI equipment. Factors such as training method, information environment, and time pressure have not been systematically considered. Thus, the need was recognized for a low-cost but realistic simulator for aircraft inspection. Its purpose is <u>not</u> to provide a point estimate of the probability of detection of a given crack, but rather to determine how inspection performance is affected by manipulable human factors such as those above. There is sufficient knowledge of models of human inspectors (e.g., review by Drury, 1991) to be able to determine which aspects of the real task to retain if a simulator is to be "realistic".

Two simulation programs were implemented on a SUN Sparc station 1 workstation, one for an NDI task (eddy current inspection of rivets) and the other for a visual task (visual inspection of rivets and sheet metal). These programs are discussed below.

5.3.1.1 NDI (Eddy-Current) Inspection Program

The inspection task consists of inspecting rows of fuselage rivets for cracks using an eddy-current probe. The simulator display consists of four windows (**Figure 5.1**) as follows:

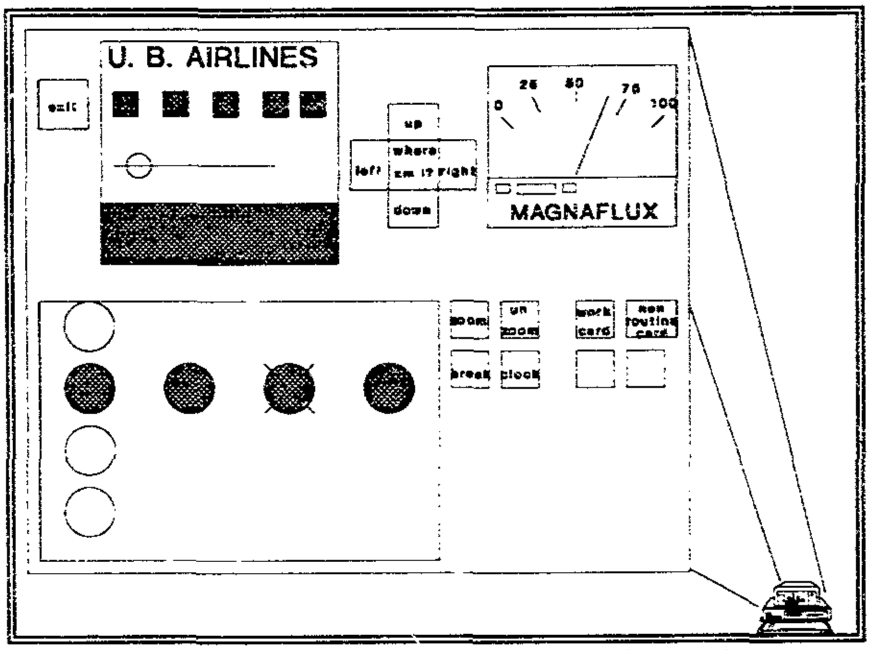

Figure 5.1 NDI Inspection Task Simulation

Inspection Window. This window displays the rivets to be inspected. Six rivets per row are displayed at a time. The simulation program has the capability to display multiple rivet rows at a time. During the training session a circle is placed around each rivet to help the subjects in defining the optimal probe path around the rivet for defect detection. On the upper right hand corner of this window there is an indicator that is green when the subject is in the inspection mode. During this mode, the subject is able to inspect and classify (defective/non-defective) the rivets, but has no access to any of the functions outside the current window. To obtain access to these functions, the subject has to click the left mouse button near any of the rivets. This results in a circular marker being placed around that rivet and the inspection indicator light turns white, indicating the inspection mode is switched off.

Macro-View and Directionals. The macro-view in the upper left window allows the subject to have a view of the total inspection area and its relation to the aircraft fuselage. Thus, for a 400 rivet inspection task, while only six rivets are seen in the inspection window, the entire 400 rivets are marked (on a smaller scale) in the macro-view. A click on the where-am-I button places a circle around the area of the macro-view currently in the inspection window. Thus, the subject is able to determine where he/she is at any point in time with relation to the entire task.

The directionals consists of four square areas marked left, up, right and down (L/U/R/D, clockwise). Clicking the left mouse button on any one of these areas shifts the view (scrolls) in the inspection window in the indicated direction.

Eddy Current Meter. The defect indication is displayed on the meter indicator in the upper right window of the monitor screen. The meter has a fixed scale with divisions marked from 0 to 100, and a moving indicator. A red marker is provided that can be set by the subject at any point on the scale. The deflection of the needle (from its resting position at zero) beyond this set point (default = 60) produces an auditory alarm as well as a red flash of the indicator light at the apex of the meter.

The point of the needle is deflected if any of the following happen:

1. The mouse cursor is moved over a crack on the rivet (the cracks themselves are not visible).
2. The mouse cursor is moved over a grey spot (indicating corrosion, or dent; randomly placed across rivets).
3. The mouse cursor is very close to, or moved over, the rivet head itself.

Subjects are instructed that if the deflection is greater than 60% and they judge it to be from a crack, then the rivet should be marked bad.

Lower Right Window. This area contains functional (dialogue) buttons. Activation of the zoom button allows the subject to take a closer look at the current rivet to be inspected. The zoom is incremental and magnifies the area to twice its original size (within the inspection window) at every click. A mouse click on the unzoom area restores the inspection window to its original condition. Clicking on the "break" area stops all clocks and covers the inspection window to allow the subject to take breaks. Clicking on the "clock" area displays the time elapsed in the task. The other functional buttons includes "display non-routine card," "display workcard," and "turn rivet numbers on/off."

The program also has the facility for recording the subject's assessment of workload using the Pearson Feeling Tone Checklist and the Modified Cooper-Harper Scale. These two scales appear for response at the end of pre-set intervals.

5.3.1.2 Visual Inspection Program

To simulate visual inspection, the SUN Sparc station 1 is used with a program having similar logic and displays to the NDI program. The major differences are that detection is visual, and that the eddy-current meter is obviously absent. In this task the inspector searches for multiple defect types and classifies them into different severity categories. The various fault types with their descriptions are:

1. Missing Rivet: A rivet missing from the rivet hole.
2. Damaged Rivet: Part or all of the rivet head is damaged resulting in jagged edges.
3. Pooched/Dished Rivets: Rivets with a center which appears raised or sunken.
4. Loose Rivets: Rivets running loose in the rivet holes.
5. Rivet Cracks: Cracks which originate at the edges of the rivets and propagate upwards and outwards.
6. Dents: Sheet metal damage in the aircraft fuselage represented by sunken areas.
7. Corrosion: Damage to sheet metal surface represented by patches of discolored or raised skin.

Depending upon the severity of the defect type, the defects can be classified into critical and noncritical defects.

The layout of the multi-window simulated inspection task is shown in **Figure 5.2**. The function of each window is as follows:

Inspection Window. The area currently being inspected is shown in the left (large) window. To simulate the use of local lighting, such as a flashlight beam, only a smaller window within this area is fully illuminated. Within this smaller window, faults can be seen and responded to by clicking them using the mouse button. The entire area of the inspection window can be viewed by successive movements of the smaller illuminated window.

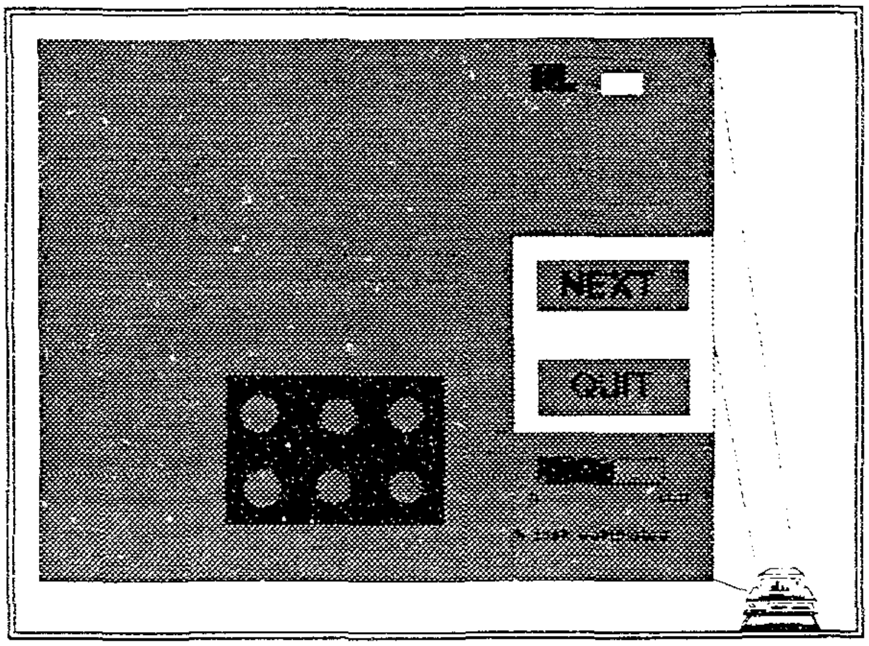

Figure 5.2 Layout of the Simulated Inspection Task

Search Monitor Window. This is a monitoring device which helps the inspector keep track of the window movement in the inspection window. It provides the inspector feedback as to the:

1. Point of previous fixation
2. The sequence (pattern) adopted by the inspector
3. The area covered (viewed through the window) up to the current time.

The small illuminated window in the inspection window is represented by a tile in the search monitoring window. As the window is moved, so does the tile. The tile has a different color from its illuminated background area. The background color changes to the color of the tile as the tile passes over it, indicating that the corresponding areas have been fixated (covered by the window). The darkest shade of the tile is the point of previous fixation. The sequence is given by the shade of the color--lighter shades indicate earlier fixations in sequence while darker shades indicate later fixations.

Macro View Window. This window represents the entire task to be inspected, and can be looked upon as the global coordinate referencing system. Thus, it provides information to the inspector as to his current position with reference to the entire task.

5.3.2 A FRAMEWORK FOR HUMAN RELIABILITY IN AIRCRAFT INSPECTION

Maintaining civil aircraft worthiness requires the reliability of a complex, socio-technical system. This system's reliability is dependent on the reliability of its components (i.e., equipment, inspectors, the physical environment), and on how reliably these components interact. Most errors in aircraft inspection and maintenance can ultimately be attributed, at some level, to a human-system mismatch. Operators may cause errors outright, or more likely, human information processing limitations and characteristics may be "catalytic" factors (Rouse and Rouse, 1983), combining with other component characters to evolve "sneak paths" (Rasmussen, 1982) to error situations.

The assessment of human error in complex systems is currently undergoing somewhat of a renaissance (Brown and Groeger, 1990). Classification schemes of errors have expanded from the early "omission/commission" classification (Swain and Guttman, 1983 and Meister, 1971) to more behavior-based classifications (e.g., Norman, 1981; Rasmussen, 1982; Rouse and Rouse, 1983, and Reason, 1990).

While error classifications based on task characteristics may provide a convenient descriptive format for errors, error models based on human behavior can define causal mechanisms of errors. Identification of causal mechanisms and catalytic factors is necessary for predicting errors and thereby designing error tolerant systems. The approach taken here is to use a behavior-based and system-based human error classification scheme to identify, predict, prevent or reduce, and report errors in aircraft inspection and maintenance.

This section focuses on describing a methodology to accomplish these goals. **Section 5.3.2** provides more detail in defining information flow, and deriving information requirements which will prevent or mitigate the effects of information flow-related errors. Both this section and **Section 5.3.3** are responses to FAA project activities and exist elsewhere as two self-contained separate reports (Latorella and Drury, 1991, and Drury and Prabhu, 1991, respectively). These reports have been considerably abbreviated for their presentation in this report. Both efforts use Rasmussen's (1986) cognitive control levels and Rasmussen and Vicente's (1989) systemic error mechanisms extensively as a conceptual foundation. Both efforts also begin with Drury's (1991) Failure Modes and Effects Analysis (FMEA) of errors in aircraft inspection and maintenance. These concepts and the FMEA are presented only in the first section to avoid redundancy. As a result, some of the material presented in **Section 5.3.3** is dependent on the theoretical and data analysis foundation described in this section.

5.3.2.1 Approaches to Human Error

5.3.2.1.1 Quantitative Approaches

Early efforts to incorporate human performance in the evaluation of system reliability spawned the field of Human Reliability Assessment (HRA). These methods attempt to assess human reliability with the same techniques used to assess equipment reliability (Meister, 1971). They seek to: (1) develop extensive databases of human reliability data for elemental tasks, (2) provide a method for combining these estimates to generate a measure of human reliability within the system, (3) use this measure of human reliability directly, *as the reliability of the human as a system component, in evaluations of total system reliability* by Probabilistic Risk Assessment (PRA). Early HRA methods are criticized for their overly-structured, and hence cumbersome, representations of the human's involvement in systems. HRA methods are also criticized for their inability to adequately represent the behavioral mechanisms of human errors and hence for their inability to prescribe, rather than merely describe, systems in terms of their propensity for error situations. Quantitative human error assessment techniques include decompositional probabilistic methods (e.g., Fault Trees, Event Trees, Failure Modes and Effects Analysis), classical reliability theory based on Markov modeling, stochastic simulation modeling, and a variety of other techniques (e.g., HCR, TESEO, SLIM-MAUD). These approaches are each described and critiqued in Latorella and Drury (1991). Lock and Strutt (1985) have investigated quantitative human error modeling in the aircraft inspection and maintenance context.

5.3.2.1.2 Qualitative Approaches

Several researchers have arrived at behavior-based classification schemes for human errors. Those of Norman, Hollnagel, Rasmussen, and Rouse and Rouse are described below. Elements of these schemes have been in approaches to managing errors in aircraft maintenance and inspection.

Norman. Norman (1980, 1981) classifies human error into two fundamental categories: slips and mistakes. Slips result from automated behavior when the intention, the goal, is correct but some aspect of the execution is flawed. Mistakes, in contrast, are the result of flawed cognitive processes, such as formation of the wrong goal. Slips are usually minor errors and are often evident and corrected by the perpetrator. Mistakes, however, are more serious errors, and are sometimes opaque to the perpetrator. Mistakes are therefore usually difficult to observe and recover. Slips are partially due to limitations in attention and therefore are more likely to occur in distracting, time-sharing, boring, or stressful situations. Norman identifies six types of slips: capture errors, description errors, data driven errors, associative activation errors, loss of activation errors, and mode errors. Descriptions of these types of slips and examples related to aircraft inspection and maintenance can be found in the original report (Latorella and Drury, 1991). Norman's (1981) classification is intuitively appealing and useful for describing errors. However, the slip/mistake classification is not detailed enough to describe what specific aspects of human information processing generate errors.

Hollnagel. Hollnagel (1989) introduces the conceptual distinction between error phenotypes and error genotypes. Error phenotypes are observable states which are deemed undesirable. Error genotypes are the generative mechanisms of these observable states. Error phenotypes are manifestations of error genotypes expressed in a particular environment. While Hollnagel allows that combining genotypes and phenotypes provides a more complete psychological description of human error, he holds an empiricist's view for the purpose of system design: in order to automate error detection, errors can only be expressed in terms of phenotypes. He therefore proposes a taxonomy to operationalize phenotypes, describe complex phenotypes (combinations of simple phenotypes), and to provide a basis for a computer program which detects error situations. Hollnagel's distinction between error phenotypes and error genotypes is important and is used in the development of this paper's approach to managing aircraft inspection and maintenance errors.

Rasmussen. Rasmussen has contributed to HRA in two veins: he has developed models of human performance in an effort to identify fundamental causes of human error, and he has related and defined the importance of qualitative human error modeling to system reliability. Rasmussen departs from the more traditional approaches in his conceptualization of human error. He does not rely on the constrained definition of human error presented in most HRA techniques, rather he states that what is human error is defined by not only the human, but by system and operational tolerances (Rasmussen, 1982). Rasmussen also argues that human errors defined by the outcome of events should not necessarily be attributed to a human having performed incorrectly. For example, should an error resulting from a new situation be attributed to the human? If an error provides feedback about the system without compromising system functioning, should it still be considered something to avoid? Rasmussen also defines stipulations for collecting HRA error rate probabilities and states the case for qualitative error modeling to aid HRA in ways that error rates can not, such as prediction and corrections of errors, especially of low probability, high impact "sneak paths". Rasmussen (1982) developed a classification of human error towards this end.

The skill-rule-knowledge (SRK) framework proposed by Rasmussen (1986) classifies human behavior into three categories of ascending complexity: skill-based behavior, rule-based behavior and knowledge-based behavior. Any decision is made at the lowest level possible, with progression to higher levels only when a lower level fails to reach a decision.

Skill-based behavior represents psychomotor behavior without conscious control, consisting of automated routines that are driven by sensory data received as "signals" from the environment (Rasmussen, 1986). Signals represent information that is a quantitative indicator of the temporal and spatial aspects of the environment, and may trigger skill-based behavior by activating the automated behavioral routines of the human. Skill-based behavior is normally based on feedforward control and proceeds without conscious attention.

From the aircraft inspection viewpoint, the movement of the pencil probe around a rivet or a sliding probe along a stringer (a row of rivets) during, for example, an eddy current inspection or an ultra-sonic inspection, represents skill-based sensorimotor performance involving some amount of feedback control. Similarly, the pre-attentive phase of visual search, as well as the extra-foveal process in extended visual search can be considered to be skill-based behaviors that are data driven and based on feedforward control.

Rule-based behavior represents consciously controlled, goal-oriented behavior guided by rules or procedures for action. These rules are stored patterns of behavior that have been empirically derived during previous occasions or communicated as instructions from an external source (Rasmussen, 1986). Information during rule-based performance is perceived as "signs" which represent information that activates or modifies the rules and depicts situations or environmental features along with the conditions to act (Rasmussen, 1986). Rule-based behavior proceeds towards a goal, utilizing feedforward control through rules and without demanding any deeper reasoning on the part of the human.

In aircraft inspection, an experienced inspector interpreting the deflection of the ultra-sonic meter, or the pattern traced on an oscilloscope during eddy current testing, can be assumed to be indulging in a rule-based behavior if the "signs" are familiar. Similarly, the extra-foveal process in search where cues on the periphery guide the next fixation can be considered a rule-based behavior. Rule-based search can also result from information gathered in the foveal component, for example bulging of aircraft skin triggers search for corrosion. Pre-determined search strategies, as a result of past experience, training, or work card instructions, can also lead to a rule-based behavior.

Knowledge-based behavior represents goal-controlled, problem-solving performance in unfamiliar situations. It requires a functional understanding of the system, analysis of the current state, and response of the environment based on conscious, advanced reasoning while utilizing feedback control for error correction (Rasmussen, 1986). During knowledge-based behavior, the human perceives information as "symbols", i.e., concepts about the functional aspects of the environment which refer to an internal representation that can be used by the human for reasoning (Rasmussen, 1986).

In aircraft inspection, knowledge-based behavior can occur in NDI, for example during eddy current testing of rivets, when the inspector sees a curve traced on the oscilloscope screen of a shape never encountered before. In this case the inspector has to use the knowledge of eddy current technology, knowledge about the instrument, knowledge about the aircraft, etc., to interpret whether the signal represents a crack or not. Along similar lines, the use of cues to detect visual defects needs active reasoning (knowledge-based behavior) until the association of the cue to the defect is confirmed, in which case the cue will trigger rule-based behavior.

Rasmussen (1982) provides a framework for classifying causes of human error as a function of situational and task characteristics and the error phenomenon. Basic error mechanisms are derived through the use of a human information processing model, linking human decision-making and responses to internal processes. His model can be used to describe human behavior over the three levels of cognitive control, and can be used to indicate decision aiding devices and training needs at these different levels. He specifically mentions that systems must be designed with interlocks and barriers where it is unreasonable to expect operators not to err and that systems should allow errors to be observed and reversed. A related work (Rasmussen and Vicente, 1989) identifies four systemic error mechanism categories: (1) effects of learning and adaptation, (2) interference among competing control structures, (3) lack of resources, and (4) stochastic variability of individuals. Rasmussen and Vicente (1989) describe examples of errors within these categories and cognitive control levels (see **Table 5.5**). Similarly, Drury and Prabhu (1991) used the cognitive control classification to organize error shaping factors (see **Table 5.6**).

EFFECTS OF LEARNING AND ADAPTATION:	
• *Knowledge-based:*	Search for information and hypothesis testings in novel situations may lead to acts which are judged as errors after the fact;
• *Rule-based:*	The law of least effort may lead to underspecified cues;
• *Skill-based:*	Optimization of motor skill needs feedback from boundaries of acceptable performance (speed-accuracy tradeoff);
INTERFERENCE AMONG COMPETING CONTROL STRUCTURES:	
• *Knowledge-based:*	False analogies; interference in means-end hierarchy;
• *Rule-based:*	Functional fixation; adherence to familiar rules;
• *Skill-based:*	Capture by frequently used motor schemata;
LACK OF RESOURCES:	
• *Knowledge-based:*	*Limitations of linear reasoning in causal networks; insufficient knowledge, time, force, etc.;*
• *Rule-based:*	Inadequate memory for rules;
• *Skill-based:*	Lack of speed, precision, force;
STOCHASTIC VARIABILITY:	
• *Knowledge-based:*	Slips of memory in mental models,
• *Rule-based:*	Erroneous recall of data or parameters related to rules;
• *Skill-based:*	Variability of attention; variability of motor parameters, motor noise (variation in force, precision of movements);

Table 5.5 Potential Errors Described by Level of Cognitive Control and Systemic Error Mechanisms (*Rasmussen and Vicente, 1989*)

Rouse and Rouse. Rouse and Rouse (1983) propose a behavioral classification scheme for human errors which borrows heavily from Rasmussen's contributions. They attempt to analyze human error in terms of causes, as well as contributing factors and events. Their scheme organizes human errors around Rasmussen's flow model (1976) of an operator's information processing task. This model gives the following steps in task performance:

KNOWLEDGE-BASED ERROR SHAPING FACTORS	
Information Overload	• Excessive demands on memory.
Incomplete Knowledge	• Knowledge lacking on system dynamics, parameters, side effects, etc.
Delayed Feedback	• Delays in feedback concerning the execution of decisions.
Bounded Rationality	• Limited cognitive capacity relative to problem size leads to satisficing behavior.
Memory Cueing	• Familiar information in LTM is cued by problem content.
Insufficient Consideration of Process	• Past history disregarded when handling dynamic current events.
Causal Series Vs. Nets	
Attentional Limitations	• Oversimplification of causality, thinking in terms of immediate goals.
Confirmation Bias	• Finite resources of attentional processes.
Vagabonding	• Tendency to maintain current hypothesis facing contradictory evidence.
Overconfidence	• Moving amongst issues without detailed consideration of any one.
Memory Slip	• Exc ıssive belief in the correctness of one's own knowledge.
Selectivity	• Memory failure due to faulty activation of schemata.
	• Selectively process information. Attention to wrong features of task can result.
Biased Reviewing	• Error in reviewing planned course of action.
Illusory Correlation	• Failure to detect correlation or understand the logic of covariation.
Lack of Resources	• Lack of mental capacity for causal reasoning, insufficient knowledge.
Complexity Problems	• Problems in understanding system due to its complex nature.
RULE-BASED ERROR SHAPING FACTORS	
Availability	• Tendency to use intuitive rules or use rules that readily come to mind.
Countersigns	• These are input indications that the more general rule is inapplicable.
Rigidity	• Mindset (cognitive conservatism) results in refusal to change familiar procedure.
Encoding Deficiency	• Encode inaccurately or fail to encode the properties of the problem space.
Inadvisable Rules	• Rules that satisfy immediate goals but can cause errors due to side effects.
Wrong Rules	• Rules that are wrong for the current situation.
Inelegant Rules	• Rules that achieve the goal but are inefficient.
First Exceptions	• Errors caused on first occasion that is an exception to the general rule.
SKILL-BASED ERROR SHAPING FACTORS	
Omissions	• Omission of actions/action sequences needed to achieve a specified goal.
Perceptual Confusion	• A familiar match is accepted instead of the correct match.
SATO	• Speed accuracy tradeoff.
Motor Schemata Capture	• Focussed attention absence leads to takeover by frequently used schemata.
Stochastic Variability	• Variability in control of movements.
Reduced Intentionality	• Delay between intention and action.
Repetitions	• Actions that are unnecessarily repeated.
Reversals	• Unintentionally reversing an action just committed.
Interference	• Potential problems stemming from concurrent activities.

Table 5.6 Definitions of Error Shaping Factors (Prabhu, Sharit and Drury, 1992)

1. Observation of system state
2. Choice of hypothesis
3. Testing of hypothesis
4. Choice of goal
5. Choice of procedure
6. Execution of procedure.

This classification scheme has been used to record and analyze human errors in several contexts: (1) detection, diagnosis, and compensation of engine room failures in a supertanker (van Eckhout and Rouse, 1981), (2) human errors in troubleshooting live aircraft power plants (Johnson and Rouse, 1982), and (3) aircraft pilots in mission flights (Rouse, Rouse and Hammer, 1982). Results of these studies have been applied to the improvement of training programs and the development of checklists and other decision aids.

5.3.2.1.3 Human Error in Aircraft Inspection and Maintenance

Whereas previous research in aircraft inspection and maintenance has utilized various empirical human factors techniques, this effort uses a behavior-based human error modeling approach, housed in a conceptual aircraft inspection and maintenance system model (see **Figure 5.3**). The system model provides a framework for error classification and therefore, a basis for improved error management. The following section describes the system model of aircraft inspection and maintenance. The final section details how the model might be useful for managing aircraft inspection and maintenance errors.

5.3.2.2 A System Model for Human Error in Maintenance and Inspection

The fact that errors emerge from, and are defined by, the interaction of system characteristics, indicates the necessity of a system approach to the description and control of these errors. Such a system view of aircraft inspection and maintenance includes not only the traditional interaction of the operator and task requirements, but also includes operator interactions with equipment, documentation, and other personnel within the constraints imposed by the environment. The system model (Latorella and Drury, 1991) contains four components: operators (personnel), equipment, documentation, and task requirements. These components are subject to constraints of both the physical environment and the social environment. The job component can also be considered as a subset of the organizational environment in which tasks are defined. Similarly, the workspace component is a subset of the physical environment. This conceptual model is two dimensional as shown in **Figure 5.3**. The temporal sequence of the individual tasks defines an axis orthogonal to the page. All other system elements interact with the current task component as shown in the plan view. Each individual task is subject to different combinations and degrees of influences from other system components, presented below.

Operators. Aircraft maintenance and inspection **operators (O)** differ between organizations but belong in the same basic categories: inspectors (perhaps distinguished as either visual or NDT), maintenance, utility, lead inspectors, lead maintenance, inspection foremen, maintenance foremen, production foremen, and engineers. In addition to carrying out sequences of activities, personnel serve as informational resources to each other. Communication between personnel can be viewed as an information processing task similar to referencing a document. The organizational structure of the system imposes constraints on the amount of, format of, and the personnel likely to engage in, collaborative problem-solving communications. The affective and physical characteristics of people are also important. An individual's affect can influence motivation and hence, performance. Physical characteristics affect perception (e.g., visual acuity), access (e.g., anthropometry), and other tasks.

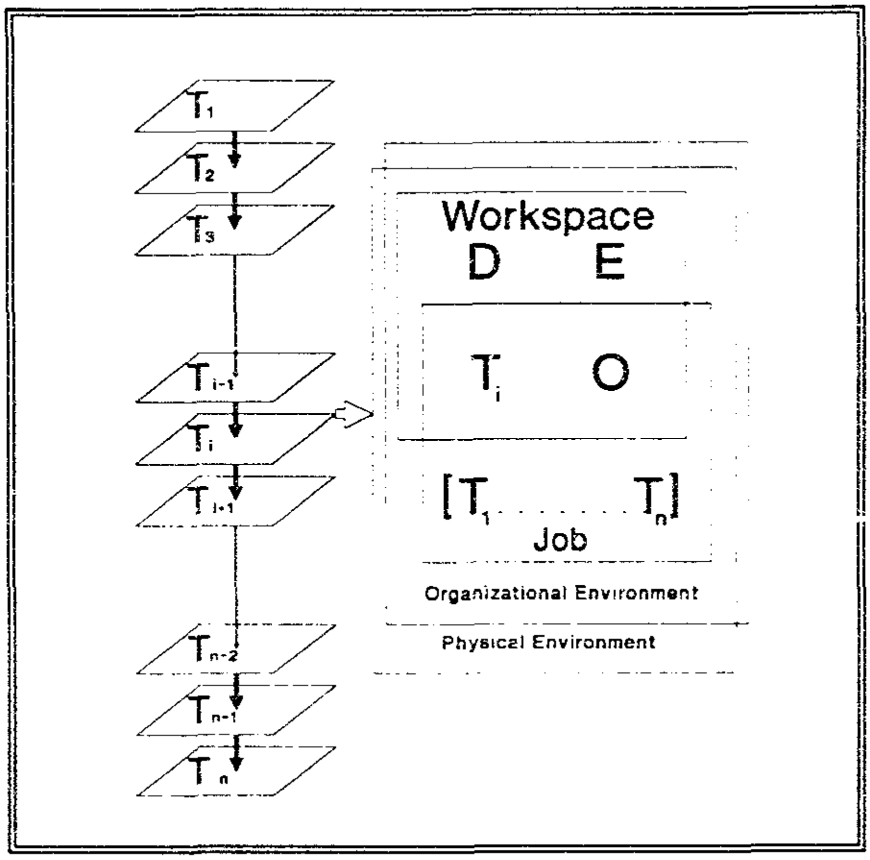

Figure 5.3 System Mode

Equipment. Both visual and NDT inspection use **equipment (E)**. There is specialized equipment for different types of NDT, including: eddy current, ultrasonic, magnetic resonance, X-Ray, and dye penetrant. Visual inspection requires flashlights, mirrors, and rulers. Use of this equipment requires specialized knowledge of its operating principles, and equally specialized knowledge for the interpretation of its output. Interpretation of visual stimuli or NDT output necessarily requires information processing by the operator, but may also require communication with other personnel. The ability to perceive the information present in the visual stimuli or NDT output may be affected by environmental conditions, such as poor lighting. The ability to operate NDT equipment properly may also be affected by environmental factors. For example, some temperature and humidity combinations make precise movements difficult..

Documents. A variety of **documents (D)** is required for inspection and maintenance. Workcards, which may include graphics and references to more comprehensive standards manuals, specify the task to be performed. Forms (shift turnovers, NRRs) are used to communicate between personnel and to document procedures, while additional documentation is used for training and retraining purposes. The ability to communicate effectively through documentation is based on many factors. The fields specified on forms dictate the information and the structure of that information. Physical characteristics of forms, documents, and graphics affect the legibility of information and therefore, impact the ability to accurately perceive this information. Issues of comprehension are important for understanding the content of documents. Issues of representation are central to ensuring that graphics are appropriate and useful.

Task. A **task (Ti)** is defined as the actions and elements of one workcard or similar task order. Task characteristics which have been found to influence inspection include: defect probability, physical characteristics of the defect, the number of serial inspections, feedforward and feedback availability, and whether standards are used (Rodgers, 1983). These aspects of the task necessarily interact with personnel, organizational, job, and environmental characteristics. Personal information processing biases may interact with the task structure and present problems such as searching in the wrong area. The definition of a defect is part of the task which is ultimately established by the organization. An indication, which implies a defect, is defined as that magnitude which indicates that, given the cost/benefit tradeoff of repairing versus not repairing, a repair should be performed. The organization also dictates whether feedforward, feedback, and standards are used in inspection. The interaction of task characteristics and job characteristics may produce effects on inspection performance. The probability of defects affects the arousal level of an inspection and the expectation of finding a fault, which is also affected by the length of time an inspector performs a task and by physical factors such as fatigue.

Job. **Jobs (J)** are defined by the collection of tasks that an individual is expected to perform. However, there are many characteristics of the job which can not be described by the characteristics of its individual tasks. Job factors are derivative of the organizational environment and provide constraints for tasks (e.g., shift durations, work/rest cycles, day/night shifts, job rotation policies). These can further impact personnel physical (e.g., fatigue, eyestrain), affective (e.g., motivation, job satisfaction), and information processing (e.g., attention allocation) characteristics.

Workspace. The workspace, a subset of the physical environment, contains the task and the equipment, documentation, and personnel required to perform the task. While illumination is an attribute of the physical environment in general, task lighting (such as a flashlight) is an attribute of the workspace. The degree of physical access afforded by the workspace is an important constraint on performance. Both these issues are currently being researched under continued funding on this contract (Gramopadhye, Reynolds, and Drury, 1992).

Physical Environment. The physical environment is described by several parameters: temperature, noise level and type of noises, lighting level and light characteristics, and electrical and chemical sources. While some of these factors can either enhance or degrade performance, others indicate potentially hazardous conditions. The level and spectral characteristics of lighting affects the perception of fault indications. Impulse noises interrupt tasks and may result in skipped or unnecessarily repeated procedures. The level and frequency characteristics of noise affect the ability to communicate. Examples of hazardous conditions in the physical environment are exposure to X-rays emitted during X-ray NDT and fuel fumes encountered when inspecting the inside of a fuel tank.

Organizational Environment. The organizational environment, often ignored in the analyses of maintenance systems, has been shown to be influential in the patterns of work (Taylor, 1990) and therefore, possibly in the patterns of errors. Factors which have been identified as important include: the organization of work groups (or conversely, the isolation of workers), reporting structures, payoff structures associated with task performance, trust within one class of personnel, trust between classes of personnel and levels of personnel, selection/placement strategies, and human-machine function allocation of control and responsibility. Organizational constraints are infused into every level of the organization. Regulatory agencies such as the FAA, JAA, and CAA mandate organizational form to some extent. Each organization has operational strategies and goals. These external and internal goals of the system, and constraints on the system are operationalized into changes in organizational structure, physical environment, task procedures, job descriptions, and personnel (skilled or trained).

Using the System Model. The model in **Figure 5.3** is useful for depicting the goals of the system and therefore the functions that should be supported. The goals of the system are defined by the requirements of the personnel component in isolation and in conjunction with other system components. The personnel component is primarily described in terms of information processing characteristics and limitations. These characteristics influence the behavior of individuals and their experience with other system components. The functions associated with the performance of tasks, use of equipment, and communication with co-workers are subject to error and are therefore of primary concern. These functions are then considered within the constraints of environmental factors which may affect error formation and/or propagation. Drury, Prabhu, and Gramopadhye (1990) have compiled a generic function description of the maintenance inspection task requirements as presented in **Section 5.1**. The desired outcome for each of the task functions (Drury, 1991) which can be considered as the task's goal can be stated and, following Drury (1991), decomposed into the steps taken to accomplish the desired outcome (see **Table 5.7**).

Task 1 - INITIATE	1.1	Correct instructions written.
	1.2	Correct equipment procured.
	1.3	Inspector gets instructions.
	1.4	Inspector reads instructions.
	1.5	Inspector understands instructions.
	1.6	Correct equipment available.
	1.7	Inspector gets equipment.
	1.8	Inspector checks/calibrates equipment.
Task 2 - ACCESS	2.1	Locate area to inspect.
	2.2	Area to inspect.
	2.3	Access area to inspect.
Task 3 - SEARCH	3.1	Move to next lobe.
	3.2	Enhance lobe (e.g. illuminate, magnify for vision, use dye penetrant, tap for auditory inspection).
	3.3	Examine lobe.
	3.4	Sense indication in lobe.
	3.5	Match indication against list.
	3.6	Remember matched indication.
	3.7	Remember lobe location.
	3.8	Remember access area location.
	3.9	Move to next access area.
Task 4 - DECISION	4.1	Interpret indication.
	4.2	Access comparison standard.
	4.3	Access measuring equipment.
	4.4	Decide on if it is a fault.
	4.5	Decide on action.
	4.6	Remember decision/action.
Task 5 - RESPOND	5.1	Mark fault on aircraft.
	5.2	Record fault.
	5.3	Write repair action.
Task 6 - REPAIR	6.1	Repair fault.
Task 7 - BUY-BACK	7.1	Initiate.
	7.2	Access.
	7.3	Search.
	7.4	Decision.
	7.5	Respond.

Table 5.7 Detailed Breakdown of Aircraft Maintenance and Inspection by Task Step

Note that the use of equipment has been included within these task descriptions and therefore would not be considered separately. The most ambiguous situations encountered during aircraft inspection and maintenance typically result in an individual referencing another individual or a document for additional information. These situations are underspecified and are usually unanticipated. It is for these reasons that understanding the communication errors which may occur at these junctures is important. The type of communication of interest here is only that related to task performance, although other forms of casual communication, not discussed here, may indicate important aspects of the organizational and social structure of the system.

Errors must be described in the situational context in which they occur in order to identify contributing factors. **Table 5.8** shows some relevant characteristics of system components with which the individual may interact for the 'initiate' task. Relevant characteristics of each system component can be identified for observed errors. The effect of these factors on performance has been suggested in many studies; however, the manner in which performance is affected, especially by combinations of factors, requires additional empirical investigation.

1.0 PERSONNEL	5.0 JOB
1.1 Physiological	5.1 Physical Factors
1.2 Psychological	5.2 Social and Organizational Factors
1.3 Personality	6.0 ORGANIZATIONAL/SOCIAL
2.0 EQUIPMENT	6.1 Structure
2.1 Hand Tools	6.2 Goals
2.2 Displays	6.3 Trust
2.3 Control	6.4 Motivational Climate/Incentives
3.0 DOCUMENTATION	6.5 Function Allocation/Job Design
3.1 Type of Information Included	6.6 Training/Selection Methods
3.2 Style (Intelligibility)	7.0 PHYSICAL ENVIRONMENT
3.3 Formatting (Visual Clarity)	7.1 Lighting
3.4 Content (Usefulness,	7.2 Noise
Appropriateness, Veridical)	7.3 Temperature/Ventilation
3.5 Legibility (Physical)	7.4 Chemical Hazards
4.0 TASK	7.5 Vibration
4.1 Physical Requirements	7.6 Electrical Shock Hazards
4.2 Informational Requirements	8.0 WORKSPACE
4.3 Characteristics	8.1 Proximity
	8.2 Anthropometrical Constraints

Table 5.8 System Component Influencing Factors

5.3.2.3 Previous Research in Human Error and Aircraft Inspection and Maintenance

There has not been a great deal of research on human error specifically related to inspection and maintenance, less still targeted to the inspection and maintenance of aircraft. Three approaches are discussed below which address this specific research area. Lock and Strutt (1985) employ a fault tree analysis approach to investigating and quantifying human error in aircraft inspection. Drury (1991) developed an error taxonomy of aircraft inspection based on a failure modes and effects analysis. Drury (1991) also has shown a classification scheme for aircraft inspection errors based on Rouse and Rouse's (1983) behavioral framework for investigating errors. These contributions are reviewed below.

Lock and Strutt (1985) begin their reliability analysis of inspection with a microstructural model of the inspection process. They use this model to "develop a flow chart (**Figure 5.4**) which describes a typical inspection activity in which visual information is used to trigger further investigation using other senses"

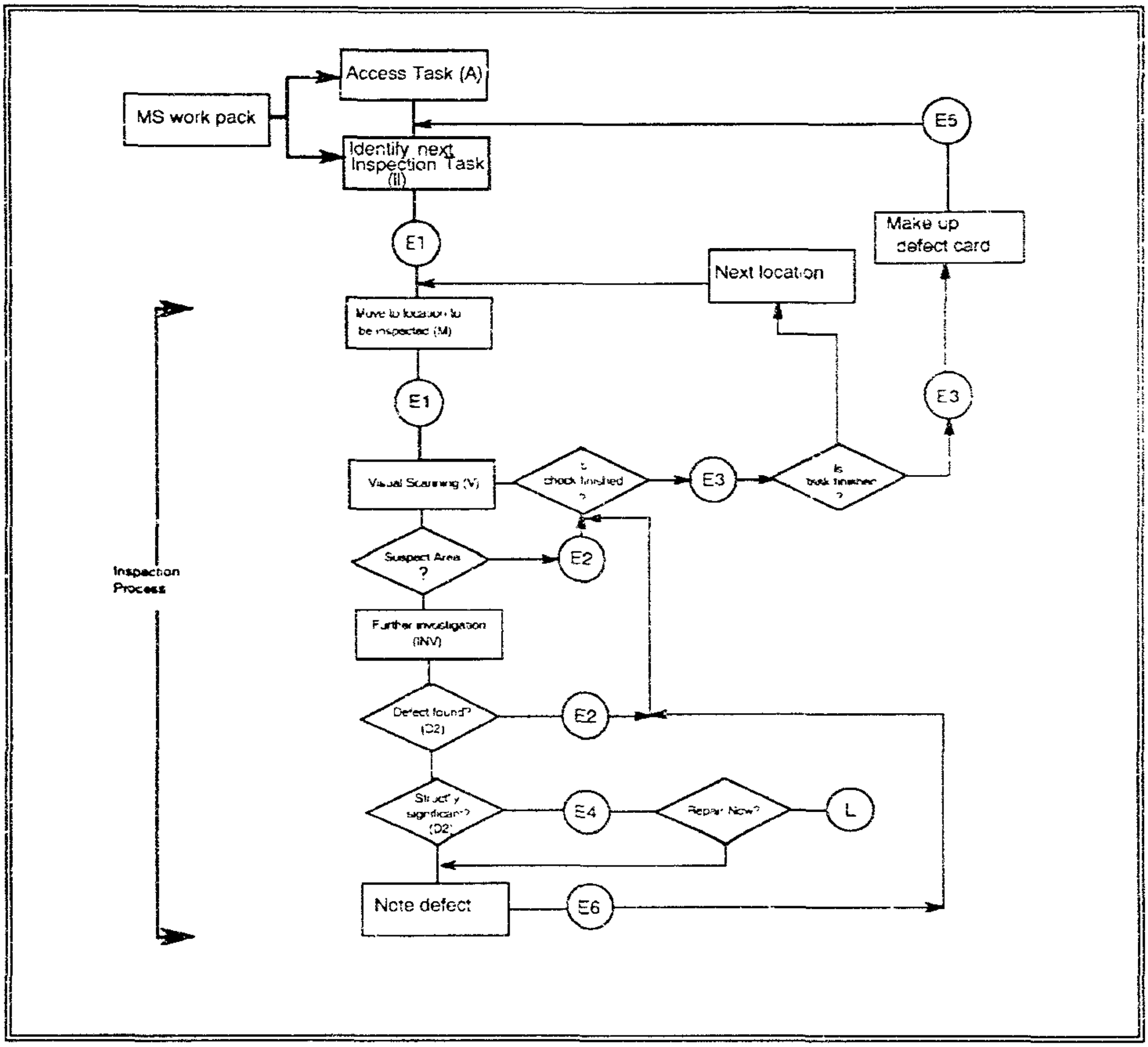

Figure 5.4 Inspection Model Flowchart (Lock and Strutt, 1985)

(Lock and Strutt, 1985, p. 71). They note that while particularly suited to area checks, the scenario is generally applicable to a wide range of inspection tasks. These authors then analyze the flow chart for error-likely situations and they identify six potential errors in the inspection process:

Schedule Error (E1)	Wrong execution of either of the two tasks: "identify next [illegible] location."
Inspection Error (E2)	Not [illegible] a defect when one exists
Inspection Error (E3)	[illegible] (either "forgetting to cover an [illegible] area inadequately"). May also be a [illegible]
[illegible]	[illegible] the area in which a defect [illegible]
[illegible]	[illegible] may not be [illegible] immediately as [illegible]
[illegible]	[illegible] at all

[illegible] and Straff (1985) [illegible] as the top event (**Figure 5.5**). [illegible] this type of analysis and [illegible] relevant to inspection, [illegible] different conditions in [illegible] aircraft inspection: [illegible] enhancement tools, motivation and [illegible]. These PSFs were given relative weights to indicate their importance for each step of the inspection process. The authors propose, but do not actually perform, the fault tree analysis.

Drury (1991) developed an error taxonomy from the failure modes of each task in aircraft inspection. This taxonomy has been developed based on the recognition that a pro-active approach to error control is needed to help identify potential errors. Thus, the taxonomy is aimed at the phenotypes of error (Hollnagel, 1989), that is, observed errors. Using the generic function description of the maintenance and inspection system (Drury, et al., 1990), the goal or outcome of each function was postulated as shown in **Table 5.7**. These outcomes then form the basis for identifying the failure modes of the task. Towards this end, the tasks within each function were listed and the failure modes for each identified. These included operational error data obtained from observations of aircraft inspectors, and discussions with inspectors, supervisors, and quality control personnel involved in the aircraft maintenance task, over a period of two years (Drury, Prabhu and Gramopadhye, 1990; Drury, 1991). A sample of the error taxonomy (Drury, 1991) is shown in **Table 5.9**.

The error framework developed by Rouse and Rouse (1983) has been used to record and analyze human errors in several contexts: (1) detection, diagnosis and compensation of engine control room failures in a supertanker (van Eckhout and Rouse, 1981), (2) human errors in troubleshooting live aircraft power plants (Johnson and Rouse, 1982), (3) aircraft pilots in mission flights (Rouse, Rouse, and Hammer, 1982). Results of these studies have been applied to the improvement of training programs and the development of checklists and other decision aids. Drury (1991) has shown how this scheme may be used to classify errors occurring in both visual and NDT inspection tasks (see **Table 5.10**).

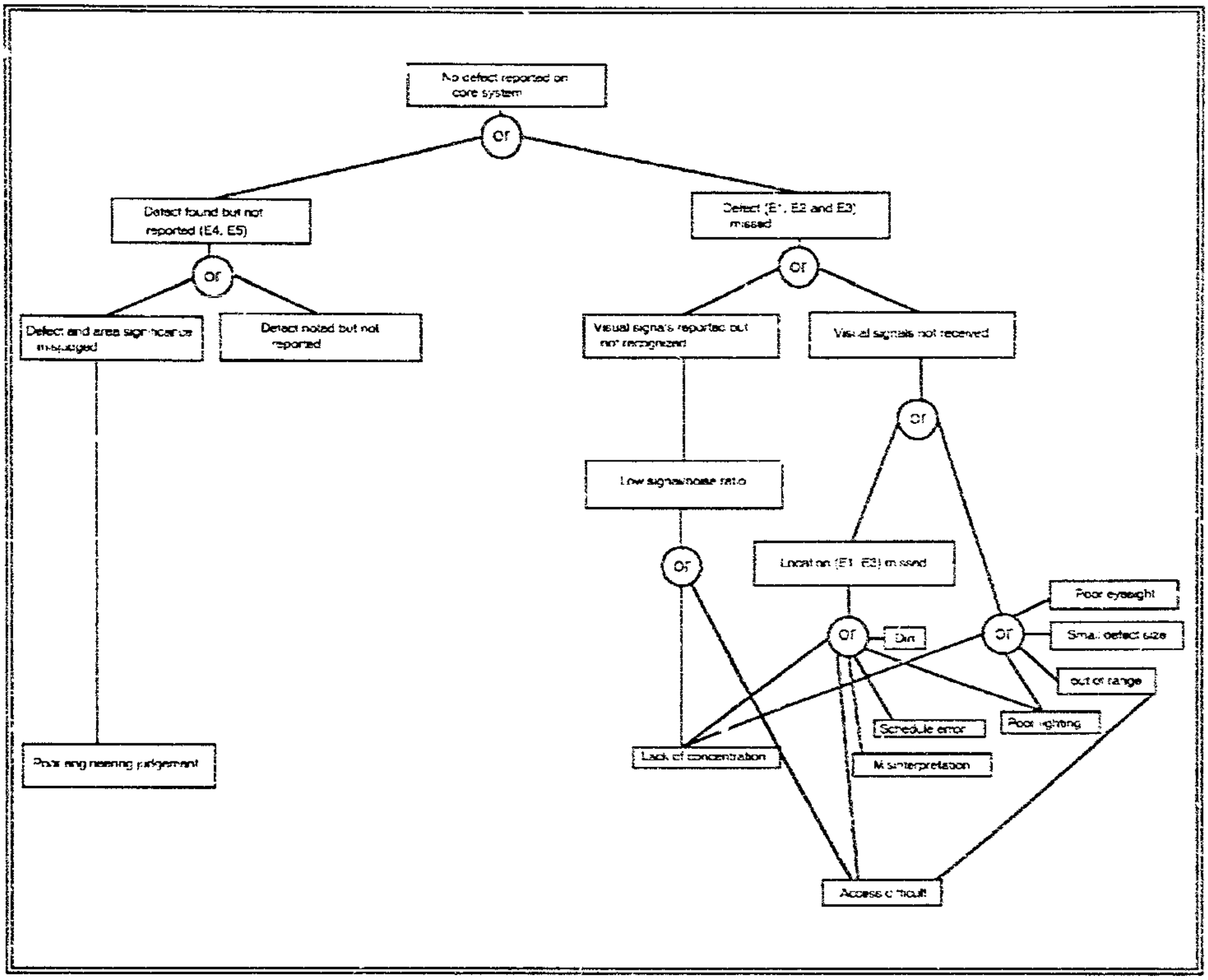

Figure 5.5 Inspection Error Fault Tree (Lock and Strutt, 1985)

5.3.2.4 An Approach to Aircraft Inspection and Maintenance Error Management

Error management may be considered as a three part objective. Errors which are evident in an operational system (error phenotypes) must be identified and controlled. Secondly, in order to reduce the likelihood of unanticipated error situations, errors must be predicted and systems must be designed to be error tolerant. Thirdly, error reporting systems must provide error and contextual information in a form which is appropriate as feedback to personnel. Operators may then use this information to adjust their error control and prevention strategies or alter environmental characteristics. This section presents strategies for error control and prevention through error-tolerant systems. Finally, the need for a context-sensitive error reporting scheme is discussed. Error phenotypes (Hollnagel, 1989), the specific, observable errors in a system, provide the foundation for error control. Error prevention and the development of design principles for error avoidance rely on genotype identification (Hollnagel, 1989), associated behavioral mechanisms, and their interaction with system characteristics (Rasmussen and Vicente, 1989). Here, error phenotypes are obtained empirically and from a failure-mode-and-effects analysis of task and communication models. These phenotypes are considered in light of their ability to be self-correcting and the type of error which they represent. They are further characterized by the relevant aspects of the system components with which they interact. The resulting list of phenotypes, their error correctability and type, and the pertinent situational factors, allow designers to recognize these errors and design control mechanisms to mitigate their effects. Rasmussen and Vicente's (1989) methodology is used to identify genotypes associated with each phenotype. This methodology yields the mechanisms of error formation within the task context.

TASK		ERROR(S)	
TASK 1 – INITIATE			
1.1	Correct instructions written.	1.1.1	Incorrect instructions.
		1.1.2	Incomplete instructions.
		1.1.3	No instructions available.
1.2	Correct equipment procured.	1.2.1	Incorrect equipment.
		1.2.2	Equipment not procured.
1.3	Inspector gets instructions.	1.3.1	Fails to get instructions.
1.4	Inspector reads instructions.	1.4.1	Fails to read instructions.
		1.4.2	Partially reads instructions.
1.5	Inspector understands instructions.	1.5.1	Fails to understand instructions.
		1.5.2	Misinterprets instructions.
		1.5.3	Does not act on instructions.
1.6	Correct equipment available.	1.6.1	Correct equipment not available.
		1.6.2	Equipment is incomplete.
		1.6.3	Equipment is not working.
1.7	Inspector gets equipment.	1.7.1	Gets wrong equipment.
		1.7.2	Gets incomplete equipment.
		1.7.3	Gets non-working equipment
1.8	Inspector checks/calibrates equipment.	1.8.1	Fails to check/calibrate.
		1.8.2	Checks/calibrate incorrectly.

Table 5.9 Sample of Aircraft Maintenance and Inspection Errors by Task Step

This information in conjunction with consideration of influencing situational variables can predict the forms of novel errors and suggest design principles to prevent error formation and/or contain error propagation.

5.3.2.4.1 Error Control and Prevention

Error control is appropriate for the expedient eradication or mitigation of error-situation effects. However, there is much wisdom in the adage "an ounce of prevention is worth a pound of cure:" error prevention is more efficacious than error control. Error prevention requires error prediction and the design of error-tolerant systems.

LEVEL OF PROCESSING	POSSIBLE ERRORS
1. Observation of System State	Fails to read display correctly.
2. Choice of hypothesis	Instrument will not calibrate: inspector assumes battery too low.
3. Test of hypothesis	Fails to use knowledge of NiCads to test.
4. Choice of goal	Decides to search for new battery.
5. Choice of procedure	Calibrates for wrong frequency.
6. Execution of procedure	Omits range calibration step.

Table 5.10 Example of Possible Errors for Task Step of Calibrate NDI Equipment (from Drury, 1991)

Error control strategies can be derived by classifying error phenotypes according to components of the system model (see **Figure 5.3**) and according to Rasmussen and Vicente's (1989) systemic error mechanisms. This classification framework aids in suggesting intervention strategies appropriate to the error and the system components involved. The system model provides a useful means of classifying observed errors and relating them to specific human factors interventions. There are a number of personnel factors of general importance to controlling errors. Personnel interactions are extremely important aspects of the performance of the inspection and maintenance tasks. These interactions can be immediate but are also accomplished through the use of forms and notes which allow personnel to communicate with fewer temporal and spatial constraints. Communication is information transferred between not only personnel but between personnel and documentation. This extension of the common use of "communication" is logical given that documentation can be considered as a limited, static representation of some individual's (or group's) knowledge. Equipment should be designed to support task requirements and accommodate human information processing characteristics. The job and the individual tasks should be designed such that they can be accomplished at the desired level of performance, for the desired duration of performance, without physical or affective stress. The physical and organizational environments should be designed to enhance task performance and ensure the safety and motivation of personnel.

Various intervention strategies have been suggested for the control and prevention of errors. Rouse (1985) identifies five general interventions and proposes a mathematical model for describing optimal resource allocation among the strategies. These five general categories are also reflected in the more detailed listing of intervention strategies proffered by Drury, et al., (1990). These interventions have been tailored to the aircraft inspection context and were classified as either short-term or long-term strategies. The intervention strategies from these two sources are described in detail in **Tables 5.11, 5.12, and 5.13**. **Table 5.11** presents a compilation of the intervention strategies and design guidelines proposed by Rasmussen and Vicente (1989), Drury, et al., (1990), and Rouse (1985). These intervention strategies and guidelines are classified by the level of cognitive control (Rasmussen, 1986) which they affect and the type of systemic error (Rasmussen and Vicente, 1989) they address (see **Table 5.12**). Intervention strategies can also be classified by the component(s) of the aircraft inspection and maintenance system they alter. **Table 5.13** presents the compiled intervention strategies and design guidelines classified by levels of cognitive control, systemic error and system component. Further refinement of classification within system components (see **Table 5.8**) is possible with the aid of a more detailed decomposition of these components (see Latorella and Drury, 1991).

SHORT-TERM INTERVENTIONS (Shepherd, et al., 1991)
1. Worksheet design
2. NDI equipment calibration procedures
3. NDI equipment interface
4. NDI equipment labeling of standards
5. Support stands
6. Area localization aids
7. Stands/areas for NDI equipment
8. Improved lighting
9. Optical enhancement
10. Improved NDI templates
11. Standards available at the workplace
12. Pattern recognition, job aids
13. Improved defect recording
14. Hands-free defect recording
15. Prevention of serial responding (inadvertent signoff)
16. Integrated inspection/repair/buy-back - improve written communication
17. Integrated inspection/repair/buy-back - improve verbal communication
LONG-TERM INTERVENTIONS (Shepherd, et al, 1991 and Rouse, 1985)
18. Identification of errors - error reporting
19. Integrated information systems (feedback, feedforward, directive)
20. Training
21. Selection/placement
ERROR REDUCTION RESOURCES (Rouse, 1985)(also notes training and selection)
22. Equipment design
23. Job design
24. Aiding
RASMUSSEN'S "COPING" GUIDELINES (Rasmussen and Vicente, 1989)
25. Make limits of acceptable performance visible while still reversible.
26. Provide feedback on the effects of actions to cope with time delay.
27. Make latent conditional constraints on actions visible.
28. Make cues for action put only convenient signs, but also represent the necessary preconditions for their validity (symbolic).
29. Supply operators with tools to make experiments and test hypotheses.
30. Allow monitoring of activities by overview displays.
31. Cues for action should be integrated patterns based on determining attributes (symbolic representations).
32. Support memory with externalization of effective mental models.
33. Present information at level most appropriate for decision making.
34. Present information embedded in a structure that can serve as an externalized mental model.
35. Support memory of items, acts, and data which are not integrated into the task.

Table 5.11 Error Management Strategies

The above methodology was developed to control errors, i.e., for error phenotypes which are observable errors in the system. An extension of this methodology provides a means by which intervention strategies can be identified to control unanticipated errors once they occur. In this extension, error genotypes, rather than the aforementioned phenotypes, are classified according to the system model, using Rasmussen and Vicente's (1989) systemic error categories and Rasmussen's levels of cognitive control (Skill, Rule, Knowledge). This characterization of error genotypes allows prediction of possible, but so far unanticipated, error phenotypes. Unanticipated errors can be predicted by considering tasks at each level of cognitive control and each error mechanisms' possible perturbation of performance within the context of the specific system components involved. Given an error genotype cell, intervention strategies (which also have been classified by system component, systemic error mechanism, and cognitive control level (see **Table 5.13**) can be identified for its control.

SYSTEMIC ERRORS	LEVELS OF COGNITIVE CONTROL		
	SKILL	RULE	KNOWLEDGE
Learning and Adaptation	6, 11, 12, 20, 22, 24, 25	1, 2, 11, 20, 22, 24, 28	1, 13, 16, 17, 18, 19, 20, 22, 24, 26, 27, 29
Interference Among Competing Control Structures	12, 14, 23, 24, 30	3, 11, 20, 22, 23, 24, 31	1, 3, 15, 16, 17, 19, 20, 23, 24, 32
Lack of Resources	33	33, 34	1, 3, 4, 13, 16, 17, 19, 20, 21, 22, 23, 24, 33, 34
Stochastic Variability	2, 3, 5, 6, 7, 8, 9, 10, 12, 14, 16, 17, 20, 21, 22, 23, 24, 35	2, 11, 14, 16, 17, 20, 21, 22, 24, 35	4, 16, 17, 20, 21, 22, 35

Table 5.12 Error Management Strategies by Systemic Error and Level of Cognitive Control

5.3.2.4.2 Error Tolerant Design in the Aircraft Inspection and Maintenance System

An error tolerant system has been defined as a system which ensures that recovery from errors is possible, in the sense that actions are reversible and/or that the system is resilient to inappropriate actions (Rouse, 1985). Reason (1990) suggests that one way of making systems more error tolerant is to identify "those human failures most likely to jeopardize the integrity of the plant and to defend against them by engineered safety devices or procedures" (p. 233). For example, the "30-minute rule" allows nuclear power plant operators 30 minutes of thinking time in an emergency through the use of automatic systems which can return a plant to a safe state without human intervention. Reason also notes that, where these safety devices are themselves subject to human errors, independent, redundant systems should be provided (p. 233). The design of error tolerant system procedures and devices can be guided by the error control and prediction framework previously described by incorporating interventions in plant and operating procedure design.

5.3.2.4.3 An Approach to Reporting Aircraft Inspection and Maintenance Errors

Currently, error reports are primarily used for documenting error situations for administrative purposes by internal or external regulatory agencies. There are many different regulatory mechanisms for reporting errors to the FAA. In addition, the Air Transport Association (ATA) has proposed modifications to those. All of these reporting systems have the following common features:

Systemic Errors	Levels of Cognitive Control	SYSTEM ELEMENTS: Task	Personnel	Job	Workspace	Equipment	Documentation	Physical Environ.	Organiza Environ.
LEARNING	Skill	6,11,12	20		6	6,22,24,25	6,24	25	
	Rule	11,28	20			11,22,24,28	1,2,24,28		
	Knowledge	13,19, 26	16,17,18,20	16,17, 26,29		13,19,22, 24,26,27,29	1,16,19,24		17,18,29
INTERFERENCE	Skill	12,14		23,30		14,24,30	24		
	Rule	11	20	23		3,11,22,24, 31	24		
	Knowledge	19,32	16,17,20	15,16, 17,23, 32		3,19	1,16,19,24,32		15,17,32
LACK OF RESOURCES	Skill					33			
	Rule					33	33,34		
	Knowledge	13,19, 34	16,17,20,21	16,17, 23,34		3,4,13,19, 22,24,33,34	1,16,19,24,33,34		17
STOCHASTIC VARIANCE	Skill	6,12,14	16,17,20, 21,35	23	5,6,7,8	3,5,6,7,9, 10,14,22, 24,35	6,24	8	
	Rule	11	16,17,20, 21,35			11,22,24,35	2,24,35		
	Knowledge		16,17,20, 21,35	16,17		4,22,35	16,35		17

Table 5.13 Error Management Strategies by Systemic Error, Levels of Cognitive Control, and System Component from Figure 5.3

1. They are event driven. The system only captures data when a difficulty arises or a defect is found.
2. Aircraft type and structure serve as the classification parameters for reporting.
3. Expert judgements of error criticality are used to further classify data and determine its urgency.
4. To some extent in all systems, the feedback of digested data to users is not well-engineered. Thus, for the end-user level, the data collection effort is largely for naught.
5. They can result in changes in maintenance and inspection procedures; for example, by issuing Airworthiness Directives (ADs).

Error reports in maintenance and inspection produced for administrative purposes are typically concerned with establishing accountability for an error and its consequences rather than understanding the causal factors and situational context of the error. This type of information is not appropriate for use as performance feedback to inspectors or maintenance personnel, nor is it helpful information for error tolerant system design. Error reporting schemes are developed from within an organization and therefore vary greatly among organizations. The framework of these error reporting schemes is event driven and developed iteratively, thus additions are made only with the occurrence of a new error situation. To a large extent, the information recorded about a situation is constrained by the format of the error reporting scheme. For example, in one error reporting scheme, the reviewer is required to attribute the error to some form of human error unless the situation can be described as an "act of God" (Drury, 1991). Analysis of the data collected by such a scheme will invariably find the human at fault, rather than working conditions, equipment, procedures, or other external factors. This biased representation has serious implications for error prevention, especially considering that equipment design and job aiding have been found to be more efficacious than selection or training approaches in error prevention (Rouse, 1985). To alleviate the difficulties of inconsistency, and provide an appropriate and useful structure for error data collection, an error reporting scheme should be developed from a general theory of the task and the factors which shape how the task is performed. Principally, the behavioral characteristics of the operator, but ideally also organizational environment, job definition, workspace design, and the operators' physical, intellectual and affective characteristics should be considered. Effective error categorization systems are not only descriptive but are prescriptive, providing information for specific intervention strategies (i.e., Langan-Fox and Empson, 1985 and Kinney, et al., 1977).

As Rasmussen, Duncan, and Leplat (1987) note, it is necessary to shift the focus of analysis from the task to the interaction of the task and the operator for classifying errors. Furthermore, taxonomies of human error must encompass the analysis of not only the task characteristics but also the information processing mechanisms associated with the subtasks. It is apparent that other situational characteristics (i.e., environmental conditions) are also useful for the sensitive classification of errors (Stager and Hameluck, 1990). Correlations of errors with situational factors, with remedies attempted, and with the effects of these remedies, may provide important feedback for identifying error situations, assessing error criticality, and determining error consequence-minimizing solutions. Both error control and error prevention would benefit from an error reporting system which captures the causal factors and situational context of an error situation.

Both the taxonomic approach of Drury and Prabhu (1991) and the taxonomy for error management strategies developed here can be used as a basis for formulating error reporting schemes. Upon occurrence, errors can be classified by level of cognitive control, type of systemic error, and by causal or catalytic elements of the system. As previously mentioned, the categories of system elements can be refined as illustrated in **Table 5.8** to provide a more descriptive error characterization. Identification of these parameters will likely involve detailed investigation of the error situation, including extensive operator interviewing. This data store can be analyzed for trends in error sequences, effects of different intervention strategies on error-type frequency, and for the efficacy of intervention strategies over all types of errors. Identification of error sequences and the effects and interactions of system elements provides important feedback information for performance and feedforward information for training, equipment, and job design. A prototype error reporting system based on the above considerations has been proposed as a short-term project with an airline partner.

5.3.3 A FRAMEWORK FOR INFORMATION ENVIRONMENT DESIGN FOR AIRCRAFT INSPECTION

Inspection is information processing. Other aspects of the inspector's task, such as physical access to the work and body posture during work, are subordinate to this central task. If information processing is the essence of inspection, we must examine the sources of information used (and not used) by the inspector: how information is received, processed and generated. Hence, the inspector's information environment is a critical part of the inspection system.

Any system involving a human is typically closed loop (e.g., Sheridan and Ferrell, 1974). Obvious examples are in flying an aircraft or driving a car, but the concept applies equally to inspection tasks. As shown in **Figure 5.6**, the human in the task receives some instruction, or command input to use systems terminology. The operator and any associated machinery transform this command input into a system output. To ensure stable performance, the system output is fed back to the input side of the system, where it is compared against the command input. If there is any difference (command minus output) the system responds so as to reduce this difference to zero.

From the model in **Figure 5.6**, it is obvious that two types of information can be distinguished. The input is command information, while the output is feedback information. Both have been shown to be amenable to manipulation to improve system performance. Not obvious from **Figure 5.6** is that the command input may be complex, and includes both what needs to be accomplished and help in the accomplishment. Thus, input may give both directive and feedforward information. A work card may contain "detailed inspection of upper lap joint" in a specified area (directive) and "check particularly for corrosion between stations 2800 and 2840" (feedforward). Thus, there are

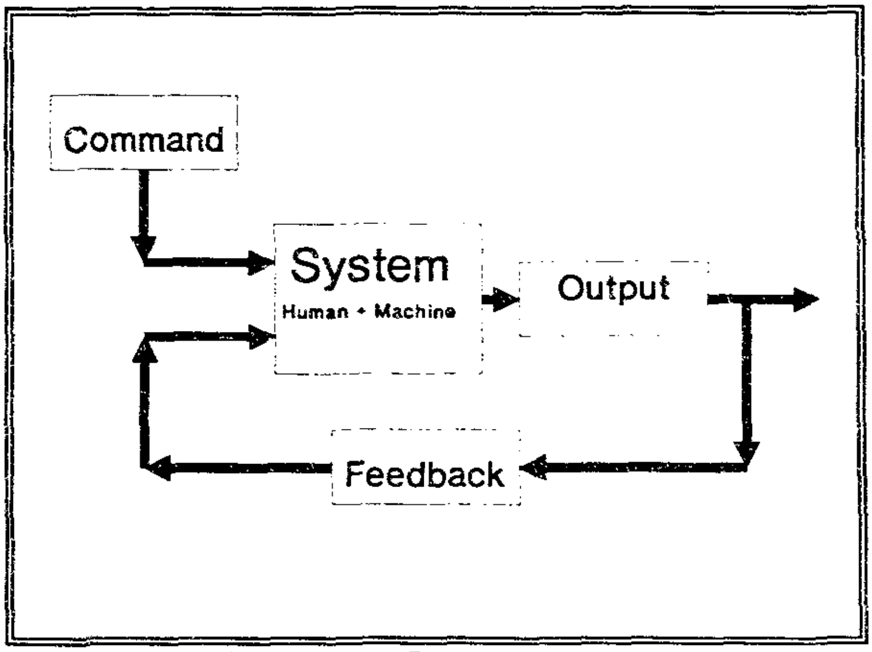

Figure 5.6 Closed-Loop Control

really three potential parts to the information environment: directive information, feedforward information, and feedback information.

Three of the strongest influences found in case studies of inspection performance are time pressure on the inspector, feedforward of information to the inspector, and feedback of detailed performance measures. We restrict ourselves to examining the various aspects of feedforward and feedback information in the context of aircraft inspection; the time pressure aspect is dealt with under speed accuracy tradeoff in **Section 5.3.4**.

In the subsequent sections we present a model of the information flow in aircraft inspection. This model serves as the basis for understanding the information environment that the inspector is a part of. We then present two approaches to analyze the information requirements of the inspection task: (a) skill-rule-knowledge (S-R-K) based approach, and (b) error taxonomic approach. Finally, a study to investigate the effect of feedback information is described.

5.3.3.1 A Model of Information Flow in Aircraft Inspection

To perform optimally in the system, the inspector has to have access to the relevant information and the information environment has to provide this information. We have to reconcile the, perhaps conflicting, issues of:

- What information to present.
- When to present this information.
- How to present this information.

In designing the flow of information, the designer must take into account human processing of information and the cognitive abilities of humans. It is important to develop a model of the information environment in order to analyze the current system and propose design changes based on identified problems. Towards this end we propose a feedforward/feedback information model of aircraft inspection (see **Figure 5.7**). This model represents both the physical work flow and the information flow. It also highlights the cognitive aspects of the inspection task and its interaction with the information environment.

This model allows us to target the components of feedforward (training, documents, etc.) and feedback (missed defects, defect rate, etc.) that have to be analyzed for efficient design of the information environment.

5.3.3.1.1 Feedforward Information

From the model (**Figure 5.7**), feedforward information to the inspector is seen to come from the following sources:

1. Initial Training
2. Manufacturer/FAA/Airline Operator documents.
3. On-the-Job experience on a particular aircraft.
4. Information gathered from co-workers.

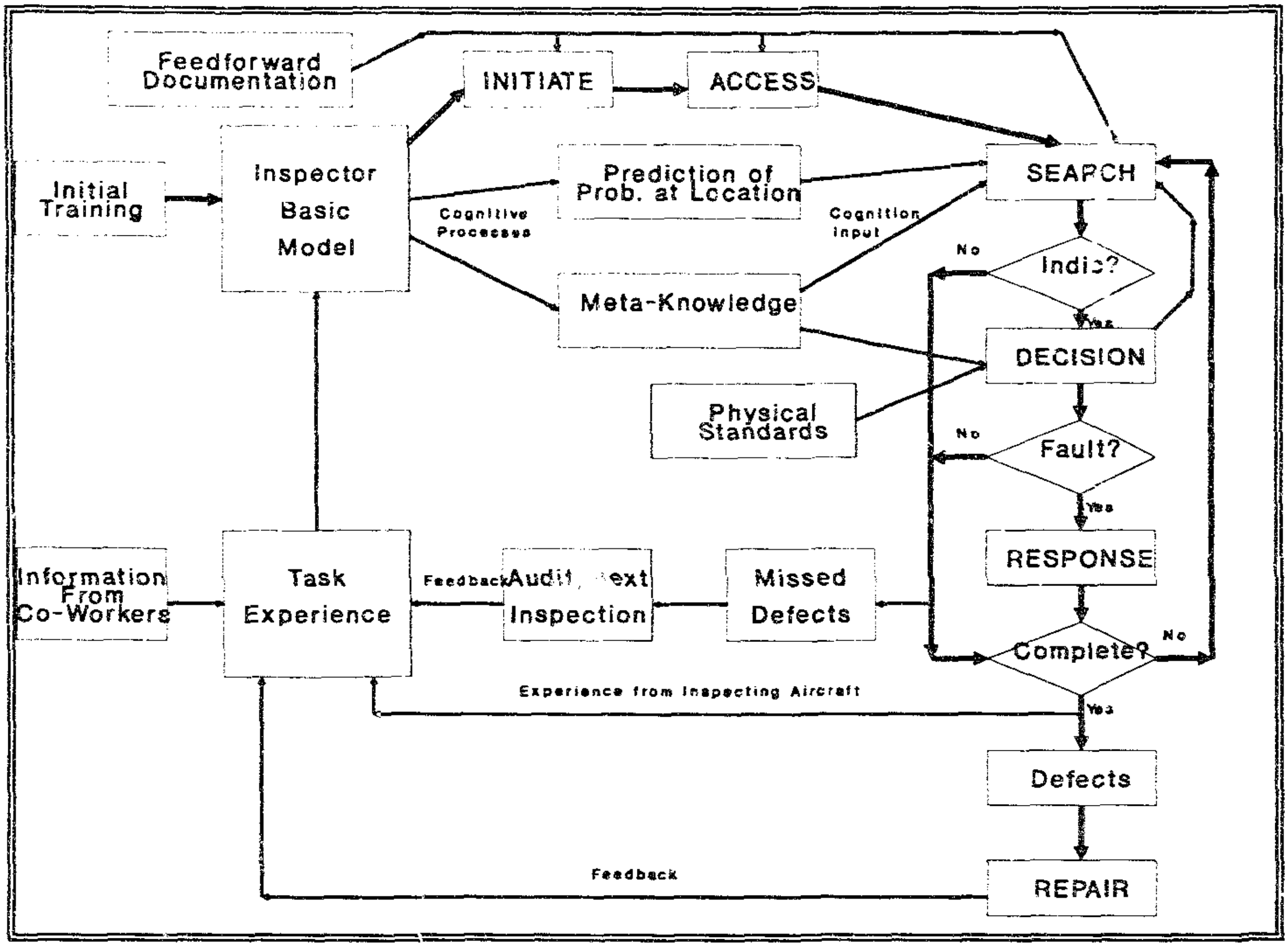

Figure 5.7 Model of Information Flow in Aircraft Maintenance and Inspection (Drury and Prabhu, 1991)

5. Command information in the form of standards.
6. Utilization of understanding about the fault causation mechanism in an aircraft.

Initial Training. Taylor (1990) notes aircraft orientation training for new mechanics, at large sites. However, smaller sites had no formal training programs in place. No formal inspection training programs were observed or reported at any of the airlines. Typically, inspectors hold an A and P license and have maintenance experience. Taylor (1990) found that the current hangar maintenance organization has a bi-modal experience distribution of 30 plus years and three or fewer years. The inspection group is expected to have a similar distribution with three to five years added to the lower value.

The current state of training places much emphasis on both the procedural aspects of the task (e.g., how to set up for an X-ray inspection of an aileron), and on the diagnosis of the causes of problems from symptoms (e.g., troubleshooting an elevator control circuit). However, the inspectors we have studied in our task analysis work have been less well trained in the cognitive aspects of visual inspection itself. How do you search an array of rivets -- by columns, by rows, or by blocks? How do you judge whether corrosion is severe enough to be reported?

Most of the training is on the job where an experienced inspector puts the novice through his paces and shows him the various aspects of inspection. This is highly realistic but uncontrolled and there is a high likelihood for development of inconsistent inspection practices. Our experience in training inspectors in manufacturing industries (Kleiner, 1983) has shown that a more controlled training environment produces better inspectors. If training is entirely on-the-job, then two of the main determinants of the training program--what the trainee sees and what feedback is given--are a matter of chance; i.e., of which particular defects are present in the particular aircraft inspected.

We need to develop training procedures for the search and decision making components of aircraft inspection by using human factors techniques that include cueing, feedback, active training, and progressive part-training as suggested by Drury and Gramopadhye (1990) and detailed in **Section 5.3.5**. It has been found that off-line controlled training successfully transfers to the more complex on-the-job environment. The trainee is prepared to make maximum use of what is seen on the job, rather than confining the learning process to trial and error. Because of the controlled and concentrated training experience, trainees can progress faster to the same level as experienced inspectors.

Documentation. There is an immense amount of potentially useful information available both in paper (hard copies) and paperless (computer, microfiches) form. We list below some of the important documents that form the information environment. Note that this is not a complete listing of all available documents.

The documents are generated by a triad consisting of the Federal Aviation Administration (FAA), aircraft manufacturers, and aircraft operators. There is a complex, multi-dimensional interaction in the flow of data between these three. Manufacturers require feedback from operators to determine acceptability and reliability of a product and its components. Airlines require product support information from the manufacturer. The FAA requires data from both the airlines and the manufacturers concerning product reliability and safety issues. The Air Transport Association (ATA) coordinates the flow of data among the three triad members (Shepherd, 1990).

We have to understand the problems created by the mismatches between the needs of the inspector (who is looking for information) and the design of the documents (that present data). There is a critical need for usable knowledge, which gets translated to utilized information on the job. From a document design viewpoint we have to focus on creating usable documents. Information flow design and system design should ensure the availability of documents at the right place at the right time. The demonstration project presented in **Section 5.2.1** is an example of applying document design techniques to one type of document, the workcard.

Experience on a Specific Aircraft Type. Aircraft at a maintenance facility are serviced over various lengths of time depending on the type of service. The transfer of an aircraft to a different facility (other than the one it normally goes to) is very rare and occurs in case of contingencies or in case of heavy workload at the regular facility. Similarly, movement of personnel between different facilities is very low. Thus, most maintenance and inspection personnel accumulate experience on a particular type of aircraft. The effect of such job specialization on the occasional inspection of a different aircraft type has not been studied.

Knowledge about the aircraft is accumulated over a period of time through on-the-job work. Experienced inspectors gradually develop an understanding of the cause-effect relationship of defects and also know what to look for and where. Thus, there is a store of distributed knowledge or expertise residing in the inspection organization. Individual inspectors normally have access to this distributed knowledge through informal contacts with fellow inspectors, which leads us to the next section.

Information from Co-Workers. The relevant relationships in heavy maintenance have been identified by Taylor (1990), to include:

1. Superiors with subordinates
2. Members of same group with one another
3. Members of different work groups
4. People inside enterprise interacting with people outside that system.

Airline inspectors typically work independently and occasionally in teams of two. The frequency of formal meetings amongst inspectors varies from airline to airline. In one airline, weekly safety meetings are held where any communications from management are conveyed to the inspectors. In another case there is a daily meeting at the beginning of the shift where the day's work and assignments are discussed. Drury, et al., (1990), during the task analysis of inspection in the airline industry, found few formal meetings of mechanics or inspectors despite frequent informal contact among inspectors, and less frequent contact between inspectors and mechanics.

Contact between inspectors, in different shifts, was observed at some sites where shifts overlapped by an hour or so. The mechanics and inspectors contact each other for buy-back or for approval of a repair. This contact for advice/instruction is the only formal information exchange between the inspector and the mechanic. There appears to be no formally organized forum that can channel the distributed knowledge for more efficient access by individuals who need this information.

Mechanics who find faults during scheduled maintenance notify the inspectors. Thus, an informal system of communication exists. However, there are various ways in which such a system can break down. An experienced inspector might know, for example, that the line maintenance people have in the past improperly used magnetic screws around the landing light as a contingency measure. Thus, he/she would examine the screws around the landing light in view of this knowledge. A new inspector may not have had access to this issue (which is not mentioned in a workcard or any documentation elsewhere) and could fail to catch such a fault. Similarly, an inspector who documents a fault and the inspector who approves the repair done on this fault may not be the same and thus, any inspection error in this case goes unnoticed by the inspector because of a lack of a formal feedback system.

Command Information with Comparative Standards. There seem to be almost no standards that are accessible to inspectors for defects like corrosion, cracks, dished/pooched rivets, wear, component play, etc. A small subset of standards does exist with the manufacturer, FAA, etc., but these have not been organized into a scheme for utilizing comparative standards on the job. The closest inspectors come to a standard in visual inspection is to use adjacent areas to make a comparison, which is not a reliable method (Drury, 1991).

During a decision making process, both the internal and external retrieval of information is necessary. The degree with which external and internal retrieval of information is required could be a major determinant of the strategies adopted during decision making.

As an example, during visual search for corrosion around rivets or in a door frame the inspector comes across an indication. The inspector has to make a judgement call whether this indication should be marked as a defect or let go. If the corrosion is evident without a doubt, then the decision process is simple and the task is almost like a pure search task. On the other hand, when the evidence for corrosion in the indication is not conclusive, the inspector has to:

1. Retrieve internal information about instances of corrosion to make a match (recall patterns).
2. Approach peers or supervisors for help on judgement.
3. Refer to comparison standards available at the work point.

It has been found that the higher the information load and the more likely the chance of error, the more an operator is forced to remember or recall information of relevance. Also, external information retrieval (from other inspectors) is a function of the operator's perception of criticality of this particular decision and availability of inspectors within a reasonable vicinity. For example, the inspector perched up on the horizontal stabilizer of a DC-9 is less likely to go down and call a supervisor to come up and have a look at an indication, particularly if he perceives that a wrong decision on his part may not be critical.

It has been known for many years that if comparison standards are available at the work point, more accurate inspection will result. Yet in many cases such standards are not available to the aircraft inspector. For example, if the maximum allowable depth of a wear mark is given as 0.010 inches, there is neither a convenient way to measure this, nor a readily available standard for comparison. Other examples are play in bearings and cable runs, areas of corrosion, and looseness of rivets. All are considered to be "judgement calls" by the inspector, but simple job aids, perhaps as part of the worksheet, or standard inspection tools, would remove a source of uncertainty. Leaving standards to unaided human memory may be expeditious, but it is also unreliable.

<u>Utilization of Understanding about the Fault Causation Mechanism in Aircraft.</u> Inspection of aircraft is largely composed of pure search activities followed by decision-making tasks whose output is of the form of "acceptable/non-acceptable". However, some areas of inspection involve utilization of cues, knowledge of how faults are caused, and knowledge of how the behavior of one particular aircraft component indicates behavior of related components. Examples are:

- dirt streaks around a rivet on the fuselage indicate a loose rivet.
- bulging of the paint on the aircraft skin indicates underlying corrosion.
- scraped paint at the fairings indicates underlying fairings are rubbing.
- play at the flap vanes points to worn out bearings or tracks.
- flat spots on the wheel indicate a possible problem with the anti-skid system.
- powdery material on the skin indicates probable corrosion.

Use of such indirect evidence is a powerful technique to enhance detection and discovery of a fault, particularly where faults are not directly accessible to pure visual/auditory/tactile search.

There is a necessity to gather the knowledge required for this indirect fault indication from experienced inspectors who understand the utilization of such cues. There is also a need to identify the mappings between defects and fault causation mechanisms for a wide variety of such defects. The decision-making activity can then be converted to a rule-based, procedural type of task. Rules thus formed can be used in an effective training scheme to help inspectors increase the efficiency of the search and decision making process.

This approach can be extended further to form an inspection data base which can be continually revised and updated to reflect the distributed knowledge that exists not only in a specific airline but across all airlines. Such a global knowledge-base would thus receive its input from experienced inspectors all over the aviation industry, thus consistently benefitting all users. It is also conceivable that an expert system could be developed that makes use of such a data base and supports decision-making tasks. Such a system would support queries like:

- "I am in the tail compartment. Current inspection area is aft of APU compartment bulkhead, list keypoints."
- "Inspection area is APU shroud, list past history of cracks."
- "Indications at rivet on lap joint at stringer S-34 between body station 890 and 900 points to corrosion, show graphics of likely corrosion in this area."
- "There is excessive play at the flap vanes, what are the problems indicated by this.", etc.

5.3.3.1.2 Feedback Information

Feedback information in aircraft inspection can be used either on the job or in training. Use of feedback on the job has been found to reduce the number of false alarms as well as reduce missed defects. Training schemes implementing feedback have been used to improve learning rates, to develop schemes, and for the efficient transfer of training skills to on-the-job performance.

On-The-Job Feedback. There seems to be no systematic and obvious system in place that provides feedback to the inspector. For example, feedback during access can be given by a well designed workcard system incorporating unique landmarks in the figures (Drury, 1990b). Feedback in search/decision making comes when the inspector talks to a supervisor or a fellow inspector to confirm a borderline case, although this occurs rarely. Also rare is the feedback that could come from the repairer or the buy-back inspector who both have potential data on the fault.

Feedback also seems to depend on the type of defect. Airlines have a system to classify the various defects found during inspection/maintenance. There are specific rules by the FAA for this classification. Normally, defects get classified in three broad categories: A, B, and C. Type "A" defects are the most critical ones and have to be immediately corrected. Type "B" defects are corrected immediately, or the maintenance action is deferred to a pre-specified time based on current and projected workload. The "C" defects are generally deferred to the next inspection. Thus, there exists a possibility of feedback in the case of "A" defects, and some "B" defects, because of the time frame within which maintenance action is taken. This would normally occur through buy-back inspection. However, even this opportunity would be lost if the buy-back inspector is different from the one who wrote the non-routine defect item.

There is very little feedback on any defect that the inspector misses. This feedback can only occur through audits and quality control inspections, but these systems do not ensure consistent feedback to all inspectors on a regular basis.

At this point we have to also recognize that, although it is very desirable to provide feedback, there are bound to be instances where this would be economically infeasible, and in some cases impossible, due to the nature of the task. For example, providing regular feedback on missed defects is not viable, as it would involve re-inspection similar to auditing on a regular basis. Similarly, having a system that calls for feedback on every defect may be too expensive due to time factors and logistics. In such cases, alternate schemes like periodic re-training or off-line feedback could be utilized to re-calibrate inspectors.

Feedback in Training. As explained in the earlier section, the feedback in aircraft inspection is relatively scarce, and on the occasions that the inspector gets feedback (e.g., an audit), it is delayed in time. Delayed feedback makes learning by practice alone difficult (Woods, 1989).

The use of knowledge of results (feedback) in training is well documented. The trainee needs rapid, accurate feedback in order to correctly classify a defect or to know whether a search pattern was effective. However, when training is completed, feedback is rare. The training program should start with rapid, frequent feedback, and gradually delay this until the "working" level is reached. More feedback beyond the end of the training program will help to keep the inspector calibrated (Drury and Kleiner, 1990).

We see that there is a great deal of research support to indicate that use of feedback in initial training is beneficial. From the airline inspection context this points to the necessity of developing a training methodology that incorporates performance feedback. Drury and Gramopadhye (1990) have demonstrated a training scheme for gamma ray inspection of a nozzle guide vane area of a JT9D engine. This includes part naming and defect naming (cueing and active response), search, and decision training. Feedback is used judiciously in this training scheme to help the trainee to build a schema.

5.3.3.2 Analysis of Information Requirements: An S-R-K Approach

So far it has been established that (a) errors in aircraft inspection are costly, and therefore must be minimized, (b) human performance limitations can, and do, result in inspection errors, and (c) provision of information in the correct form (physical and cognitive aspects) is critical to reducing human errors.

For effective use of feedforward and feedback information, the information requirements of human inspection have to be identified. Furthermore, the information needs of experts and novices may be very different. Thus, we can posit that studying the behavior of the human inspector interacting with the system (while performing the inspection) will help identify possible information support points, as well as provide guidance to the type of information (either feedforward or feedback) that is needed at these points. The skill-rule-knowledge based hierarchy of Rasmussen (1983) presented in **Section 5.3.2.1.2** affords us a robust framework within which this analysis can be carried out, and will be mapped onto both visual inspection and NDI.

5.3.3.2.1 Visual Inspection

Search and decision making form the critical components of visual inspection. The search component can be further decomposed into pre-attentive search, and a detailed search consisting of foveal (pure search or search plus decision making) and extra-foveal processes. Similarly, NDI can be decomposed into three broad stages: calibration, probe movement, and display interpretation. Identification of the behaviors associated with each of these subtasks results in a many to many mapping as seen in **Table 5.14** (Visual Search) and **Table 5.15** (NDI). These mappings have been identified for an expert inspector. An interesting aspect of these mappings is the existence of relatively few knowledge-based behaviors exhibited by the expert inspector. This seems logical since there is less problem-solving or active reasoning in aircraft inspection and more detection, identification, and classification.

VISUAL INSPECTION PROCESSES	BEHAVIOR CATEGOHIES		
	SKILL-BASED	RULE-BASED	KNOWLEDGE-BASED
PRE-ATTENTIVE SEARCH	Scan and Detect		
FOVEAL (PURE SEARCH)	Fixate and Detect		
FOVEAL DECISION		Identify and Classify	
EXTRA-FOVEAL SEARCH	Trigger move to next area		
DECISION-MAKING (OUTSIDE OF SEARCH)		Move to next area, Rules of what to look for	Reason and Decide

Table 5.14 Mapping a Visual Inspection Task to Cognitive Behavior for an Expert Inspector

NDI PROCESSES	BEHAVIOR CATEGORIES		
	SKILL-BASED	RULE-BASED	KNOWLEDGE-BASED
CALIBRATION	Probe Movement Over Test Specimen	Calibration Procedures	
PROBE MOVEMENT	Tracking Along Desired Path	Supportive Mode Identifying Boundary Conditions	
DISPLAY INTERPRETATION		Interpreting Familiar Signal	Interpreting Unfamiliar, Unanticipated Signals

Table 5.15 Mapping an NDI Process to Cognitive Behavior for an Expert Inspector

The SRK framework also aids understanding of how behavior will be qualitatively modified as the inspector goes from a novice to an expert. Thus, although both the novice and the expert exhibit, say, rule-based behavior, the behavior of the expert will be qualitatively different from the novice (Sanderson and Harwood, 1988). In **Table 5.16** we have mapped a specific visual inspection task (inspection of rivets) to the SRK framework, to represent the performance of an expert inspector. We can expect that some of the defects identified at the skill-based and rule-based levels by the expert will be identified at the rule-based and knowledge-based levels by the novice, indicating a rightward shift on **Table 5.16,** corresponding to an upward movement on the SRK hierarchy. Thus, this analysis points to the need for different levels of information support for the expert and the novice inspector. It can also provide guidelines to define training requirements for novice inspectors based on identifying expert inspector behaviors.

VISUAL INSPECTION PROCESSES	BEHAVIOR CATEGORIES		
	SKILL-BASED	RULE-BASED	KNOWLEDGE-BASED
PRE-ATTENTIVE SEARCH	• Missing rivet • Hole in skin		
FOVEAL (PURE SEARCH)	• Missing rivet • Hole in skin • Deep dents • Large cracks • Prominent corrosion		
FOVEAL DECISION		• Borderline corrosion • Slight wear • Dished rivets • Ripples in skin • Small cracks	
EXTRA-FOVEAL SEARCH	• Chipped paint in periphery leads to next fixation		
DECISION-MAKING (OUTSIDE OF SEARCH)		• Streaks around rivets trigger inspection for loose rivets • Powdery contamination triggers search for corrosion • Borderline defects	• Defect type not listed • Use of meta-knowledge

Table 5.16 Visual Inspection of Rivets: Cognitive Behaviors for Different Defect Types

Tables 5.14, 5.15, and 5.16 also indicate the large role that skill-based and rule-based behaviors play in visual inspection. The visual search part of visual inspection is seen to be entirely skill and rule-based for the expert inspector (or after training to criteria). The skill-based behavior can be associated to the scanning, fixating, and detecting activities (see **Table 5.14**). Since skill-based performance is essentially unconscious and feedforward controlled, we can conclude that the information aid for this part of the visual search should be <u>something that does not require active conscious use by the inspector</u>. This points to visual environment changes (better lighting, improved contrast), and improved human detection capabilities (increasing visual lobe, increasing target conspicuity). At the same time, this also indicates training as a critical need to attain satisfactory sensory performance.

Tables 5.14 and **5.16** also highlight rule-based behavior resulting in the identification and classification of defects as a significant mode of visual inspection. Thus, finding corrosion, wear, small cracks and similar difficult defects takes place because of rule-based behavior. It is pertinent to note at this point that the work card system used in the aircraft industry to control aircraft maintenance and inspection relies heavily on a linear procedural approach (Drury, 1991; Drury, Prabhu and Gramopadhye, 1990). Rule-based behavior also accounts for search strategies based on past experience and work card instructions. Thus, we reach the conclusion that it is very important to develop procedural knowledge (workcard design), checklists, and comparison standards to support this behavior.

Knowledge-based behavior is often a slow and error-prone process and creates a high cognitive workload for the human. Often in such circumstances the human will try to minimize cognitive strain by using shortcuts in the reasoning and decision making processes, which can lead to suboptimal performance. Thus, we should try to design the system and the information environment to minimize the need to indulge in knowledge-based behavior. Knowledge-based behavior in visual inspection will be more evident in a novice inspector; this provides a strong impetus to the design of adequate training programs to bring the novice to expert levels and thus minimize knowledge-based behavior. Once a certain level of expertise is attained the knowledge-based behavior will be needed only in case of unfamiliar work situations. For example, this can happen if an inspector who normally works on only a specific part of the aircraft (e.g., the wing section) is asked to inspect a cargo door. Thus, it becomes important that the workcard (feedforward environment) be designed for usability and have the information needed to make a smooth transition to an unfamiliar task. Feedback information from a buddy system, and efficient communication lines with the supervisor, also have to be considered. Also important is the development of the knowledge about the spatial and functional aspects of the aircraft, which is partly built through the years of prior experience of the inspector as an aviation mechanic. This is normally five years but is decreasing due to a shortage of inspectors, with some inspectors having as little as three years of maintenance experience. There are cognitive error implications in too rapid a promotion system.

5.3.3.2.2 Non-Destructive Inspection

Moving to NDI inspection, skill-based behavior is predominant while using the probe and is a sensorimotor, feedback-controlled movement. This indicates the need for manual control training on tracking tasks (e.g., circle drawing, tracking) which transfer to this movement control task. Similarly, thought should be given to providing tracing paths (e.g., circles around rivets) which provide adequate feedback information. Templates can and are being used (although some inspectors do not like to use them due to handling difficulties) and the improved design and use of such aids should be encouraged. The rule-based behavior component of calibration points to the necessity of developing adequate and well designed checklists, along with procedural knowledge, for reliable performance. Swain and Weston (1988) point out that during the calibration procedures, powerplant technicians who very often have followed written steps, rely on memory and this increases the probability of omissions. This points to a calibration process design that is capable of providing cues to the next step on the display screen as well as detecting wrong inputs by the operator. Where calibration can be rigidly defined, the checklist is the obvious cognitive aid, already extensively used in aviation. Those calibration tasks which have some flexibility must be clearly delineated for separate treatment.

Display interpretation forms the critical portion of NDI and as such can be either rule-based, or knowledge-based, or both. The information environment should thus support both these behaviors while trying to ensure, through system design and training, that the need for knowledge-based behavior is minimized. Since rule-based behavior is based on signs which trigger stored patterns which in turn control our choices, Rasmussen and Vicente (1989) suggest that the design of the display should be such as to provide action cues as signs which also have symbolic content, thus supporting both rule and knowledge-based performances. Display screens for NDI that allow comparisons of the current pattern (curve) with known defect curves for comparative decision making should be considered. Also, the knowledge-based component found during display interpretation indicates the need to develop feedforward information (training and documentation) to provide technology knowledge, instrument knowledge, and aircraft defect history.

It must be emphasized at this point that in aircraft inspection, skill-based, rule-based, and knowledge-based behaviors are not necessarily stand-alone, discrete behavior modes. Indeed, they overlap on some occasions and support each other on others. For example, the skill-based behavior of probe movement is supported by either knowledge-based (for the novice) or rule-based (for the expert) behavior that ascertains the boundaries of the movement. For example, the probe should not cut the rivet head and a movement too close to an edge should be avoided since both of these will show defect indications without the presence of any defects. Similarly, rule-based behavior of defect identification and classification in visual inspection is sometimes supported by knowledge-based behavior that uses active reasoning based on a deeper and functional understanding of the aircraft. For example, during visual inspection of the wing leading edge, the inspector who is looking for dents may reason that a dent forward of the aileron trim tab may be more important than one in another area because it could cause flow breakup in an area important to flight control. This and the preceding example highlight the often symbiotic relationship of the different behavior modes. Thus, while we concentrate on skill-based and rule-based behavior of the inspector (since these are the dominant behaviors), we also need to understand and support the knowledge-based behavior through adequate training schemes, documentation, and communications.

From the discussion above, it is evident that the mapping of the inspection processes to the SRK framework provides useful guidelines for, and a better understanding of, the type of information that has to be provided for aircraft inspection. This has been compiled in **Table 5.17** where the information categories (feedforward and feedback) identified in the aircraft inspection information model (**Figure 5.3**) have been assigned to the various inspection subtasks based on the type of behavior they would logically support.

5.3.3.3 Analysis of Information Requirements: An Error Taxonomic Approach

In an analysis of 93 major accidents for a 24 year period from 1959 to 1983, Sears (1986) found that 12% were caused by maintenance and inspection deficiencies. Similarly, Nagel (1988) reports that approximately four out of every hundred accidents that occurred in the worldwide jet fleet from 1977 to 1988, had maintenance error as one of the chief causes. As shown in **Section 5.3.2**, the effects of human error are becoming increasingly unacceptable and the issue of maintenance and inspection error is being closely examined and discussed in the aviation community (Drury, 1991).

Formulation of information environment requirements should include the notion of human error and its impact on aircraft inspection. Control of errors to an acceptable minimum is the implicit goal of all *human-machine systems. In aircraft inspection, where the existence of certain defects in an aircraft ready* to fly is almost unacceptable, it is pertinent to make this goal explicit, by defining information requirements based on human error avoidance. It can be argued that information provided at the right time, at the right place, in the right manner, is at least a necessary condition for minimal error performance.

INSPECTION PROCESSES	INFORMATION ENVIRONMENT	
	FEEDFORWARD	FEEDBACK
1. VISUAL (e.g. Rivet Inspection)		
• Pre-Attentive	• Training	
• Foveal Search	• Training	• Output Feedback
• Foveal Decision	• Training • Procedural Knowledge • Comparison Standards	• Cognitive Feedback • Buddy System
• Extra-Foveal	• Knowledge of Cues	• Feedback of Results
• Decision Making	• Co-Worker Information • Functional System Knowledge • *Fault Causation Knowledge* • Aircraft History (Defects)	• Communication Links • Buddy System • *Cognitive Feedback*
2. NDI (e.g. Eddy Current)		
• Calibration	• Checklists, Display Design	
• Probe Movement	• Training on Tracking and Accurate Movement Control	• Probing Aids (Templates or Markings Around Rivets)
• Display Interpretation	• Display Design • Functional System Knowledge • Technical Instrument Knowledge • Aircraft History	• Cognitive Feedback

Table 5.17 Information Requirements Identified from Mapping Inspection Processes to SRK Framework for Two Examples

5.3.3.3.1 Methodology for Information Requirement Formulation

Human error can serve as an effective platform to study and formulate the information requirements of aircraft inspection just as it was used in **Section 5.3.2** to understand the overall inspection process. We present below a methodology that attempts to guide the design of the information environment to controlling human error:

1. Identify and define the levels of the system under consideration (e.g., management, supervisory, lead inspector, inspector).
2. At the level under analysis, define the functional requirement of the level, current allocation of human-computer functions, and interactions with the other levels.
3. Develop a human error taxonomy for the level under consideration.
4. Use the taxonomy and the functions identified in step 2 to outline the failure modes (phenotypes) and associated mechanisms of human malfunction and error shaping factors (geno-types) specific to each function.
5. Identify the component of the information system that would be necessary to control human error based on understanding of the phenotypes and genotypes of step 4.
6. Define the requirements of each information component: (1) what information to present (information quality); (2) when to present such information (information flow); and (3) how to present this information (information display), so that the human error potential is minimized.

The above methodology combines a task analytic approach with a human error taxonomy so that *information requirements are formulated to control human error. Obviously, the error taxonomy* development is an important part of this approach. A framework or guideline is presented, which can be used to develop a taxonomy for use in this methodology.

Rasmussen and Vicente (1990) suggest that human error analysis can be performed from two different perspectives. The first perspective tries to identify possible human errors and their effects on system performance, while the second perspective aims at improving system design to eliminate the effects identified in the analysis from the first perspective. Based on the first perspective, Drury (1991) developed an error taxonomy from the failure modes of each task in aircraft inspection. This taxonomy has been developed based on the recognition that a pro-active approach to error control is needed to identify potential errors. Thus, the taxonomy is aimed at the phenotypes of error (Hollnagel, 1989), i.e., the way errors are observed or appear in practice. In **Section 5.3.2** it was also noted that Rasmussen and Vicente (1990) propose a taxonomy from the viewpoint of identifying possible improvements in system design with categories of errors as related to: (a) effects of learning and adaptation, (b) interference among competing control structures, (c) lack of resources, and (d) stochastic variability. They suggest that different methods have to be adopted to control the errors associated with each of the above four categories, and that it is necessary to make the system error-tolerant to achieve reliable system performance.

We propose that the failure modes identified in the taxonomy of aircraft inspection by Drury (1991) can be classified using the systemic error mechanisms categories and the cognitive control categories proposed by Rasmussen and Vicente (1989). (An example is given in **Table 5.18**, for error modes in the decision task.) In **Table 5.19**, such an assignment is shown using the failure modes for the decision task. For each behavior mode (i.e, skill, rule, or knowledge) the genotypes of errors can be then postulated. Genotypes are the contributing psychological causes of errors and are representative of the characteristics of the human cognitive system (Hollnagel, 1989). **Table 5.20** shows the genotypes assigned to the different behavior modes.

TASK	ERROR(S)
TASK 4 – DECISION	
4.1 Interpret indication	4.1.1 Classify as wrong fault type.
4.2 Access measuring equipment.	4.2.1 Choose wrong measuring equipment. 4.2.2 Measuring equipment is not available. 4.2.3 Measuring equipment is not working. 4.2.4 Measuring equipment is not calibrated. 4.2.5 Measuring equipment has wrong calibration. 4.2.6 Does not use measuring equipment.
4.3 Access comparison standards.	4.3.1 Choose wrong comparison standard. 4.3.2 Comparison standard is not available. 4.3.3 Comparison standard is not correct. 4.3.4 Comparison standard is incomplete. 4.3.5 Does not use comparison standard.
4.4 Decide on fault presence.	4.4.1 Type 1 error, false alarm. 4.4.2 Type 2 error, missed fault.
4.5 Decide on action.	4.5.1 Choose wrong action. 4.5.2 Second opinion if not needed. 4.5.3 No second opinion if needed. 4.5.4 Call for buy-back when not required. 4.5.5 Fail to call for required buy-back.
4.6 Remember decision/action.	4.6.1 Forget decision/action. 4.6.2 Fail to record decision/action.
OUTCOME 4: All indications located are correctly classified, correctly labelled as fault or no fault, and actions correctly planned for each indication.	

Table 5.18 Task and Error Taxonomy for Inspection, Task 4, Decision

The above framework, then, allows the opportunity to examine each failure mode within the context of (a) the cognitive behavior from which it results, (b) the systemic error category in which it occurs, and (c) the internal error mechanisms that are the probable causes of these malfunctions. An analysis of this information can then form the basis of system design to minimize or eliminate the failure modes. From the information requirements viewpoint, system design considerations should then drive the specifications as to the type, location, and temporal position of the information. Preliminary recommendations on the type of information component have been listed in **Table 5.20**. In actual use, **Table 5.20** should be utilized as a framework for an error taxonomy which can be applied in the task analysis methodology proposed.

5.3.3.4 Testing the Information Framework

Using the inspection program developed for NDI (**Section 5.3.1.1**) it is possible to make direct experimental tests of many of the predictions coming from the framework being developed in **Sections 5.3.3.2** and **5.3.3.3**. As a demonstration of the use of the NDI inspection program, a relatively simple experiment based on the information requirements was conducted. It involved training two groups of subjects on the inspection task, then either providing or not providing off-line feedback of performance, and finally measuring inspection performance of both groups.

SYSTEMIC ERROR	BEHAVIOR CATEGORIES		
	SKILL-BASED BEHAVIOR	RULE-BASED BEHAVIOR	KNOWLEDGE-BASED BEHAVIOR
1.Effects of Learning and Adaptation	4.2.1, 4.2.4, 4.2.6, 4.3.1, 4.3.5, 4.5.1, 4.6.2	4.2.4 Fail to calibrate meas. eqpt. 4.2.6 Fail to use meas. eqpt. 4.3.5 Fail to use comp. std. 4.6.2 Fail to record decision. 4.2.1 Choose wrong meas. eqpt. 4.3.1 Choose wrong comp. std. 4.5.1 Choose wrong action 4.2.5 Meas. eqpt. wrongly calib. 4.1.1 Classify as wrong fault. 4.4.1 False alarm. 4.4.2 Missed fault.	4.1.1 Classify as wrong fault. 4.4.1 False alarm. 4.4.2 Missed fault 4.5.2 Wrong decision on getting. 4.5.5 Second opinion. 4.5.4, 4.5.5 Wrong decision on calling for buyback. 4.2.5 Wrong calibration of meas. eqpt.
2. Interference Among Competing Control Structures		4.2.5 4.1.1, 4.4.4, 4.4.2 4.5.1 4.5.2, 4.5.3, 4.5.4, 4.5.5	4.1.1, 4.4.1, 4.4.2, 4.5.2, 4.5.3, 4.5.4, 4.5.5
3. Lack of Resources			4.6.1 Forget decision 4.5.2, 4.5.3 4.5.4, 4.5.5
4.Stochastic Variability		4.1.1, 4.4.1, 4.4.2	4.6.1

Table 5.19 Assignment of Systemic Error Mechanisms to Failure Based on Behavior Types for the Decision Making Component of Aircraft Inspection

As shown in **Section 5.3.3.1**, on-the-job feedback can be a powerful performance enhancer, but it is an expensive one to implement. It involves re-inspection of an inspector's work by a (presumably more reliable) auditor, a process which adds cost in proportion to the percentage of work audited. A more realistic approach would be to provide feedback, for example by having the inspector inspect a test piece with a known set of faults, between regular inspection tasks. Feedback can easily be provided from such a test piece, but we need to measure the effectiveness of such feedback. A test of this effectiveness also provided a useful practical test of the NDI program, and indeed many pilot subjects were run and program modifications were made before the complete experiment reported here was started. The following is a brief description of the experiment and its results. These results are being presented in more detail in a separate project report.

5.3.3.4.1 Methodology

Two groups of eight subjects each were chosen randomly from a population replying to advertisements. All were currently unemployed members of the work force, with males and females and a variety of ages represented. Each subject was given two pre-tests, both of which had been shown to correlate with performance on industrial inspection tasks. The first was the Embedded Figures Test (EFT) which classifies the cognitive style of a person as Field Dependent (i.e., highly influenced by the visual context of a task) and Field Independent (i.e., more able to cognitively restructure a task independent of its visual

Table 5.20 Framework to Formulate Information Requirements: Example for the Decision-Making Component of Aircraft Inspection & Systematic Error Category of Learning and Adaption

BEHAVIOR TYPE	FAILURE MODE (PHENOTYPES)	MECHANISMS OF HUMAN MALFUNCTION AND ERROR SHAPING FACTORS (GENOTYPES)	INFORMATION REQUIREMENTS
KNOWLEDGE-BASED	4.1.1 Classify as wrong fault. 4.4.1 False alarm. 4.4.2 Missed fault.	o Selectivity o Incomplete mental model o Lack of knowledge o Confirmation bias	Training in fault causation mechanisms
	4.5.2, 4.5.3 Wrong decision on getting second opinion. 4.5.4, 4.5.5 Wrong decision on calling for buy-back	o Overconfidence o Incomplete knowledge o Biased reviewing	Crew resource management training Outcome and cognitive feedback
	4.2.5 Measuring equipment wrongly calibrated.	o Overconfidence o Incomplete knowledge	Training and aiding for understanding NDI system physics
RULE-BASED	4.2.4 Fail to calibrate measuring equipment.	o Recall error o Memory slip	Checklists Feedback in NDI instrument
	4.2.6 Fail to use measuring equipment. 4.3.5 Fail to use comparison standards.	o Recall error o Overconfidence o Memory slip o Mindset or rigidity	Checklist
	4.6.2 Fail to record decision.	o Recall error, memory slip o Availability o Mindset o Wrong rules	More field-usable fault-recording devices
	4.2.1 Choose wrong measuring equipment. 4.3.1 Choose wrong comparison standards. 4.5.1 Choose wrong action.	o Stereotype takeover o Memory slip o First exceptions o Availability	Checklist Computer entry and checking of equipment and standard ID's for feedback
	4.2.5 Measuring equipment wrongly calibrated	o Familiar shortcut o Misinterpretation	Checklist, enforcement of rules
	4.1.1 Classify as wrong fault. 4.4.1 False alarm. 4.4.2 Missed Fault	o Encoding deficiency o Familiar pattern not recognized	Training in fault classification Cognitive feedback
SKILL-BASED	4.2.1, 4.2.4, 4.3.1, 4.3.5, 4.2.6, 4.5.1, 4.6.2	o Omissions o Recency and frequency of use o Speed accuracy tradeoff	Skills training Skills maintenance for infrequently-used behaviors

context). The second test was the Matching Familiar Figures Test (MFFT) which measures the tendency of subjects to opt for speed or accuracy in their speed/accuracy tradeoff (see **Section 5.3.4**). Foveal visual acuity was also measured.

Both groups were given the same training in the principles of eddy-current inspection of rivets for cracks, in controlling of the pointer using the mouse, and in interpreting the meter needle movements. This training occupied about four hours. Following training, the eight subjects in the control group were tested on a task involving 420 rivets followed by a task involving 80 rivets, on each of four days. The experimental group was given the same task except that they were provided with feedback on the missed cracks, false alarms, and performance time on the 80 rivet task.

In the main task, the same measures of misses, false alarms, and task time were taken for each subject.

5.3.3.4.2 Results

Analyses of covariance were performed on the measures of total time, misses, false alarms, and derived measures from Signal Detection Theory (**Section 5.3.5**) of sensitivity (d') and criterion (X_c). Each analysis tested for differences between the two groups (G), for differences between the four days (D), as well as for their interaction (D X G). Two sets of covariates were derived from factor analysis to contain the following components:

Covariate 1: EFT Errors, EFT Times, MFFT Errors
Covariate 2: MFFT Time (negative), Visual Acuity

Covariate 1 represents poor accuracy performance and field dependence, while Covariate 2 represents fast performance with good vision. **Table 5.21** summarizes the analyses of covariance of the measures taken. There were no significant group effects, and only a single day effect, that on total time for the task. Covariate 2 was significant for total time and for criterion X_c. **Figure 5.8** shows plots of the results for times, misses, false alarms, and sensitivity (d') comparing the experimental and control groups across the four days of the experiment.

Measured Analyzed	Groups (G)	Days (D)	G X D	Covariate 1	Covariate 2
Total Time	—	P < 0.0001	—	—	P = 0.0235
Misses	—	—	—	—	—
False Alarms	—	—	—	—	*
Sensitivity (d')	—	—	—	—	—
Criterion (X_c)	—	—	—	—	P = 0.0355

* Indicates that the Visual Acuity component of covariate 2 was significant at P < 0.0244

Table 5.21 Summary of Analyses of Covariance for Off-Line Feedback Experiment

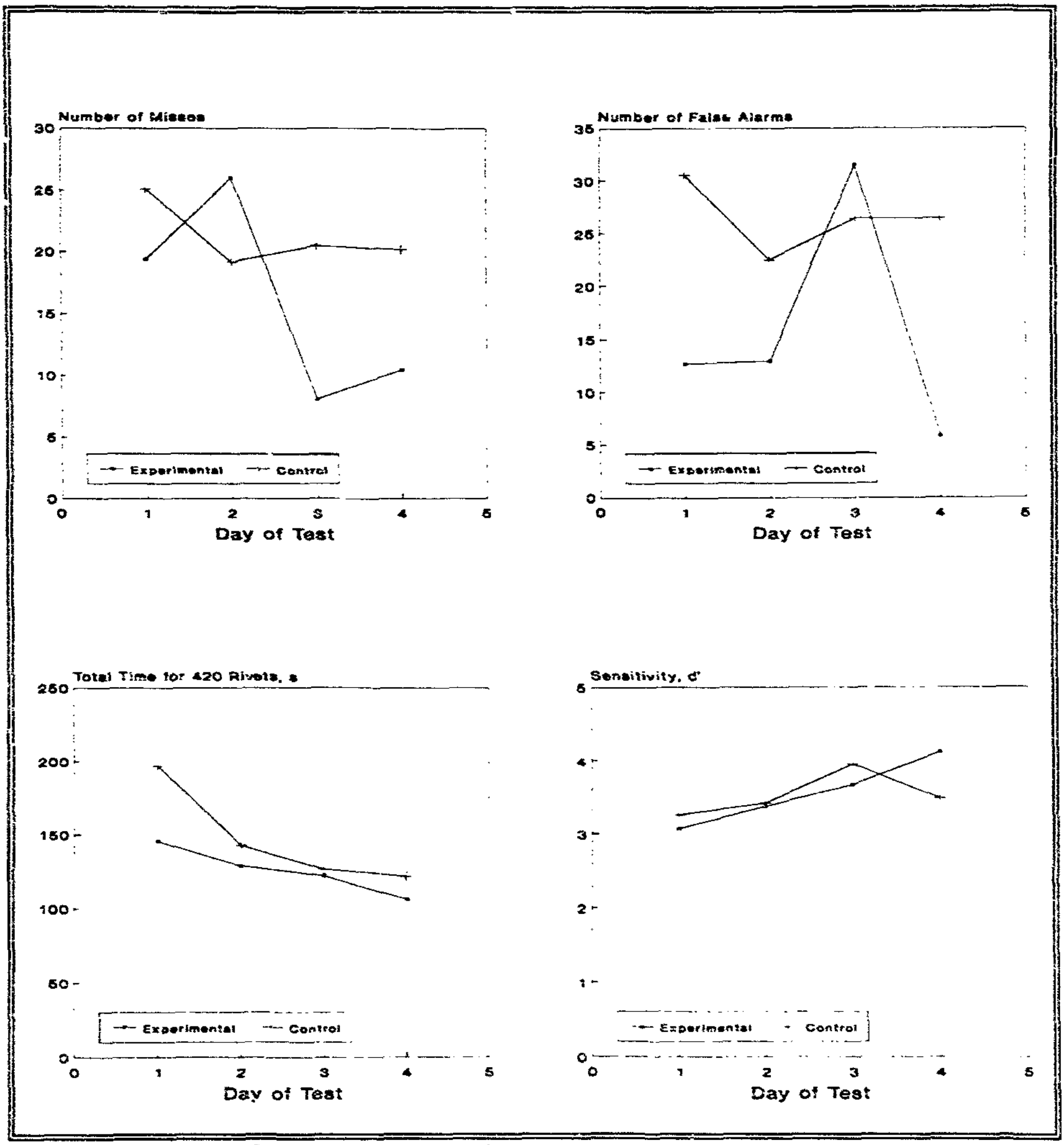

Figure 5.8 Day X Group Interactions for Off-line Feedback Experiment

5.3.3.4.3 Discussion

The major finding of this first experiment using the NDI program was one of very high between-subject and day-to-day variability. The between-subject variability was expected, and it appears that some of this variability at least is predictable using the covariates derived. Because of this variability, the effects shown in **Figure 5.8** do not reach statistical significance with only eight subjects per group. Having said this, there is an indication in all four parts of **Figure 5.8** that the experimental group outperforms the control group by the end of the experiment.

Over the four days of the experiment, accuracy performance, as measured by misses and false alarms, improved slightly for the control group and somewhat more for the experimental group. Despite this overall improvement, the day-to-day improvement was erratic. Total time decreased for both groups, with the experimental group being more rapid than the control group throughout. Sensitivity, as defined in Signal Detection Theory, marginally favored the control group until the final day, when the experimental group continued to improve while the control group regressed slightly.

During the course of the experiment, it was clear that the experimental group was using the off-line feedback to modify their inspection strategy. However, this process involved trial and error, which gave considerable variability of performance. The performance feedback helped somewhat, but would have been much easier to interpret if it had contained hints and steps that the inspectors could take to make the improvements they knew were needed. Cognitive feedback, as postulated in **Section 5.3.3.1** appears to be required if inspectors are to make use of their own performance data.

5.3.3.4.4 Conclusions

While off-line performance feedback was marginally effective, the high variability between subjects prevented significant results from being obtained. At least part of the day-to-day variability was due to subjects using the feedback in an unguided manner in an attempt to improve, suggesting that cognitive feedback may be needed to supplement off-line performance feedback. The small size of the feedback task (80 rivets) might also have failed to provide sufficient data to significantly aid in transfer of feedback results. The significant covariates for total time and criterion also indicate influence of other independent factors, namely visual acuity and cognitive style.

5.3.4 A FRAMEWORK FOR SPEED/ACCURACY TRADEOFF IN AIRCRAFT INSPECTION

In almost any discussion with aircraft maintenance personnel, maintenance managers, regulatory bodies, or the traveling public, the general issue of inspection accuracy arises. More specifically, in the post-deregulation environment of U.S. commercial aviation, the effect of time pressures on the inspection system (particularly the human inspector) is causing concern. This section reviews the functions and tasks of aircraft inspection, based upon a two-year observational study of the system, and uses prior studies of human inspection to examine the possibilities of time pressure affecting accuracy. A Speed/Accuracy Tradeoff (SATO) perspective is taken, i.e. how do speed and accuracy co-vary in inspection.

Both speed and accuracy are relatively easy to define in inspection.

Speed:	The rate of inspecting items, usually measured as the reciprocal of the time(t) taken to inspect a single item or defined area.
Accuracy:	False Alarm (Type 1 error) The probability of an inspector responding that a defect exists, when in truth it does not. Miss (Type 2 error) The probability of an inspector failing to respond that a defect exists, when in truth it does exist.

This section is concerned explicitly with the co-variation of (t), False Alarms, and Misses.

From an airline management perspective, two goals need to be achieved by the system: safety and profitability. The profitability goal can only be achieved by first ensuring that the safety goal is achieved economically. These objectives are passed through sometimes complex organizational systems (Taylor, 1990) to supervisors and finally to inspectors. At the inspector's level two goals need to be achieved by the inspection system: accuracy and speed. Accuracy means detecting those indications (faults) which must be remedied for the safe operation of the aircraft while not activating the maintenance system for non-faults. Speed means the task must be performed in a timely manner without the utilization of excessive resources. These two criteria of the inspection system can be expected to be inversely related at the inspection level (Drury, 1985).

When inspection is split into its task steps (**Table 5.1** of **Section 5.1.1**), it can be seen that all of the tasks require both speed and accuracy for their completion. However, the most error-prone activities in industrial inspection are the search and decision making tasks (Drury, 1984) while access is an activity whose time must be minimized for efficient operation.

The speed and accuracy with which each of the components is performed depends upon the relative utilities of the various outcomes to the inspectors. Utility is a concept that can be used in models of the inspector as a maximizer or optimizer (Drury, 1992) to give a normative model as a starting point for more realistic inspector models. Thus, the optimum speed and accuracy is not defined in terms of minimizing or maximizing one particular aspect of inspection but is defined in terms of a performance which yields the highest overall utility.

If a task can be performed at various levels of speed and accuracy, then it is possible (Wickens, 1984) to generate an operating characteristic curve (see **Figure 5.9a**) relating the two measures. Any point on the speed/accuracy operating characteristic (SAOC) curve shows the accuracy with which the task can be performed at a particular speed. Hence to meet the designed system objectives of speed and accuracy, it is essential that the inspectors operate at the correct point on the correct operating-characteristic curve.

In order for an inspector to choose a particular strategy from the set of available strategies, it is necessary to determine the utility of all the candidate strategies, as a function of speed and accuracy. The utility can be computed for every point in the joint performance space (Speed, Accuracy), whether that point is achievable or not. Now by knowing the utility function it is possible to determine the optimal operating point, i.e. that which maximizes the expected utility. Typically, contours of equal utility are superimposed upon the SAOC to show where this optimal operating point occurs (see **Figure 5.9b**). This section considers access, search, and decision making in turn, and uses models of each to show the form of the

SAOC. Models are not developed in detail. For more information the original report (Drury and Gramopadhye, 1991) can be consulted. Each model is an optimization model, showing how an inspector may be expected to choose between alternative strategies. In large decision tasks, there is considerable evidence that they are satisfiers rather than maximizers (Wickens, 1991). However, in small task components such as those found in inspection, optimization models represent a good starting point for consideration of the factors involved (Drury, 1988; Chi, 1990).

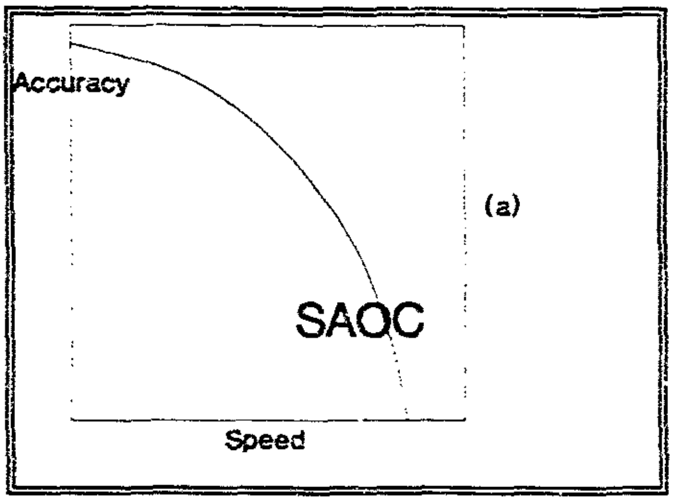

Figure 5.9a Generalized Speed/Accuracy Operating Characteristics (SAOC)

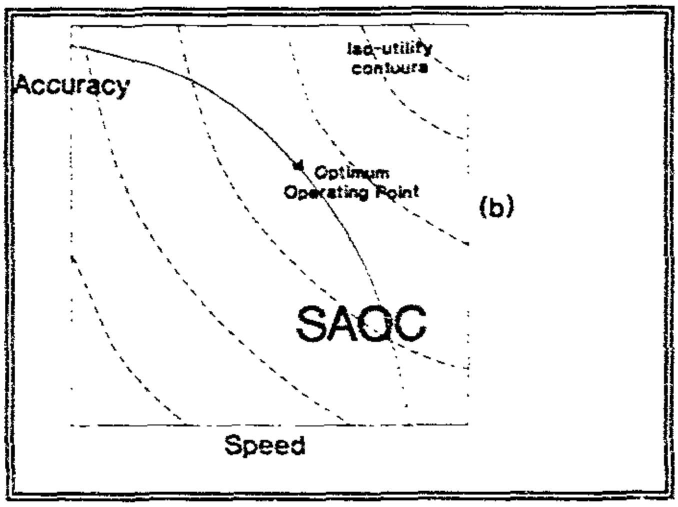

Figure 5.9b Generalized Speed/Accuracy Operating Characteristics (SAOC)

5.3.4.1 Factors Affecting Access Tasks

The access task consists of physically reaching the area to be inspected. This may be an unaided human task (e.g., area inspection of lower fuselage skin), aided by access devices (e.g., steps, scaffolding, cherrypickers), or require access through intervening structure (e.g., inspection of interiors of wing fuel tanks through access holes). All of these activities involve controlling the movement of the inspector's body, or body parts, within a restricted space. In general, control theoretic models of the human operator in control tasks (Sheridan and Ferrell, 1974; Wickens, 1984) show that as more speed is demanded, tracking accuracy decreases--a typical SATO. If the access task is modelled as moving accurately between two boundaries without making an error of exceeding a boundary, then the self-paced tracking models of Drury (1971) and Montazer, Drury and Karwan (1987) can apply. Thus, moving the body along the walkway of a scaffold without hitting (and possibly damaging) the aircraft structure on one side or the scaffold rail on the other is such a task. Moving the hand (or head) through an access hole or moving a cherrypicker along the fuselage upper skin, (although only one physical boundary exists here) are further examples.

The self-paced tracking model considers the inspector, or a vehicle controlled by the inspector, as choosing a speed which will maximize the utility to the inspector. Utility is composed of rewards for speed and penalties for error, in this case the error of exceeding the fixed boundaries. Model results, and experimental data from a variety of studies, have shown that the speed chosen increases with space available (e.g., width) until some limiting speed is reached. The three factors affecting performance are thus space available, the ease of control (controllability) of the vehicle, and the inspector's perception of the relative utilities of speed and accuracy. Each will be considered in turn.

5.3.4.1.1 Space Available

Space available can be controlled relatively easily around the aircraft, but access within the airframe itself is largely determined at the design stage. With older aircraft there has been a history of unpleasant surprises for maintenance personnel when they reached service, but manufacturers are now using computer-manipulable human anthropomorphic models (e.g., CREWCHIEF, SAMMIE) to examine access for maintenance before structures are finalized. Note, however, that the SATO model shows that more space improves performance, so that the minimum necessary for physical access (e.g., for a 95th percentile male) will not provide optimum performance. A human anthropomorphic model only gives the space required for a person to statistically assume a posture. For movement (the essence of maintenance and inspection) more access room is required beyond this minimum. The same considerations apply to access around the aircraft. Steps and walkways should be made wide enough to provide unhindered movement, not just wide enough to accommodate a large static human. As an example, Drury (1985) reports that for movement through a doorway both performance time and errors decrease from the anthropometric minimum width of about 20 inches to the unhindered width of 36 inches. Very similar findings are used in the aviation industry to determine sizes of emergency doors for passengers.

During Phase III of this work, explicit models and experiments will be developed to test the effects of space available, and human posture, on performance and stress in inspection and maintenance activities.

5.3.4.1.2 Controllability

Controllability of the system having access is a major determinant of access performance. For most tasks, the "system" is the inspector's own body, the most naturally controllable system. However, controllability can be adversely affected by equipment carried (flashlight, tools, work cards, NDI equipment) and by the quality of clothing worn. Thus, coveralls and shoes should be minimally restrictive. Shoes should also provide good grip on a variety of surfaces under both wet and dry environmental conditions. Controllability will be decreased by any impairment of the human, for example sickness, alcohol, or drugs, reinforcing the control required over such conditions at the work place.

For control of systems such as vehicles (e.g., cherrypickers, wheeled steps, moveable access scaffolds) a considerable body of information exists (e.g., Wickens, 1984) on the human as controller. Most of these recommendations apply equally to the self-paced access tasks considered here. Thus for example, controls should move in the same directions and sense as the element they control. It should be noted that many cherrypickers have hydraulic or electrical controls which violate this principle. Direction of motion errors are to be expected with such systems, causing at best a slowing of the task and at worse damage to the aircraft structure, depending upon the operator's SATO choice. These same controls are often not progressive in operation, but "bang-bang" controls, either fully on or fully off. With such a degraded control system, any designed speed setting is a poor compromise. At times it is too slow, causing delay and frustration in making long movements, while at other times it is too rapid, causing errors and time-consuming multiple corrections in making the final accurate positioning movements. In addition, any time lags or inertia in the system controlled will have a negative impact on controllability.

Within the maintenance hangar, there are other constraints on design (or choice) of access equipment. Any equipment must be available if it is not to cause delays, suggesting both that a sufficient supply exists, and that it is well-scheduled. The difficulty with maintaining a sufficient supply is that such equipment is both expensive and space-consuming. The typical management response is to have a mixture of special-purpose equipment, such as empennage access scaffolding, and standardized. flexible equipment, such as stepladders, cherrypickers, and standard moveable platforms. When only a single aircraft type is to be serviced, as in most large airlines and specialist repair centers, purpose-built equipment should, and does, predominate. In more general purpose organizations, the emphasis is on standardized, flexible equipment. However, there are still times when schedules demand more access equipment than is instantaneously available. It is at these times that available equipment is substituted for correct equipment to avoid delays. The result is lower system controllability, with the potential for errors affecting both job performance and personnel safety.

5.3.4.1.3 Perception of Utilities

Given the space available and the controllability of the system, the balance between speed and accuracy is still finally chosen by the operator's own SATO. As discussed earlier, this is where any gate pressures or schedule demands can have an effect. As access is a task of inspection which appears non-critical, it can be one where time is saved for tasks perceived as more important. In addition, access is where pressures from other members of the maintenance team can be acute. Co-workers will at times need the access equipment the inspector is using or *vice versa*, leading to time pressures over a short time scale even where none exist on the longer-term scale of a whole maintenance visit.

Inspectors' errors in access are defined as reaching or exceeding the boundary of available space. They thus include both damage to aircraft structure, and injury to the inspector. Humans are likely to misperceive the risks associated with such rare events, both in terms of the consequences and probabilities involved. Particularly with highly experienced personnel, such as inspectors, the probabilities of error are typically rated lower than their objective values. This can be expected to lead to a choice of SATO strategy favoring speed rather than accuracy.

5.3.4.2 Factors Affecting Search Tasks

The process of visual search of an extended area, such as the area called out on a workcard, has been successfully modeled since the start of human factors engineering. A human searcher (e.g., the inspector) makes a sequence of fixations, centered on different points in the area. During a fixation, which typically lasts 0.25-0.5 seconds, the inspector can detect defects in an area, called the visual lobe, around the fixation center. Between fixations the eye moves very rapidly and can take in very little information. The sequence of fixations can either be modelled as random (e.g., Krendel and Wodinski, 1960) or systematic with repeated scans (e.g., Williams, 1966). For both of these models, equations can be developed relating the probability of detection to the time spent searching (Morawski, Drury and Karwan, 1980).

In general, the longer an inspector searches an area, the greater the probability of a target being located, with diminishing returns as search time is increased. Such curves are the SAOC's of visual search, and are shown in **Figure 5.10.** Given such SAOC's, then the optimum time for searching can be calculated (Morawski, Drury and Karwan, 1992) based upon the reward for speed and the penalty for error.

From the visual search models, three groups of factors determine search performance:

1. Factors affecting the visual lobe.
2. Factors affecting the search strategy.
3. Factors affecting the SATO and stopping policy.

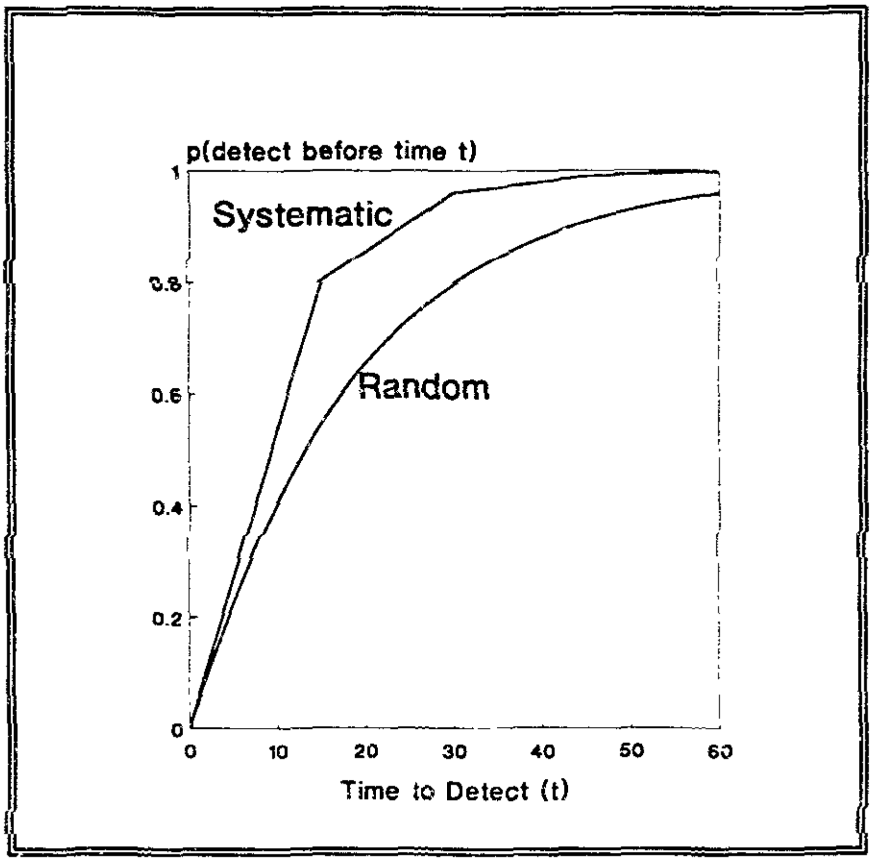

Figure 5.10 Typical Cumulative Search Time Distribution, Giving the SAOC for Visual Search

Based on the defect type, severity level, and location, the defects can be classified into critical and non-critical defects. Critical defects are those defects which affect the airworthiness of the aircraft, hence whose detection is critically important. Non-critical defects do not immediately affect the airworthiness of the aircraft but have to be detected in the long run. There is clearly a heavy penalty for missing critical defects, but the entire area needs to be searched for both critical and noncritical defects within a specified time period. Thus, two goals need to be achieved by the inspector, speed and accuracy, for which the inspector needs to be efficient as well as effective. In order to understand the Speed/Accuracy Tradeoffs in search where the inspector is looking for multiple defect types, the factors which affect this tradeoff and indeed the whole search process must be examined.

5.3.4.2.1 Visual Lobe Factors

According to Engel (1971) fault conspicuity is defined as that combination of properties of a visual object in its background by which it attracts attention via the visual system, and is seen as a consequence. Monk and Brown (1975) have shown that mean search times increase as a function of the number of non-targets in the target surroundings. They have also shown that isolated targets are more easily detected than those surrounded by non-targets. Williams (1966) has shown that the color and size of the targets can be used by subjects to direct their eye movements. Studies of information processing within a single fixation have shown that the probability of target detection increases with increased target size and brightness contrast, and decreases with angular distance from the fixation point (Overington, 1973). This decrease with off-axis angle provides the basis for determining visual lobe size, i.e., the area within which a target may be detected (Bloomfield, 1975).

In aviation, this search performance has been extensively studied and modeled to determine human performance in detection of military targets (for example, ground targets or hostile aircraft). In terms of aviation maintenance inspection, the implication is that lighting and other target/background amplification devices should be used to make the conspicuity of a defect as high as possible, and hence increase visual lobe size.

There are, of course, individual differences in visual lobe size. Eye movement studies have shown that subjects who have larger visual lobes are more efficient, or they detect targets (faults) earlier on in the search process (Schoonard, et al., 1973; Boynton, 1960). Johnston (1965) provided evidence to suggest that subjects who obtain high peripheral acuity scores exhibit relatively shorter search time. There is evidence that the visual lobe size is amenable to training (Gramopadhye, Palanivel, Knapp, and Drury, 1991). There is no evidence that better inspectors have shorter fixation times, only that they make fewer fixations, presumably because of the larger visual lobe size.

The implication for aviation inspectors is that individual differences may be quite large, but are amenable to training. Other evidence (Gallwey, 1982; Drury and Wang, 1986) suggests that selection tests for visual lobe size may well be task-specific, in that the ability to search for defect (D) in background (B) may be unrelated to the ability to search for a different defect (D') in a different background (B'). As Drury and Gramopadhye (1990) have noted, training appears to be a more powerful intervention strategy than selection for inspection tasks.

5.3.4.2.2 Search Strategy Factors

As noted earlier in this section, search strategy can be modeled as random or systematic, with humans believed to lie in between these two extremes. A systematic search strategy is always more efficient than a random strategy. Scanning strategy is dependent on an inspector's:

1. Familiarity with the task (experience).

2. Ability to obtain and utilize feedforward information from cues regarding defect locations and defect types uncertainty). Gould and Carn (1973) and Monk (1977) have shown that in tasks which do not lend themselves readily to the adaptation of systematic search strategy, search times increase with increased fault uncertainty.

Search strategy in visual search is a global term which reflects many parameters of saccadic movement. The speed with which search is performed is dependent on the eye movement parameters, such as those listed by Megaw and Richardson, 1979: fixation times, spatial distribution of fixation, interfixation distance, duration of eye movements, and sequential indices. Fixation times have already been considered in the previous section on visual lobe factors.

Inspectors do not have uniform coverage of the area inspected (Schoonard, et al., 1973), with the central portions given more attention than the edges. In addition, inspectors may not always choose a correct distance between successive fixation centers (Gould and Schaffer, 1967; Megaw and Richardson, 1979). The scan path of an inspector changes with experience (Kundel and Lafollette, 1972; Bhatnager, 1987) to reflect a more consistent path, more even coverage, and more coverage where there is a higher probability of a fault being located.

The studies of search strategy are not conclusive on how to take practical steps to improve that strategy, although they do point to structuring of the search field as a way to increase the likelihood of systematic search.

With a structured field, the current fixation point will serve as a memory aid to which areas have already been searched. Suitable structuring devices may be panel lines, physical elements of complex parts (doors, landing gear), or superimposed temporary structures, such as inspectors' markings on aircraft.

Any such structuring lines should be made clear on the graphics included with workcards, and in any training materials.

There are likely to be large individual differences in search strategy, differences which are relatively stable over time. The issue of training of search strategy is the subject of one of the experiments presented in the training section (**Section 5.3.5**).

5.3.4.2.3 SATO and Stopping Policy Factors

Choice of operating point on the SAOC is determined by the perceived utilities of speed and accuracy. The only error possible on a search task is a Miss, so that high accuracy implies locating all potential defects in the structure. Inspectors are highly motivated for accuracy, as noted earlier (Shepherd, et al., 1991), so that one would expect an operating point on the SAOC representing long search times, with repeated search being common. In practice, inspectors appear to stop at the end of a single scan of the area, only repeating a fixation if some indication has been found. It appears that inspectors recognize the "diminishing returns" aspect of search performance, and are confident enough in their abilities that a single scan at the appropriate level of detail is seen as optimal. Such a policy certainly reduces the memory load and potential vigilance effects associated with multiple scans. However, the inspector will need to be "recalibrated" at periodic intervals by retraining or by providing test sessions to ensure that the speed of inspection chosen is appropriate to the accuracy demanded.

5.3.4.3 Factors Affecting Decision Making

Decision making is the task during which any potential defect (indication) located by the search task is evaluated to determine whether it should be reported. In this task both Type 1 errors (False Alarms) and Type 2 errors (Misses) can occur. These have their own tradeoff relationship so that some combined accuracy measure must be derived before any tradeoff between speed and accuracy can be considered.

One particular model of the human as a rational economic maximizer which has received widespread support in inspection is Signal Detection Theory (SDT). Originally proposed by Swets and various co-workers (e.g., Swets, 1967) as a model for how humans detect signals in noise, it was subsequently applied successfully to inspection (Wallack and Adams, 1969, 1970; Sheehan and Drury, 1971; Drury and Addison, 1973).

In the SDT, the inspector is assumed to be making a choice for each item inspected of whether the item contains a defect ("signal") or does not ("noise"). As the evidence for signal or noise is somewhat equivocal, there is assumed to be an "evidence variable" which increases when a signal is present and decreases when only noise is present. An example would be the judgement of whether a dent in a stabilizer leading edge should be reported. Dents can range from almost imperceptible to obviously reportable. The evidence variable (dent visual severity) must be judged against both written size standards and the likely effect of the dent on flight characteristics.

SDT shows that the two error probabilities, p (miss) and p′ (false alarm), can be derived from a model in which the inspector chooses a criterion (X_c) to report on the presence of a defect. As this criterion varies from high (defects rarely reported as present) to low (defects often reported as present), an Operating Characteristic Curve is traced out. This curve has become known as the Receiver Operating Characteristic (ROC) in SDT literature. A different ROC curve is traced out for different levels of signal/noise ratio, known as discriminability and symbolized by d' .

Wickens (1984) has divided tasks into those which are resource limited and those which are data limited. In the former tasks, as the operator brings more resources to bear on a problem (e.g. devotes greater time to it) performance improves. In a data limited task, the quality of the data received by the operator is the limiting factor, so that more resources yield no better performance. It appears that SDT tasks are only resource limited up to short times, after which they are data limited. Because aircraft inspection is typically a matter of minutes and hours rather than seconds, a reasonable assumption is that its decision making aspects are data limited. Thus there is unlikely to be a marked SATO for decision making during the inspection task. However, the grosser aspects of decision may still show a SATO. For example, if the inspector is unable to reach a decision, the supervisor (or other senior personnel) may be called in to assist. Here the inspector is attempting to improve accuracy at the cost of increased time.

From the SDT model, there are three groups of factors which can affect the overall speed and accuracy:

1. Discriminability or sensitivity.
2. Choice of criterion.
3. Choice of SATO operating point.

5.3.4.3.1 Factors Affecting Sensitivity

Most factors affecting discriminability or sensitivity are physical, and can be characterized as the perceived difference between the observed indication and a standard. Thus, indications obviously well above or below the standard will have high d′ values. Examples would be large areas of corrosion, cracks noticeably larger than those allowed, or completely missing rivets. None would require difficult (i.e., error prone) decisions. But "perceived difference" implies both high signal and low noise in SDT terminology. Low noise means low levels of visual distraction (i.e., competent cleaning), low levels of fatigue (i.e., frequent task breaks), and very clear standards (i.e., well-defined and well-presented job aids). All of these can be improved in aircraft inspection.

Comparison standards at the work place have been shown to be effective in improving discriminability (Drury, 1990b). It should be possible for the inspector to make a direct side-by-side comparison of an indication with a standard. For example, the critical amount of corrosion beyond which a report must be made should be indicated by a life-sized diagram on the workcard. Also, if different corrosion types are present, life-sized photographs help in positive identification (Harris and Chaney, 1969).

5.3.4.3.2 Factors Affecting Criterion

From SDT, the two factors affecting the choice of criterion are the relative costs of errors (misses and false alarms) and the true rate of defects (p'). From these factors, the optimum criterion can be calculated, but this is rarely the exact criterion used by the inspector. In laboratory tasks, and in non-aviation inspection tasks, inspectors choose a criterion in a conservative manner. Thus, if the criterion should be low (i.e., they should be very willing to report indications as defects), inspectors choose a criterion which is not low enough. Similarly, they choose a criterion which is not high enough when the criterion should be high. Because of this conservatism inspectors may not react quickly enough in changing their criterion as costs and probabilities change. Thus, it is important to provide accurate and up-to-date feedforward information on the probabilities of defects in different areas to allow the inspector to make rapid criterion changes.

There are also known criterion shifts with both changing defect rate and time on task. There is little to be done about increasing the defect rate: it is fixed by the state of the aircraft. The reduction in hit rate at very low defect rates may well set a limit to the use of humans as detectors of rare events. Paradoxically, as maintenance improves to give fewer defects, the capability of the inspector to detect the few remaining defects worsens. There is clearly a need for more research into human/machine function allocation to alleviate this low defect rate problem. Time on task, the vigilance phenomenon, only causes a reduced detection rate due to criterion shift under special circumstances, i.e. uninterrupted performance. This may not be a problem in aircraft inspection, although the heavy use of night shift inspection where interruptions are less frequent and the human less vigilant, requires further study.

5.3.4.3.3 Factors Affecting SATO

The influence of decision time on sensitivity (d') was seen earlier, where it was suggested that it may not be of great importance. The ability of the inspector to integrate signal information over time may only extend for very short periods, at least compared to the time spent on search. However, this signal integration is not the only temporal aspect of decision making. When an indication is found from search, time is taken not so much in obtaining signal input as in locating and using standards, and performing the response. Thus, an inspector may have to locate the relevant standard on the workcard (which is a relatively rapid task) or in a manual (a longer task), or even through interpretation by others in management, quality control, or engineering (a much longer task). The response requires time to write, and a memory load. This response will also produce more work for the maintenance team, and hence potentially delay return to service. All of these represent indirect time pressures on the inspector.

In practice, inspectors do not appear to respond to such time pressures as much as may be expected. Their training and management reinforcement is biased towards accuracy in any SATO. However, the managers of inspectors do feel these pressures, and also feel the need to insulate "their" inspectors from the pressures.

5.3.4.4 A General Framework for Improving Speed/Accuracy Tradeoff

In this section, a wide variety of temporal effects on inspection have been noted. In addition to the direct effect of time pressures (SATO), effects of time-on-task and time-of-day can be expected where vigilance or fatigue are relevant issues.

The main focus, however, has been on the joint performance measures of time-per-item and inspection errors, or their complements--speed and accuracy. Models have been presented which show how speed and accuracy are jointly determined. Access, search, and decision making all show a predictable speed/accuracy tradeoff.

If the objective is ultimately to bring speed and accuracy jointly under control, then the same concepts apply to all three key tasks. The equations defining the speed/accuracy operating characteristics have been given in detail, but the essence of all is the same: the SAOC defines the envelope of possible performance, determined by the physical functioning of the human operator within a physically-defined system. The choice of operating point on the SAOC is determined by the perceived costs of time and errors, and by the perceived probability of a defect being present. Thus, there are two control modes, hopefully applied in sequence:

1. Obtain the best SAOC envelope.
2. Obtain the best operating point on the envelope.

Clearly, the first control mode gives the prospect of simultaneous improvement in speed and accuracy, whereas the second control mode only substitutes one undesirable consequence (time) for another (errors). The analogy with inspection instrumentation (a close analogy for decision making) is that the first control mode represents increasing the signal-to-noise ratio of the instrument, while the second control mode is equivalent to choosing an optimum threshold setting.

The first control mode can be represented for the three tasks considered as:

Access:	Changing the controllability of the vehicle or the unaided human movement.
Search:	Changing the visual lobe size, area to be searched, and fixation time.
Decision Making:	Changing the sensitivity/discriminability of the defect.

All of these three parameters (k, t, d') will take effort to improve, as they imply a change in either the physical system or the human training to deal with that system. The benefit from these changes, however, is seen in both speed and accuracy, and will be obtained. However, the speed/accuracy tradeoff is set (within broad limits).

In contrast, the second control mode implies altering the human's perception of costs/payoffs and probabilities to ensure that the balance the inspector chooses between speed and accuracy is the one which is optimal. For all of the models, this comes down to the costs and probabilities of errors and the costs of time. Error costs come from peers and other co-workers, from the management, and ultimately from society and its institutions (e.g., FAA) Costs of time come from perceived urgency of job completion. Examples are gate pressures, and the requirement for inspection to be completed early so that repairs can be scheduled. If there are conflicts and inconsistencies between these costs from different sources, or even their perceived costs, then confusion and inconsistency will result. For all convex SAOC curves, averaging of two different operating points will produce an apparent operating point (*C*) on a lower SAOC. Inconsistency in the second control model can thus appear as a worsening in the first control mode.

Control of perceived costs is largely a function of the organization: its structure and its information flows. With a complex system such as aircraft maintenance and inspection (e.g., Taylor, 1990), intervention must follow careful technical analysis of the organization. For example, the more separated the inspection subsystem is from the maintenance subsystem, the fewer the direct pressures on the inspector. However, the price of this independence may well be lack of coordination and technical understanding between two of the major groups involved in maintaining airworthiness. Observations made during this project have pointed towards a lack of perceived time pressure on inspectors, largely due to their managers' function as insulators. No quantitative data (e.g., from surveys, questionnaires, or ratings) are available to substantiate this observation, but an obvious next step is to collect such data in a formal manner. The outcome of such a data collection effort would be a baseline of how (and where) inspectors choose their operating point on the SAOC. The options available for changing the SAOC and the operating point are still those given in this section.

5.3.5 A FRAMEWORK FOR TRAINING FOR VISUAL INSPECTION

In parallel with development of training systems for diagnostic tasks (e.g., Johnson, 1990) the predominance of visual inspection requires studies of visual inspection training. Earlier reviews of training in aircraft inspection (Drury and Gramopadhye, 1990; Shepherd, et al., 1991) have shown how the component tasks of inspection are amenable to training interventions. Literature from industrial inspection training was reviewed and applied to aircraft inspection.

Training is aimed at reducing both search errors (all misses) and decision errors (misses and false alarms). From a review of the various training interventions available (Gramopadhye, 1992), it becomes apparent that some interventions are better suited to some component tasks. The following section presents part of this review as a research rationale which will lead to specific experimental tests of training interventions. The review in **Section 5.3.5.1** covers three areas which are critical to inspection performance: search, decision-making, and perception.

5.3.5.1 Results of Inspection Training Literature Review

5.3.5.1.1 Search

As noted in **Section 5.3.4.2**, search task performance is a function of visual lobe size and search strategy. Visual lobe training has been studied by Leachtenaver (1978) for photo-interpreters, who found that practice on a search task increased visual lobe size. However, practice on a visual lobe measurement task may also increase lobe size and transfer this increase to search performance.

Search strategy training is an under-represented area in the literature. From the literature it is seen that systematic search is always more efficient than random search, so that a useful assumption is that the searcher is always trying to be systematic (Arani, Drury and Karwan, 1984). One training objective should be to ensure systematic search, i.e. search in which all areas are fixated, and none are refixated during a single scan. The major difference between systematic and random search is whether or not an area is refixated. The only logical reason for an inspector to refixate an area before a total scan is completed is that the searcher does not remember whether or not that area has been fixated already. Hence, it is seen that it is necessary to provide a memory-aid to the inspector to indicate the points of previous fixations to avoid refixations. This could be done by training the inspectors to use feedback from eye movements, either continuously (on-line), or in a discrete manner at the end of a search task.

Feedback from eye movements can be provided regarding both the number of fixations and the interfixation distance. Literature suggests that these parameters are correlated with an inspector's efficiency in locating possible defects. Providing this sort of feedback would be expected to result in the inspector developing a more efficient search strategy.

5.3.5.1.2 Decision Making

Wickens (1984) states that training for decision making can be provided in the following ways:

- Make the decision maker aware of the nature of limitations and biases. Training operators to consider alternative hypotheses might reduce the likelihood of cognitive tunnel vision.
- Provide comprehensive and immediate feedback so that the operators are forced to attend to the degree of success or failure of their rules.
- Capitalize on the natural efforts of humans to seek causal relationships in integrating cues when correlations between variables are known beforehand. Hence, providing information to the operator so as to emphasize the co-relational structure would help in entertaining particular hypotheses.

5.3.5.1.3 Perception

When the separate features that define all objects within a category may be variable, objects are assigned to different perceptual categories. Thus, the operator needs to develop a perceptual schema, a form of knowledge or mental representation that people use to assign to ill-defined categories. The schema is a general body of knowledge about the characteristics of a perceptual category that does not contain a strict listing of its defining features (e.g., features which must all be present for a particular instance to be termed a category). Because of such fuzzy defining characteristics, the schema is normally acquired as a result of perceptual experience with examples rather than learning a simple defining set of rules.

According to Posner and Keele (1968, 1970) the development of a schema consists of two components:

- a general representation of the mean, i.e., the basic form from which all the forms are derived;
- an abstract representation of the variability.

Research in schema formation suggests that the nature of mental representation which people use to classify stimuli into categories is not a strict list of the characteristics of the prototype but that the mental representation also contains information concerning the variability around the template. This is suggested by Posner and Keele (1968) who found that exposure to a variety of instances of a schema induced better performance than repeated exposure to a single instance.

Theories proposed by Medin and Schaffer (1978) state that assignment is not made by relating each new instance to a central prototype but rather relating it to the exemplar to which it is most similar and then assigning each new instance to the residence category of that exemplar.

Thus, from the above discussion, it is seen that to help in the development of the schema the training provided should be of variable instances of the category rather than a single instance of a prototypical member or rules defining the features which would classify the members into categories. The amount of variability provided in the training should be similar to that existing in the real setting.

5.3.5.2 Rationale for Research on Visual Inspection Training

From the above discussion, training for visual search would be expected to result in reduced search errors (Type 2 errors) and reduced search time. Similarly, training for decision making and perception would be expected to result in reduced Type 1 and Type 2 errors. Although training can be used to improve visual inspection performance, specific training schemes are not associated with factors that determine improvement in visual inspection performance. Hence, ad hoc training schemes are developed that guarantee improvements for a particular task without consideration whether such a training scheme could be extended to a similar task or a different task, or whether the training is optimizing the use of instructor and trainee time. Hence, the first step in the development of a rational training scheme is to identify the factors that affect visual inspection performance. The next step is to determine which of the functions of the inspection task are trainable. This in turn will establish the sensitivity of the inspection parameters to training.

For any training scheme to be effective it should minimize both search errors and decision errors. Thus, referring to the earlier proposed model of visual inspection, it is observed that intervention strategies could be developed at various stages of the inspection process which could be hypothesized to change the inspection parameters, resulting in improved performance.

The following factors are critical to the search process:

- ability to identify salient features which can be associated with a particular defect (so that features can be searched in parallel instead of requiring foveal attention);
- visual lobe;
- eye movement scanning strategy.

In order to improve visual inspection performance, it is necessary to develop training schemes which predict improvements in the above factors. In the following section various training schemes are briefly described.

5.3.5.2.1 Visual Lobe Training

The visual lobe is a very important determinant of search performance. Johnston (1965) states that observers with a larger visual lobe require fewer fixations than observers with a smaller visual lobe. He concluded that a large visual lobe or peripheral acuity may account for superior search performance. We still need to know how a large visual lobe can affect search performance and how people can be trained so as to increase the size of the visual lobe. If the above questions are answered, this would then result in a strategy for improving the visual lobe. The more general question which arises is: how does lobe size training generalize across tasks (e.g., targets and backgrounds). We are interested in understanding whether the visual lobe training on a given target type would result in an improved search performance for a different target type and the sensitivity of the search parameter to this type of training. Thus, it is essential to identify whether such a cross-over effect exists. If it does, then it is sufficient to train the person on one target type. If not, then it is essential to identify various target subsets, say T_1, T_2, within which cross-over does occur. The people could be provided visual lobe training on a single target belonging to each target subset.

5.3.5.2.2 Feedback Training

A person needs rapid and accurate feedback in order to correctly classify a defect, or to know the effectiveness of a search strategy. Every training program should begin with frequent feedback and gradually delay this until a level of proficiency has been reached. Additional feedback beyond the end of the training program will help to keep the inspector calibrated (Drury and Kleiner, 1990). The following feedback could be provided:

- Feedback regarding the correctness of classifying defective items into categories.
- Feedback of search strategy from monitoring eye movements.
- Feedback of fixation times from the eye movement search.

The first is known to be essential to learning in perceptual tasks (Annett, 1966). It provides the novice information regarding the critical difference between a defective item and perfect item, thus helping to develop a mental template which has the internal characteristics of the defective item. We are, however, still unsure as to what has improved. For example, has learning resulted in a new internal conceptual model of the task (i.e., is the inspector using only certain dimensions of the fault to classify it)?

It has been shown that an important difference between the best and the poorest search performance is the length of the sweeps between eye fixations during a search task (Boynton, Elworth, and Palmer, 1958). Thus, there exists a difference between how a novice and an expert move their eyes across the visual field. Gould (1973), in a visual inspection study of circuit chips, found that most of the eye fixations occur within a definite boundary, which is the area most likely to contain the targets. It is demonstrated that eye movements in a visual search scenario occur based on knowledge of the location of faults and on the probability of them occurring. The question that needs answering is: does feedback information regarding the eye movements help improve the scanning strategy? Here we hypothesize that providing such feedback information would aid the inspectors by allowing them to identify areas not covered or areas where one spends excessive time, and helping them develop a strategy to cover the entire area more effectively.

5.3.5.2.3 Feedforward Training

When a novice inspector has no knowledge of the type of faults, probability of faults, and occurrence of faults, visual search would be expected to be inefficient. Providing feedforward information should result in an improved search strategy because the uncertainty is reduced by the inspector knowing both where to look and what to look for. Perhaps the inspector could use the information to achieve a more systematic search strategy, guided by the knowledge of the fault characteristics. The inspector could use feedforward information in the following ways: 1) to ignore the information completely, 2) to selectively incorporate some of the information, or 3) to incorporate this information only at later stages of inspection, that is, only after gaining some verification. Kleiner (1983) suggests that experienced inspectors make use of feedforward information that complements their sensitivity to the fault. If the fault is one that is not easily detected, then the inspector relies heavily on the information provided. According to McKernan (1989), inspection tasks that will most likely benefit from the addition to prior information include those in which the value of the fault is greater than the value of inspection time, those in which the fault is particularly difficult to detect, and those in which the product may contain rare, detrimental, and easily overlooked, faults.

5.3.5.2.4 Attribute Training

Consider an item A. Let the item be faulty on attributes A1, A2, A3 and A4. The inspector could be trained on each of the above attributes. Such training would allow the inspector to set a response criterion for each attribute. The training should be generalizable in the sense that the inspector should be able to classify the items as defective if the items are faulty on one or more of the attributes. The inspector could be trained on which attributes to match first based on the probability of the item being faulty on the attributes and the ease with which the matching occurs. Experience and training of the inspectors determine how defect attributes are arranged (Goldberg and Gibson, 1986).

A similar training scheme has been proposed by Salvendy and Seymour (1973) for developing industrial skills. Here, separate parts of the job are taught to criterion, and then successively larger sequences of the job are integrated. Czaja and Drury (1981) and Kleiner (1983) used such progressive part training very effectively in inspection.

5.3.5.2.5 Schema Training

It is essential that the subject develop a valid mental template (internal representation) schema of the fault. The key to the development of a schema is that it should provide for successful extrapolation to novel situations which are still recognizable instances of the schema.

We need to know how schemas are developed, whether inspectors can be trained to develop schemas, and what sort of training (rule based or knowledge based) should be provided to the inspectors for effective development of such schemas.

The effects of two methods of training need to be evaluated in schema development: "active training" and "passive training". In active training, the inspector is presented with various instances of the fault and no-fault, and has to classify them as defective/non-defective. Feedback is provided regarding the correctness of classification. In contrast, passive training is where the inspector is merely presented with various instances of the faults without requiring an active response.

5.3.5.3 Testing the Visual Inspection Training Framework

In order to test whether the above predictions of training intervention/task component match are correct, a sequence of five experiments are to be undertaken as follows. All use the visual inspection simulator described in **Section 5.3.1**. Brief synopses of each experiment are presented, with more detail given for Experiment 5, which has been completed.

Experiment 1: Feedback Training. This compares a control group and three feedback groups, using on-line and off-line feedback of both cognitive factors and performance factors (c.f. **Section 5.3.3**).

Experiment 2: Feedforward Training. Again, a control condition is used as a baseline against which to compare rule-based feedforward, knowledge-based feedforward, and combined feedforward.

Experiment 3: Attribute Training. Training for decision making using attributes training, i.e., providing the trainee with several levels of severity and complexity, is compared to a control condition where narrative descriptions are provided for the fault attributes.

Experiment 4: Schema Training. Schema development will be encouraged by exposing trainees to a wide variety of schema instances (corrosion levels and patterns) in both active and passive schemes.

Experiment 5: Visual Lobe Training. This experiment tests for the possible cross-over effects on the size of visual lobe measured for different fault types.

The objectives of this experiment were to determine the relationship between visual lobe and search performance, relate changes in lobe size to search performance, and evaluate the effectiveness of lobe training. In particular, the experiment measured whether crossover effects exist in visual lobe training. It used two types of rivet fault (cracks and loose rivets) and two types of area fault (corrosion and dents) to determine whether visual lobe training on one fault would generalize to other faults of the same or different classes.

5.3.5.3.1 Method

Twenty-four subjects were used for this study and were randomly assigned to four different groups, G1, G2, G3 and G4. Subjects were tested for 20/20 vision and color blindness. All the subjects were administered the EFT (Embedded Figure Test) and MFFT (Matching Familiar Figure Test), which have been shown to correlate with different aspects of industrial inspection performance.

Group G1: Subjects assigned to this group initially performed the visual search task on the above four fault types (randomly ordered) followed by visual lobe training on rivet cracks. The visual lobe training consisted of performing the visual lobe task five times. The training session was followed by a search task on the four fault types.

Group G2: Subjects assigned to this group also initially performed visual search tasks on all four targets (ordered randomly). They followed this by visual lobe training on one area fault and dent. The visual lobe training consisted of performing the lobe task five times. The training session was followed by a search task on all four fault types.

Group G3: Subjects assigned to this group performed the visual search task in a similar manner to subjects in Groups G1 and G2. However, this was followed by visual lobe training on a neutral target, a computer-generated character. This training session was followed by a similar visual search task.

Group G4: Subjects assigned to this group performed similar visual search tasks. However, they did not undergo any visual lobe training. Subjects in Group 4 performed a computer task for a duration equal to the time required for the completion of the visual lobe training session in Groups G1, G2, and G3. This was followed by a visual search task.

5.3.5.3.2 Tasks

Visual Search Task. The visual search task was the simulated airframe visual inspection task described in **Section 5.3.1**. Subjects had to search for a single fault type in a given area. Visual search performance of the subjects was evaluated on four faults which were classified into two types:

1. Area Faults - 1) corrosion, and 2) dent
2. Rivet Faults - 1) rivet crack, and 2) loose rivets (indicated by streaks of dirt on the rivet edge).

The task was unpaced. During each of the four visual search tasks, the subjects had to search for one of the predefined faults. Subjects were instructed to work as rapidly as possible consistent with accuracy. Subjects verified their response by clicking on the fault with the mouse button. Once a fault was located in a given area subjects inspected the next area.

Visual Lobe Task. The purpose of the lobe task was to determine the size of the visual lobe; i.e., how far into the periphery a subject could see in a single fixation. The basic procedure consisted of determining at what distance from the central fixation point the target was completely seen by the subject in a single fixation of the fault screen. The exposure duration was kept sufficiently short (0.33 s) to allow the subject a single fixation only. Subjects had to identify a single fault (a rivet fault in group G1, an area fault in group G2 and a neutral fault in group G3). The fault would appear on the horizontal center line of the target screen, at six equally spaced predetermined locations on the horizontal center line, three positions on either side of the central fixation point. No prior information concerning the position of the target was provided to the subjects. The subjects identified the position of the target, either to the left or to the right of the origin and accordingly pressed the key "Q" and "P" to register their response. Subjects were requested to avoid guessing and register responses only if they were sure as to the position of the targets. The fault screen alternated with a fixation screen, consisting of crosswires at the central fixation point exposed for a period of 2 seconds. The purpose of the fixation screen was to help the subjects fixate in the center of the screen after each viewing of the target screen.

5.3.5.3.3 Hypotheses Tested

1. Visual lobe training on one rivet fault (rivet crack) will result in improved visual search performance in detecting rivet faults (rivet cracks and loose rivets).
2. Visual lobe training on one area fault (dent) will result in improved search performance in detecting area faults (dents and corrosion).
3. Search performance on a fault will be superior in the case of subjects who underwent visual lobe training on the particular fault than for subjects who under went training on a neutral target, or subjects who did not undergo any visual lobe training.

Hypotheses 1 and 2 tested for crossover effects of visual lobe training and hypothesis 3 tested for the effectiveness of visual lobe training in improving visual search performance.

5.3.5.3.4 Experimental Design

The design was a 4 groups x 2 trials factional design with six subjects nested within each group. The following performance measures were collected:

1. Number of correct responses for each of the six fault positions in the visual lobe task.
2. Time to detect a fault in each screen for the visual search task.

5.3.5.3.5 Results

To determine whether the visual lobe increased in size during the training, an Analysis of Variance (ANOVA) was conducted for the lobe size for the three groups (1, 2, and 3) receiving lobe training. Over the five training trials, significant effects of group ($F(2,15) = 11.05$, $P < 0.0011$), training trial ($F(4,60) = 13.46$, $P < 0.0000$) and their interaction ($F(8,60) = 1.75$, $P < 0.1046$) were found. To test whether the visual lobe training transferred to the visual search task, ANOVAs were performed on the mean search times for each fault type. These analyzes are summarized in **Table 5.22**, showing no main effects of groups, but highly significant group X trial interaction. **Figure 5.11** shows these group X trial interactions, where it can be seen that the two faults trained in the visual lobe training had the largest improvement. For the faults not trained by visual lobe training, the improvement was greater where there was more similarity to the visual lobe fault. Neutral training had a smaller amount of transfer, while no training, i.e., spending equivalent time on other computer tasks, had no beneficial effect.

Search Time Analyzed	Group (G)	Trial (T)	Group X Trial
Loose Rivet	P > 0.25	P < 0.005	P < 0.05
Rivet Crack	P > 0.25	P < 0.005	P < 0.10
Dent	P > 0.25	P < 0.01	P < 0.05
Corrosion	P > 0.15	P < 0.05	P < 0.05
Overall	P > 0.25	P < 0.0001	P < 0.005

Table 5.22 Summary of Analyses of Variance of Mean Search Times

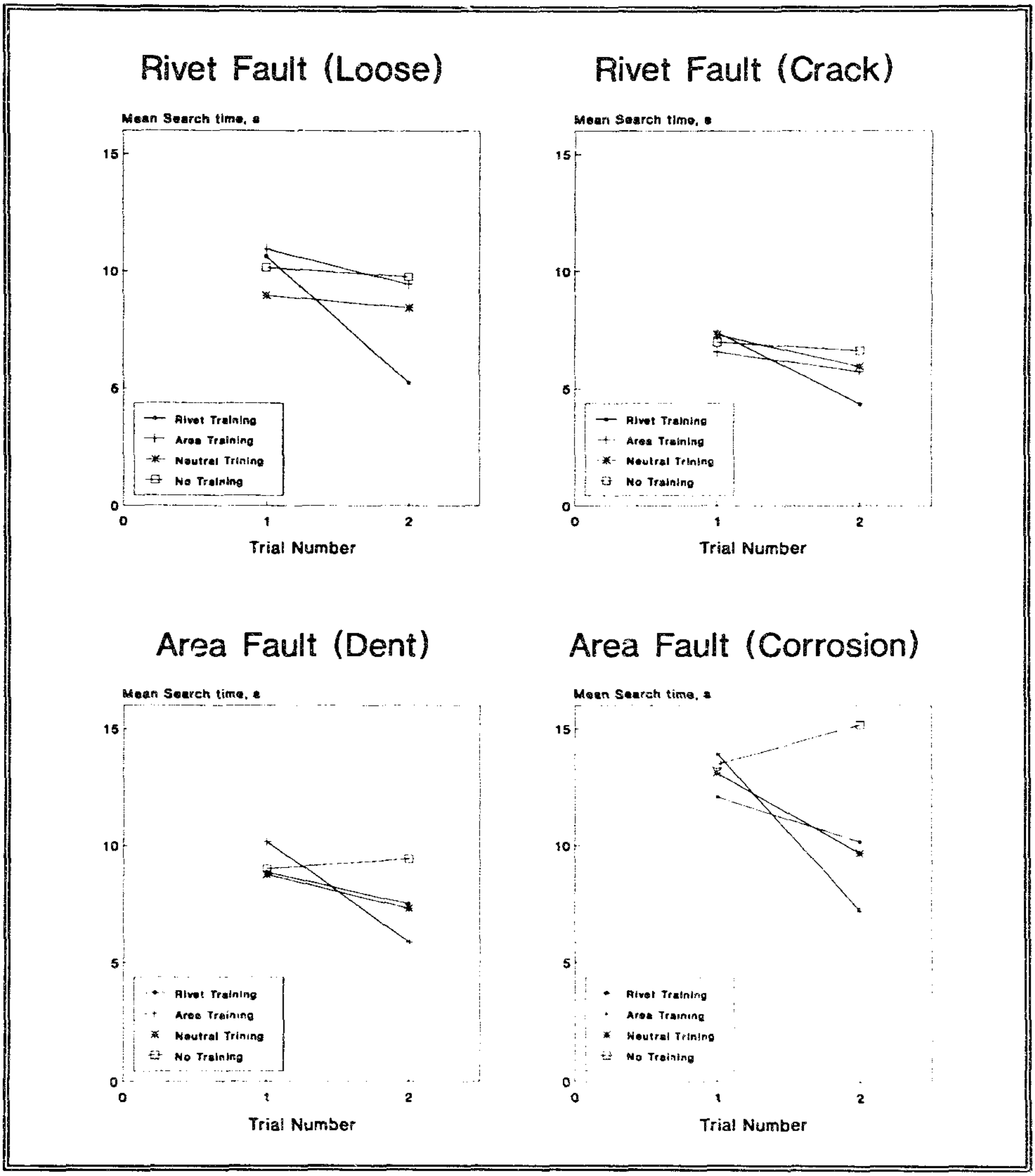

Figure 5.11 Search Performance Before and After Visual Lobe Training

Similar results can also be seen when the changes in visual lobe size during training are related to the changes in search time after training. **Table 5.23** relates the dependence of search time for each fault type to the increases in lobe size, using the coefficient of determination (r^2) as the measure of dependence.

Percent Increase in Visual Lobe Size For:	Percent Decrease in Search Time For:			
	Loose Rivet	**Rivet Crack**	**Corrosion**	**Dent**
Group 1 (Loose Rivet)	0.75	0.36	0.01	0.21
Group 2 (Dent)	0.09	0.00	0.68	0.85
Group 3 (Neutral)	0.16	0.05	0.74	0.00

Table 5.23 Dependence (r^2) of Percent Changes in Search Time on Percent Changes in Visual Lobe Size for Each Group

There was a direct transfer from the fault used in visual lobe training to that fault in visual search, with a smaller transfer to the other fault in the same group (rivet or area). The neutral fault visual lobe training transferred only to one area fault.

5.3.5.3.6 Discussion and Conclusions

Providing training, even just repeated practice, in rapidly detecting a fault in peripheral vision, does indeed increase the size of the area in which that fault can be detected in a single glimpse, i.e., the visual lobe. This increased visual lobe is not merely a result of increased familiarity with the experimental visual lobe task, as it transfers to a more realistic inspection task, visual search. Thus, even such a basic aspect of inspection performance as the visual lobe can be improved through training. For each fault type there was a 20-30% increase in lobe size over just five practice trials. This transferred to the search task with percentage changes in overall visual search time of:

Group 1 (Loose Rivet)	30%
Group 2 (Dent)	32%
Group 3 (Neutral)	18%
Group 4 (No Training)	-4%

There is a close correspondence between the training on actual faults (Groups 1 and 2) and improvement in search times, and even some improvement for training on a neutral fault, i.e., one which did not appear in any search tasks. No training, as expected, produced no effect.

From **Section 5.3.4**, it was seen that visual search follows a speed/accuracy tradeoff curve, so that what has been measured here as search times, can also be interpreted as search accuracy in a given, fixed time. Thus, this experiment has demonstrated the value of training in increasing the inspector's ability to receive and interpret peripheral visual information. The implication is that tasks similar to the visual lobe task given here need to be derived and used with inspectors. The benefits of a simple, simulator-based study in rapidly determining the feasibility of new training techniques has also been demonstrated. A study based on actual faults on a real aircraft structure would have been impossible as single glimpses cannot be repeated without the inspector learning the true identity of each fault. A study using hardware to simulate the faults would be extremely cumbersome, with hundreds of fuselage samples identical apart from fault location being required.

5.3.5 INTERNATIONAL COMPARISONS IN AIRCRAFT INSPECTION

As noted in **Section 5.1**, a joint study of inspection practices in the U.K. and U.S.A. was undertaken as part of a Memorandum of Agreement between the CAA and FAA. The Lock and Strutt report (1985) was in fact prepared earlier in that decade, so that the CAA, for whom the report was produced, initiated an update by M. W. B. Lock in 1990. As the techniques of observation were similar to those used by the FAA/AAM team, a joint venture was created to allow direct comparison of U.S.A. and U.K. practices. Both C. G. Drury and M. W. B. Lock were participants, and have issued a joint report (Drury and Lock, 1992), so that only a briefer summary is presented here.

The aircraft to be maintained are designed and sold for world-wide markets, so that much of the inspection and maintenance is pre-determined by the manufacturers. However, the various regulatory authorities around the world (e.g., FAA, CAA, JAA) have different requirements. In addition, the way in which an airline chooses to meet these requirements leaves some latitude for local and cultural variations.

Although many points of difference were noted, perhaps the most obvious is in the way in which the inspection/maintenance job is scheduled and controlled. In the U.K., the management structures of maintenance and inspection are usually closely intermeshed. In the past it was frequently the case that the engineering manager and the quality control chief were the same person. Although this not the case in large transport aircraft, it can still be the case in smaller commuter airlines. Work arising from an inspection can be allocated by the inspector, who is often also a supervisor, or by a senior person who has responsibility for both inspection and maintenance. The inspector is frequently consulted during the defect rectification, in some cases is the actual supervisor of that work, and will usually be the person to buy back the repair.

In the U.S.A. the management structures of maintenance and inspection are separated up to a level well beyond the hangar floor. A wide variation of management authority was found whereby either maintenance, inspection, or even planning, could dominate (Taylor, 1990). In a few companies visited there was provision for coordination between maintenance and inspection by an engineer whose job was to ensure some cross talk. The engineer served as shift change coordinator. Typically though, work arising from an inspection is allocated by a maintenance supervisor so that the inspector who raised the defect has no responsibility for defect rectification and may not be the inspector who does the buy-back inspection.

The separation of the two management structures in the U.S.A. is dictated largely by the existing Federal Airworthiness Regulations, driven by a deeply-felt need for checks and balances as an error reduction mechanism. At the hangar floor level the general view is that repair and maintenance would suffer if the repairer knew that certain inspectors were 'buying back' the work, as some are known to be less stringent than others. The general view in the U.K. was that the system of having the same inspector responsible throughout for any particular defect and its rectification was preferable as the repair could be monitored at appropriate stages, ensuring that the job had been performed correctly.

Both systems lead to different requirements for training in managerial skills. Despite the greater direct management responsibilities of inspectors in the U.K., little formal training in managerial skills was evident.

A number of visits were undertaken by each participant in each country, either separately or together. There was no attempt at comprehensive sampling; rather the knowledge of each participant was used to select sites which would be illustrative of various features. For example, in the UK, visits were made to specialist third-party NDT companies which serviced civil aviation because they represent a major source of NDT expertise utilized by some airlines.

At each site, the visit was divided into two sections, although these often overlapped in coverage:

- Systems Overview. First the management of the maintenance of the site was probed in management interviews. The structure of the maintenance and inspection organization(s) was elicited during discussions with managers, shift supervisors, foremen, and often with staff who were outside the line management structure. These could include training personnel, archive keepers, work card preparers, planners, and so on depending upon the initial discussions with management. The aim was to be able to write a short description of how the system should operate, and the management philosophy behind this system structure and functioning.

- Hangar-Floor Operations. Detailed observations of the practice of inspection, and its organizational constraints, were made by following an inspector for all or part of a shift. As the inspector progressed through a job, questions were asked concerning the inspection itself and ancillary operations, such as spares availability from stores, or time availability for training. Thus a reasonably complete task description and analysis could be written on the inspection task itself, while obtaining information on the wider context of the inspector's job. This technique also allowed the collection of anecdotal recollections of previous jobs, and other events from the past. While these had an obviously lower evidence value than direct observation of task performance, they did provide a valuable adjunct to the data collection process.

Sites visited included major air carriers, regional or second-level airlines, repair stations, and NDT companies. In addition visits were made to FAA and CAA personnel and to a Royal Air Force base where maintenance and inspection procedures are written.

5.4 CONCLUSIONS

As the FAA/AAM program on human factors moves from its second to third phases, work has progressed from observation to demonstrations of concepts for doing maintenance and inspection. The original approach, developed in Phase 1 and reported in Shepherd, et al., (1991) was to have human factors engineers study aircraft inspection and maintenance so as to determine a strategy. Enough depth and breadth of study was maintained to be able to find critical intersections between human factors knowledge and techniques on one hand, and field problems of inspection and maintenance on the other. This involved both top-down analysis, taking a systems view, and bottom-up analysis, performing detailed task analyses of inspector's jobs.

Phase II has rather closely followed the recommendations made in Phase I. Observation of field activities has been scaled down and re-focussed onto very specific areas. These have evolved into the on-going sequence of demonstration projects. While results from the first two such projects are not scheduled to be available until the summer of 1992, the concept appears to be working well. Airline personnel at all levels recognize that improvements are possible, and thus, are being most cooperative with the human factors team.

As Phase III approaches, more of the projects listed in the Phase I report will be performed, as well as new ones added. For example, the whole field of inspection and maintenance scheduling could benefit from human factors research into combined human/automated scheduling systems (e.g., Sanderson, 1989). When projects are completed, a dissemination of results and lessons learned will be needed, presumably by presentations and published papers. Both the FAA and the airline maintenance organizations need to consider the best ways for rapid dissemination and application of demonstration project results.

The detailed application of human factors knowledge (often models) to specific problems (**Sections 5.3.1-5.3.5**) has yielded insights for the experimental program and the demonstration projects. Feedback is now required from the industry on whether it finds this work adds to its operational understanding. The experimental program is just starting, following hardware procurement and software development. As this progresses, the same simulations should be available for specific experiments supported by industry, as well as for the on-going programs presented here.

The long-term aim of the whole project is to provide phased solutions of practical use to industry to improve the already high performance of aircraft inspection and maintenance.

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Chapter Six
A Human Factors Guide For Aviation Maintenance

6.0 INTRODUCTION

The U.S. air carrier industry and the Federal Aviation Administration are dedicated to the highest level of safety in commercial aviation. To achieve this goal, they must rely on effective and efficient maintenance operations. Proper maintenance support is indispensable to safety, to aircraft availability, and to airline profitability. The safety requirements dictate that maintenance be effectively error-free. Aircraft inspectors and aircraft mechanics must work in an environment and use procedures and equipment all carefully structured to work well and to minimize any potential for error. The design of procedures and equipment must ensure that errors are not built into the system.

The maintenance effort to ensure continuing airworthiness of the air carrier fleet is demanding and costly. The maintenance industry continues to grow in parallel with that of airline operations. **Table 6.1** shows that, in 1991, about 59,000 mechanics were employed in this industry, with maintenance expenses of approximately $9 billion. These numbers reflect significant growth over the last decade but do not indicate the changing character of the industry. Maintenance operations are being recast to account for the introduction of new and more complex aircraft and the use of more sophisticated maintenance and inspection procedures.

Aviation maintenance is in fact a large industrial system which includes many elements such as the aircraft, the maintenance facility, supervisory forces, inspection equipment, repair equipment, and the maintenance technician. All of these elements together comprise the "maintenance system" (**Figure 6.1**). Within this system, the technician functions and should be viewed as one would view any other element. A maintenance technician has a set of operating characteristics. Conceptually this human can be considered in essentially the same manner as other system elements such as, for example, items of electronic equipment. The major difference is that the human is significantly more complex and not nearly as predictable. However, anyone responsible for designing or operating a system, such as a maintenance system, must understand the operating characteristics of each element within the system, and this includes the human.

Mechanics employed	=	58,819
Maintenance expenses	=	$8.8 billion (11.5% of operating expenses)
Major carriers contract approximately 11% of maintenance work		

Table 6.1 Maintenance Parameters for U.S. Scheduled Airlines (1991 data) *ATA (1992); Office of Technology Assessment (OTA) (1988).*

Human factors is a discipline which seeks to understand the laws of human behavior, the capabilities and limits of humans, and the effects of environmental and other factors on human behavior. A key goal of human factors is to provide guidelines for the optimum use of humans in operating systems. An allied goal is to define the manner in which variables internal and external to a system affect human performance within the system.

The operation of any system can only be optimized if every system element is working properly and if each element is carefully coordinated with every other element. The manager of a system such as a maintenance operation should have all necessary information concerning maintenance technicians and, in particular, those features of the maintenance environment which serve either to enhance or to degrade technician performance. The manager or supervisor of a maintenance activity can be aided through use of a Human Factors Guide that will provide this information in a form suitable for day-to-day reference use.

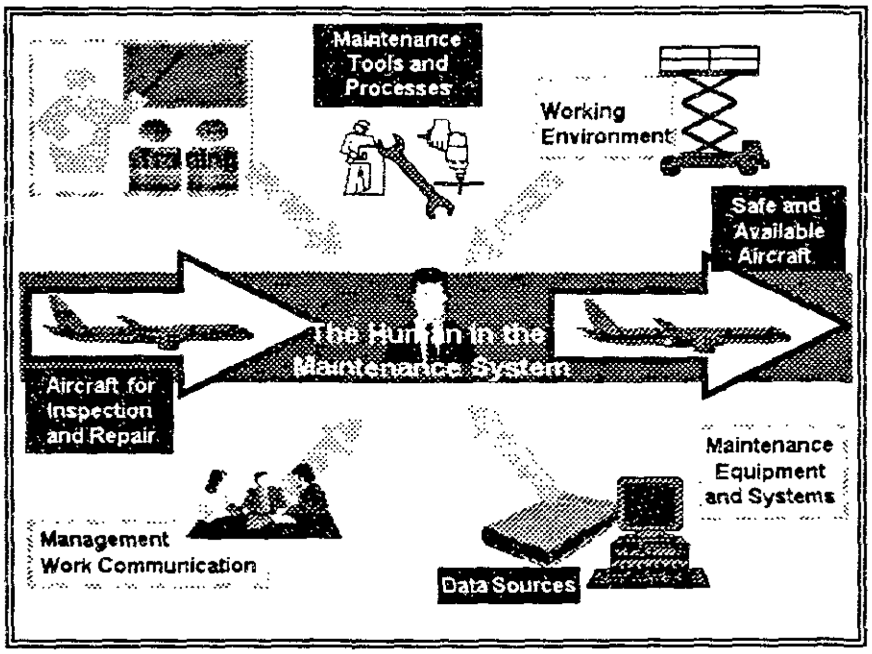

Figure 6.1 The Maintenance System

A Human Factors Guide will present established principles of job design and work. These principles, if well applied, can make a major contribution toward the control of human error in aircraft maintenance and inspection. Issues of communications, equipment utilization, work scheduling and load, work environment, and management relations all are of importance in determining worker effectiveness. A Human Factors Guide should cover these and other issues of human performance that can be applied in aviation maintenance. In presenting these principles, the Guide should see that the information is especially addressed to aviation maintenance and inspection needs.

The preparation of a Human Factors Guide is timely for a number of reasons. The most important of these reasons include:

1. There is a need. Safety is always a matter of concern. The Guide can contribute to maintenance efficiency and to the control of human error in maintenance. This in turn will support continuing safety. There also is the matter of cost control. Maintenance effectiveness contributes to cost reduction.
2. Human factors is a mature and growing discipline. The knowledge within this discipline should be used to support maintenance operations in the same manner as information from the engineering sciences support specific maintenance procedures.
3. Considerable information concerning human factors in aviation maintenance has been developed both through the research conducted by the FAA Human Factors Team and through the conduct of human factors meetings during which beneficial recommendations have been made by representatives of air carrier maintenance. All of this information should be incorporated into a Human Factors Guide.

The Human Factors Guide, as envisioned now, will be directed primarily toward those concerned with the development and operation of air carrier maintenance organizations. However, the Guide will be structured to meet the needs also of a larger audience interested in and responsible for aviation maintenance. In general, the Guide should provide human factors principles and data of use to:

Maintenance planners and supervisors
Maintenance inspectors and technicians
FAA management and FAA inspectors
Air carrier operators
Designers of maintenance equipment
Aircraft design teams
Aircraft manufacturers

6.1 DEVELOPMENT OF A HUMAN FACTORS GUIDE

The development of a Human Factors Guide for Aviation Maintenance is underway. The first step in this development was to consider the premise on which the Guide should be constructed. This premise is that the Guide, or any such document, is of little if any value if it is not used. The aviation maintenance community must the Human Factors Guide if the Guide is to serve any real purpose. For the Guide to be used, it must meet ongoing needs of maintenance personnel and must be prepared in such a manner as to foster use by this group.

In order to collect information to satisfy the above requirements, a sampling of aviation maintenance personnel was conducted. The information solicited was designed to ensure that the real needs of maintenance personnel would be met and that the Guide could be consistent with the ways in which this sample stated they were likely to use such a Guide.

Approximately 60 individuals affiliated in some manner with the air carrier maintenance industry were contacted to provide guidance on significant maintenance topics. Names were selected from the list of attendees at earlier FAA Human Factors Meetings. The list included persons both from the United States and from foreign countries. The role of these persons in aviation maintenance, based on their replies, is shown in **Table 6.2**. The fact that most replies were received from "Inspection/ Maintenance Managers" is to be expected since this job category constituted the bulk of the initial mailing.

The next question concerned the value users would place on a Human Factors Guide for their work. Not surprisingly, almost all of those who replied indicated a Human Factors Guide would be "very valuable" or "valuable." Since these replies were given by persons who had evidenced interest in this topic by attending human factors meetings, these replies were anticipated.

Work Classification	Number
Inspection/Maintenance Manager	22
Educator/Trainer	7
Aircraft Designer	2
Other (Senior Management, Quality Assurance, Consultant, Research, AMT Associate, Crew Systems Analyst)	7

Table 6.2 Occupation of Respondents

The individuals were questioned on the anticipated frequency of use for a Human Factors Guide, if the Guide contained appropriate information. This question was asked in order to determine whether the Guide should be prepared as a working document (as a job aid) or as a reference manual. **Table 6.3** presents the replies to this question.

The replies indicate the preferred use for a Human Factors Guide would be as a working document consulted on a number of occasions during the year.

6.2 HUMAN FACTORS COVERAGE

The coverage provided in a Human Factors Guide is of great importance if the Guide is to be truly useful. Certainly, the topics included in this Guide should be those which members of the maintenance community consider important. In order to collect information concerning desired coverage, an outline of a prototype Guide was prepared. Each person was presented a list of chapter headings from the prototype outline and asked to judge the importance of the topic on a five-step scale ranging from "very important" (weighting of five) to "not important" (weighting of one). With this system, had each of the respondents judged a given topic to be "very important," that topic would have received a total score of 190. Results for this question are presented in **Table 6.4**. While there is a dispersion of total scores, it is quite apparent that most topics were judged either as "very important" or "important." The topics in **Table 6.4** are listed in terms of decreasing order of judged importance.

Frequency of Use	Number of Replies
Review initially	1
Daily	3
Weekly	20
Monthly	13
Rarely	1

Table 6.3 Frequency of Anticipated Use for a Human Factors Guide

Topic	Weighted Score
Human Error in Maintenance	178
Information Exchange and Communications	178
Maintenance Training and Practices	173
Human Capabilities and Limits	168
Human Performance	166
Work Requirements	163
The Maintenance Workplace	160
Job Performance Aids	157
Man-Machine Interface	156
Workplace Features	152
Automation in Aircraft Maintenance	151

Table 6.4 Importance of Specific Topics for Inclusion in a Human Factors Guide

Prior to the contact with the 60 individuals, a question had arisen about the desirability of including a section within the Human Factors Guide concerning emotional factors. For this reason, a separate question was included that asked "Should the Human Factors Guide contain a section, not usually included in texts of this type, that addresses social and emotional factors that can affect the performance of a worker?" The following responses were received:

<u>Yes</u> = 32 <u>No</u> = 6

Obviously, the majority of the respondents believe that a section containing the above information should be included in the Guide.

To ensure that no appropriate topics were missed, each respondent was asked to note any additional topics believed important for a Guide of this type. Quite a few replies were received; most appeared to be variants of the topics in the initial list presented in the mailing. However, a few were indeed new and are listed below:

1. Requalification, limitations, and competency verification for aviation maintenance technicians.
2. Minimum individual qualifications (eyesight, color blindness, and manual dexterity) for specific maintenance functions.
3. Sexual harassment. (This could become increasingly important as workforce demographics change.)
4. Working with the handicapped. (The recently passed Americans With Disabilities Act gives impetus to this topic.)

6.3 FORMAT

For a Guide to be useful, it not only must contain appropriate information but also must be presented in a manner designed to make it easy to use. Several questions addressed the general issue of format. The first question concerned optimum length. The contacted individuals were asked "To be most usable, what size should a Human Factors Guide be?" **Table 6.5** presents the responses.

Length	Responses
Less than 100 pages	18
100 - 300 pages	14
Over 300 pages	0
Size is of no concern	6

Table 6.5 Desired Length of a Human Factors Guide

The above replies clearly point to a shorter rather than a longer Guide. These data are supported by a comment submitted by one respondent:

A Human Factors Guide should be 50-75 pages for handout to line management personnel. It should be 100-300 pages for managers and supervisors with decision making capabilities for resources and monies.

The next item asked "What format would you find most useful?" This question is considered quite important

Format	Number of Selections
Key information and recommendations in bullet form, with illustrations	20
Short statements, with illustrations	8
Running prose, with illustrations	8
Other (Please Specify) (Combine short statements, with illustrations, and key information and recommendations in bullet form, with illustrations; use running prose - segmented by topic statements; use electronic/digital format with key word search.)	2

Table 6.6 Preferred Format for a Human Factors Guide

since the manner in which information is presented can affect the extent to which individuals will seek and use information concerning the topic being presented. **Table 6.6** shows the results for this question.

Results indicate the desired format would be one in which information is presented tersely and concisely, either in bullet form or using short statements. Illustrations should support the materials as needed.

A question next was asked which relates both to the length of the Guide and the manner in which materials are presented. Two alternatives were given with a request for a preference between these two. **Table 6.7** lists the two alternatives and shows the replies.

Alternatives	Number
A shorter guide, presenting brief discussions and recommendations, with supporting data elsewhere (possibly in another book or in a computer data base)?	21
A longer guide, with supporting data included as appendices?	17

Table 6.7 Preference for Physical Structure of a Human Factors Guide

These results show a slight preference for a shorter Guide, even if one has to look elsewhere for data supporting and elaborating the concise information presented in the Guide. One supporting comment illustrates this: "A shorter Guide. Computerized supporting data would be very nice."

6.4 SUMMARY

The replies of the maintenance personnel, combined with other discussions with those likely to use a Human Factors Guide, lead to the following conclusions concerning the content and structure of the Guide.

Audience. The principal users of a Human Factors Guide will be air carrier maintenance planners and supervisors. However, care must be taken that the structure of the Guide not be oriented entirely toward this group. A Human Factors Guide also can be used to advantage by other groups, including FAA management and FAA inspectors as well as aircraft design teams and designers of maintenance equipment. The document also could be used profitably in training operations.

Content. Three topics have been identified as most important for inclusion in a Human Factors Guide. These topics are:

- Human error in maintenance
- Information exchange and communications
- Maintenance training and practices

All topics must be given appropriate coverage in the Guide. Greatest attention, however, will be given to the three topics listed above.

Size. The Human Factors Guide should not be a large document and probably should not exceed 200 pages in length. A larger document might well impact use, particularly if the document is to be carried around within the maintenance facility. Current thinking is that supporting materials, which could be quite lengthy, would best be contained in a computerized data base in a CD-ROM system. With proper search strategies, data supporting the Guide could be obtained quite rapidly.

Style. Information within the Human Factors Guide, such as basic human factors principles applied to specific maintenance labor, should be presented concisely, possibly using a bullet format, with supporting illustrations. Introductory chapters and materials can be more in a running prose form. The language should be simple and straightforward English. This will make it more likely that the message is conveyed as intended. Use of simple English also will help should the Guide be translated into a foreign language for use in overseas maintenance activities.

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Chapter Six Appendix

Sample Section Of A Human Factors Guide

The following section illustrates the manner in which the above concepts and rules would be applied in the preparation of a section for the Human Factors Guide. The section is presented in highly abbreviated form simply to show the appearance and general content of a part of the Guide. This section does not indicate the depth of coverage planned for individual topics.

1.0 SECTION I: AREA AND TASK LIGHTING

1.1 Importance of Lighting in Industrial Operations

Lighting conditions in an industrial workplace are important both for worker productivity and for worker comfort. Numerous studies have examined the effect on worker productivity of varying levels of task illumination (see Cushman, 1987). In general, these studies show that performance under low illumination improves to a point as the illumination level is increased. **Figure 1** shows the reduced time required to complete a typical industrial task (reading a micrometer) as the level of illumination on the task is increased. Note that when the illumination reaches about 100 footcandles, no additional improvement is seen. In general, industrial tasks show smaller and smaller improvement in performance as illumination is increased. However, the point where performance finally levels off is task-dependent. Tasks that are visually difficult, as might be true for inspection activities, will require more light to achieve best performance than will easier tasks.

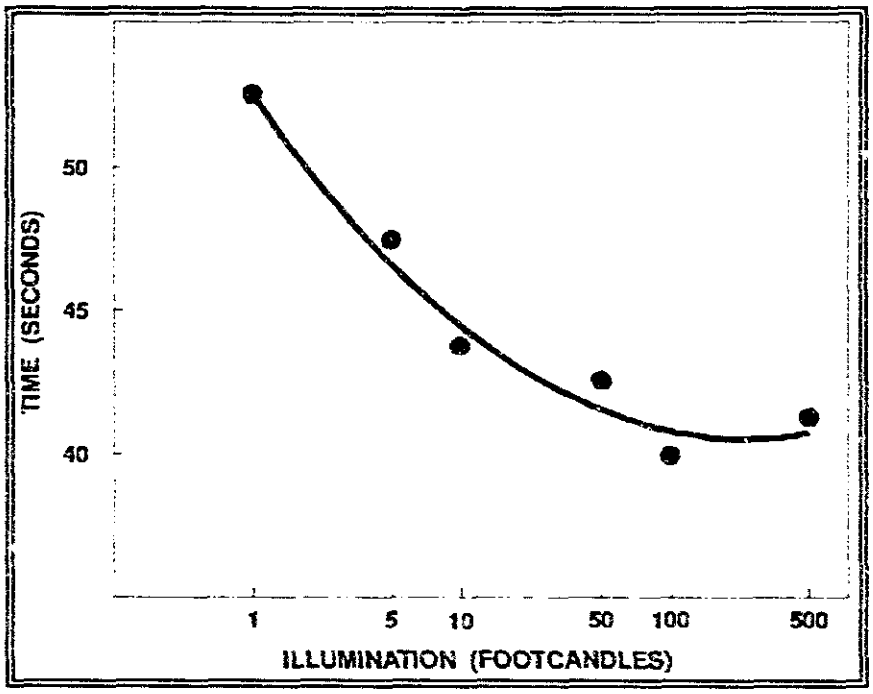

Figure 1 Effect of illumination level on time to complete a typical industrial task (micrometer reading). Adapted from *Sanders and McCormick, 1987.*

Research conducted to assess the effectiveness of illumination on performance must deal with two issues which can affect the results. First, motivational factors must be controlled. Subject, or workers, who know they are in a study will tend to perform better independent of the illumination level. Second, the age of subjects is important. Workers who are over 45 years

of age will show more improvement with increasing illumination than will younger workers. If a work group contains older workers, illumination should be increased to account for this.

Recommendations for proper illumination levels for various activities have been prepared by the Illuminating Engineering Society and are presented in **Table 1**.

Sanders and McCormick (1987) point out problems in arriving at recommendations for adequate illumination to ensure proper task performance. Interestingly, they note that recommended levels continually increase through the years. Current recommended levels are about five times greater than levels recommended 30 years ago for the same tasks.

Activity	Level (footcandles)
Working spaces with occasional visual tasks	10 - 20
Performance of visual tasks of high contrast or large size	20 - 50
Performance of visual tasks of medium contrast	50 - 100
Performance of visual tasks of low contrast or very small size	100 - 200
Performance of visual tasks of low contrast and very small size over a prolonged period	200 - 500

Table 1 Recommended Illuminance Values for Different Types of Activity. Adapted from *Kantowitz & Sorkin, 1983.*

Even though proper levels of illumination are provided, task performance can be degraded if glare sources are present. Glare is of two types. Direct glare is produced when a bright light source is in the visual field. Indirect glare, often called reflected glare, is reflected from the work surface and reduces the apparent contrast of task materials. Either direct or indirect glare can degrade task performance. **Table 2** offers suggestions concerning ways to control the effects of glare sources.

1.2 Lighting Conditions in Aviation Maintenance

A study of illumination conditions within major air carriers was accomplished as part of an FAA audit (Thackray, 1992). In these facilities, overhead lighting typically is supplied by mercury vapor, metal halide, or high-pressure sodium lights. The principal difference here is in terms of the color rendition of the lights. While color rendition is probably not too important for aircraft exterior maintenance tasks, the level of illumination could be. **Table 3** shows average illumination levels measured at different maintenance work areas, both for day shifts and night shifts. **Table 3** also presents recommended illumination levels for aircraft repair and inspection tasks. Although slightly below recommended levels, the illumination for work on upper and lateral surfaces of an aircraft appear adequate. For repair and inspection conducted below wings, the fuselage, and within cargo and engine areas, measured illumination levels are not adequate and supplemental light sources are required. In general, supplemental lighting is provided through quartz halogen stand lights, dual 40-watt fluorescent stand fixtures, single hand-held fluorescent lamps, and flashlights.

To Control Direct Glare	To Control Indirect Glare
Position lighting units as far from the operator's line of sight as practical	Avoid placing lights in the indirect-glare
Use several low-intensity lights instead of one bright one	Use lights with diffusing or polarizing lenses
Use lights that produce a batwing light distribution and position workers so that the highest light level comes from the sides, not front and back	Use surfaces that diffuse light, such as flat paint, non-gloss paper, and textured finishes
Use lights with louvers or prismatic lenses	Change the orientation of a workplace, task, viewing angle, or viewing direction until maximum visibility is achieved
Use indirect lighting	
Use light shields, hoods and visors at the workplace if other methods are impractical	

Table 2 Techniques for Controlling Glare. Adapted from *Rodgers, 1987.*

Use of supplemental lighting does not necessarily solve existing lighting problems. The FAA audit of major carriers found that supplemental lighting systems frequently were placed too far from the work being performed and were too few in number. The result was that, even with supplemental lighting, the illumination directly at the work site was less than adequate.

Measured (Footcandles)	Day	Night
Hangar area	66	51
Below wings, fuselage and in cargo areas	26	15
Within fuselage	23	18
Visual inspection (2 D-cell flashlight)	100-500	

Recommended (Footcandles)	Min. Level
Aircraft repair, general	75
Aircraft visual inspection	
Ordinary area	50
Difficult	100
Highly difficult	200

Table 3 Measured Illumination Levels at Major Air Carriers Compared with Recommended Levels. Adapted from *Thackray, 1990.*

Aircraft inspectors generally use small flashlights as supplementary sources. At times, small lights mounted on headbands may be used. The flashlights provide illumination ranging from 100 to 500 footcandles and are acceptable for visual inspection. However, use of the flashlight means that one hand cannot be used for manipulation of the systems being inspected.

In an attempt to produce more even lighting within maintenance bays, some carriers have painted the walls and even the floors with a bright white reflective paint. While this does tend to reduce shadow effects, other problems can arise. The principal one is glare. Reflected light from bright sources produces glare which can both cause discomfort and reduce visibility of key features of the maintenance task. The glare tends to obscure or veil part of the visual task.

1.3 Guidelines

The goal of controlling human error in aviation maintenance requires that maintenance be conducted under proper lighting conditions. This is true both for area lighting, that which illuminates the full working area, and task lighting, that directed toward specific work activities. Improper or insufficient lighting can lead to mistakes in work tasks or can simply increase the time required to do the work. In a program directed toward proper lighting conditions, the following guidelines should be observed:

Guidelines

- Area lighting within a maintenance facility should be a minimum of 75 footcandles. A level of 100-150 footcandles is preferred.
- Care must be exercised to see that the light level available for night maintenance activities in particular does not drop below recommended levels. Any lighting studies must be conducted both during the day and at night.
- Task lighting for aircraft inspection requires a minimum of 100 footcandles of illumination. For difficult inspections or fine machine work, 200-500 footcandles of illumination is necessary.
- Supplemental lighting must be adequate for the task at hand, best judged by the worker. Task lighting should be placed close to the work being done and, if feasible, should leave both of the worker's hands free for the work. If systems must be manipulated, lights mounted on headbands are preferred to flashlights.
- If the workforce contains a substantial percentage of older workers, i.e. those greater than 45 years of age, recommended lighting levels should be increased, probably on the order of 50 percent.
- Glare sources should be controlled. Supplemental lighting should be placed as far from a worker's line of sight as practical. Reflected glare can be changed by reorienting the work surface or changing the position of lights. Worker complaints are the best means for identifying offending glare sources.

1.4 Procedures for Evaluating Light Conditions

The best procedure for determining if lighting conditions are adequate is through the services of either the industrial hygiene department or the safety department of the air carrier. Individuals in these departments typically are trained in procedures for conducting an environmental audit, possess the necessary measurement equipment, and understand the problems involved in obtaining meaningful measurements. Specialists from these departments also will be able to provide a proper evaluation of the audit results.

If the services of specialists are not available, maintenance managers can assess lighting conditions themselves. Photometric equipment is available which will provide accurate (generally plus or minus five percent) measurement of facility lighting. Illuminometers/photometers are available commercially for a price in the order of $1,000. Catalogs of scientific equipment describe these items.

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Chapter Seven
The Effects of Crew Resource Management (CRM) Training in Maintenance: An Early Demonstration of Training Effects on Attitudes and Performance

7.0 INTRODUCTION

There are encouraging results from initial data on the effects of a CRM training program for technical operations managers on attitudes and maintenance performance.

The study is intended as an illustration of results beginning to emerge after only a few months experience in a long term program of effective communication to improve safe, dependable and efficient performance. Specifically, the analyses reported here compare managers' pre- and post-training attitudes about a variety of management and organizational factors as well as pre- and post-performance measures in several maintenance (and related) departments. Some highlights are as follows:

1) Participants' immediate response to the training was very positive. They were even more positive than those from other studies investigating CRM in maintenance or in flight operations.

2) Changes in relevant attitudes measured immediately before and after training reveal strong and positive changes following training, for three of the four indices measured[1]. Follow-up results several months after training, reveal that these changes are stable; forthcoming data should continue to strengthen these conclusions.

3) Most maintenance performance measured before and after the CRM training sessions, examined in the present paper, show significant changes in the expected direction, indicating a positive effect of training.

4) A pattern of relationships in the expected direction were observed between the post-training attitudes and the post-training performance. In particular, those measures predicted (by the program's trainers and managers) to be particularly sensitive to the effects of the CRM training were affected.

5) Finally, in follow-up surveys[1], managers responses indicate that, when transferring skills and knowledge, they tend to initiate interactive behaviors instead of passive ones. Anecdotal evidence is also beginning to confirm these changes and their positive impact on performance.

7.1 THE EFFECTIVE-COMMUNICATION PROGRAM: CREW RESOURCE MANAGEMENT TRAINING

Resource management training for airline flight crews was introduced in the late 1970's (Helmreich, 1979). It has spread to many air carriers in the U.S. commercial aviation industry, to several foreign carriers and to various sectors of U.S. and Canadian military aviation. That training has been extended from the

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[1]All surveys and questionnaires were distributed by the airline to airline employees. The survey instruments were not developed or distributed by the FAA.

cockpit to cabin crews, to maintenance teams and to air traffic centers and is now referred to as Crew Resource Management (CRM) training. Although specific programs differ from one organization to another, Crew Resource Management typically involves training in several team-related concepts: communication skills, self-knowledge, situational awareness, and assertiveness skills.

The effect of Crew Resource Management training in airline flight operations has been widely studied during the 1980s. Numerous reports document CRM's positive impact on the attitudes and performance of flight crews (cf., Helmreich, Foushee, Benson, & Russini, 1986; Helmreich, Predmore, Irwin, Butler, Taggart, Willhelm, Clothier, 1991). Taken together, the evidence shows that team coordination among aviation "managers," and between them and subordinates, improves system effectiveness and safety.

As a result of recent work researching team concepts in aviation maintenance, further investigations have been recommended by both industry and government groups as a national priority (Federal Aviation Administration, "The National Plan for Aviation Human Factors," Washington, DC: 1991). A first instance of an airline applying CRM to maintenance operations was reported by Taggart (1990). Others are in beginning or planning stages. This report describes the case of a second company's program to apply CRM-type training in maintenance.

7.2 THE PRESENT STUDY

The analyses reported below will assess the relationships among managers' pre- and post-training attitudes about a variety of management and organizational factors and the levels of maintenance performance measures in a large U.S. airline (hereinafter called "the company").

7.2.1 The Purpose of the Program and the Course

The program's champion is the company's Senior Vice President for Technical Operations. He has stated that his aim for the training and evaluation program is to improve human resource (HR) management using science-based tools and techniques for diffusion and evaluation. Further, the effectiveness of this training, as measured by the ongoing evaluation of it, can help to direct the industry's HR practices in the future; and to guide the development of future ATA and FAA training policies and regulations. The training is a technical operations program entirely. It is managed and administered by technical operations people, and the trainers (assisted by professional communications training consultants) are technical operations people too. An Editor from *Aviation Week & Space Technology* participated in the training at the invitation of the company. The two articles he wrote (Fotos, 1991) further describe top management's reasons for undertaking the program, and provide impressions of the training itself.

<u>Course objectives.</u> The purpose of the training, as stated by trainers on the first day of each training session, is "To equip all Technical Operations personnel [management first] with the skill to use all resources to improve safety and efficiency." The objectives (the more specific goals of the training) are also clearly stated during the trainers' introductory remarks. They are as follows:

1. Diagnose organizational "norms" and their effect on safety.
2. Promote assertive behavior.
3. Understand individual leadership styles.
4. Understand and manage stress.

5. Enhance rational problem solving and decision making skills.
6. Enhance interpersonal skills

The course as designed for the objectives. The aims and objectives of the training are facilitated through a course syllabus containing 12 modules (Appendix A contains the current syllabus).

State of training completed. To date, less than half of the technical maintenance operations stations, departments, or functional divisions in the company have been able to send all of their managers to the training -- this can only be done over time to avoid the absence of all managers and supervisors, at the same time, from their departments or stations while training is conducted. Thus, the present analysis uses data from roughly one-quarter of the whole technical operations management staff who will eventually complete the training. Overall, however, most cities among the company's 31 locations have had at least one-third of their maintenance managers attend a session. By the end of 1991, the majority of people remaining to complete the course are located in the company's three largest cities -- they comprise mainly maintenance supervisors (over 50% of whom still need to attend); and assistant supervisors (nearly 75% who have yet to attend).

Maintenance work units as the focus of the analyses. The analyses described in this report are intended to illustrate the effect of changes in work-unit attitudes (data collected from individual managers who underwent the training, combined into averages for the units to which they belong) and the performance data (classified into safety, dependability, and efficiency categories) constructed into measures for the same work units.

How is the course experienced? Summary results of answers to a post-training question concerning the perceived usefulness of the CRM training are shown in **Figure 7.1.** This figure compares the sample from the present study with two flight operations samples from other companies (Helmreich, 1989) and with one other technical operations sample (Taggart, 1990). Like the other maintenance department measured, the data from the Technical Operations division of the present company reveals high enthusiasm about the training. None of the respondents in either maintenance department sample said that the CRM training was either a "waste of time" or only "slightly useful." In addition, a very high percentage (68%) of the present company found the training to be "extremely useful." This training appears to be very well received by its "customers."

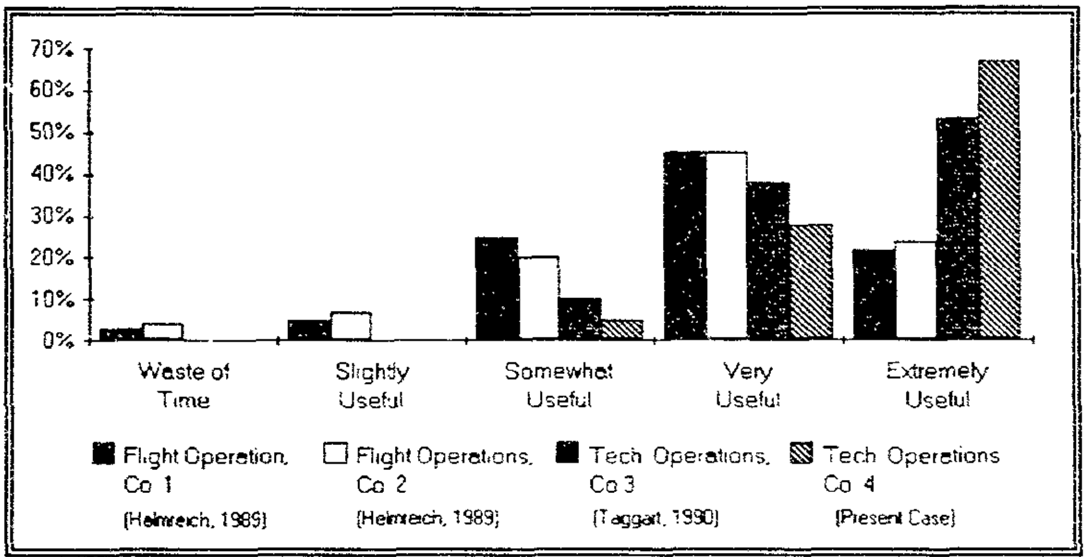

Figure 7.1 Ratings of Usefulness of CRM Training for Flight Operations and Technical Operations

7.3 CREW RESOURCE MANAGEMENT/TECHNICAL OPERATIONS QUESTIONNAIRE

7.3.1 Background Related to Measurement of CRM Training

A questionnaire called "CMAQ" (for Cockpit Management Attitudes Questionnaire) has long been a recognized measure for assessing flight crew attitudes (Helmreich et al., 1986). The CMAQ contains 25 items measuring attitudes that are either conceptually or empirically related to CRM. Taggart (1990) revised the CMAQ for use in a technical operations department, and reported positive initial results following CRM training.

A recent study involved the analysis of the CMAQ instrument through the use of Factor Analysis, a technique to explore for a consistent internal structure (Gregorich et al., 1990). In their study these authors showed the relationships among the 25 CMAQ items clustered into the following four constellations of attitudes: Sharing Command Responsibility, Value of Communication and Coordination, Recognizing Stressor Effects, and Avoiding Conflict.

Because multiple items tap into specific aspects of CRM (e.g., "communication," and "interpersonal skills"), Gregorich et al., (1990) combined the items into composite indices. Such index scales permit more detailed assessment of separate but related attitudes than a single total score for the entire questionnaire, and they also provide more accurate and reliable results than are available from each of the individual questionnaire items alone.

7.3.2 Survey Used in the Present Study

Measurement of attitudes. The "Crew Resources Management/Technical Operations Questionnaire" (CRM/TOQ) as used in the present study is a modified version of Taggart's (1990) revised CMAQ.

The CRM/TOQ contains 26 multiple response items. The company's modifications of the CMAQ involved removing five questions and adding six others. The five questions were removed because they either lacked predictive validity (as reported by earlier flight crew studies; Helmreich et al., 1986) or, in the company's opinion, lacked relevance to technical operations.

Six questions were also added to the CRM/TOQ, based on items intended to measure respondents' perceptions of behaviors dealing with attainment of work goals (Geirland & Cotter, 1990).

Measurement over time. At the time of this writing (some six months into an 18 month training process) the data sets are necessarily incomplete. Over 500 of 1,800 total managers have already attended the two-day training program. Virtually all those attending the training have completed the CRM/TOQ both pre- and post-training. Some 400 of the 500 pre- and post-training CRM/TOQ completed have been entered into the data base and will be used in the present demonstration. It is still too early in the training and evaluation process to have abundant data for the CRM/TOQ follow-up (two and six month), or many months of performance data subsequent to the training; but the present report will describe the results of some 60 two-month and 50 six-month follow-up questionnaires returned so far. This follow-up version of the CRM/TOQ was mailed in early October, 1991, to the homes of those managers who had attended the CRM training in May or June for the "six-month" measure, while attendance during July and August qualified for the two-month follow-up.

Collecting baseline data for testing statistical goodness of data. During the last week in May 1991 and before the training program began, the CRM/TOQ was sent to the homes of all directors, managers, supervisors, and assistant supervisors (1,787 total). Within five weeks over 900 questionnaires had been returned for a return rate of over 50%. A return rate this high is considered quite acceptable with paper and pencil surveys of this type (Borg & Gall, 1986) -- especially since a reminder or prompt was not possible, given that the training program was due to be announced and start within two weeks of the mailing. This questionnaire was termed the **"baseline"** survey. A sample of the "baseline" questionnaire and one of the "follow-up" questionnaires are included here in Appendix B and Appendix C, respectively.

The mean scores of the baseline results could reveal bias with a 50% return, but continuing comparisons between those baseline data and immediate pre-training results (where very close to 100% return rates are realized) similar relative levels for the six composite index scales are revealed. **Figure 7.2** presents the comparison profiles. These results show few differences in absolute scores and similar profiles.

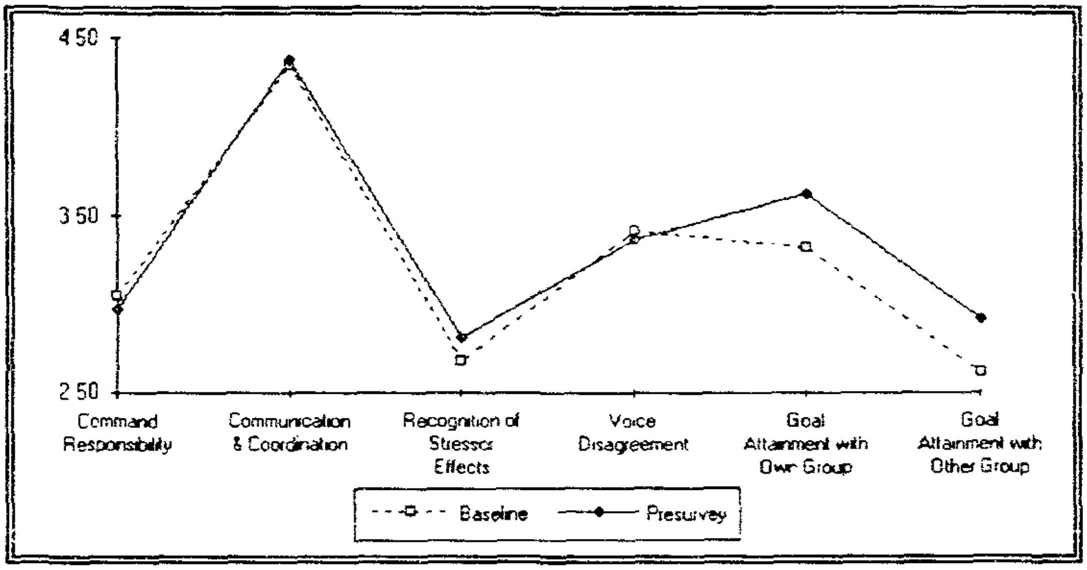

Figure 7.2 Mean Scores of Indexes for Baseline and Pre-Seminar for Technical Operations

7.4 PERFORMANCE DATA DESCRIBED

Technical Operations managers in the company already collect performance data in abundance. **Table 7.1** presents the 14 measures used as end-result criteria in the present study. Three conditions were met in order to include these measures in the work-unit analysis reported here. First (and obviously) the performance measures need to be available by work unit, and not just by department or function. Second the measures must be ones that people in the work unit can affect by their actions and not merely ones that are conveniently assigned to a unit -- but for which it can do little. The third condition applied was that the measures not be directly related to or completely determined by, other measures in the set.

The 14 measures are classified into three performance categories: Safety, Dependability and Efficiency; and this classification is shown in **Table 7.1.** The trainers and administrators of the CRM course evaluated the 14 performance measures and predicted which of them would be more sensitive to effects of CRM training. Their conclusions were that six measures were the most readily improved by the training. These six performance measures included both aircraft safety items (ground damage and turnbacks), days lost to occupational injury, dependability based on departures within 5 and 15 minutes and delays due to maintenance error. Their second ranked performance measures likely to improve in response to training included sick days lost, departures within 60 minutes, canceled flights due to late from maintenance, base maintenance performance to plan, hours applied to production and overtime paid. The performance indicators rated least likely to improve as a function of the training were departures later than 60 minutes and warehouse parts service levels.

I. MEASURES OF SAFETY

A. Safety of Aircraft
1. Number of Ground Damage Incidents[a] (44)
2. Number of Air Turnbacks/Diversions caused by human error[a,d] (31)

B. Personal Safety
3. % Occupational Injury Days Lost[a] (60)
4. % Sick Days Lost[b] (60)

II. MEASURES OF DEPENDABILITY

A. Departure Performance (Line Station data only, n=31)
5. % Departure within 5 minutes[a]
6. % Departure within 15 minutes[a]
7. % Departure within 60 minutes[b]
8. % Departure over 60 minutes, but not canceled[c]
9. Number of Delays due to late from Maintenance[a,d] (n=35)

B. Service Levels (Materials Services only, n=9)
10. % Rotable parts available[c]
11. % Expendable parts available[c]

C. Base performance to plan (n=4)
12. % Heavy Checks on time to initial plan[b]

III. MEASURES OF EFFICIENCY

A. Productivity
13. Ratio of Hours paid to those applied to production[b] (7)

B. Cost
14. % Overtime paid to total wage bill[b] (60)

(maximum number of work units possible are in parentheses)

----

a= Measures evaluated **most** sensitive to effects of CRM training
b= Measures evaluated **moderately** sensitive to effects of CRM training
c= Measures evaluated **least** sensitive to effects of CRM training
d= These measures exhibit skewness and lack of variability

Table 7.1 Technical Operations Performance Measures Available by Work Unit

The present analysis employs four months of performance data. June and July 1991 are considered "pre-training," since they are coincident with, or precede, most of the training sessions measured here. August and September are used as the post-training measures. These performance data are available for 31 line maintenance stations, 4 base maintenance stations, 3 shops, 9 materials services warehouses, and 13 inspection/quality assurance units, for a maximum of 60 data points each month. The planning and engineering units in technical operations do not yet have unit performance data which they can be measured against, although the company is developing such measures for inclusion in later analyses. As noted above, the attitudinal data are not yet available for all 60 work units; and in some cases performance data is unavailable for certain work units for the four months analyzed for this report. Because of this, the full number of maintenance units available for the present analysis is somewhat less than the full set.

7.5 THE ANALYSIS PLAN DESCRIBED

7.5.1 A Model for Testing Relationships

The theory tested is that training in teamwork and communications influences maintenance personnel attitudes and perceptions, and these in turn produce positive changes in group behavior which impact performance. The analysis of the model, specified in **Figure 7.3**, tests these influences by postulating systematic relations among a set of explanatory variables. **Figure 7.3** provides a diagram of the supposition or small "theory" examined in this model.

The conclusive assessment will be a causal analysis proving the strength of influence the training has on subsequent safety, dependability and efficiency. The present data do not yet establish true causal linkages. However, the present data do show associations between pre- and post-training attitudes and perceptions (measured by the CRM/TOQ), and between post-training CRM/TOQ results and performance.

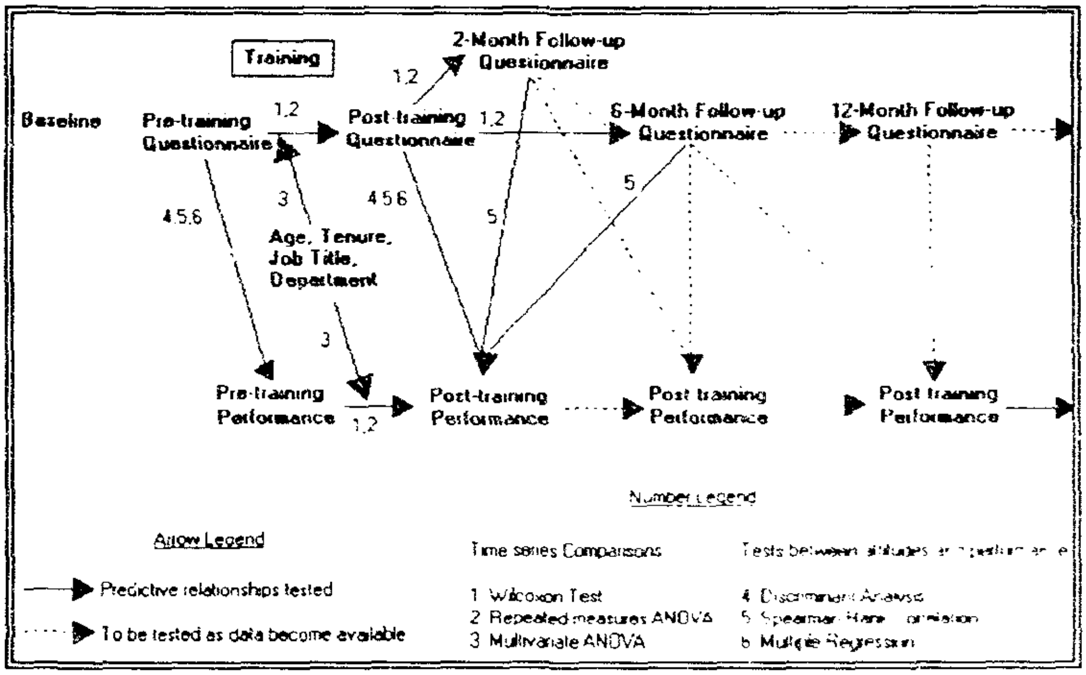

Figure 7.3 A Model of CRM Training, Attitude Change, and Technical Operations Performance

7.6 RESULTS OF STATISTICAL ANALYSIS

7.6.1 Factor Analysis of Survey Items

Among other statistical procedures undertaken to assess the goodness of the CRM/TOQ measure, two Factor Analyses were performed, using data from the 900-plus completed questionnaires from the "baseline" survey. The first Factor Analysis was conducted to determine the underlying internal structure among the answers to the 20 attitude questions, and the second was run for the six questions that measured perceptions of behaviors dealing with attainment of work goals.

First, the structure of the attitude data was found to be very similar to the structure reported by Gregorich et al. (1990). On the strength of this similarity, it was decided to apply the same names to the first three of the four CRM/TOQ factors that Gregorich applied to the CMAQ. Because all factors derived from the revised CMAQ were statistically strong, even the "avoiding conflict" composite (not subsequently used by Gregorich, et. al., (1990)) was retained here as the reflected index "Willingness to Voice Disagreement." The item sums for each factor were averaged to form four index scores for each respondent. The four factors were titled (1) Command Responsibility, (2) Communication and Coordination, (3) Recognition of Stressor Effects, and (4) Willingness to Voice Disagreement. The reliabilities were good for scales of this length, ranging between .54 and .56 for Indices 1, 2, and 4. The reliability coefficient of .39 for Index 3 was lower than desired for confidence in a stable index, but the association among the contributing items "communalities" were reasonably high at .58 and .59.

Secondly, items measuring attainment of work goals loaded on two separate factors. One factor consisted of items assessing "Goal Attainment with My Group and the other "Goal Attainment with Other Groups;" their respective reliability coefficients were .77 and .74. Two additional indices were formed based upon these results.

7.6.2 Attitude Changes Over Time

Pre- and post-training scores. The "before" and "after" scores for the four composite attitude scales were compared and scores of the 385 individual managers (whose pre- and post- questionnaires could be matched) combined and averaged by the work units they belong to. Several analyses allow comparison of pre-training attitudes, to post-training attitudes, as measured by the CRM/TOQ. Both the Wilcoxon Matched-Pairs Signed-Ranks Test and the Repeated-Measures Analysis of Variance tests were used to assess differences between pre- and post-measures and each test has its advantages, depending upon the nature of the data set (SPSS - User's Guide, 1990). In addition, Multivariate Analysis of Variance (MANOVA) was employed to test the effects, across time, of demographic variables, such as job title, job tenure or age, on attitudes and of different departments on performance measures. **Figure 7.4** shows the comparison of overall averages for the four composite attitude scales.

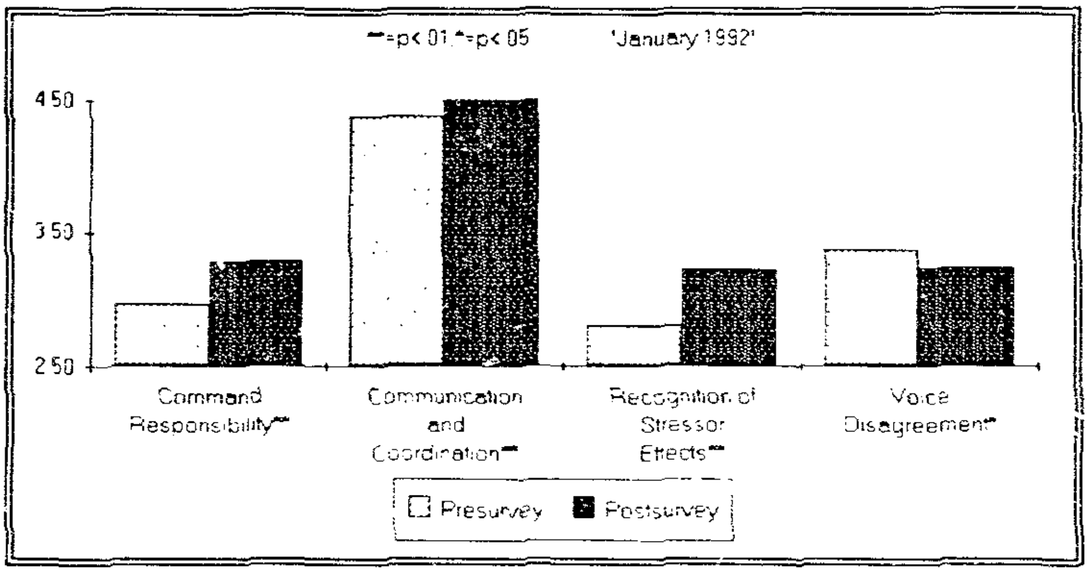

Figure 7.4 Mean Scores of Indexes for Pre- and Post-Seminar Technical Operations

All of the pre-training and post-training changes are in the expected direction except for "Willingness to Voice Disagreement," which shows a shift away from voicing disagreement and toward avoiding conflict. All of the differences are significant at the .05 level or better.

Willingness to Voice Disagreement: Effect of Age and Job. **Figures 7.5** and **7.6** present the change in "Willingness to Voice Disagreement" for the age of the maintenance personnel and for the given categories of job classifications, respectively. Each of these categories interacted with the repeated variable (pre-post survey), affecting the magnitude of negative shift (Pre-Post x Age. F=1.96, p <.10; Pre-Post x Job: F=5.20, p <.01).

These interactions are interesting because they further explain the negative shift in attitude on the "Willingness to Voice Disagreement" scale.

Figure 7.5 shows that the oldest and youngest members of the sample exhibit the greatest negative shift, whereas the remainder show very little change in "Willingness to Voice Disagreement" immediately following the training. In addition, **Figure 7.6** shows that the assistant supervisors (who are over-represented by the youngest and oldest members of the sample) and managers have the greatest negative shift in attitude.

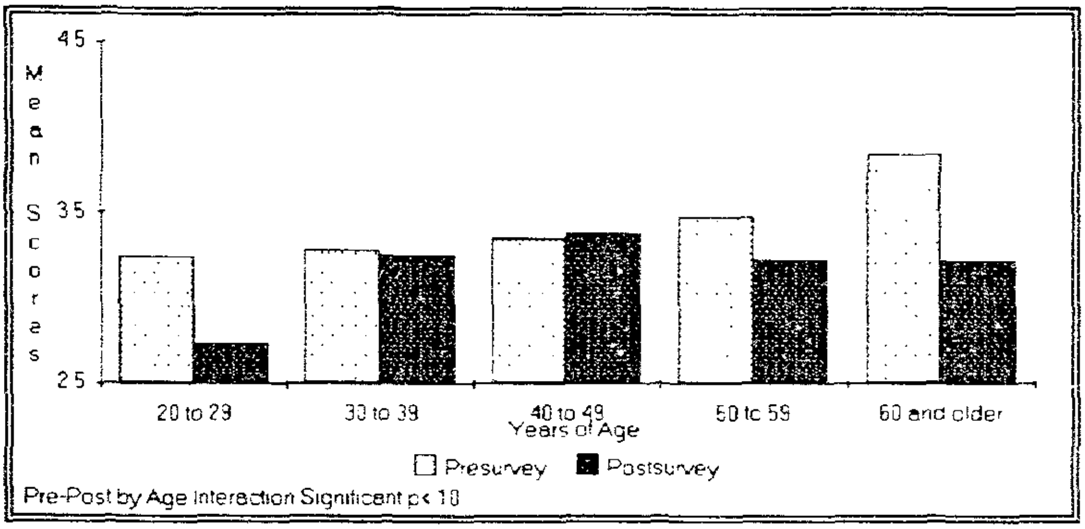

Figure 7.5 Mean Scores for Pre- and Post-Seminar "Willingness to Voice Disagreement" by Years of Age

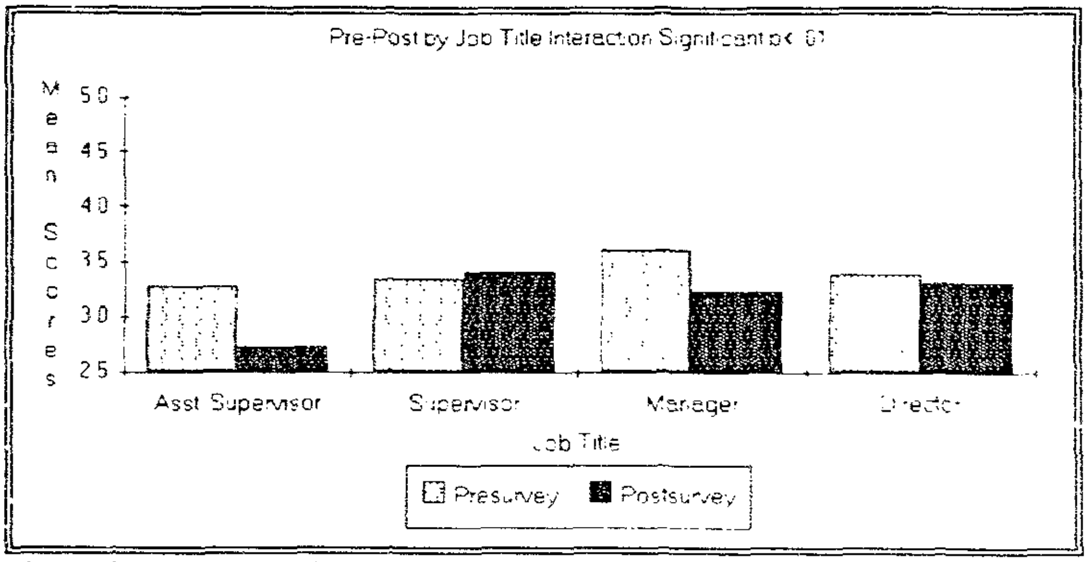

Figure 7.6 Mean Scores for Pre- and Post-Seminar "Willingness to Voice Disagreement" by Job Title

Recognition of Stressor Effects: Effects of Department. The magnitude of change in attitudes on the index "Recognition of Stressor Effects" were affected by the department affiliation of the respondent, revealing a significant interaction between attitude change and department (Pre-Post x Dept: F=2.25, p<.05). **Figure 7.7** shows that the attitudes of base maintenance and quality departments change little over time whereas those of line maintenance and planning departments improve considerably.

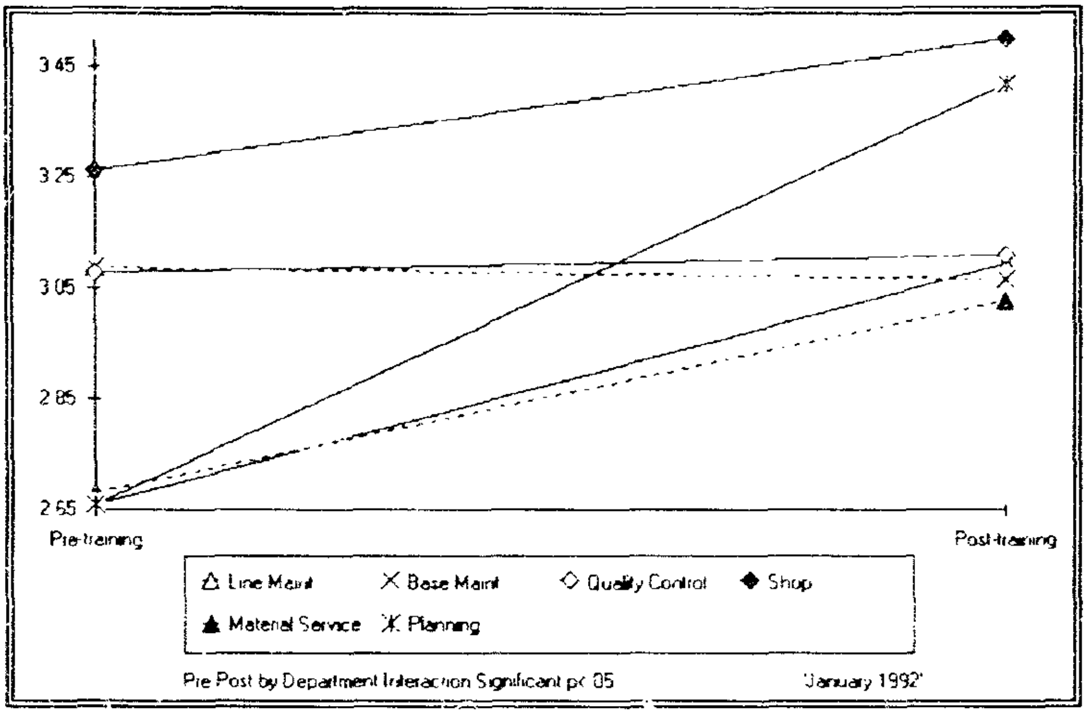

Figure 7.7 Mean Scores, Pre- and Post-Training, for "Recognition of Stressor Effects" by Department

Goal Attainment. The scores for two goal attainment scales can also be compared before and after training. Since these are perceptions of behavior, and not measures of attitudes, goal attainment scales were initially not expected to show changes because there would not be time to change the behaviors which were the focus of the measures. Because perceptions are not behavior, like attitudes, they can be more quickly influenced by exposure to new information, or by reconsidering initial assessments. One statistically significant change was found in the goal attainment with one's group immediately following training. **Figure 7.8** shows the pre-post averages for both of these measures.

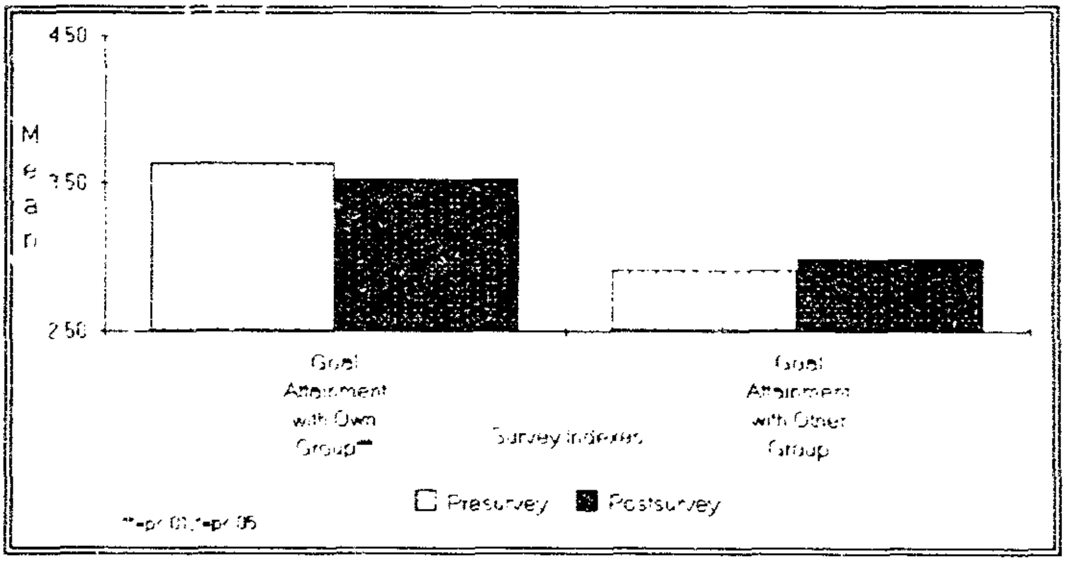

Figure 7.8 Mean Scores Pre and Post-Seminar for Goal Attainment Indexes

It is interesting to note the direction of changes in **Figure 7.8**. For the scale focused on behaviors to achieve goal attainment in one's own group a negative change occurred (i.e., the levels of discussion and encouragement were reported to be higher before the training than afterwards). This might be explained as unrealistic assessments (i.e., over-optimistic view of their own groups) of this group behavior which were challenged by exposure to the case analyses and discussions during the CRM training.

The slight positive shift in perception of activity to share goals with other groups' approaches shows a tendency, but is not significant ($p > .15$). This trend may also be explained as a probable effect of training which provided new information (and more importantly new experiences with people from other departments during the training) about the similarity of goals pursued by other groups and functions in technical operations.

Post-training attitudes compared with two- and six-month follow-up. Scores for the four indexes were compared with results from the follow-up surveys These results compare the post-test scores with the 50 or 41 individual managers whose post-training and 2-month or 6-month follow-up questionnaires could be matched. None of the differences are significant at the .05 level or better (in fact none approached significance any stronger than $p < .15$).

Taken together, the results show that attitudes about communication/coordination and sharing command responsibility remain high in the months following CRM training. The goal attainment measures were not included in **Figures 7.9 and 7.10** and no statistically significant changes were found for them either.

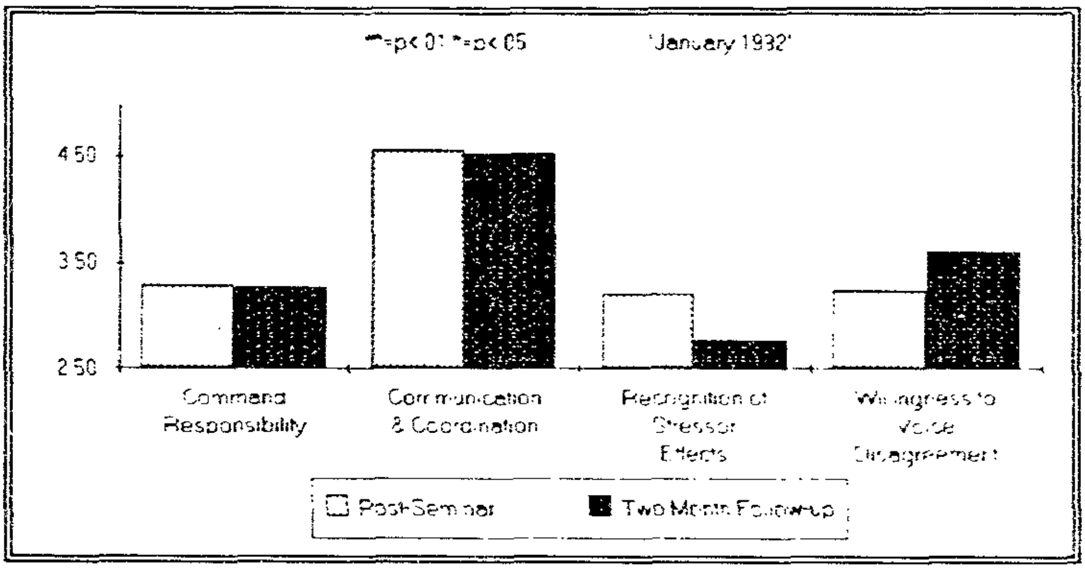

Figure 7.9 Mean Scores of Indexes for Post-Seminar and Two Month Follow-up for Technical Operations

7.6.3 Performance Changes Over Time

Pre- and post-training scores. The "before" and "after" scores for the 14 performance measures were compared and tested for statistical significance. Once again the Wilcoxon test, the Repeat d-Measures analysis and the Multivariate Analysis of Variance (MANOVA) were used. These tests represent a unit by unit comparison of the scores of the work units for which the specific measures applied. Many of the differences are significant at the .05 level or better, but some are in the opposite direction from that expected if the changes are to be attributed to changes from the CRM training. The next four **figures (7.11, 7.12, 7.13 and 7.14)** present the overall scores averaged over all the work units for which the performance measures apply. The statistically significant differences are displayed with the histograms in the figures as noted below.

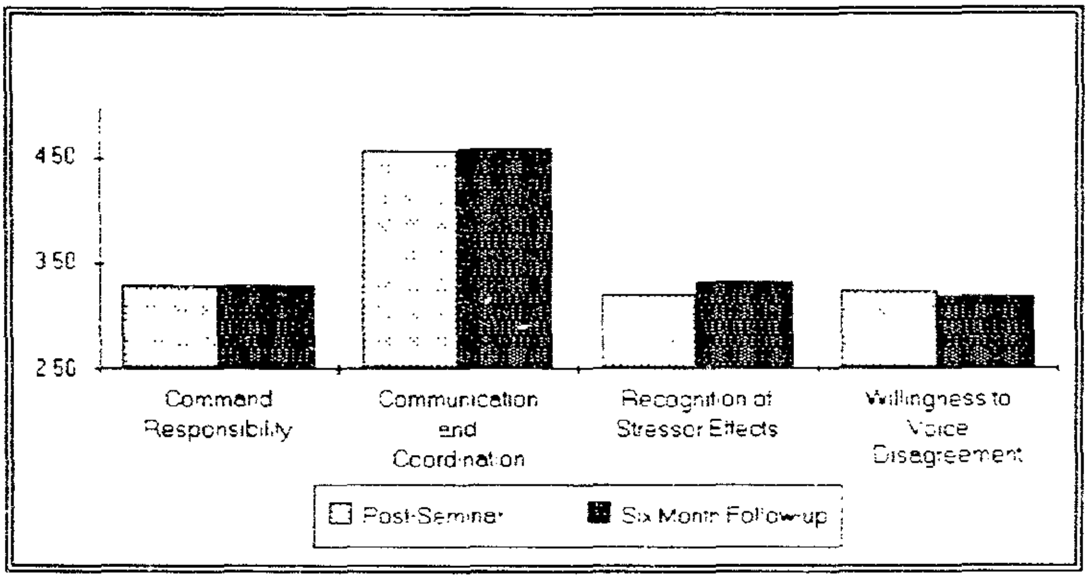

Figure 7.10 Mean Scores of Indexes for Post-Seminar and Six Month Follow-up for Technical Operations

<u>Measures of Safety Performance: Safety of Aircraft.</u> **Figure 7.11** presents before-and after-training comparisons of two measures of aircraft safety performance -- number of Ground-Damage incidents for 44 work units, and number of Turnbacks or Flight Diversions caused by human error for 31 line stations. Both of these differences are in the predicted direction and significant (p<.05). Although there are ample alternative explanations for these improvements between June/July and August/September, it is important to note that CRM training could be responsible for at least some of the observed changes. The trainers and training administrators had predicted that these two safety measures would be among the most likely to improve because of the training.

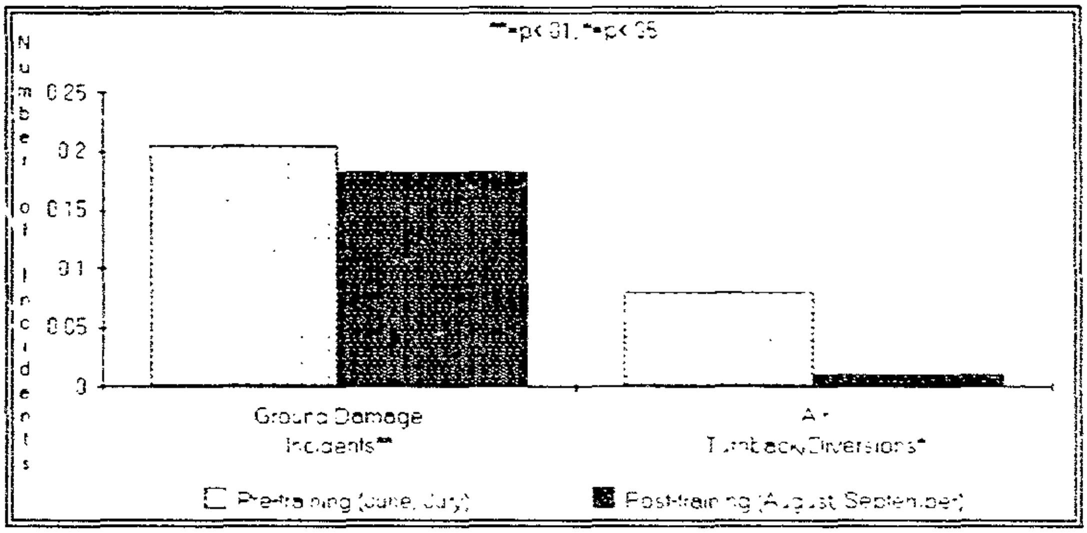

Figure 7.11 Mean Scores, Pre- and Post-Training, for Safety of Aircraft Performance Measures

<u>Measures of Safety Performance: Personal Safety.</u> **Figure 7.12** presents comparisons for the two measures percent Days Lost to Occupational Injury, and percent Sick Days Lost for the 55 and 54 work units respectively for which data were available.

Both of these differences are statistically significant, but only one is in the predicted direction. Occupational Injury days decreased significantly from the pre- to post-training period. Sick days lost, on the other hand, significantly increased during the period. The training planners and managers had predicted that improved lost time due to injury would improve more readily than sick days lost following the training.

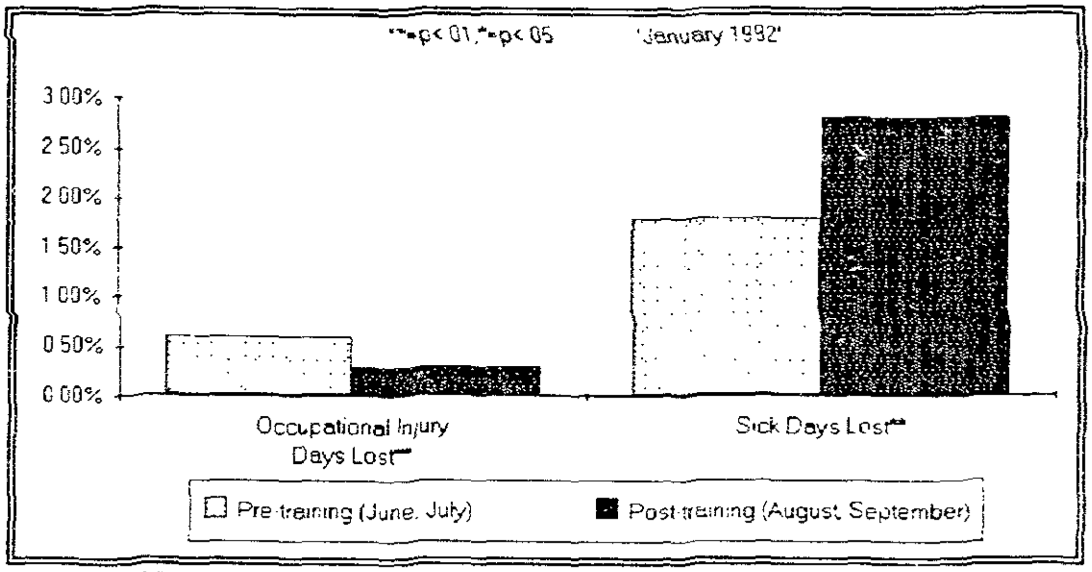

Figure 7.12 Mean Percentage, Pre- and Post-Training, for Personal Safety Performance Measures

Measures of Dependability. **Figure 7.13** presents before- and after-training comparisons for departures within 5 minutes, within 15 minutes, within 60 minutes, over 60 minutes, and an overall departure performance measure which includes all of the above.

Three of these differences are statistically significant, two of which are in the expected direction. Departures within 5 minutes and the overall measure improve significantly from pre- to post-training periods and this result is consistent with the assessments of the trainers.

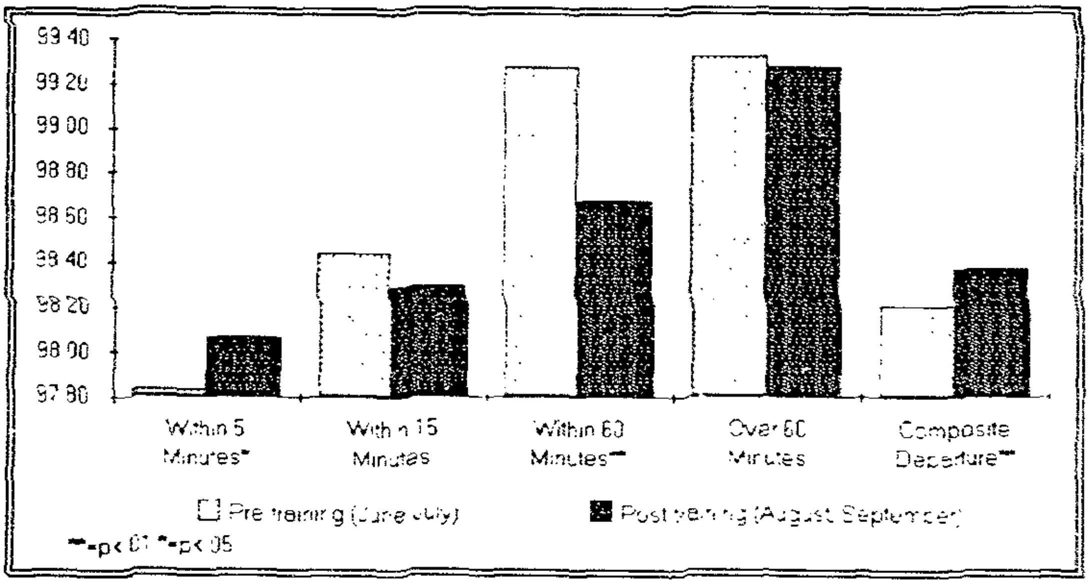

Figure 7.13 Mean Percentage, Pre- and Post-Training, for Departure Performance

Percent of departures within 60 minutes significantly decreases (the reverse direction to that predicted) pre- to post-training. Initially, this result appears puzzling, but, upon refection, it is not unexpected. The two performance indicators (departures within 5 minutes, and within 60 minutes), although not completely independent of one another in their measurement, can vary widely in practice. To illustrate this, consider the busy summer season when all line stations strive for on-time performance. The typical station (unable to substantially increase its manpower or overtime) could decide to sacrifice the schedule of aircraft that require as much as an hour to repair, in order to assign the line maintenance crews to those aircraft which can be dispatched "on-time." This tactic causes performance on the 5 minute mark to improve while performance on the 60 minute mark declines.

One other measure of dependability, "expendable parts service level," decreases (an unexpected result) between pre and post periods (pre=95% < post=93.3%; Z=-1.83, n=4, p=.07.). The other measures of dependability -- "number of delays due to late from maintenance" (n=35), "rotable parts service" (n=8) and "heavy checks on time to initial plan" (n=4) -- did not show measurable change in pre and post levels of performance.

Measures of Efficiency. **Figure 7.14** shows the pre-post comparisons for the percentage of hours applied to production and for overtime charged.

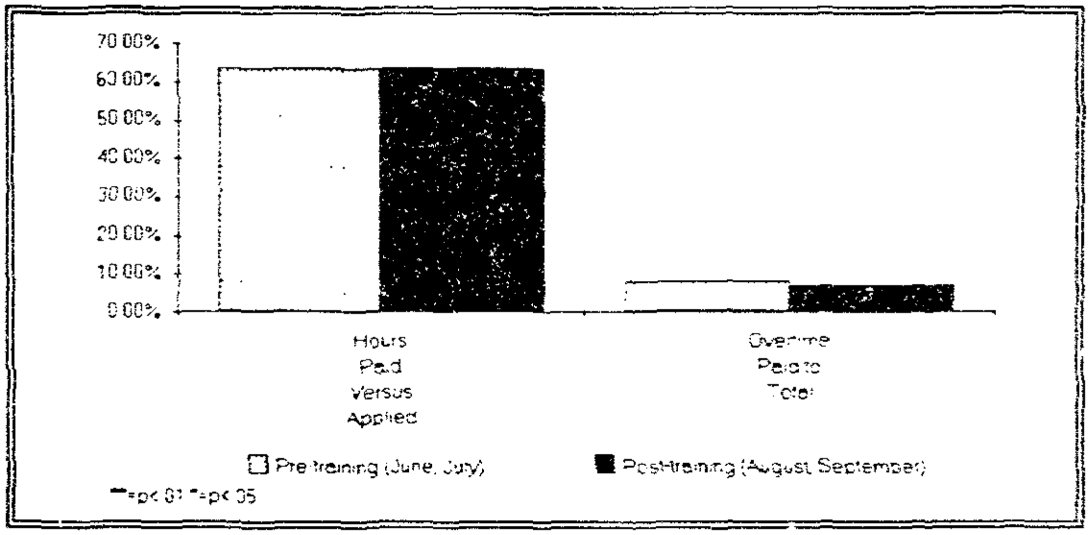

Figure 7.14 Mean Percentage, Pre- and Post-Training, for Efficiency Performance Measures

Although, neither measure shows change after training, the results of a series of analyses conducted to assess possible relationships between department and performance measured revealed that only overtime charged was related to department. These results show significant main effects of Pre-Post change (F=4.14, P < .05) **and** department (F = 2.71, p < .05), indicating all departments, except Quality control, reduced overtime after training. **Figure 7.15** displays these changes in bar chart form.

7.6.4 Relationships Between Post-training Attitudes and Performance

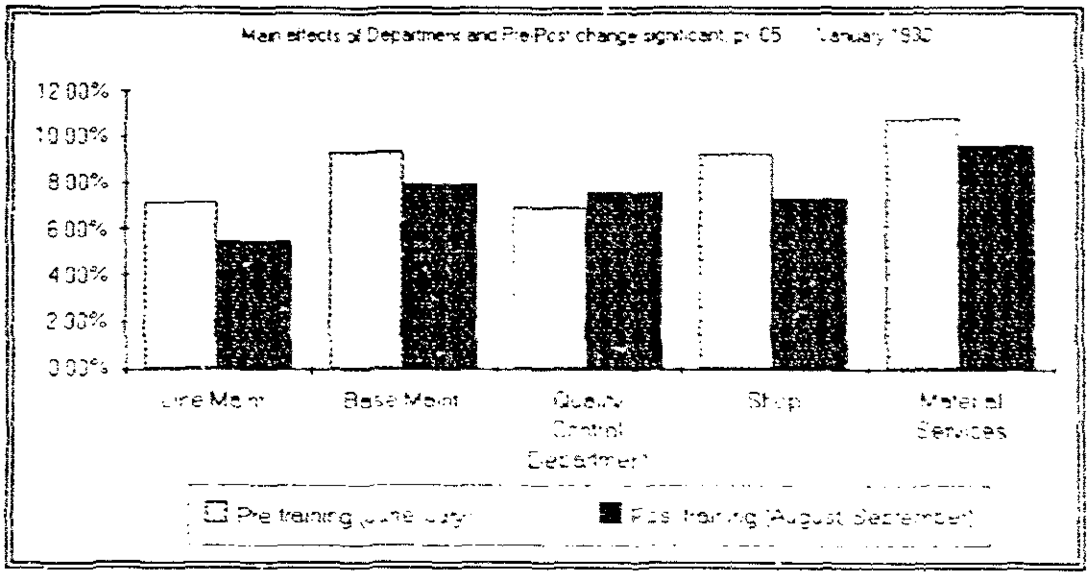

Figure 7.15 Mean Percentage, Pre- and Post-Training, for Overtime Paid to Total by Department

The predictor variables to be tested include only the post-training results of the four attitude indices: "Sharing Command Responsibility," "Communication and Coordination," "Recognition of Stressor Effects," and

"Willingness to Voice Disagreement." Spearman Rank-order Correlations that test the relationship between these indices and the 12 performance measures are presented in **Tables 7.2, 7.3, and 7.4**. Because the present data are limited in sample size statistical significance conventions are extended to show not only probability levels of 1% and 5%, but also 10% and 15% to aid in examining patterns of expected results.

<u>ATTITUDE INDEX</u>

"SHARING COMMAND" RESPONSIBILITY"	"COMMUNICATION AND COORDINATION"	"RECOGNITION OF STRESSOR EFFECTS"	"WILLINGNESS TO VOICE DISAGREEMENT"
MEASURES OF SAFETY			
Number of Ground Damage Incidents[1] (n=35)			
-.04	+.19	-.03	+.30*
% Occupational Injury Days Lost[1] (n=37)			
+.28*	+.14	-.09	-.08
% Sick Days Lost[1] (n=36)			
-.29*	-.12	-.02	-.05

** $p < .01$; * $p < .05$
[1]: These items score lower when performance is positive, thus the direction of the statistics are mirrored to reflect positive when relationships are in the expected direction.

Table 7.2 Spearman-Rho Correlations Between Post-Training CRM/TOQ Results and Post-Training Maintenance Safety Performance

The matrix of results reveals that post-training attitudes predict the performance of the work units. These relationships are especially consistent for attitudes regarding the willingness of units to <u>share command responsibility</u> and to <u>voice disagreement</u>. These results are discussed below in more detail.

It's useful to note that the **total** number of **positive** and **significant** relationships relative to their proportion to the total number of tests presented in **Tables 7.2, 7.3, and 7.4** is substantially above that expected by chance alone. Twenty Spearman "Rhos" were less than or equal to a probability of .15, from a total of 48 tests conducted (20/48 = 42%); and seven of them were less than .05 (7/48 = 15%).

<u>Measures of Safety Performance.</u> Post-training responses for some of the attitude indices were associated with the measures of Safety performance (See **Table 7.2**). Specifically "Willingness to Voice Disagreement" was related to the number of ground-damage incidents. This relationship implies that the more willing managers were to voice disagreement the better that their units performed (e.g., had fewer incidents of ground damage).

Similarly, attitudes about "Sharing Command Responsibility" were positively associated with percentage of occupational injury days lost. That is, the more favorable the attitudes were about "Sharing Command Responsibility" the better were the outcomes; positive attitudes were associated with fewer days lost to occupational injury. Finally, attitudes on this same index, "Sharing Command Responsibility," were negatively related to percentage of sick days lost. This relationship is not in the expected direction, suggesting that more sick days are taken among units who are more willing to share command responsibility.

<u>Measures of Dependability.</u> Departures within 5 and 15 minutes of schedule (the two most salient Dependability measures) and 60 minutes display significant positive relationships with most or all of the four attitudes (See **Table 7.3**).

Taken together, these results suggest that positive attitudes toward the concepts learned in training have a facilitative effect on the departure performance of units. For example, those units favorable towards the sharing command responsibility tend to have better departure performance measured within 5, 15, and 60 minutes. A similar pattern of positive relationships between recognition of stressor effects and these departure performance assessments emerged as well. Line managers who advocate the importance of recognizing stress are more likely to guide their mechanics to perform well on the percentage of goal achieved for departure in 5, 15, and 60 minutes.

Warehouse service levels show few positive relationships with post-training attitudes (see **Table 7.3**). Percentage of rotable parts available is moderately correlated ($p < .10$) with attitudes on the index "Sharing Command Responsibility." Warehouse service levels in expendable parts, however, show a negative relationship ($p < .10$) to "Willingness to Voice Disagreement."

Finally, the dependability measure, heavy-checks-on-time-to-plan, shows two perfect positive correlations with "Sharing Command Responsibility" and "Recognition of Stressor Effects" as well as a marginally significant but high correlation with "Willingness to Voice Disagreement." Although the number of units available for this measurement are unavoidably low (available n=4) the consistent pattern of positive relationships suggest that positive post-training attitudes are related to achieving the standards of the initial plan.

<u>Measures of Efficiency.</u> **Table 7.4** shows that attitudes about sharing command responsibility predict units' performance for one of the measures of efficiency, "ratio of hours paid to applied to production." This relationship suggests that the more the unit agrees with the principle of sharing command responsibility the better will be the ratio of efficiency. Such a positive relationship, however, is not evident when considering the percentage of overtime-paid-to-total-wage. In fact, there is a modest negative relationship between this efficiency measure and both "Sharing Command Responsibility" and "Willingness to Voice Disagreement."

ATTITUDE INDEX

"SHARING COMMAND" RESPONSIBILITY"	"COMMUNICATION AND COORDINATION"	"RECOGNITION OF STRESSOR EFFECTS"	"WILLINGNESS TO VOICE DISAGREEMENT"
MEASURES OF DEPENDABILITY			
% Departure within 5 minutes (n=26)			
+.32*	+.30†	+.27†	+.24‡
% Departure within 15 minutes (n=26)			
+.29†	+.31†	+.25‡	+.15
% Departure within 60 minutes (n=26)			
+.34*	+.09	+.25‡	+.21‡
% Departure over 60 min, but not canceled(n=26)			
+.06	+.09	-.09	+.22‡
% Rotable parts available (n=4)			
+.80†	-.20	-.20	-.20
% Expendable parts available (n=4)			
-.40	+.40	-.50	-.80†
% Heavy checks on time to initial plan (n=4)			
+1.0*	+.40	+1.0*	+.80†
** $p < .01$ * $p < .05$ † $p < .10$ ‡ $p < .15$			

Table 7.3 Spearman-Rho Correlations Between Post-Training CRM/TOQ Results and Post-Training Maintenance Dependability Performance

7.7 QUALITATIVE DATA OBTAINED AFTER THE CRM TRAINING

Not all indicators used are quantitative. The case study approach is also beginning to provide evidence for the program's success. In addition, there are several open-ended questions included in the immediate post-training CRM/TOQ, as well as in the 2- and 6-month follow-up questionnaires. These two potential sources of evidence will be described and illustrated below.

ATTITUDE INDEX

"SHARING COMMAND" RESPONSIBILITY"	"COMMUNICATION AND COORDINATION"	"RECOGNITION OF STRESSOR EFFECTS"	"WILLINGNESS TO VOICE DISAGREEMENT"
MEASURES OF EFFICIENCY			
Ratio of Hours paid to applied to production (n=6)			
+.77*	+.23	+.20	+.31
% Overtime paid to total wage' (n=37)			
-.19‡	-.09	-.12	-.20‡

** p < .01   * p < .05   † p < .10   ‡ p < .15
': These items score lower when performance is positive, thus the direction of the statistics are mirrored to reflect positive when relationships are in the expected direction.

Table 7.4 Spearman-Rho Correlations Between Post-Training CRM/TOQ Results and Post-Training Maintenance Efficiency Performance

7.7.1 The Case Study Approach

One such anecdote involves participant reaction to the stress-management module of the CRM course, and how it led to discovering how effective the course could be in heavy maintenance planning. Meeting objectives for completion times (called estimated time for return, or "ETRs") from base maintenance overhaul are always raised as examples of "high stress" parts of the job by managers in the CRM course. During a CRM session in November 1991, six months after the onset of the CRM training in Technical Operations, Planning and Maintenance Managers from one maintenance base **did not** report ETRs as a source of stress. With a little encouragement these managers revealed that, beginning two or three months before, Maintenance and Planning functions meet together frequently to confirm ETRs, or to change them if required. The net effect is an improvement not only in the performance to plan, but in the timeliness and quality of the aircraft delivered from base maintenance. The Director of Maintenance for that base, it turned out, had attended a CRM session three months earlier where he had shown an increased acceptance for the concepts -- having ended the two day training saying, "Maybe this stuff has a place in management after all." It should be noted that quantitative results, presented earlier, evidence the relationship between several attitude indices and heavy maintenance performance to plan.

7.7.2 Written Comments from the Post-training and Follow-up CRM/TOQ

"How will the CRM training be used on the job?" Immediately following the training this question was most frequently answered "Better communication" (active transferring of information), "Better listening" (a passive improvement made within the person), "Being more aware of others" (a passive, reactive behavior), and "Dealing better with others" (interactive, problem-solving).

"How did you use the CRM training on the job?" For the sample of respondents who returned the first 2-month and 6-month follow-up questionnaires (in October, 1991) the largest numbers, saying what they had used from the CRM training, reported actions in those same four categories. **Tables 7.5** and **7.6** show these comparisons for the immediate Post-training survey with the two-month and six-month follow-up surveys, respectively.

Most respondents in both samples emphasized that they had tried to listen better, and to "deal better with others" *(often specifying team work, decision making and problem solving as ways of doing this). The* largest numbers in both the two- and six-month follow-up samples stated emphatically that "Communicating better," and "Using more teamwork" (the latter accounting for over half of the responses included in "dealing better with others") was what they intended to further use from what they learned in CRM training.

These open-ended responses tend to confirm that improved interpersonal behaviors have resulted from the positive attitudes which followed the training. *Furthermore, the preferred behaviors tend to have shifted* from those people could do by themselves (e.g., "be a better listener" and being more aware of others), to those behaviors which involve others, such as "communicating better," and dealing better with others.

	SURVEY PERIOD		
RESPONSE	POST-TRAINING WILL USE	TWO MONTH WAS USED	TWO MONTH WILL USE
Better Communication	20%	15%	17%
Better Listening	16	20	3
Be More Aware of Others	11	15	11
Deal Better with Others	10	25	25
Use in Daily Tasks	6	5	3

Table 7.5 Percentage of Written-in Responses Indicating How Training Will be Used and Was Used on the Job for Post-training and Two Month Follow-up

	SURVEY PERIOD		
RESPONSE	POST-TRAINING WILL USE	SIX MONTH WAS USED	SIX MONTH WILL USE
Better Communication	20%	20%	26%
Better Listening	16	17	6
Be More Aware of Others	11	14	6
Deal Better with Others	10	21	23
Use in Daily Tasks	6	2	2

Table 7.6 Percentage of Written-in Responses Indicating How Training Will be Used and Was Used on the Job for Post-training and Six Month Follow-up

"What could be done to improve the training?" Most answers to this question, immediately after training were "do nothing" or "it's fine as it is." Two and six months later the largest single category of answers was "do more of this" or "bring us back for follow-up training." **Table 7.7** presents these results for both the two month and six month follow-up surveys compared with the immediate post training questionnaire. From this sample, at least, participants clearly believe they would benefit from further CRM type training.

	SURVEY PERIOD		
RESPONSE	POST-TRAINING	TWO MONTH FOLLOW-UP	SIX MONTH FOLLOW-UP
Needs Nothing	35%	16%	12%
More Training & Follow-up	11	27	28
More Role Playing	7	11	4
Add Time to Training	7	5	4
More Case Studies	6	7	7
Better Mix of Participants	6	5	7

Table 7.7 Percentage of Written-in Responses Indicating How Training Might be Improved for Post-training, Two, and Six Month Follow-up

7.8 CONCLUSIONS

7.8.1 Strengths of the CRM Training Program

The CRM training for maintenance managers evaluated here has been successful, after as short a time as six months, in improving attitudes which appear to have influenced safe, dependable and efficient performance. Some specific findings should be emphasized:

1) The timing and content of the program has been well received by participants. The immediate evaluation of the training was even more positive than had been the case in other companies using CRM in maintenance as well as flight operations. **Figure 7.1** presented this dramatic difference.

2) The training produces a significant improvement in most attitudes measured. Changes in relevant attitudes measured immediately before and after training reveal strong and positive changes following training, for three of the four indices measured (cf., **Figure 7.4**). Follow-up results several months after training tend to confirm that most (if not all) these changes are stable (**Figures 7.9 and 7.10**).

3) Performance appears to improve due to CRM training. Changes in most maintenance performance measured before and after the CRM training sessions examined in the present paper show significant changes in the expected direction (e.g., **Figures 7.11-7.13**).

4) Specific attitude changes seem to cause specific performance. A pattern of significant relationships in the expected direction was noted between the post-training attitudes and the post-training performance. Those measures predicted (by the program's trainers and managers) to be especially sensitive to the effects of the CRM training were affected (cf., **Tables 7.2, 7.3**). In particular, positive attitudes about "Sharing Command Responsibility" and "Willingness to Voice Disagreement" both show the most association with improved performance.

5) More active change is occurring. Finally, the program is reported in follow-up surveys to be stimulating changes from the "easier" more passive behaviors (such as "better listening"), to the more interactive ones in working with others, such as holding meetings and undertaking joint problem-solving. Anecdotal evidence is beginning to confirm these changes and their impact on performance.

Continuous Improvement. A few of the strengths, such as the final one noted above, also provide guidance where the training design for this, and future programs, can be improved.

The results presented in this report reflect the program as it was in November, 1991. The training facilitators and administrators of the program receive abundant verbal participant feedback at the end of each training session. They have also received the earlier reports issued through this research project. A watchword of those managing this program is its flexibility and adaptability to the needs (as well as constraints) of the company, as well as to increased learning about this new kind of maintenance training. Several of the concerns and opportunities noted below have been successfully addressed by the trainers since November, 1991. These efforts will be briefly described.

The ambitious syllabus for the two-day training evaluated here (Appendix A) contains many important content categories; and it has little room for added exercises or activities. This tight program has created a dilemma for the trainers from its onset. For them, the opportunities for program improvement usually require classroom time to exploit. The trainers have devised an innovative solution to this dilemma in at least one area of potential improvement described below.

7.8.2 Opportunities for Improvement in Maintenance CRM Training

1) Help participants plan what and how to use their new-found skills back at work. The finding that a substantial portion of participants months later report that they are ready and willing to try more active behaviors -- those actually involving others as well as themselves -- suggests that the training program might be improved to help the "graduates" to design or develop their own approach to implementation. Such implementation could help participants actually plan, during the training, how and what they would try to change when they returned to work. Part of this awareness could include research results (such as those contained in this report) for participants so that they understand that listening and stress-management skills are useful and important, but that the assertiveness and team leadership skills could impact safety even more. Another avenue to impact active improvement would be to expand the course module on assertiveness training.

2) Focus directly on assertiveness skill training. The research evidence presented in this report shows that, of the four major attitude clusters derived from the CRM/TO questionnaire, "Willingness to Voice Disagreement" forms a mixed picture. Although assertiveness is mentioned throughout the training, the average scores reveal less positive attitudes about voicing disagreement (or wanting to

"avoid conflict") following the course than before it. This shift is most marked for the youngest and the oldest; and for the lowest and highest in the management hierarchy. Those in the middle of the age range and hierarchy tend to show some shift toward addressing disagreements." What is intended of the CRM training in this regard? As an active social skill, assertiveness forms a theme throughout the two-day program, but it hasn't been emphasized at the expense of other aspects of the course. Perhaps more time directly with assertiveness skills is required. There are ample materials already developed and included in the participants' CRM handbook, which contain theory and skill practice sections, on assertiveness, but limited classroom time has not permitted the intensive coverage this material deserves. Greater use of role-playing exercises could also help participants' learn how to be assertive and participative, and to give them confidence that they can skillfully employ these behaviors, but this too requires time.

Trainers in the present program feel very strongly about the need for practical application of all of the CRM concepts -- and assertiveness in particular. They are also sensitive about the contrived nature of even the best role-playing cases as seen by the very pragmatic audience they are training. In an effort to emphasize "real life" rather than contrived situations, the trainers have replaced one of the two role-plays dealing with "supporting and confronting others" (a major aspect of assertiveness skill) with intensive small-group and whole-group discussions dealing with the same concepts, but focused on personal illustrations volunteered from the participants. It is too soon to quantitatively measure the effects of this innovation, but trainers' initial reports are encouraging.

The results of association between post-training attitudes and unit performance (i.e., **Table 7.2**) tend to show that positive feelings about assertiveness and sharing authority are most related to safety and dependability. Further improving and/or expanding the training design could well leverage this advantage by increasing the numbers of participants with a positive opinion about assertiveness.

3) Plan and publicize recurrent CRM training. Another way to develop active leadership and follower skills, while recognizing the ambitious syllabus in a two-day training course, would be to plan and publicize a CRM program that includes a follow-up training module (or even successive *recurrent* training). Given that many CRM graduates say that they would like to receive additional training like this, expansion of the program curriculum could provide a real advantage. For instance, the CRM training program could be designed to first awaken awareness of CRM and develop easily attainable successes and then subsequently develop and exercise team and assertiveness skills.

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Technical Operation Division
Crew Coordination Concepts Syllabus

Module	Time	Facilitator	Method	Objective
Day 1				
Introduction	8:15 (30 min)	TO	*Introduce self.* Cover facilities, restrooms, telephones, breaks, lunches, closing time. What have you heard about course? Review PURPOSE, OBJECTIVES, WORKING AGREEMENTS. Collect Pre-seminar questionnaire. Explain purpose & importance of ID#. Group introdaces themselves.	*Position program as helpful in dev. mgmt. skills* Get group talking and energized Set the tone of the workshop. Clarify expectations, yours/theirs. Remove teacher-student relationship
Portland Video	8:45am (45 min)	*HF*	Show video; identify resource mgmt problems; relate Portland problems to work place. Prepare flipchart.	Attention getter. Identify mgmt problems faced. problems become course focus/overview.
Expectations	9:30am (15 min)	HF	Develop expectations of individuals in course. Write on chart, compare to course objectives.	Get expectations from group, compare to course illustrate differences if any.
Break	9:45am (15 min)			
Testing Assumptions/ DC-10 Video GUM	10:00am (120 min)	TO	Introduce concept of Perception vs Reality Show DC-10 Video GUM. Tablework: What were "Chain of Events" that led to the accident? Discuss "ASSUMPTIONS" that led or contributed to accident. How can we test our assumptions? What could each person have done differently?	Test Assumptions by: Advocacy - "Speaking Out" Inquiry - "Ask Questions" Active Listening - "Listening"
Lunch	12:00pm (60 min)			

Technical Operations Division
Crew Coordination Concepts Syllabus

Module	Time	Facilitator	Method	Objective
Behavior	1:00pm (75 min)	HF	Discuss use of Instruments; admin SDI; develop Behav Dim Model; discuss concept of "Assertive Behavior."	Understand behavior differences; understand strengths and weakness of behavior styles; assertiveness involve using a variety of styles positively).
Break	2:15pm (15 min)			
Behaviors Comt'd	2:30pm (60 min)	HF	Scores SDI; Interpret SDI; draw arrows; discuss/apply "Assertiveness" Behavior modification approx. for effective supervision.	People are different; behaviors influence communication, values, perceptions of others, decision making & conflict resolution methods.
Break	3:30pm (15 min)			
Stress Management	3:45 pm (60 min)	TO/HF	TO-Introduce/understand stress What are sources of stress in our jobs? Develop list of Stressors. HF-Identify body's reaction to stress. Ways to deal with stress. TO-Work on how to deal with 2 examples. ETR'S, MANPOWER, PARTS AVAILABILITY	Stress is normal; stress can be managed; Recognize signs of excess stress. Effects of safety & effiency. Application of CCC to reduce stress.

Technical Operations Division
Crew Coordination Concepts Syllabus

Module	Time	Facilitator	Method	OBJECTIVE
Day 2				
Opening DC-10 Video GUM 041	8:15am (30 min)	TO	Show GUM 041 video with breakfast. Address loose ends from Day 1; Outline schedule for Day 2. Review lessons learned in context of video (Gum 041)	Transition and clarification; group at ease where they've been and are heading; NOT A REVIEW!
Sub Artic Survival	8:45am (60 min)	TO	Purpose of simulation. Make individual decisions (step 2).	Tie into Day 1; position as a competition This is fun!
Break	9:45am (15 min)			
SAS II	10:00am (60 min)	HF	Define/develop rational decision process; apply process to simulation; complete SAS; critique team effect develop lossons learned/apply to job.	Problem solving involves a rational process; consensus decisions are better than individual Interpersonal Skills impact decision-making.
Break	11:00am (15 min)			
Norms/ EAL 855	11:15am (45 min)	TO	Identify role of norms in Tech Ops. Introduce concept, give examples. Allow time to review EAL 855. Assign each table a role. What were norms that led to accident? Groups develop lists of good/bad CO Norms. Discuss how to manage norms and prevent accidents.	Norms play powerful role in organizations. Have a direct impact on safety & efficiency. Assumptions must be tested. Norms are unwritten rules enforced by the group. MGMT & FAA are powerless to change norms.
Lunch	12:00pm (60 min)			

Technical Operations Division
Crew Coordination Concepts Syllabus

Module	Time	Facilitator	Method	Objective
Listening & Communicating	1:00pm (60 min)	HF	Tie into SAS; Sleep exercise Communication model, listening barriers; listening tips	Listening is a learned skill. Poor listening [illegible] quality decision making
Break	2:00pm (15 min)			
Supporting/ Confronting	2:15pm (60 min)	TO/HF	Use interactive dilemmas Conduct 1st dilemma Critique/lessons learned from 1st Conduct second dilemma	Application of behavioral skills [illegible] [illegible] and the variety of approaches, language [illegible] role play to [illegible] [illegible] and need of practice
Break	3:15pm (15 min)			
Wrap-up Evaluation/ Questionnaire	3:30pm (45 min)	To/HF	Take Home concepts? USC/CAL Questionnaire explanation I.D #s on questionnaires	Pledge to do something different/better Feedback for program enhancement; participants [illegible] about our experience

Chapter Seven Appendix B

Date__________

Airlines
Technical Operations Division
CCC WorkShop Survey

BASELINE

Please answer by writing beside each item the number that best reflects your personal opinion. Choose the number from the scale below.

*** Scale ***

1	2	3	4	5
Disagree Strongly	Disagree Slightly	Neutral	Agree Slightly	Agree Strongly

_2_ 1. Tech. Ops. team members should avoid disagreeing with others because conflicts create tension and reduce team effectiveness.

_2_ 2. It is important to avoid negative comments about the procedures and techniques of other team members.

_5_ 3. Casual, social conversation on the job during periods of low workload can improve Tech. Ops. team coordination.

_5_ 4. Good communications and team coordination are as important as technical profiency for aircraft safety and operational effectiveness.

_5_ 5. We should be aware of and sensitive to the personal problems of other Tech. Ops. team members.

_5_ 6. The manager, supervisor, or asst. supervisor in charge should take hands-on control and make all decisions in emergency and non-standard situations.

_5_ 7. The manager, supervisor, or addt. supervisor in charge should verbalize plans for procedures or actions and should be sure that the information is understood and acknowledged by the other Tech. Ops. team members.

_1_ 8. Tech. Ops. team members should not question the decisions or actions of the manager, supervisor, or asst. supervisor except when they threaten the safety of the operation.

_2_ 9. Even when fatigued, I perform effectively during critical phases of work.

*** SCALE ***

1	2	3	4	5
Disagree Strongly	Disagree Slightly	Neutral Slightly	Agree	Agree Strongly

_5_ 10. Managers, supervisors and asst. supervisors should encourage questions during normal operations and in special situations.

_5_ 11. There are no circumstances where the subordinate should assume control of a project.

_5_ 12. A debriefing and critique of procedures and decision after each major task is an important part of developing and maintaining effective team coordination.

_4_ 13. Overall, successful Tech. Ops. management is primarily a function of the manager's, supervisor's, or asst. supervisor's technical proficiency.

_4_ 14. Training is one of the manager's most important responsibilities.

_5_ 15. Because individuals function less effectively under high stress, good team coordination is more important in emergency or abnormal situations.

_5_ 16. The start-of-shift team briefing is important for safety and for effective team management.

_5_ 17. Effective team coordination requires each person to take into account the personalities of other team members.

_5_ 18. The responsibilities of the manager, supervisor, or asst. supervisor include coordination between his or her work team and other support areas.

_4_ 19. A truly professional manager, supervisor or asst. supervisor can leave personal problems behind.

_5_ 20. My decision-making ability is as good in abnormal situations as in routine daily operations.

*** SCALE ***

1	2	3	4	5
Disagree Strongly	**Disagree Slightly**	**Neutral**	**Agree Slightly**	**Agree Strongly**

In the following questions, "my management group" refers to those people who report to the same manager that I do.

____21. I am kept informed by others in my management group about the goals and objectives of this organization (e.g., cost, quality, service, etc.).

____22. Work goals and priorities are understood and agreed to by members of my management group.

In the following items, "my work group" refers to those people who report to me.

____23. Employees in my work group receive detailed feedback regarding the organization's performance.

____24. If employees in my work group disagree with the goal and priorities that have been established, they feel free to raise their concerns with supervision.

____25. Employees in other groups within Tech. Ops. plan and coordinate their activities effectively together with people in my work group.

____26. Employees in other groups, departments and divisions through the company act as if they share many of the same organizational goals that we do.

BACKGROUND INFORMATION

Year of Birth	______
Total Years at	__✓__
Sex (M or F)	______

Current Department

______	**Maintenance**
______	**Engineering**
__✓__	**Quality Control**
______	**Planning**
______	**Logistics**
______	**Shop**
______	**Material Services**

Job Title: ______________________

Years in present position: __✓__

Past Experience/Training (# of Years):

Military	________
Trade School	________
College	___✓___
Other Airlines	___✓___

Chapter Seven Appendix C

Date ____________

AIRLINES
TECHNICAL OPERATION DIVISION
CCC WORKSHOP SURVEY

"Two-month Follow-up" Questionnaire

Please enter the five digit Personal Identification Number that you selected at the beginning of the seminar.

Identification Code ____ ____ ____ ____ ____ ____

Now, please answer by writing beside each item the number that best reflects your personal attitude. Choose the number from the scale below. All date are strictly confidential.

**** SCALE ****

1	2	3	4	5
Disagree Strongly	Disagree Slightly	Neutral	Agree Slightly	Agree Strongly

___1. Technical Operations team members should avoid disagreeing with others.

___2. It is important to avoid negative comments about the procedures and techniques of other team members.

___3. Casual, social conversation on the job during periods of low worked can improve Technical Operations team coordination.

___4. Good communications and team coordination are as important as technical proficiency for aircraft safety and operational effectiveness.

___5. We should be aware of and sensitive to the personal problems of other Technical Operations team members.

___6. The manager, supervisor, or assistant supervisor in charge should verbalize plans for procedures or actions and should be sure that the information is understood and acknowledged by the other Technical Operations team members.

___7. The manager, supervisor, or assistant supervisor in charge should verbalize plans for procedures or actions and should be sure that the information is understood and acknowledged by the other Technical Operations team members.

1	2	3	4	5
Disagree Strongly	**Disagree Slightly**	**Neutral**	**Agree Slightly**	**Agree Strongly**

2 8. Technical Operations team members should not question the decisions or actions of the manager, supervisor, or assistant supervisor except when they threaten the safety of the operation.

2 9. Even when fatigued, I perform effectively during critical phases of work.

5 10. Managers, supervisors, and assistant supervisors should encourage questions during normal operations and in special situations.

1 11. There are no circumstances where the subordinate should assume control of a project.

5 12. A debriefing and critique of procedures and decisions after each major task is an important part of developing and maintaining effective team coordination.

5 13. Overall, successful Technical Operations management is primarily a function of the manager's, supervisor's, or assistant supervisor's technical proficiency.

5 14. Training is one of the manager's most important responsibilities.

5 15. Because individuals function less effectively under high stress, good team coordination is more important in emergency or abnormal situations.

4 16. The start-of-snift team briefing is important for safety and for effective team management.

5 17. Effective team coordination requires each person to take into account the personalities of other team members.

5 18. The responsibilities of the manager, supervisor, or assistant supervisor include coordination between his or her work team and other support areas.

1 19. A truly professional manager, supervisor, or assistant supervisor can leave personal problems behind.

2 20. My decision-making is as good in abnormal situations as in routine daily operations.

*** SCALE ***

1	2	3	4	5
Disagree Strongly	**Disagree Slightly**	**Neutral**	**Agree Slightly**	**Agree Strongly**

In the following questions, "my management group" refers to those people who report to the same manager that I do.

____21. I am kept informed by others in my management group about the goals and objectives of this organization (e.g., cost, quality, service, etc.).

____22. Work goals and priorities are understood and agreed to by members of my management group.

In the following items, "my work group" refers to those people who report to me.

____23. Employees in my work group receive detailed feedback regarding the organization's performance.

____24. If employees in work group disagree with the goals and priorities that have been established, they feel free to raise their concerns with supervision.

____25. Employees in other groups within Technical Operations plan and coordinate their activities effectively together with people in my work group.

____26. Employees in other groups, departments and divisions throughout the company act as if they share many of the same organizational goals that we do.

27. How useful has the CCC training been for others? (Circle one)

A Waste of Time	Slightly Useful	Somewhat Useful	Very Useful	Extremely Useful

28. How much has the CCC training changed your behavior on the job? (Circle one)

No Change	A Slight Change	A Moderate Change	A Large Change

29. What changes have you made as a result of the CCC training?

trying to better communicate

30. How will you further use the CCC training in the coming months?

Station meetings trying to get everybody's input

31. Looking back on it now, what aspects of the training were particularly good?

32. What do you think could be done to improve CCC training?

Year of Birth	5-13-51
Total years at	5
Sex (M or F)	M

CURRENT	DEPARTMENT
✓	Line Maintenance
	Base Maintenance
	Quality Control
	Planning
	Shop
	Material Servic.
	Engineering
	Other

Work Location - City ______________________

Job Title: Asst. Supervisor

Years in present position: 2

Past experience/training (# of years): ________

Military	
Trade School	2
College	
Other Airline	1

This completes the questionnaire
Thanks for your help.

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