Corrosion Detection Technologies

Sector Study

FINAL REPORT

The North American Technology and Industrial Base Organization

A Forum for Cooperation

NATIBO

Prepared by BDM Federal, Inc.

March 1998

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(NATIBO)

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FOREWORD

In February 1996, the North American Technology and Industrial Base Organization's (NATIBO) Steering Group commissioned a study of corrosion detection technologies and their implementation throughout North America's defense and commercial industrial bases.

This report provides the results of the study of corrosion detection technologies, which was conducted between March 1997 and March 1998. It gives a complete and thorough analysis of present and emerging corrosion detection technologies and the industry outlook for these technologies; highlights land, sea, and air applications of corrosion detection technologies; identifies corrosion detection proponents, equipment developers, and researchers in government, industry, and academia; and pinpoints barriers and impediments blocking the expansion of corrosion detection technologies into the industrial base. From this analysis, the report provides a roadmap of recommendations for government and/or industry action to eliminate barriers and address issues hindering more widespread use of these technologies.

This report was prepared for the NATIBO by BDM Federal, Inc. (BDM), 1501 BDM Way, McLean, VA 22102.

ACKNOWLEDGMENTS

The authors would like to express their appreciation to the many individuals whose cooperation in providing essential information made this effort possible. This study could not have been completed without the dedicated efforts of the North American Technology and Industrial Base Organization Corrosion Detection Technologies Working Group members (including Australia), listed here in alphabetical order:

Major Dennis Clark	Directorate Defense Research and Engineering
Ms. Cynthia Gonsalves	Directorate Defense Research and Engineering
Mr. Michael Ives	Embassy of Australia
Ms. Julie Jacks	Marine Corps Systems Command
Mr. Al Moore	Air Force Research Laboratory
Mr. Bryan Prosser	Marine Corps Systems Command
Mr. Dilip Punatar	Air Force Research Laboratory
Mr. Arthur D. Schatz	Embassy of Australia
Mr. Michael Slack	Canadian Department of National Defence
Mr. Rod White	U.S. Army Industrial Engineering Activity
Commander Spence Witten	Office of Naval Research

The authors would also like to express their appreciation to the many companies, government agencies, and academic institutions who supplied us with timely, important information necessary to conduct this assessment:

Aging Aircraft Nondestructive Inspection System Validation Center at Sandia

Aging Aircraft Office

Aerospace and Telecommunications Engineering Support Squadron

Air Canada

Air Force Office of Scientific Research

Air Vehicle Research Detachment

Aloha Airlines

Army Aviation Missile Command

Army Research Laboratory

Boeing

Carnegie Mellon Research Institute

Center for Aviation System Reliability at Iowa State University

College of William and Mary

Corpus Christi Army Depot

C. W. Pope & Associates

Defence Science and Technology Office

Diffracto

Engineering Testing and Research Services

FAA Airworthiness Center

FAA Hughes Technical Center

Jacksonville Naval Aviation Depot

Jet Propulsion Laboratory

Johns Hopkins University

Kennedy Space Center

Lawrence Berkeley Laboratory

Lawrence Livermore National Laboratory

Lewis Research Center

MARCORSYSCOM

McDonnell Douglas

Mid-Atlantic Regional Maintenance Facility

NASA Kennedy Space Center

NASA Langley Research Center

National Research Council Canada/Institute for Aerospace Research

Naval Air Systems Command

Naval Research Laboratory

Naval Surface Warfare Center

NIST

North Island, NAVAIR

Northwest Airlines

Northwestern University

NSWC-Carderock

Oklahoma City ALC

Office of Naval Research

Pearl Harbor Naval Shipyard

Penn State University

Picatinny Arsenal

PRI Instrumentation, Inc.

Qantas

Quality Engineering Test Establishment

RAAF Amberley

RAAF Richmond

RAAF Williamtown

Royal Australian Air Force

Royal Military College

Sacramento ALC

San Antonio ALC

Southwest Research Institute

TACOM

Thermal Wave Imaging, Inc.

Tektrend International

TPL, Inc.

UCLA

University of Dayton Research Institute

University of Pennsylvania

University of Washington

U.S. Army Pacific

U.S. Coast Guard

Utex Scientific Instruments

Warner Robins ALC

Wayne State University

Wright Laboratories/AFRL

ES.1. EXECUTIVE SUMMARY

ES.1.1 Introduction

The North American Technology and Industrial Base Organization (NATIBO) undertook this corrosion detection technologies study to assess the industrial base, maturity, level of use, utility, and viability of corrosion detection technologies for land, air and sea applications. From this analysis, conclusions regarding these technologies and their further commercialization are discussed. The recommendations addressing these conclusions are then provided for potential future action. Joining the NATIBO in this effort for the first time is the Australian Department of Defence.

ES.1.2 Technology Overview

ES.1.2.1 Corrosion Fundamentals

Corrosion of metal in military systems is a highly complex phenomenon and takes many different forms. The result of all corrosion is the loss of strength of the material and the structure. Understanding the various forms and combinations of corrosion is essential to determining the importance of each and to finding the most appropriate technologies for detection and characterization of corrosion.

The following table summarizes the types of corrosion that can damage structures and their characteristics.

Table ES-1. Corrosion Types and Characteristics.

Corrosion Type	Cause	Appearance	By-Product
Uniform Attack	Exposure to corrosive environment	Irregular roughening of the exposed surface	Scale, metallic salts
Pitting	Impurity or chemical discontinuity in the paint or protective coating	Localized pits or holes with cylindrical shape and hemispherical bottom	Rapid dissolution of the base metal
Inter-granular or Exfoliation	Presence of strong potential differences in grain or phase boundaries	Appears at the grain or phase boundaries as uniform damage	Produces scale type indications at smaller magnitude than stress corrosion
Crevice	Afflicts mechanical joints, such as coupled pipes or threaded connections. Triggered by local difference in environment composition (Oxygen concentration)	Localized damage in the form of scale and pitting	Same as scale and pitting

Corrosion Type	Cause	Appearance	By-Product
Filiform	High humidity around fasteners, skin joints or breaks in coating cause an electrolytic process	Fine, meandering, thread-like trenches that spread from the source	Similar to scale. Lifting of the coating.
Galvanic Corrosion	Corrosive condition that results from contact of different metals	Uniform damage, scale, surface fogging or tarnishing	Emission of mostly molecular hydrogen gas in a diffused form
Stress Corrosion Cracking	Mechanical tensile stresses combined with chemical susceptibility	Micro-macro-cracks located at shielded or concealed areas	Initially produces scale-type indications. Ultimately leads to cracking

The various processes of corrosion are affected by several factors. Among these are the type of material selected for the application, the heat treatment of the material, the environment of the application, and the presence of any contaminants in the material itself.

ES.1.2.2 Corrosion Detection Technology Areas

Corrosion detection is a subset of the larger fields of NonDestructive Evaluation (NDE) and NonDestructive Inspection (NDI). Many of the technologies of NDE/NDI lend themselves to the detection, characterization and quantification of corrosion damage. The following table summarizes the major advantages and disadvantages of the primary corrosion detection and characterization technologies.

Table ES-2. Summary of Corrosion Detection NDE/NDI Technologies.

Technology	Advantages	Disadvantages
Visual	• Relatively inexpensive • Large area coverage • Portability	• Highly subjective • Measurements not precise • Limited to surface inspection • Labor intensive
Enhanced Visual	• Large area coverage • Very fast • Very sensitive to lap joint corrosion • Multi-layer	• Quantification difficult • Subjective - requires experience • Requires surface preparation
Eddy Current	• Relatively inexpensive • Good resolution	• Low throughput • Interpretation of output

	• Multiple layer capability • Portability	• Operator training • Human factors (tedium)

Technology	Advantages	Disadvantages
Ultrasonic	• Good resolution • Can detect material loss and thickness	• Single-sided • Requires couplant • Cannot assess multiple layers • Low throughput
Radiography	• Best resolution (~1%) • Image interpretation	• Expensive • Radiation safety • Bulky equipment
Thermography	• Large area scan • Relatively high throughput • "Macro view" of structures	• Complex equipment • Layered structures are a problem • Precision of measurements
Robotics and Automation	• Potential productivity improvements	• Quality assurance • Reliability

The study team encountered a great variety of technologies in various stages of maturity. These technologies are being pursued in university research labs, industry R&D programs and government laboratories. Table ES-3 below summarizes the observed trends in the directions that the various technologies seem to be headed, based on the research and site visits performed in the generation of this sector study.

Table ES-3. Corrosion Detection Technology R&D Trends.

Technology	Observed Trend
Enhanced Visual	• Quantification of corrosion • Automation of image interpretation • Film highlighters for temporary surface modification • Scanner-based systems
Eddy Current	• More sophisticated signal and data processing (pulsed eddy current, C-scan imaging) • More sophisticated sensors (multi-frequency)
Ultrasonic	• More efficient scanning methods (dripless bubbler, gantrys, etc.)

	• Dry couplants (including laser stimulation) • Air coupled ultrasonics
Radiography	• Single-sided methods (backscatter) • Three-dimensional image processing (computed tomography)
Technology	**Observed Trend**
Thermography	• Time domain analysis (thermal wave imaging) • Multi-spectral (dual-band infrared) • Three-dimensional image processing (computed tomography)
Robotics and Automation	• Attached computer-controlled positioning mechanisms • Gantrys (multi-axis) • Crawlers (including vertical and inverted surfaces)
Data fusion	• Image processing (color coding, three dimensional, etc.) • Image correlation (C-scan, etc.) • Multi-mode NDI
Sensor fusion	• Currently only attempted within a single technology (e.g., eddy current, infrared) • No observation of research into combining two different sensors into a single probe for simultaneous measurements

We note that it is also very important to know that corrosion does not exist. If deep corrosion could be detected reliably and efficiently, the substantial costs associated with teardown inspections would be dramatically reduced. Maintenance plans typically call for teardown of certain structure to determine their condition. If an NDI method could accurately determine the level of corrosion, including the probability that there is no corrosion present, then the huge costs asssociated with teardowns could be avoided. This would support the concept of condition based maintenance by providing an accurate assessment of the condition of the system in question.

ES.1.3 Technology Applications

The areas where corrosion occurs, the materials in which it occurs, and the conditions under which it occurs all combine to make the inspection for and detection of corrosion a very difficult matter. All defense systems experience some sort of corrosion and there are certain known problem areas for land, air and sea applications. The typical process of finding and identifying corrosion begins with visual inspection. Clearly, any damage that can be observed by visual means will require closer inspection. Field inspection by other means usually entails eddy current and/or ultrasonic inspection. These types of inspections can generally be accomplished during routine maintenance without impacting operational availability. If additional inspection is determined to be necessary, it is normally done by specialists under controlled conditions, such as in a protected space or in an NDI laboratory.

ES.1.3.1 Corrosion Costs

Combined, the defense establishments of the three NATIBO sponsor countries - the U.S., Canada, and Australia - expend on the order of $2.1 Billion per year on corrosion related activities and equipment. These costs could be reduced with better NDE/NDI and corrosion detection technology, and productivity improvements in the maintenance areas. The magnitude of these expenditures would make the area of corrosion detection, characterization, and prevention a tempting target for future R&D.

One interesting point that was uncovered during the costs analyses is that the cost per aircraft for most types, and especially for large aircraft, has increased dramatically in the past seven years. The general trend, as would be expected, is that as aircraft age, the relative cost of maintenance and repair attributable to corrosion increases significantly.

ES.1.3.2 Corrosion Detection Technologies R&D and Application Activities

There are a number of different research and development activities ongoing in the field of corrosion detection technologies. A major thrust of the research being conducted is for detecting hidden corrosion in aircraft. The military is considered the primary corrosion detection technology driver. This is due in part to the fact that military systems typically are fielded longer, have higher cycle rates and operate in more corrosive environments than commercial systems. And with the continual decline in defense spending, the service life for defense systems will be extended even longer with a consequent focus on reducing maintenance costs for these existing systems.

As systems age, corrosion becomes one of the largest cost drivers in life cycle costs of weapon systems. Technology has been identified as one of the primary means of reducing the impact of corrosion on weapon systems. Throughout the military, corrosion is regarded as less a safety or technical issue but rather more of an economic issue. This is because the corrosion problems encountered by the military in their defense systems has been detected and repaired before it could become a safety problem. Currently, corrosion prevention is a higher priority within the military sector. The DoD S&T community is researching a number of different technologies to achieve corrosion reduction in defense systems.

Within the United States, the USAF is considered to have the largest corrosion detection technology development program among the three Services. The Navy has the largest monetary investment in corrosion research. The Navy is also considered to have the best corrosion maintenance and training practices. The DoD, NASA, and FAA have all established Aging Aircraft Programs to address such key problems as corrosion prevention and detection.

The Canadian Department of National Defence (DND) has several different departments and laboratories researching corrosion detection and corrosion prevention technologies. These groups are extremely effective in coordinating their research activities. A predominant focus of their research is on corrosion prevention and detection in aircraft. The AVRD/E Structures and Materials Group oversees R&D efforts in corrosion prevention and detection.

The major Australian DoD research arm involved in studying corrosion detection technologies is the Defence Science and Technology Office. The Office has a number of divisions addressing different corrosion issues and technologies to employ to detect and correct corrosion. There is a high level of coordination between these divisions. The main focus of their work is on aging aircraft as well.

ES.1.3.3 Corrosion Detection Technology Industry Demographics

Corrosion detection is one small niche market of the NDE/NDT industry. NDE/NDT equipment suppliers and service providers are not dependent upon the corrosion detection market for their livelihood. In fact, the NDE/NDT end user industries run the gamut, including defense aerospace, commercial aerospace, automotive, shipbuilding, chemical/petrochemical, construction infrastructure, electronics/electrical, energy (utilities), ordnance, and railroad.

The industry outlook for each of these technologies varies as does the industrial base supporting development of them. However, the NDE/NDT equipment suppliers are very amenable to custom adapting their equipment for specific applications for a fee.

The industrial base for visual, ultrasonic, and eddy current equipment is relatively stable.

The base for film-based radiography equipment has been dealt some setbacks in recent years as film use is on the decline with the emergence of real-time radiography, military cutbacks, and user concern with environmental impacts of film processing. The number of major radiographic film suppliers has decreased from four to three, with competition fierce among those remaining fighting for market share in an ever shrinking market.

Non-film based radiography suppliers market is in a state of flux. The market for radioscopy systems has declined due to military cutbacks. However, in response to this, suppliers have branched out to other commercial markets such as the automotive and the electronics industries to shore up their marketplace stance. And, with the development of portable radioscopic systems, new uses for this technology have opened up, such as in-field inspections of pipelines and aircraft.

The number of thermographic equipment and service providers is expanding from a handful to a larger number as the technology matures.

ES.1.4 CONCLUSIONS

ES.1.4.1 Facilitators

ES.1.4.1.1 Heightened Awareness

Due to the 1988 Aloha Airlines incident and the Military Forces' need to extend the service life of military systems three to four times their original design life, there is heightened awareness to the issue of corrosion and how it is a key contributor to system failures and a driving factor in terms of safety, downtime and costs. This need has been underscored by shrinking defense budgets, reduced procurements of new equipment, and increased reliance on modifications and upgrades to current systems.

ES.1.4.1.2 Established Working Groups

There are a number of established associations and working groups addressing the issue of corrosion, both within North America and internationally. The U.S., Canadian and Australian Governments also coordinate on their research in the field of corrosion detection technologies via the Corrosion Sub-Panel of the Technology Panel for Advanced Materials (part of Project Reliance).

ES.1.4.1.3 New Emphasis on Cost Effectiveness/Condition Based Maintenance

As a cost savings strategy and to eliminate the need for unnecessary maintenance, the Services are moving away from routine maintenance where components are replaced based upon length of time in service rather then real need. They are instituting programs where components are replaced based on their condition rather than to conform to a given time-in-service. This move to condition based maintenance will provide incentives to employ newer, more efficient corrosion detection techniques so that personnel will be better able to pinpoint the extent of their corrosion problems and its effect on the structural integrity of the system.

ES.1.4.2 Barriers

ES.1.4.2.1 General Barriers

ES.1.4.2.1.1 Data Not Readily Available

While collecting data for this study, we discovered that recently published NDE/NDT and corrosion detection reports are not showing up in DTIC, Dialog and other literature searches. Most of the publications that are in these databases are dated. Also, in trying to gain data from the depot/field level in regard to maintenance and failure analysis and the role of corrosion in the need to repair and replace parts, it became apparent that this type of information is not easily obtainable and, hence, is not given the visibility it needs at different levels to ensure that these recurring corrosion problems are effectively communicated and that procedures are put in place to rectify the situation. This was true also in the case of trying to quantify the cost of corrosion to defense systems. There is no uniform equation or standard economic model developed of the elements for determining the corrosion costs (though Warner Robins has released a 1998 report that breaks these elements down for aircraft). In a recent development, Tinker Air Force Base has initiated (late 1997) a project to establish an Aging Aircraft database.

ES.1.4.2.1.2 Research is Dispersed

There are a number of different research organizations conducting studies in the area of corrosion detection technologies. However, these groups are widely dispersed within DoD, DND, and the Australian DoD, reducing the visibility of the work being performed. Until recently, there was not a great deal of coordination in the U.S. between these different groups, especially outside of their respective Services, though more coordination has been initiated between these groups as of late. The Canadian and Australian organizations are more effective in communicating their research results within their countries; however, all three countries could benefit by increased coordination and sharing of findings between their research communities. And, there appears to be a disconnect between the operators and the R&D community. The R&D community is focusing on 6.1 and 6.2 research whereas the operators are conducting program specific research, and there does not seem to be effective communication occurring between the different groups.

ES.1.4.2.2 TECHNOLOGY BARRIERS

ES.1.4.2.2.1 Need for Newer Techniques Not Widely Recognized

The general impression that was formed through the numerous site visits conducted by the research team was that most users are satisfied with current techniques. Commercial users are wont to invest in additional corrosion detection technology that cannot be clearly justified in economic terms. Overall, they are satisfied that current technologies and techniques have served to prevent catastrophic losses. They are not informed as to the potential for reduced maintenance and repair costs that could be realized through improved corrosion detection technologies and techniques. There is agreement that the direct and indirect costs of corrosion are substantial; there is not agreement that these costs can be substantially reduced through further investment in corrosion detection and quantification technologies and tools. This dichotomy is best described as a "cost-benefit" question typical of the application of new technologies to existing problems. Particularly in the commercial arena, there is a sense that improved corrosion detection technologies would lead to additional and, in many cases, unneeded maintenance actions.

ES.1.4.2.2.2 NDE/NDT Technologies Developed for Applications Other Than Corrosion

The first concern of structural and materials engineering has been the detection and characterization of defects that can be adequately modeled and therefore predicted; i.e., cracks. NDE/NDT technologies have evolved to support the science of fracture mechanics, a discipline that is now highly developed and quite reliable in predicting the life of complex structures in known cyclic loading environments. These technologies, notably eddy current and ultrasonic, have proven useful for detecting and characterizing the material loss caused by corrosion. However, this is after the fact. The difficulty, and near impossibility, of predicting corrosion has pointed the work in detection technologies more toward detection of cracks than detection of material loss due to corrosion. The fact that corrosion is caused by many interacting processes contributes to this situation.

ES.1.4.2.2.3 Efficiency/Reliability of Newer Techniques and Cost/Benefits Not Well Established

The transition of a new technology from laboratory to field application is difficult. The government has been able to invest in some of the more sophisticated technologies (such as neutron radiography) that would be beyond the reach of commercial enterprises, airlines for example. Typically, a new technology that has been developed in a laboratory is commercialized by a small company, often a start-up. Basically, the marketplace determines the success or failure of a particular technology through customer determination of the cost-effectiveness of each new offering. Without some history that would support improved cost-effectiveness, a new technology or technique faces a large hurdle to implementation on a wide basis.

ES.1.4.2.2.4 Safety Concerns About Radiography Techniques

Although radiography is perhaps the most precise of the corrosion detection, and especially corrosion quantification, technologies, it presents the most serious hazard to the users. Indeed, in many jurisdictions radiographic facilities and operators are required to be licensed. Field operation of x-ray equipment requires that personnel be kept at some distance from the radiation sources. The emphasis on worker safety and concerns for liability judgments serve to impede the wider implementation of radiographic techniques.

ES.1.4.2.2.5 Thermography Perceived as Not Effective or Reliable

Thermography depends on operator interpretation of how an image of the structure in question differs from an image of a perfect or, at least, acceptable, structure. Thus, for every image produced, there must be a means to compare that image against that of a similar undamaged structure. Combined with the fact that thermographic images are somewhat "fuzzy" compared to other imaging techniques (visual, radiographic, etc.), many users remain skeptical of the precision and reliability of thermography as a corrosion detection technology. This is due to the fact that thermographic images are captured by IR cameras that are made up of an array of detectors, each detector contributing one pixel to the overall picture. Thus, IR cameras have much lower resolution than visual photographic processes (in much the same way that a photograph has much better resolution than a television image).

ES.1.4.2.2.6 Human Factors Limitations

Much of the work in inspecting for corrosion is repetitive and, in a word, tedious. Take into account that much of the work is done in awkward locations and sometimes under adverse environmental conditions (darkness, cold, etc.) Added together, the problem of inspection for corrosion goes well beyond that of just the technology of the sensing device and the processing of the information. It must include an array of human factors that will limit the overall effectiveness of the inspection process.

ES.1.4.2.3 Policy/Fiscal Barriers

ES.1.4.2.3.1 Cost of Corrosion Difficult to Calculate

Determining the costs of corrosion in the life cycle of a system is difficult to calculate. There currently is no baseline for this type of measurement and no good cost data at present. Hence, the costs of corrosion are not considered upfront in the acquisition cycle since no benchmark for measuring the impact of corrosion has been established. In addition, an effective cost/benefit analysis of the cost savings generated by implementing a corrosion detection technology is difficult to quantify.

ES.1.4.2.3.2 Commercial Airlines/Military Have No Economic Incentive to Improve Probability of Detecting More Corrosion

In commercial operations, there are cases where original equipment manufacturers have specified that when corrosion is determined to be less than 10% loss per layer, the operator has the choice of repairing the damaged area immediately or deferring the repair until the loss reaches 10%. However, the second option requires that the corroded area be re-inspected periodically. This is a heavy disincentive to the deployment of systems capable of detecting corrosion below 10% if a system capable of detection of 10% is defined to be adequate. Correcting corrosion damage at short intervals is inefficient, even though the immediate maintenance action may prevent larger repairs later. Operators typically want to perform all corrosion repairs during a single downtime to minimize overall downtime. This leads operators to defer corrective actions until the greater 10% material loss is detected.

Perhaps the most attractive economic incentive to the commercial airlines would be improving the productivity of the inspection process, thereby reducing the cost of maintenance, assuming that that can be done without compromising the safety or the service life of the aircraft. Economic incentives would surface if more developments were to occur in the area of condition based models where they could use the knowledge and exert control over how a corroded component is repaired and treated and tracked (such as what is presently used for fatigue and crack growth analysis), rather than simply removing all corrosion in all cases, which can end up damaging the structure even more. In other words, corrosion models are needed to determine the consequence of repairing it or treating it, or leaving it alone to make better informed decisions. (The models would take the effects of the corrosion damage on the fatigue life of the aircraft, and require accurate quantitative NDT input).

With regards to the military, employing new technologies cost money and, as with the airlines, this cost must be weighed against the return on investment to the facility. Without quantitative cost data to support a decision to invest in new technologies, most of the actual users would not incur such an expense at the depot level.

ES.1.4.2.3.3 Cumbersome, Lengthy Process for Emerging Techniques to Gain Wide Acceptance/FAA-OEM Approval

Currently, Service Bulletins are developed by the Original Equipment Manufacturers (OEMs) to deal with specific maintenance problems. The FAA may issue Airworthiness Directives (ADs) to deal with problems of a more urgent nature. Service Bulletins receive FAA approval before issuance. Airline maintenance operations may implement the Service Bulletin through an Alternate Means of Compliance (AMC). While the AMC is valid for the developing airline, it is not useable by another maintenance organization. In their quest to control costs, airlines seek lower cost alternatives to mandated inspection and repair requirements. The approval process for an AMC is lengthy and expensive. Thus, any new technology that has promise to improve the inspection process and the productivity of the maintenance operation faces a not inconsequential approval cycle before it is generally accepted in the customer community.

ES.1.4.2.3.4 Increased Training Requirements for Technicians to Use Different Technologies

Every different corrosion detection technology will entail different training requirements. Eddy current and ultrasonic sensors produce displays that require a high degree of sophistication to properly interpret. Improved processing of newer techniques, such as stepped pulsed eddy current, provide c-scan images that are much more intuitive but still require expert interpretation, especially in determining when a particular threshold has been exceeded and some expensive repair process is required. The range of technologies also expands the knowledge required to interpret the results. Thus, for a technician to be considered fully qualified in all areas necessary to perform a complete corrosion inspection, many more skills are required than before. Coupled with this is the fact that the number of trained NDT inspectors is dwindling due to base closures and consolidations and turnover at the maintenance level. Hence, the Services are experiencing a loss of corporate memory through retirement of key personnel.

ES.1.5 RECOMMENDATIONS

ES.1.5.1 Request the Corrosion Sub-Panel of TPAM Perform Added Coordination Activities

To ensure the widespread dissemination of published reports on corrosion and that information regarding corrosion detection techniques, advances, and implementation are effectively coordinated throughout the NDE/NDI community, the Corrosion Sub-Panel of TPAM should be approached about taking on the responsibility of:

- Coordinating and promoting interaction between the Services and identifying common problems
- Establishing a central repository of reports and other corrosion related information
- Improving report distribution
- Pooling information on system failures/corrosion problem areas
- Establishing a Point of Contact database of technology experts (placed online and updated annually) so that timely consultation on specific corrosion related issues can be achieved.

If buy-in to these coordination activities is achieved, perhaps this panel could enlist the aid of the NTIAC to support these efforts.

ES.1.5.2 Appoint Recognized Champions to Push for Corrosion Agenda and New/Higher Fidelity Techniques

To ensure that the entirety of system life cycle costs are considered in the procurement process, identify and enlist military champions to “market” the savings to Programs/Program Managers from 1) building into the design of the system protective measures to protect against corrosion and 2) including processes for detecting corrosion problems early in a system’s life cycle. Additionally, the logistics community should be made aware of the importance of corrosion prevention and corrosion control in planning for the life cycle support of systems and in developing R&D requirements for extending the life cycle of weapon systems. These champions could emphasize the importance of considering corrosion costs as an independent variable for determining life cycle costs and push for establishing benchmarks for measuring the impact of corrosion on the service life of a system. In order to better define these costs, the champions could recommend that economic models be developed that address the costs of corrosion in the life cycle of the system and address the savings realized by planning for corrosion detection upfront and detecting corrosion early on in the system’s maintenance life. In addition, these champions could strive to establish an integrated approach to tackling corrosion issues, ensuring that Integrated Product Teams consisting of structural engineers, NDE/NDI personnel and researchers address these issues in a joint fashion.

ES.1.5.3 Target Insertion/Demonstration Program

In order to demonstrate the benefits derived from employing a certain corrosion detection technology(s), a widely applicable, high payoff, dual use insertion/demonstration program would be an ideal mechanism. A candidate for an insertion/demonstration program might be multi-sensor and multiple data fusion, incorporating automation/robotics as deemed feasible. These suggestions support the findings of the National Research Council, and have met with widespread backing from the members of the NDE/NDI community. Industry and government input would need to be solicited to develop a DoD/DND/Australian-specific program that involves the fusing of as many NDE techniques as possible. Researchers, developers and end-users would participate in the identification and selection process.

ES.1.5.4 Streamline Process for Inserting Newer Techniques into OEM Maintenance Procedures

The feedback from the research community through the OEMs back to the users and operators of the systems should be shortened. It should be possible to incentivize this process to reward improvements that can enhance system reliability and extend the life of a system while reducing the cost of inspection and repair. The use of electronic updates to inspection and repair manuals can reduce the administrative delay.

ES.1.5.5 Increase Collaboration Between the Military Departments and University NDE/NDT Departments on Training

Training is usually an afterthought following the development of new inspection technologies and tools. It should be possible to procure integrated training along with any new inspection tools. Such training would be essential until each using organization was able to develop a core of expertise and thereby be able to conduct their own training programs.

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1. INTRODUCTION

1.1 Background

The North American Technology and Industrial Base Organization (NATIBO) is chartered to facilitate cooperative technology and industrial base planning and program development among the U.S. military Services and Canada. To further this mission, the NATIBO has spearheaded an effort to address the challenges of advancing and maintaining technological superiority in light of reduced government research and development funding. The criteria used for selecting technologies to study through this program are:

- The candidate is a key technology area of high interest
- There is potential for both military and commercial applications
- Development and/or production exists in both the U.S. and Canada
- There is a good window of opportunity for investment and application.

Through this initiative, common areas of interest are assessed jointly, allowing participating organizations to capture the information they need cost effectively, avoid duplication of effort, and capitalize on scarce resources.

Through a lengthy selection process, the area of corrosion detection technologies was chosen as the technology area to address through the NATIBO's technology base enhancement program. Joining the NATIBO in this effort for the first time is the Australian Department of Defence. In the course of high level, trilateral discussions, the Australian Government determined that this technology area of study was of keen interest to them as well and decided to become involved in this NATIBO study.

Corrosion involves a number of issues which need to be taken under consideration when addressing the seriousness of the corrosion problem throughout the U.S. Department of Defense, the Canadian Department of National Defence, and the Australian Department of Defence. Corrosion is a force structure issue. Every year, some number of weapons systems (aircraft, vehicles, etc.) are retired based on being too expensive to repair. These assets are not replaced on a one-for-one basis, thus the overall force structure is reduced, for a net result of a loss of capability. As systems age, their associated maintenance and repair needs increase. For example, the depot overhaul time for KC-135 aircraft has nearly doubled in recent years. This means that each asset will be out of the active (combat coded) fleet for longer periods, reducing the number of assets available for operations at any given time.

Corrosion is an economic issue. It costs the three Governments millions of dollars per year to manage corrosion. Corrosion is, in many instances, difficult to detect and difficult to repair. The expected service life of an older system is harder to predict when corrosion damage has been incurred. Increased expenses for inspection, maintenance and repair inevitably mean fewer resources available for operations, training and contingencies. Furthermore, some of the most accurate methods for detection and characterization of corrosion are also very expensive.

Corrosion is a technical issue. The causes and effect of corrosion are not well understood. There are many forms and combinations of corrosion just as there are many different means to detect and characterize corrosion. No single means of detection is either ideal or even suitable for all forms of corrosion. As in so many other areas, the area of corrosion detection is limited by a probability of detection and by the characterization and accuracy of the results. Thus corrosion is a highly complex technical issue. Even so, it is often treated as a subset of nondestructive testing and evaluation.

Corrosion is a long-term issue. Newer systems are designed and built using better materials, adhesives, coatings, etc. They incorporate many of the lessons learned from building, operating and maintaining older systems. The corrosion problem occurs slowly and is obviously most advanced in older systems. The maintenance requirements of older systems increase with the age of the system, though this increase is not entirely predictable.

Corrosion is an education and training issue. Corrosion involves many different disciplines, including mechanics, strength of materials, electrical engineering, chemistry, and others. Corrosion is often treated as a technician-level problem in the field. While this is not a glamorous career field, it typically takes on the order of ten years experience to become considered highly qualified in the field. The typical corrosion inspector, if he does his job well, will likely generate only bad news, i.e., the need for more than planned maintenance and repair, and therefore higher than planned expenses. The education and training of corrosion inspectors tends to be ad hoc rather than defined by specific curricula and career progression ladders.

Corrosion is a safety issue. This study is not intended to exhaustively examine the safety impact of corrosion, but it cannot be ignored. Within previous case studies, there is evidence to suggest that corrosion is a primary cause factor and a contributing cause factor in a substantial number of safety incidents and accidents.

In addition to these considerations, the DoD, DND, and Australian corrosion technology infrastructure is being affected by a number of factors that are having an impact on resources to combat corrosion and extend the life of existing systems. These include:

- Possible reduction of current budget levels
- Loss of manpower through base closures and consolidations
- Loss of corporate memory through retirement of key personnel
- Turnover at the maintenance level
- Increased environmental restrictions.

1.2 Purpose

The purpose of this study is to assess the industrial base, maturity, level of use, utility, and viability of corrosion detection technologies for land, air and sea applications. Non-destructive evaluation/non-destructive inspection (NDE/NDI) equipment manufacturers have not been focused on developing corrosion detection technologies for military systems. Rather, they have concentrated on developing technologies to detect cracks in pipes in the electric, nuclear power and pipeline industries because these industries offer a higher payoff.

This report investigates corrosion detection technologies from technological, policy, financial, cultural, and effectiveness points of view and develops conclusions regarding the status of these technologies from each of these perspectives. Recommendations are presented regarding actions that the defense and industrial community might consider in response to these conclusions.

1.3 Objectives

This study identifies and assesses the maturity and applicability of corrosion detection technologies to solve the problem of detecting corrosion that is found in both the defense and commercial industry.

The objectives of this study are to:

- Conduct a complete and thorough analysis of present and emerging corrosion detection technologies
- Identify land, sea, and air applications of corrosion detection technologies
- Identify corrosion detection proponents, equipment developers and researchers in government, industry and academia
- Identify barriers and impediments blocking the expansion of corrosion detection technologies into the industrial base
- Develop recommendations for government and/or industry action to eliminate barriers and address issues.

This report explores the military and commercial applications of these technologies and the transfer of the technologies among government organizations and between government and private industry. Advantages and limitations of these technologies are discussed and compared. From this analysis, conclusions regarding these technologies and their further commercialization are discussed. The recommendations addressing these conclusions are then provided for potential future action.

1.4 Scope

This study encompasses the collection and analysis of technical, business, and policy information related to corrosion detection technology research efforts and industrial capabilities in the U.S., Canada and Australia. The corrosion detection technologies investigated and analyzed in this report are:

- Visual - used for quick inspection of welds and components; can be used with television camera systems and enhanced by using low power magnifying glasses
- Enhanced Visual - optical inspection using CCD cameras, special optical and illumination systems and sometimes scanners. Can generate digital output for use with other systems.
- Radiography - technique using x-rays, neutrons, or gamma rays to image material flaws on film or magnetic media
- Ultrasonics- technology that uses sound waves to detect flaws or measure material thickness
- Eddy current - an electromagnetic technique used on conductive materials
- Thermography - infrared imaging to identify abnormal thermal characteristics.

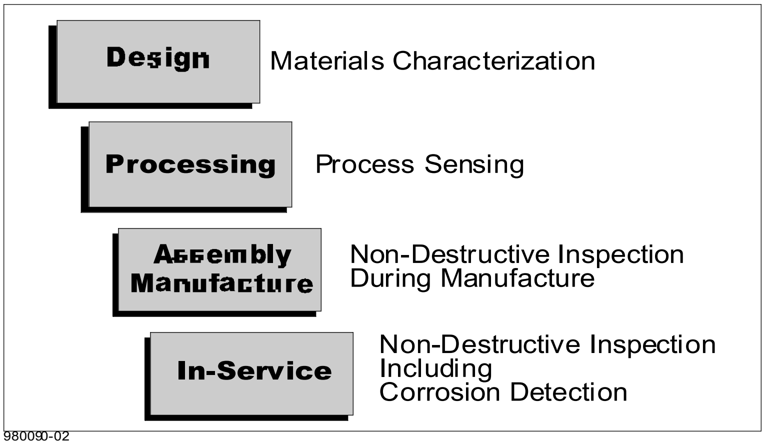

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Figure 1-2. Corrosion Detection Technology Application.

Within each of these technology areas, emerging technological advances are explored (see Figure 1-1 below).

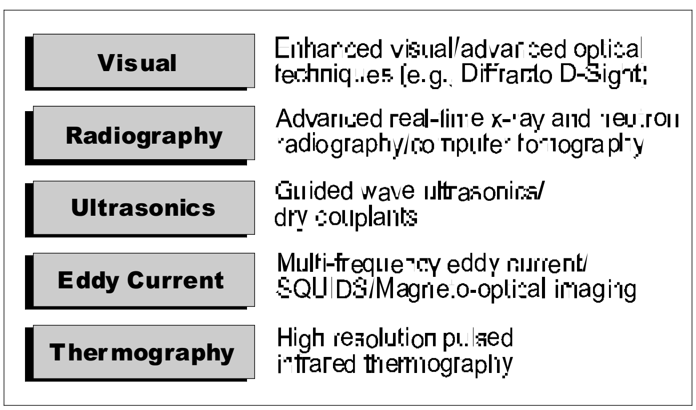

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Figure 1-1. Technology Advancements.

Other technologies that are addressed include liquid penetrant, microwave NDE, acoustic emission, electrochemical sensors, embedded fiber-optic sensors, laser speckle and laser moiré, galvanic thin film sensors, neural net and classifier development, and electrochemical impedance spectroscopy (EIS).

Though these technologies are used in a wide range of applications throughout the course of manufacturing, this study is focused on NDI as it relates to corrosion detection of systems that are in service (see Figure 1-2 above).

1.5 Methodologies

The corrosion detection technology study required a clear, concise, and well-defined methodology to survey government, industry and academia effectively and compile military, commercial, political, marketplace and academic perspectives. The data collected and analyzed for this study were drawn from previously published reports, conference proceedings, journal articles, Internet home pages and other online sources, as well as from discussions with U.S., Canadian and Australian representatives from industry, government and academia. The methodology employed is depicted in Figure 1-3.

The study group's goal was to meet with a representative sample of corrosion detection technology researchers, equipment providers, end users, proponents and policy makers. Factors taken into consideration in selecting sites to visit included volume and business with the individual Services and with industry, industrial sector involved, market niche, state of the technology, applications, and new technology development. Site visits were conducted in six regional areas: U.S. West Coast, U.S. Midwest, U.S. Southwest, U.S. Northeast, Canada, and Australia.

When it was determined that an industry, university, or government site would not be visited, an extensive phone interview was conducted. Data collection guidelines were developed and used to facilitate obtaining data from all points of contact either through telephone interviews and/or site visits.

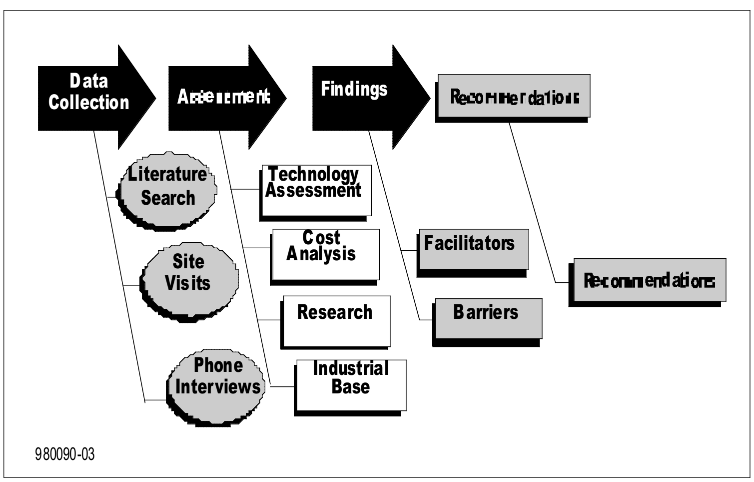

Figure 1-3. Study Methodology.

Data collected from relevant documents, World Wide Web sites, site visits, and phone interviews were analyzed and incorporated into key sections of this report: technology overview, applications, corrosion costs, research activities, industry demographics, facilitators, barriers, and recommendations. This report functioned as a working document throughout the data collection and analysis phases of this study.

1.6 Report Structure

Section 2 of this report discusses the fundamentals of corrosion, defines the different types of corrosion, and factors affecting corrosion. It describes the different technologies, the types of techniques employed in the technology area, and the advantages and disadvantages of the technologies.

Section 3 provides an overview of current and potential applications of corrosion detection technologies. Both military and commercial land, air and sea applications are considered.

Section 4 addresses the issue of corrosion costs and demonstrates how corrosion is an increasingly expensive problem.

Section 5 presents an overview of the government, commercial and academic institutions currently active in the corrosion detection technologies field.

Section 6 highlights the industry demographics of the corrosion detection technologies arena, and projects the industry outlook for each technology.

Section 7 addresses facilitators enabling advancement of current and emerging corrosion detection technologies.

Section 8 then addresses barriers affecting the widespread adoption of these technologies.

Section 9 provides relevant recommendations made by the National Research Council in a related study.

Section 10 provides specific recommendations for capitalizing on the facilitators and addressing the barriers discussed in the report.

Helpful appendices are also provided to assist in the reading of the report.

2. Corrosion Technology

This section provides an overview of the physical phenomena of corrosion, a description of its various forms and complexities, and an overview of the prominent technologies employed and under development to detect and characterize corrosion.

2.1 Corrosion Fundamentals

Corrosion is a physical phenomenon that results in the loss of structural material and the generation of the products of corrosion, i.e., scale and metallic salts. The presence of the products of corrosion are one of the symptoms of the process. The result is the reduction of structural strength and therefore the useful life of a system. In general, corrosion is time related whereas fatigue and crack growth are cycle related. However, both produce the same result, a loss of physical strength of the structure of the system in question.

Both structural fatigue and corrosion give rise to the entire Non Destructive Evaluation and Inspection (NDE/NDI) industry. This industry and its research activities in industry, academia and government focus on technologies that are useful for detection of structural flaws in the form of cracks and corrosion, both of which reduce the inherent strength of the structure.

Over the past 30 years or so, great progress has been made in the modeling and understanding of crack growth. This is exhibited in the relatively new field of science known as fracture mechanics. It is now possible to predict with high accuracy and assurance the growth of cracks in various structural materials. This science is now the basis for calculating the useful life of systems, such as aircraft, exposed to a predictable stress history.

Similar progress in the modeling and understanding of corrosion has not been made. This is at least partially due to the many forms and combinations of corrosion, each with different outcomes. Prediction of corrosion damage now relies heavily on periodic inspection, often requiring disassembly of the structure to find and measure the effects of the many forms of corrosion.

Research in NDE/NDI for corrosion is now being conducted by many organizations for many different applications. Research is being sponsored under programs such as the FAA's Aging Aircraft program. Much of the basic research is still at the academic stage with few transitions to commercial application. Most researchers agree that there is no single "silver bullet" that will enable affordable, large improvements in corrosion related NDE/NDI technology in the near term.

Corrosion itself is insidious. It occurs more or less continuously and tends to seek out areas that are not amenable to inspection, washing or periodic re-coating. It occurs in areas that are hidden from direct view and in areas that are difficult to predict. It is frequently masked by structural features.

Corrosion of primary structure, the load bearing structure subject to the highest stresses and therefore accelerated stress corrosion, can be masked by secondary structure. For example, corrosion in an aircraft's wing spar can be hidden by skin, fillets and fuel tanks that cover the affected area of the spar. Furthermore, repair of corrosion in many cases tends to hasten its recurrence and its subsequent rate of propagation. Finally, because corrosion is a multi-disciplinary phenomenon and its determination is only part science and somewhat subjective, the education and training of corrosion specialists is a particular challenge.

2.1.1 Definition of Corrosion

Corrosion is typically defined as the degradation of a material, usually a metal, because of a reaction with its environment. The reactions by which corrosion damage occurs are varied, but can be generally classified as electrochemical, chemical, or physical. Corrosion is especially important because of its insidious nature, occurring within materials and structures in places and timeframes that are difficult to predict and locate. Corrosion is the destruction of metals by chemicals or electrochemical action and is caused by a chemical reaction between metals (serving as electrodes) and an aqueous solution containing different ions and/or dissolved oxygen, acting as the electrolyte. Corrosion is to be distinguished from erosion, which is primarily destruction by mechanical action, such as occurs in high pressure, high flow rate tubing.

2.1.2 Types of Corrosion

Degradation of material properties by corrosion, or corrosion damage, can take many forms. There have been several different organizations of this information, each useful from a particular viewpoint.

For example, the mechanisms of corrosion can be divided into time dependent, time related, and time independent categories. Other categorizations are useful. For the purposes of this report, we shall consider the types of corrosion listed and described in the following sections. The wide variety of forms of corrosion gives emphasis to the difficulty of detecting all forms with equal assurance and accuracy. In general, detection of corrosion is concerned with measuring the amount of material lost through the corrosion process. Such material loss is an indication of the residual strength of the material and therefore the remaining useful life of the structure in question.

The following descriptions of the various forms and types of corrosion and corrosive processes are those generally used by J. J. DeLuccia, Ph.D., former Senior Materials Engineer with the Naval Air Development Center and now a Professor at the University of Pennsylvania, as described in AIAA paper 91-0953.

2.1.2.1 General Corrosion or Uniform Attack

As its name implies, general corrosion attack causes the metal to be consumed uniformly over the entire surface that is wetted within the corrosive environment. When a metal experiences general corrosion, the anodes and cathodes on the surface continually switch their behavior (polarization) so that a relatively uniform consumption of the metal surface occurs with time. This type of corrosion is most easily treated, but it is not a particularly critical problem on aircraft where localized corrosion is a greater problem. General corrosion attack would be of greater concern where large areas are exposed without surface treatments or periodic cleaning. This occurs, for instance, on ships and trucks which have large surface areas vulnerable to surface damage and subsequent corrosion.

2.1.2.2 Pitting

Pitting is a form of corrosion that occurs locally and thus results in consumption of metal in a non-uniform fashion at a specific location. This localized attack, pitting, is more insidious and hence more dangerous than general corrosion. Unfortunately, most of the common metals used in defense system construction are susceptible to this type of corrosion. Aluminum alloys and stainless steels are prime examples of metals that will pit in the presence of certain reducing anions. The ubiquitous chloride ion falls into this category. The hydrolysis reaction that occurs in a pit produces a metal hydroxide and hydrochloric acid. The hydrochloric acid perpetuates the process, making pitting corrosion a difficult form to counter.

Pitting corrosion is common on aircraft, ship and land vehicle structures since age hardenable, high strength aluminum alloys and steels are particularly susceptible to this type of attack. The localized corrosion of pitting is itself deleterious. Additionally, the negative geometrical aspect of pits, acting as notches or cracks, can trigger more damage when stresses are superimposed on the part. This phenomenon will be further described in Sections 2.1.2.7 and 2.1.2.8.

2.1.2.3 Intergranular and Exfoliation Corrosion

All solid metals are crystalline in nature. All metallic structures therefore consist of a multitude of tiny crystals called grains. When corrosion occurs preferentially along the boundaries of these grains, the metal is said to experience intergranular corrosion. A large percentage of all aircraft structures consist of aluminum alloys that have been worked (rolled or pressed during forming) and hence exhibit an elongated grain structure. When intergranular corrosion occurs in an elongated grain structure, it is called exfoliation. The buildup of intergranular corrosion products along the elongated grains is exhibited as bulging or expansion of the material, caused by a buildup of the corrosion products within the material. This type of corrosion typically starts at a machined surface (such as a fastener hole) where the machining process exposes and slightly opens the inter-grain boundaries. Thus, this type of corrosion is typically discovered as a bulging or "pillowing" around rivets and fasteners used in aircraft, ships and land vehicles.

2.1.2.4 Crevice Corrosion

If a stagnant area in the form of a crevice or debris deposit occurs on the surface of a metal exposed to an aqueous environment, accelerated corrosion can be expected to occur within the crevice or debris deposit. The area within the crevice or under the deposit becomes a total anode (the electrode where active corrosion occurs). The areas immediately adjacent to the crevice or debris become the operative cathode. A classic example of crevice corrosion is that which occurs at lap joints that allow ingress of the environment. Much of the crevice corrosion observed on aircraft is a result of differences in oxygen concentration within the crevice and adjacent to it. Crevice corrosion as well as the previously defined pitting is further exacerbated by the stagnant corrosive products becoming more acidic with time. The same hydrolysis reaction described earlier occurs within a crevice.

It should be noted that bonded aircraft joints can experience bond material (usually epoxies) deterioration. When these bonding resins deteriorate, they become brittle and subject to moisture accumulation. Thus the presence of a deteriorated surface bond can act to retain moisture and lead to crevice corrosion of the joint. Even in the absence of resin bonding, fastened joints can experience crevice corrosion at the interface of the joined surfaces. This form of crevice corrosion can also cause surface bulging or "pillowing."

2.1.2.5 Filiform Corrosion

Filiform corrosion occurs under paint films in hot and humid environments. It may start as a corrosion pit at a paint defect or at an unpainted edge. Instead of the pit progressing deeply into the metal, it remains close to the surface and meanders about under the paint film or even under the cladding of some clad aluminum alloys. This form of corrosion is more prevalent in aircraft, vessels, and land vehicles operated in hot, wet conditions. The appearance of filiform corrosion, once the paint or surface film is removed, gives the visual impression of surface worm damage as sometimes occurs in wood products.

2.1.2.6 Galvanic (Dissimilar Metal) Corrosion

If two different metals are brought into contact in an electrolytic solution, the resulting system is the familiar galvanic cell. The metal nearer the top of the galvanic series (or galvanic scale) forms the anode; the other metal is the cathode. The electrical connection needed to complete the circuit is provided by the contact between the two metals. The rate of corrosion activity is governed by the relative positions of the metals in the galvanic series, the more widely separated metals corroding faster due to the greater difference in electrical potential between them.

As in all electrochemical corrosion processes, damage is observed as metal loss at the anode, accompanied by the formation of corrosion-product deposits on one or both surfaces. The rate of corrosion will be a function of the galvanic differential or separation on the galvanic scale. As an example, boats designed for operation in seawater typically employ sacrificial anodes (usually zinc, near the bottom of the galvanic series) to intentionally draw the corrosion process away from critical components, such as propellers and shafts made from more noble metals or alloys.

Another example of galvanic corrosion is in aircraft between the aluminum structure and steel fasteners. Aluminum, higher on the galvanic scale than steel, will corrode where the two metals are in contact. To prevent this, steel fasteners are cadmium plated to reduce the galvanic effect between steel and aluminum. Thus, the metals in contact are aluminum and cadmium, which are not subject to serious galvanic attack. Note that modern composites, such as graphites, may also form galvanic couples with adjacent dissimilar metals and materials leading to corrosion deterioration. The dissimilar metals and composite materials used in exposed equipment onboard ships and land vehicles will also exhibit galvanic corrosion.

2.1.2.7 Environmental Embrittlement and Stress Corrosion Cracking

It is well known that metals will corrode and lose strength faster in the presence of tensile stress and other environmental conditions. The phenomenon of a superimposed static tensile stress on a corroding metal is known as stress corrosion. The rapid deterioration of high strength aircraft alloys by stress corrosion, hydrogen embrittlement, and mercury embrittlement fall into this category of corrosion. This type of corrosion occurs by the combined and simultaneous action of corrosion and a static tensile stress. Neither stress nor corrosion acting separately would cause such damage.

Unfortunately, all of the high strength aerospace alloys, including aluminum, steel and titanium, are susceptible to this type of attack in such environments as fresh water, moist air, sea water and other non-specific mild environments. Certain alloys, particularly those of titanium, do not corrode or pit in fresh or salt water at ambient temperatures, so that smooth specimens of such alloys do not experience stress corrosion in these environments. Environmental embrittlement and stress corrosion cracking are found in aircraft, ships and land vehicles where the exposed structure is also under constant or cyclic stress.

2.1.2.8 Corrosion Fatigue

Whereas stress corrosion or environmental embrittlement requires an enduring tensile stress, metallic failure due to corrosion fatigue is caused by cyclic stressing in mildly corrosive environments. The speed of failure for corrosion fatigue is cyclic dependent and not directly dependent upon the time of exposure. In general, a metal can withstand an infinite number of stress cycles if the stress does not exceed a certain value, called the fatigue or endurance limit. If the same metal is subjected to alternating or cyclic stresses in a corrosive environment, fatigue cracking will occur much more readily, and a fatigue or endurance limit is no longer accurate.

Cyclic loading that leads to fatigue occurs in many ways on modern airframes. Some of these are: airborne maneuvers, vibrations (especially in helicopters), gust loadings, and cabin pressurization cycles.

2.1.2.9 Combined Mechanisms

Some time dependent mechanisms, such as pitting and exfoliation, can serve to initiate failures by stress corrosion and/or corrosion fatigue. For example, corrosion that begins as pitting on a helicopter blade can lead to stress corrosion at that point as the blade is loaded in flight. Cyclic loads, including vibrations, can accelerate the fatigue process, which can then lead to ultimate failure of the component.

2.1.2.10 Summary

Corrosion of metal in military systems is a highly complex phenomenon and takes many different forms. The result of all corrosion is the loss of strength of the material and the structure. Understanding the various forms and combinations of corrosion is essential to determining the importance of each and to finding the most appropriate technologies for detection and characterization of corrosion.

Table 2.1 summarizes the types of corrosion that can damage structures, and their characteristics.

2.1.3 Factors Affecting Corrosion

The various processes of corrosion are affected by several factors. Among these are the type of material selected for the application, the heat treatment of the material, the environment of the application, and the presence of any contaminants in the material itself.

2.1.3.1 Effect of Material Selection

A fundamental factor in corrosion is the susceptibility of the material itself. High-strength, heat-treatable aluminum alloys are susceptible to intergranular corrosion as well as to pitting and general attack. All magnesium alloys are highly susceptible to general and pitting attack when exposed to corrosive environments. Materials must be selected primarily on the basis of structural

Table 2-1. Corrosion Types and Characteristics.

Corrosion Type	Cause	Appearance	By-Product
Uniform Attack	Exposure to corrosive environment	Irregular roughening of the exposed surface	Scale, metallic salts
Pitting	Impurity or chemical discontinuity in the paint or protective coating	Localized pits or holes with cylindrical shape and hemispherical bottom	Rapid dissolution of the base metal
Inter-granular or Exfoliation	Presence of strong potential differences in grain or phase boundaries	Appears at the grain or phase boundaries as uniform damage	Produces scale type indications at smaller magnitude than stress corrosion
Crevice	Afflicts mechanical joints, such as coupled pipes or threaded connections. Triggered by local difference in environment composition (Oxygen concentration)	Localized damage in the form of scale and pitting	Same as scale and pitting. May induce stress due to expansion of the corrosion product. In lap splices, this is called “pillowing.”
Filiform	High humidity around fasteners, skin joints or breaks in coating cause an electrolytic process	Fine, meandering, thread-like trenches that spread from the source	Similar to scale. Lifting of the coating.
Galvanic Corrosion	Corrosive condition that results from contact of different metals	Uniform damage, scale, surface fogging or tarnishing	Emission of mostly molecular hydrogen gas in a diffused form
Stress Corrosion	Mechanical tensile stresses combined with chemical	Micro-macro-cracks located at shielded or	Initially produces scale-type indications

efficiency; therefore, corrosion resistance is at times a secondary consideration at the design level. Use of more corrosion resistant materials normally involves additional weight, which is considered to outweigh the cost of preventing corrosion by proper maintenance or by chemical surface treatments and finishes.

2.1.3.2 Effect of Heat Treatment

Heat treatment of the alloy is a vital factor in establishing resistance to corrosion and is a factor over which definite control is exercised. A rigid inspection procedure is maintained, for both the heat-treating processes and the facilities used, to ensure proper heat treatment. To make certain that replacement parts meet the heat-treating specifications, it is essential that parts be procured either directly from the manufacturer or from approved sources, and that heat-treatment processes be controlled at qualified repair facilities.

2.1.3.3 Effect of Environment

Exposure to salt water, moisture condensate, chemicals, and soil and dust in the atmosphere affect the degree of corrosion. The geographical flight routes and bases of operation will expose some airplanes to more corrosive conditions than others. The same is true of ships and land vehicle fleets. Ships operated in fresh water do not deteriorate as quickly as similar vessels operated in salt water. The truck fleets positioned in Hawaii and the Pacific are significantly more damaged by corrosion than those in Europe, for instance. Corrosion prevention and control requirements (and therefore detection equipment) will vary from one area to another.

2.1.3.4 Effect of Contamination

A corrosive action can result when a contaminating material comes into contact with a metal surface; the degree of corrosive action is determined by the composition of such contaminating materials and the length of time they remain in contact. The extent of corrosive attack can be minimized by frequent cleaning to remove contaminating deposits. In addition, anodic and chemical treatments as well as proper paint finishes should be maintained in clean and intact condition. The primary purpose of these coatings is to provide a barrier and temporarily to prevent the corrosive media from contacting the underlying metal, thereby allowing time for their removal by periodic washing

2.2 Corrosion Detection Technology Areas

This study will concentrate on five corrosion detection technology areas: 1) visual/optical, 2) electromagnetic eddy current, 3) acoustic ultrasonic, 4) radiographic, and 5) thermographic. These are the five most mature technology areas.

2.2.1 Visual

Visual inspection is the oldest and most common form of NDI used to inspect aircraft for corrosion. The physical principle behind visual inspection is that visible light is reflected from the surface of the part to the inspector's eyes. By observing the appearance of the part, the inspector can infer its condition. Visual inspection is a quick and economical method of detecting various types of defects before they cause failure. Its reliability depends upon the ability and experience of the inspector. The inspector must know how to search for critical flaws and how to recognize areas where failure could occur. The human eye is a very discerning instrument and, with training, the brain can interpret images much better than any automated device.

Optical devices are available to aid the naked eye in visual inspection and flaw detection. This equipment can be used to magnify defects that could not be seen by the unaided eye or to permit inspection of areas otherwise hidden from view.

Visual inspection is often conducted using a strong flashlight, a mirror mounted on a ball joint, and a magnifying aid. Magnifying aids range in power from 1.5X to 2,000X. Fields of view typically range from 3.5 to 0.006 inches with resolutions ranging from 0.002 to 0.000008 inches. A 10X magnifying glass is recommended for positive identification of suspected cracks or corrosion. Other inspection methods, such as eddy current, ultrasonic and others, can be used to verify questionable indications.

2.2.1.1 Techniques and Technologies

Borescopes: A borescope is a long, thin, rigid rod-like optical device that allows an inspector to see into inaccessible areas by transmitting an image from one end of the scope to the other. Certain structures, such as engines, are designed to accept the insertion of borescopes for the inspection of critical areas. A borescope can be thought of as a highly specialized periscope that can focus at extremely close distances.

A borescope works by forming an image of the viewing area with an objective lens. That image is transferred along the rod by a system of intermediate lenses. The image arrives at the ocular lens, which creates a viewable virtual image. The ocular can be focused for comfortable viewing. Borescopes typically range from 0.25 to 0.50 inches in diameter and can be as long as six feet. Borescopes often incorporate a light near the objective lens to illuminate the viewing area. Different borescopes are designed to provide direct, forward oblique, right angle and retrospective viewing of the area in question.

Fiberscopes: Fiberscopes are bundles of fiber optic cables that transmit light from end to end. They are similar to borescopes with the difference that they are flexible. They can be inserted into openings and curled into otherwise inaccessible areas. They also incorporate light sources for illumination of the subject area and devices for bending the tip in the desired direction. Like the borescope, fiberscope images are formed at an ocular or eyepiece.

Video imaging systems: Video imaging systems (or "videoscopes") consist of tiny charge coupled device (CCD) cameras at the end of a flexible probe. Borescopes, fiberscopes and even microscopes can be attached to video imaging systems. These systems consist of a camera to receive the image, processors, and a monitor to view the image. The image on the monitor can be enlarged or overlaid with measurement scales. Images can also be printed on paper or stored digitally to obtain a permanent record.

2.2.1.2 Advantages and Disadvantages

Surface corrosion, exfoliation, pitting and intergranular corrosion can be detected visually when proper access to the inspection area is obtained. Obviously, visual inspection can only detect surface anomalies. However, some internal corrosion processes do exhibit surface indications, such as pillowing or flaking. The primary advantages of visual inspection include its ability to be performed quickly and inexpensively without the need for complicated equipment. Modest training is required, and typically no special safety precautions need to be taken. Where necessary, permanent records can be obtained by photography or digital imaging and stored.

The disadvantage of visual inspection is that the surface to be inspected must be relatively clean and accessible to either the naked eye or to an optical aid such as a borescope. Typically, visual inspection lacks the sensitivity of other surface NDI methods. Further, visual methods are qualitative and do not provide quantitative assessments of either material loss or residual strength. Additionally, visual inspection techniques can be man-hour intensive and monotonous, leading to errors.

2.2.1.3 Current Research

Advanced visual inspection methods include moiré and structured-light-based optical profilometry, Diffracto Sight (a patented process developed by Diffracto, Ltd. of Canada), "edge of light", and video image enhancement analysis. Moiré and structured light are methods to visualize and quantify surface height irregularities. Diffracto Sight is a surface slope visualization technique. Video image processing is a computer-based methodology for enhancing and analyzing video images for flaw detection. The most promising applications for these advanced visual techniques are detection and classification of corrosion-induced paint liftoff and pillowing induced by corrosion between fraying surfaces and in areas that would normally require disassembly. Diffracto Sight, or D-Sight as it is known, is in the process of commercialization.

Moiré interferometry is a family of techniques that visualize surface irregularities. Many variations are possible, but the technique most applicable to corrosion detection is shadow moiré (sometimes called projection moiré) for surface height determination. The Naval Air Development Center has developed a hand-held test system that employs shadow moiré for field inspection of possible damage sites in composite structures on aircraft. A projection moiré system built and marketed by WYKO Corp. of Tucson, Arizona, generates fringes interferometrically and uses a fringe shift algorithm to compute the surface contour. Improvements in CCD camera resolution should improve height resolution beyond the current 0.01 inches.

The structured light technique is geometrically similar to projected or shadow moiré methods, and can be thought of as an optical straight edge. Instead of fringe contours being the resultant observation, the departure from straightness of a projected line is the observable. Using image processing techniques, the surface profile can be calculated.

D-Sight has the potential to map areas of surface waviness as well as identify cracks, depressions, evidence of corrosion and other surface anomalies. D-Sight is a method by which slope departures from an otherwise smooth surface are visualized as shadows. It can be used in direct visual inspection or combined with photographic or video cameras and computer-aided image processing. The concept of D-Sight is related to the schlieren method for visualizing index of refraction gradients or slopes in an optical system.

One possible problem with D-Sight is that the technique shows virtually every deviation on the surface, regardless of whether it is a defect or a normal result of manufacture. This statement is true of all optical/visual techniques. The more sensitive the technique, the more it will show. The key then is the ability to distinguish between these surface deviations. In this respect, enhanced visual techniques are similar to

Optical devices are available to aid the naked eye in visual inspection and flaw detection. This equipment can be used to magnify defects that could not be seen by the unaided eye or to permit inspection of areas otherwise hidden from view.

Visual inspection is often conducted using a strong flashlight, a mirror mounted on a ball joint, and a magnifying aid. Magnifying aids range in power from 1.5X to 2,000X. Fields of view typically range from 3.5 to 0.006 inches with resolutions ranging from 0.002 to 0.000008 inches. A 10X magnifying glass is recommended for positive identification of suspected cracks or corrosion. Other inspection methods, such as eddy current, ultrasonic and others, can be used to verify questionable indications.

2.2.1.1 Techniques and Technologies

Borescopes: A borescope is a long, thin, rigid rod-like optical device that allows an inspector to see into inaccessible areas by transmitting an image from one end of the scope to the other. Certain structures, such as engines, are designed to accept the insertion of borescopes for the inspection of critical areas. A borescope can be thought of as a highly specialized periscope that can focus at extremely close distances.

A borescope works by forming an image of the viewing area with an objective lens. That image is transferred along the rod by a system of intermediate lenses. The image arrives at the ocular lens, which creates a viewable virtual image. The ocular can be focused for comfortable viewing. Borescopes typically range from 0.25 to 0.50 inches in diameter and can be as long as six feet. Borescopes often incorporate a light near the objective lens to illuminate the viewing area. Different borescopes are designed to provide direct, forward oblique, right angle and retrospective viewing of the area in question.

Fiberscopes: Fiberscopes are bundles of fiber optic cables that transmit light from end to end. They are similar to borescopes with the difference that they are flexible. They can be inserted into openings and curled into otherwise inaccessible areas. They also incorporate light sources for illumination of the subject area and devices for bending the tip in the desired direction. Like the borescope, fiberscope images are formed at an ocular or eyepiece.

Video imaging systems: Video imaging systems (or "videoscopes") consist of tiny charge coupled device (CCD) cameras at the end of a flexible probe. Borescopes, fiberscopes and even microscopes can be attached to video imaging systems. These systems consist of a camera to receive the image, processors, and a monitor to view the image. The image on the monitor can be enlarged or overlaid with measurement scales. Images can also be printed on paper or stored digitally to obtain a permanent record.

2.2.1.2 Advantages and Disadvantages

Surface corrosion, exfoliation, pitting and intergranular corrosion can be detected visually when proper access to the inspection area is obtained. Obviously, visual inspection can only detect surface anomalies. However, some internal corrosion processes do exhibit surface indications, such as pillowing or flaking. The primary advantages of visual inspection include its ability to be performed quickly and inexpensively without the need for complicated equipment. Modest training is required, and typically no special safety precautions need to be taken. Where necessary, permanent records can be obtained by photography or digital imaging and stored.

The disadvantage of visual inspection is that the surface to be inspected must be relatively clean and accessible to either the naked eye or to an optical aid such as a borescope. Typically, visual inspection lacks the sensitivity of other surface NDI methods. Further, visual methods are qualitative and do not provide quantitative assessments of either material loss or residual strength. Additionally, visual inspection techniques can be man-hour intensive and monotonous, leading to errors.

2.2.1.3 Current Research

Advanced visual inspection methods include moiré and structured-light-based optical profilometry, Diffracto Sight (a patented process developed by Diffracto, Ltd. of Canada), “edge of light”, and video image enhancement analysis. Moiré and structured light are methods to visualize and quantify surface height irregularities. Diffracto Sight is a surface slope visualization technique. Video image processing is a computer-based methodology for enhancing and analyzing video images for flaw detection. The most promising applications for these advanced visual techniques are detection and classification of corrosion-induced paint liftoff and pillowing induced by corrosion between fraying surfaces and in areas that would normally require disassembly. Diffracto Sight, or D-Sight as it is known, is in the process of commercialization.

Moiré interferometry is a family of techniques that visualize surface irregularities. Many variations are possible, but the technique most applicable to corrosion detection is shadow moiré (sometimes called projection moiré) for surface height determination. The Naval Air Development Center has developed a hand-held test system that employs shadow moiré for field inspection of possible damage sites in composite structures on aircraft. A projection moiré system built and marketed by WYKO Corp. of Tucson, Arizona, generates fringes interferometrically and uses a fringe shift algorithm to compute the surface contour. Improvements in CCD camera resolution should improve height resolution beyond the current 0.01 inches.

The structured light technique is geometrically similar to projected or shadow moiré methods, and can be thought of as an optical straight edge. Instead of fringe contours being the resultant observation, the departure from straightness of a projected line is the observable. Using image processing techniques, the surface profile can be calculated.

D-Sight has the potential to map areas of surface waviness as well as identify cracks, depressions, evidence of corrosion and other surface anomalies. D-Sight is a method by which slope departures from an otherwise smooth surface are visualized as shadows. It can be used in direct visual inspection or combined with photographic or video cameras and computer-aided image processing. The concept of D-Sight is related to the schlieren method for visualizing index of refraction gradients or slopes in an optical system.

One possible problem with D-Sight is that the technique shows virtually every deviation on the surface, regardless of whether it is a defect or a normal result of manufacture. This statement is true of all optical/visual techniques. The more sensitive the technique, the more it will show. The key then is the ability to distinguish between these surface deviations. In this respect, enhanced visual techniques are similar to radiographs, which display many features and it is up to trained inspectors to distinguish between normal and defect signatures. In fact, because D Sight show such detail, it is possible to characterize different surface anomolies to reduce the number of false calls. D-Sight may be most useful to survey large areas relatively quickly to identify specific areas for inspection by more detailed methods.

The Institute for Aerospace Research (IAR), National Research Council Canada (NRCC), has developed a new enhanced optical technique. this technique is based on optical scanning of the surface using a light source passing through a slit and reflected from the inspected surface at a grazing angle to a CCD matrix. This technique needs a computer for image reconstruction. EOL resolution for lap joint corrosion is similar to that of D Sight. The technique is slower than area D Sight; however, it is better suited for automated interpretation and quantification of corrosion in areas identified by other methods.

EOL has been shown to be very effective in detecting small surface cracks. In a study comparing various NDI methods of inspection of turbine disk for bolt cracking, EOL has demonstrated higher POD than UT and penetrant methods while it was only slightly inferior to manual Eddy Current (90/95 length of 1.36 mm for EOL vs. 0.84 mm for EC).

Video image enhancement relies on digital image processing to capture and enhance images so that a human inspector might have better imagery to deal with and make judgments upon. Image processing permits the freeze-frame capture, enhancement, and display of an image. Additionally, processing algorithms may be applied which could identify, measure, and classify defects or objects of interest.

2.2.2 Eddy Current

When an electrically conductive material is exposed to an alternating magnetic field that is generated by a coil of wire carrying an alternating current, eddy currents are induced on and below the surface of the material. These eddy currents, in turn, generate their own magnetic field which opposes the magnetic field of the test coil. This magnetic field interaction causes a resistance of current flow, or impedance, in the test coil. By measuring this change in impedance, the test coil or a separate sensing coil can be used to detect any condition that would affect the current carrying properties of the test material.

Eddy currents are sensitive to changes in electrical conductivity, changes in magnetic permeability (the ability of a material to be magnetized), geometry or shape of the part being analyzed, and defects. Among the latter defects are cracks, inclusions, porosity and corrosion.

2.2.2.1 Techniques and Technologies

Most modern eddy current instruments in use today are relatively small and battery powered. In general, surface detection is accomplished with probes containing small coils (0.10 inch diameter) operating at a high frequency, generally 100 kHz and above. Low frequency eddy current (LFEC) is used to penetrate deeper into a part to detect subsurface defects or cracks in underlying structure. The lower the frequency, the deeper the penetration. LFEC is generally considered to be between 100 Hz and 50 kHz.

Initially, eddy current devices utilized a meter to display changes of voltage in the test coil. Currently, phase analysis instruments provide both impedance and phase information. This information is displayed on an oscilloscope or an integrated LCD display on the instrument. Results from eddy current inspections are obtained immediately.

A meter type of eddy current device must be calibrated against a known calibration block. The instrument is zeroed against a good portion of the block. The probe is then positioned over a crack of known size, and the meter deflection is adjusted accordingly.

The other type of eddy current instrument displays its results on planar form on a screen. This format allows both components of the coil's impedance to be viewed. One component consists of the electrical resistance due to the metal path of the coil wire and the conductive test part. The other component consists of the resistance developed by the inducted magnetic field on the coil's magnetic field. The combination of these two components on a single display is known as an impedance plane. It should be noted that proper interpretation of an impedance plane display requires extensive knowledge of all eddy current principles and therefore proper training.

Eddy current testing is used extensively to detect cracks, heat damage and corrosion thinning. HFEC is used to detect exfoliation corrosion around installed fasteners. Inspection is usually directed at specific small areas rather than large areas.

2.2.2.2 Advantages and Disadvantages

A major advantage of the eddy current method is that it requires only minimum part preparation. Reliable inspections can be performed through normal paint or nonconductive materials up to thicknesses of approximately 0.015 inch. Eddy current technology can be used to detect surface and subsurface flaws on single and multiple layered materials. It is sensitive to small defects and thickness changes. It is low cost compared to other NDI techniques, can produce a permanent record and is moderately fast. Eddy current testers are portable.

On the other hand, there are a number of factors which should be taken into account, including:

- The surface to be inspected must be accessible to the eddy current probe
- Rough surfaces may interfere with the test
- Tests can only be performed on conductive materials
- Much skill and training are required
- Reference standards are needed for comparison
- The depth of penetration is limited by the frequency of the probe
- It is a time consuming method for large areas.

Eddy current is one of the most sensitive and reliable methods for detecting surface and subsurface flaws. Its application requires considerable skill, demanding trained and qualified personnel to achieve a high degree of reliability.

2.2.2.3 Current Research

Scanned Pulsed Eddy Current. This technique for application of eddy current technology employs analysis of the peak amplitude and zero crossover of the response to an input pulse to characterize the loss of material. This technology has been shown to reliably detect and measure material loss on the bottom of a top layer, the top of a bottom layer, and the bottom of a bottom layer in two-layer samples. Material loss is displayed according to a color scheme to an accuracy of about five percent. A mechanical bond is not necessary as it is with ultrasonic testing. The instrument and scanner are rugged and portable, using conventional coils and commercial probes. The technique is sensitive to hidden corrosion and cracks and provides a quantitative determination of metal loss. The time gating feature discriminates against fasteners and liftoff, and provides an indication of which surface in a multi-layer structure is suspect. The progress here is in the control of the eddy current probe through a computer-controlled scanning mechanism and the processing of the sensed data into C-scan, or two-dimensional, images of the inspected surface.

Mobile Automated Scanner (MAUS). The Mobile Automated Scanner, currently in its third generation, was developed by McDonnell Douglas (now Boeing) under contract to the U.S. Air Force. MAUS III is a portable C-scan inspection system that integrates several traditional inspection techniques into a single package. Detection capabilities include pulse echo ultrasonics, ultrasonic resonance, eddy current, and external DC voltages. Inspection applications include metallics, monolithic composites, hybrid composite/metallic, and bonded structures. The improvement represented in this piece of equipment is the integration of several separate techniques into a single package and the ability to scan larger areas quickly and efficiently. Boeing is coming out with a MAUS IV line.

Magneto-Optic Eddy Current Imaging (MOI). MOI images result from the response of the Faraday magneto-optic sensor to weak magnetic fields that are generated when eddy currents induced by the MOI interact with defects in the inspected material. Images appear directly at the sensor and can be viewed directly or imaged by a small CCD camera located inside the imaging unit. The operator views the image on the video monitor while moving the imaging head continuously along the area to be inspected. In contrast to conventional eddy current methods, the MOI images resemble the defects that produce them, making the interpretation of the results more intuitive than the interpretation of traces on a CRT screen. Rivet holes, cracks and subsurface corrosion are readily visible. The image is in video format and therefore easily recorded for documentation.

2.2.3 Ultrasonic

Ultrasonic inspection utilizes high-frequency sound waves as a means of detecting discontinuities in parts. Ultrasonic (above human hearing range) sound waves are sent into the material to be examined. The waves travel through the materials and are reflected from the interfaces, such as internal defects and the back surface of the material. The reflected beam is displayed and analyzed to determine the condition of the part.

Ultrasonic testing is accomplished by sending an electrical pulse to a transducer.

This pulse causes the transducer to send a pulse of high frequency sound into the part. A coupling medium, such as water, between the transducer and the material is required. This pulse travels through the material until it reflects from a discontinuity or from a back surface. The reflected pulse is received by the transducer and converted back into an electrical signal. This signal is displayed on an oscilloscope for analysis. By examining the variations of a given response pattern, discontinuities are identified.

2.2.3.1 Techniques and Technologies

Techniques have been developed to employ different kinds of waves, depending on the type of inspection desired. Longitudinal waves, also called compression waves, are the type most widely used. They occur when the beam enters the surface at an angle near 90 degrees. These waves travel through materials as a series of alternate compressions and dilations in which the vibrations of the particles are parallel to the direction of the wave travel. This wave is easily generated, easily detected, and has a high velocity of travel in most materials. Longitudinal waves are used for the detection and location of defects that present a reasonably large frontal area parallel to the surface from which the test is being made, such as for corrosion loss and delaminations. They are not very effective, however, for the detection of cracks which are perpendicular to the surface.

Shear waves (transverse waves) are also used extensively in ultrasonic inspection and are generated when the beam enters the surface at moderate angles. Shear wave motion is similar to the vibrations of a rope that is being shaken rhythmically; particle vibration is perpendicular to the direction of propagation. Unlike longitudinal waves, shear waves do not travel far in liquids. Shear waves have a velocity that is about 50 percent of longitudinal waves in the same material. They also have a shorter wavelength than longitudinal waves, which makes them more sensitive to small inclusions. This also makes them more easily scattered and reduces penetration.

Surface waves (Rayleigh waves) occur when the beam enters the material at a shallow angle. They travel with little attenuation in the direction of the propagation, but their energy decreases rapidly as the wave penetrates below the surface. They are affected by variations in hardness, plated coatings, shot peening, and surface cracks, and are easily dampened by dirt or grease on the specimen.

Lamb waves, also known as plate waves and guided waves, occur when ultrasonic vibrations are introduced at an angle into a relatively thin sheet. A Lamb wave consists of a complex vibration that occurs throughout the thickness of the material, somewhat like the motion of surface waves. The propagation characteristics of Lamb waves depend on the density, elastic properties, and structure of the material as well as the thickness of the test piece and the frequency of vibrations. There are two basic forms of Lamb waves: symmetrical (dilational) and asymmetrical (bending). Each form is further subdivided into several modes having different velocities that can be controlled by the angle at which the waves enter the test piece. Lamb waves can be used for detecting voids in laminated structures, such as sandwich panels and other thin, bonded, laminated structures.

2.2.3.2 Advantages and Disadvantages

The advantages of using ultrasonic inspection techniques include:

- Its versatility in requiring access to only one surface of the specimen and the wide range of materials and thicknesses that can be inspected
- Rapid response of the system,
- The capability of automating the inspection application
- Accuracy in determining flaw position and size
- High sensitivity permitting detection of minute defects
- Detection of both surface and subsurface flaws
- Permanent data storage
- Minimal part preparation and special safety precautions.

Ultrasonic inspection yields immediate results which can be viewed on an oscilloscope or detected audibly, enabling a relatively rapid rate of inspection. Contact type ultrasonic equipment is highly portable, hand held, and lightweight.

The disadvantages of the ultrasonic test method are that, except for simple thickness measurements, it requires a high degree of experience and skill to set up the inspection and interpret the results, and both couplant and reference standards are required.

2.2.3.3 Current Research

Dripless Bubbler. One of the most promising improvements to ultrasonic testing technology is the dripless bubbler. This is a development not in the ultrasonic probe itself but in the mechanism for employing it consistently on curved, irregular, vertical, and inverted surfaces. The dripless bubbler itself is a pneumatically powered device to hold a water column between the ultrasonic probe and inspected surface. With software control of the movement of the probe, a fast and accurate map of the inspected surface can be obtained. Thus the progress is in the efficient manipulation of the sensor and the rapid processing of the data for further human analysis. The dripless bubbler is a development of the Iowa State University Center for Nondestructive Evaluation (CNDE).

Laser Ultrasound. There is also emerging interest in the area of laser ultrasonics, or laser-based ultrasound (LUS). The innovation is in the use of laser energy to generate sound waves in a solid. This obviates the need for a couplant between the transducer and the surface of the inspected material. The initial application of this new technology seems to be directed toward process control. Regardless, the technology does have application for thickness measurement, inspection of welds and joints, surface and bulk flaw detection on a variety of materials, and characterization of corrosion and porosity on metals. The Department of Energy is in the formative stages of developing and sponsoring a LUS research program. This technology is in the laboratory stage. In Canada, the Industrial Materials Institute of NRCC, in partnership with NRCC/IAR, has been developing laser UT for corrosion detection since 1996. Lap joint corrosion and exfoliation in thick section aluminum alloys are being addressed in a program sponsored by the Canadian DND.

2.2.4 Radiography

Radiographic inspection is a nondestructive method of inspecting materials for surface and subsurface discontinuities. This method utilizes radiation in the form of either x-rays or gamma rays, both of which are electromagnetic waves of very short wavelength. The waves penetrate the material and are absorbed, depending on the thickness or the density of the material being examined. By recording the differences in absorption of the transmitted waves, variations on the material can be detected. The variations in transmitted waves may be recorded by either film or electronic devices, providing a two-dimensional image that requires interpretation. The method is sensitive to any discontinuities that affect the absorption characteristics of the material.

Neutron radiography is a special purpose form of radiography that employs high energy neutrons to penetrate structures and materials to form similar images, either on film or displays, of the internal structures and possible defects due to cracks and corrosion.

2.2.4.1 Techniques and Technologies

The techniques and technologies of radiography have most to do with the design of the x-ray tube itself. There are many different types of tubes used for special applications. The most common is the directional tube, which emits radiation perpendicular to the long axis of the tube in a cone of approximately 40 degrees. Another type is the panoramic tube, which emits x-rays in a complete 360 degree circle. This type of tube would be used, for example, to examine the girth welds in a jet engine with a single exposure.

Advanced uses of radiography are being made with the aid of computers and high powered algorithms to manipulate the data. This is termed Computed Tomography, or CT Scanning. By scanning a part from many directions in the same plane, a cross-sectional view of the part can be generated, and the internal structure may be displayed in a two dimensional view. The tremendous advantage of this method is that internal dimensions can be measured very accurately to determine such conditions as wall thinning in tubes, size of internal discontinuities, relative shapes and contours. More advanced systems can generate three dimensional scans when more than one plane is scanned. CT scanning is costly and time consuming. Radiography in general and CT scanning in particular are extremely useful in validating and calibrating other, less complex and less costly methods.

Radioisotope sources can be used in place of x-ray tubes. Radioisotope equipment has inherent hazards, and great care must be taken with its use. Only fully trained and licensed personnel should work with this equipment. As with x-rays, the most common method of measuring gamma ray transmission is with film.

Neutron radiography has found application in Canada and the United States. Neutron radiography requires a high-energy neutron source, such as a nuclear reactor. The high neutron flux makes possible high resolution imaging of relatively large structures not practical with generator or isotope sources. Neutron radiography equipment is expensive and entails radiation hazards.

2.2.4.2 Advantages and Disadvantages

The advantages of radiography include the detection of both surface and subsurface flaws and the ability to use it on all materials. It is also a very useful method for detecting different types of flaws, such as corrosion, voids, and variations in density and thickness. All of the test results can be recorded permanently on film.

The disadvantages of radiography are that operators require training as interpretation is sometimes difficult, orientation of the equipment and the flaw is critical, and the equipment is relatively high in cost. Also, there is no indication of flaw depth unless multiple exposures are made. Other factors include that a radiation hazard exists and film development time is required.

Since x-rays and gamma rays are excessively harmful to living tissue, extensive care must be used during application to protect nearby personnel and equipment. X-rays and gamma rays cannot be seen, felt, or detected without special equipment. Tissue damage can occur without any physical awareness of the radiation. Protection from radiation can be obtained with barriers of high density materials such as lead or concrete. Protection may also be provided by providing a buffer zone around the radiation source. The employment of radiation producing equipment is sometimes controlled by state or other agencies.

2.2.4.3 Current Research

CT scanners are useful for small component inspections or failure analysis of assemblies that can fit within the object handling capabilities of the scanners. Many aerospace companies use CT to support their development testing and inspection efforts. Because of the high cost of equipment and facilities, CT has not yet been employed to a large degree for routine aircraft inspections, including corrosion inspections.

Compton backscatter imaging (CBI) is emerging as a near surface NDI measurement and imaging technique. CBI can detect critical embedded flaws such as cracks, corrosion and delaminations in metal and composite aircraft structures. In CBI, a tomographic image of the inspection layer is obtained by raster scanning the collimated source-detector assembly over the object and storing the measured signal as a function of position. Rather than measuring the x-rays that pass through the object, CBI measures the backscattered beam to generate the image. This enables single-sided measurement.

2.2.5 Thermography

Thermography is based on the principle that a good mechanical bond between two materials is also a good thermal bond. The temperature distribution on an aircraft skin or component can be measured optically by the radiation that it produces at infrared wavelengths. Several techniques have been developed that use this temperature information to characterize the thermal - and therefore the structural - properties of the sample being tested.

Many defects affect the thermal properties of those materials. Examples are corrosion, debonds, cracks, impact damage, panel thinning, and water ingress into composite or honeycomb materials. By judicious application of external heat sources, these common aircraft defects can be detected by an appropriate infrared survey. Several organizations have demonstrated techniques for infrared structural inspection of aircraft in field tests at maintenance facilities. However, none of these techniques is at present in widespread use in the aviation field. Use of thermography techniques currently range from laboratory investigations to fielded equipment. The more advanced systems are in the prototype stage, and their design and operational feasibility for use on transport aircraft are being evaluated.

Thermography in its basic form does not seem to be widely employed. An advanced thermographic NDI system can be purchased directly or assembled from components purchased from a variety of sources. Due to the cost of infrared detectors, the cost of a system will be in the $100K to $300K range. Because of the high price and the lack of original equipment manufacturer (OEM) and regulatory approval for use of these methods, sales for aircraft maintenance inspections have been limited.

2.2.5.1 Current Research

Wayne State University and Thermal Wave Imaging, Inc. perform research in the area of thermal wave imaging. This technology uses heat pulses to inspect subsurface features of solid objects. The thermal pulses are produced by flash lamps. Pulse reflections are recorded and viewed in the time domain much like ultrasonics. This technology can be used to assess impact damage, disbonds and delaminations in composites, and corrosion damage. It provides quantitative thickness measurement of the inspected material.

The raw image displayed by an IR camera only conveys information about the temperature and emissivity of the surface of the target it views. To gain information about the internal structure of the target, it is necessary to observe the target as it is either being heated or as it cools. Since it takes heat from the surface longer to reach a deeper obstruction than a shallow one, the effect of the shallow obstruction appears at the surface earlier than that of a deep one. You can think of this as a thermal pulse generated at the front surface, which is then "reflected" off the back surface or a subsurface defect. The thermal response to a pulse over time, color coded by time of arrival, is displayed as a two dimensional, C-scan image for interpretation by the operator.

This technology is being marketed under the name EchoTherm by Thermal Wave Imaging, Inc., which was originally created as a small spin-off from Wayne State University. It shows promise as a non-intrusive means of inspecting fairly large areas efficiently.

Lawrence Livermore National Laboratory is working in the area of dual-band infrared computed tomography (DBIR-CT). This technique uses flash lamps to excite the material with thermal pulses and detectors in both the 3-5 and 8-12 micron range to obtain the results. The DBIR-CT technique gives three-dimensional, pulsed-IR thermal images in which the thermal excitation provides depth information, while the use of tomographic mapping techniques eliminates deep clutter. This technique is computer-intensive and should be considered an extension of the thermal wave imaging technique described above.

2.2.5.2 Advantages and Disadvantages

Thermography, in its basic form, has the limitation of measuring only the surface temperature of the inspected structure or assembly. As such, it does not provide detailed insight into defects or material loss located more deeply in the structure. Because it is an area-type technique, it is most useful for identifying areas that should be inspected more carefully using more precise techniques, such as eddy current and ultrasonic methods.

Thermal wave imaging overcomes some of these limitations by measuring the time response of a thermal pulse rather than the temperature response. The thermal pulse penetrates multiple layers where there is a good mechanical bond between the layers. The benefits of thermal wave imaging technology include the ability to scan a wide area quickly and provide fast, quantitatively defined feedback with minimal operator interpretation required. Proponents state that thermal wave images are easier to interpret than images based on optical interference methods. Thermal wave imaging does not require an electrically conductive structure and can be employed on aluminum, plastics, steel, and composites such as graphite epoxy. It is less effective when dealing with highly insulating materials like rubber or glass.

As would be expected, defects more deeply contained within the structure produce blurred images compared to those close to the surface. Additionally, highly reflective surfaces must be coated with a special solution that will absorb the IR light of the flash lamps and will also provide better emissivity of the response pulse for the IR cameras.

The disadvantages of thermal wave imaging relate to its precision and cost. Complexity is also a factor in that the system is not a single, self-contained unit. Thermal wave imaging is currently an area technique that must be followed up with point techniques, such as eddy current and ultrasonic methods. With greater field experience, this limitation may diminish. The cost of a thermal wave imaging system is approximately $110K per system - $60K for the camera and $50K for the other components. In comparison, a single point ultrasound system costs approximately $2.5K and a single point eddy current system costs about $6K. More advanced techniques, such as dual band infrared computed tomography, are more complex, more expensive and less mature. Judgments regarding advantages and disadvantages of DBIR-CT would be premature.

2.2.6 Other Technologies

There are several other NDI/NDE technologies that are useful for discovering and characterizing defects such as cracks or inclusions. However, these technologies do not lend themselves to application to the problem of corrosion detection. These technologies include dye penetrant testing, magnetic particle testing, and acoustic emission testing.

One technology that encompasses many of the individual technologies described above is that of data fusion. While not unique to the field of NDE/NDI, data fusion is mentioned by many researchers as having very interesting potential. Already, the MAUS is a means for employing two different sensors to the same problem, although not simultaneously. The DBIR-CT combines two different IR spectra with computed tomography to generate three dimensional information. Even so, there is only isolated instances of data fusion research applied to the NDE/NDI and that only in certain combinations. Most researchers in the field agree that this is an under-explored area. It does have implications of complexity and cost, which may have limited its development thus far.

Several researchers are working on embedded sensors that will indicate the presence of corrosion. One such sensor is a thin film device that is used to measure the small currents between two metals subject to galvanic corrosion. This device is quite good at indicating the presence of a corrosive environment and, by implication, corrosion activity. To be useful for determination of material loss, this device would require an extensive data acquisition system to determine the life history of corrosion exposure. As such, it may be more useful for correlating environmental exposure to rate of corrosion in a prospective rather than retrospective sense. Also, evaluation of adhesives, coatings and sealants may be possible without long exposure tests.

In addition to sensors themselves, there is some work being done relative to automation that has the potential to improve the productivity of the inspection process. The mobile automated scanning (MAUS) concept was described earlier. In addition, McDonnell Douglas (now Boeing) Aerospace of St. Louis has developed a gantry-based automated scanning system. The Automated Ultrasonic Scanning System - Generation Five (AUSS-V) was designed for inspection of solid laminates and adhesively bonded composite assemblies which have complex contoured shapes. AUSS-V provides simultaneous coordinated control of nine axes of motion to maintain squirter alignment relative to the inspection surface. A three dimensional map of the surface is generated and used to calculate trajectories to track the surface during inspection. The system is able to maintain transducer alignment within 0.030 inch and is especially useful for complex aerospace composite structure inspection.

Current inspection techniques are manpower intensive. Research into auto-crawlers has demonstrated the potential to improve this situation. Robotic or remote controlled platforms that adhere to the inspection surface using suction cups and that use various articulation mechanisms for movement have been researched by the Jet Propulsion Laboratory of NASA.

If successful, these devices would reduce or obviate the need for complex work platforms, cherry picker trucks, scaffolding, gantries and other support equipment now used to gain access to remote areas, such as the tail assemblies of large aircraft. Such crawlers could carry eddy current, ultrasonic, visual or other sensor devices to perform the actual inspection. These devices could also overcome some of the human limitations associated with the repetitive and sometimes boring tasks associated with inspection. Miniaturization of both the sensors and the carrying platforms may allow access to and inspection of areas that are now normally inaccessible to conventional forms of inspection. The fuel tanks in the outer wing sections of aircraft come to mind as areas that are difficult or impossible to inspect otherwise.

2.3 Summary

Corrosion detection is a subset of the larger fields of NonDestructive Evaluation and NonDestructive Inspection. There is an entire professional field associated with NDE/NDI and a related field on corrosion engineering. Corrosion itself is an extremely complex subject, and corrosion engineering combines several disciplines, including mechanics, structures, materials science, chemistry, physics, and numerous sensor technologies. The many forms of corrosion and the attendant damage that results further complicates the subject. Furthermore, corrosion detection is frequently combined with other inspection requirements, such as crack, fatigue and hardness testing.

As more technologies are being explored for application to the corrosion detection

Table 2-2. Summary of Corrosion Detection NDE/NDI Technologies.

problem, different sensing and measurement mechanisms come into play. Eddy current, ultrasonic, and thermal wave imaging (singly or in combination) measure electrical impedance, ultrasonic attenuation, time of travel, and thermal diffusion that are dependent on the material thickness and any flaws. Comparative measurements or calibration of the parameters on known specimens enable detection of flaws or estimation of material thickness. Comparison with reference documentation allows the calculation of material lost due to corrosion. Enhanced visual techniques detect surface deformations caused by internal formation of corrosion products. Correlation with known specimens allows the estimation of material volume, and therefore material thickness, lost due to corrosion. Radiography techniques can provide a measurable image of the part in question and can highlight the presence of the products of corrosion.

Many of the technologies of NDE/NDI lend themselves to the detection, characterization and quantification of corrosion damage. As new materials find use in military systems, the strict definition of corrosion being a metallic process may serve to obscure the problem of deterioration in composite and non-metallic structures.

The larger problem is the aging of military systems to the point that they become unreliable or even unsafe. We commonly think of aircraft when considering corrosion because they are designed with smaller margins of safety and failures tend to be more dramatic. We also tend to think of primary and secondary structure as the areas most subject to corrosion. However, engines and even wire bundles experience corrosion and related damage. It is safe to say that all military systems experience corrosion to some degree. Because military systems are typically employed in hostile and severe environments, corrosion is an ever-present problem.

The users of corrosion detection (NDI/NDE) equipment generally accept a goal of being able to determine 10 percent material loss. This number is somewhat arbitrary and stems from airline experience as much as anything. The scientific community would like to be able to reliably determine material loss in the range of 1 percent. As much as anything, this will enable much greater precision in the understanding of the RATE of corrosion (and the underlying processes of corrosion, especially in newer materials for which there is not extensive field experience) and therefore more accurate predictions of useful service life and better recommendations for inspection and maintenance intervals. Therefore, much of the research and development activities are aimed at this order-of-magnitude improvement in the accuracy of NDE/NDI.

Table 2-3. Corrosion Detection Technology R&D Trends.

Table 2-2, located to the right, summarizes the major advantages and disadvantages of the primary corrosion detection and characterization technologies.

Table 2-3, located on the following page, highlights corrosion detection technology R&D trends.

The need for quantitative corrosion NDI is clear. The structural engineering community requires corrosion metrics to feed into analytical models capable of assessing the effect of corrosion damage on residual strength and residual life of systems. Without quantitative corrosion NDI techniques, probability of detection data for NDI techniques cannot be developed. Quantitative data are needed for continued inspection and maintenance planning, and for airworthiness assessments.

Technology	Advantages	Disadvantages
Visual	• Relatively inexpensive • Large area coverage • Portability	• Highly subjective • Measurements not precise • Limited to surface inspection • Labor intensive
Enhanced Visual	• Large area coverage • Very fast • Very sensitive to lap joint corrosion • Multi-layer	• Quantification difficult • Subjective - requires experience • Requires surface preparation
Eddy Current	• Relatively inexpensive • Good resolution • Multiple layer capability • Portability	• Low throughput • Interpretation of output • Operator training • Human factors (tedium)
Ultrasonic	• Good resolution • Can detect material loss and thickness	• Single-sided • Requires couplant • Cannot assess multiple layers • Low throughput
Radiography	• Best resolution (~1%) • Image inter-pretation	• Expensive • Radiation safety • Bulky equipment
Thermograph y	• Large area scan • Relatively high throughput • "Macro view" of structures	• Complex equipment • Layered structures are a problem • Precision of measurements
Robotics and Automation	• Potential productivity improvements	• Quality assurance • Reliability
Data fusion	• Potential accuracy and reliability improvements	• Unproven technology
Sensor fusion	• Potential productivity improvements	• Unproven technology

3. TECHNOLOGY APPLICATIONS

The typical process of finding and identifying corrosion begins with visual inspection. Clearly, any damage that can be observed by visual means will require closer inspection. Field inspection by other means usually entails eddy current and/or ultrasonic inspection. These types of inspections can normally be accomplished during routine maintenance without impacting operational availability. If additional inspection is determined to be necessary, it is usually conducted by specialists under controlled conditions, such as in a protected space or in an NDI laboratory.

Technology	Observed Trend
Enhanced Visual	• Solid film highlighters for consistent and repeatable reflectivity • Scanner based systems leading to quanitification of corrosion • Automation of image interpretation to reduce false call rate
Eddy Current	• More sophisticated signal and data processing (pulsed eddy current, C-scan imaging) • More sophisticated sensors (multi-frequency)
Ultrasonic	• More efficient scanning methods (dripless bubbler, gantrys, etc.) • Dry couplants (including laser stimulation)
Radiography	• Single-sided methods (backscatter) • Three-dimensional image processing (computed tomography)
Thermography	• Time domain analysis (thermal wave imaging) • Multi-spectral (dual-band infrared) • Three-dimensional image processing (computed tomography)
Robotics and Automation	• Attached computer-controlled positioning mechanisms • Gantrys (multi-axis) • Crawlers (including vertical and inverted surfaces)
Data fusion	• Image processing (color coding, three dimensional, etc.) • Image correlation (C-scan, etc.)
Sensor fusion	• Currently only attempted within a single technology (e.g., eddy current, infrared) • No observation of research into combining two different sensors into a single probe for simultaneous measurements

3.1 Air Applications

The primary technology application in the air arena is visual inspection techniques. Maintenance preflight inspections, pilot visual inspections and maintenance post-flight inspections depend mainly on visual techniques. Visual techniques are non-quantitative and rely heavily on the expertise of the individual inspector. Where visual techniques identify suspicious areas, more precise technologies and techniques are employed. The primary technologies in use are eddy current and ultrasonic. Eddy current equipment has the advantage of being both affordable and portable. Ultrasonic equipment is somewhat encumbered by the paraphernalia associated with the couplant medium. The following are some of the common areas of aircraft that are of special interest:

- Control surfaces
- Lap joints
- Surfaces under doubling material
- Fuselage and wing skins and fasteners
- Floorboards, helicopter graphite epoxy
- Bilge, galley, and latrine areas
- Shell and missile casings, and storage containers
- Windshield frames
- Access doors.

3.2 Sea Applications

Combat ships are very susceptible to corrosion, as one would expect. There are, however, specific areas on ships that comprise the top corrosion problems. These include:

- Connectors
- Launchers
- Waveguides
- Cooling Water
- Reflectors
- Radomes
- Grounding Straps
- Vents and Motors
- Pedestals
- Antennas
- Submarine tiles
- Surfaces behind or under insulation
- Composite antenna structures
- High pressure piping
- Gun barrels
- Elevator cable, wire rope
- Boilers
- Condensers
- Propulsion shafting
- Mast fairings
- Bilge, galley, latrine areas
- Shell and missile casings.

3.3 Land Applications

Field maintenance of military equipment sometimes suffers from overemphasis of cosmetic appearance which may mask serious corrosion problems. The complexity of the structure of many systems contributes to this problem. For example, cleaning and repainting of trucks and tanks may hide corrosion problems that exist behind external stowage boxes, ammunition boxes, and other areas that are not easily accessed.

Areas of special interest include:

- Welds and rivets

- Sheet metal and joints, vehicle cabs
- Shell and missile casings
- Storage container brass plugs
- Artillery fuzes
- Exposed gears and mechanisms
- Armor, depleted uranium.

3.4 Summary

The areas where corrosion occurs, the materials in which it occurs, and the conditions under which it occurs all combine to make the inspection for and detection of corrosion a very difficult matter.

4. CORROSION COSTS

As long as corrosion exists, there will always be some costs attributable to its prevention and correction. For the purposes of this study, we are primarily interested in the avoidable costs. Avoidable costs are those that could be influenced by deliberate investment in prevention, detection and correction. Decisions regarding avoidable costs are usually treated as "return on investment" economic decisions. Some commands look for a five-year or better payback on corrosion investments. Similarly, any investment that can reduce manpower requirements are especially appealing, particularly in manpower limited situations, such as onboard ships.

The point at which any system should be retired, whether it is a transport aircraft or a personal automobile, is a complex determination. In general, replacement will occur when the system or item of equipment reaches the point of economical repair, i.e., when the cost to repair exceeds some fraction of the cost of replacement. This fraction will be influenced by military need, and military need has kept many systems in the active inventory much longer than planned for initially.

Furthermore, the decision to retire an item of equipment may be driven by several different factors. For example, retirement of a transport aircraft could be determined by the fatigue age of the airframe, the cost of operation, the availability of replacement parts, or the lack of logistic support for the engines. Therefore, corrosion would be only one of several possible factors taken into account in making such a decision.

The costs attributable to corrosion will fall into two distinct categories, direct and indirect. Direct costs will be those associated with the detection, evaluation, repair and testing of defects caused by corrosion. Direct costs can be considered as avoidable. Indirect costs would include the cost associated with building appropriate facilities for accomplishing corrosion maintenance, the cost of maintaining and conducting formal schools for the training of corrosion technicians, the cost in labor hours for annual training of corrosion maintenance technicians, and the cost to procure, distribute and install specialized equipment in corrosion control shops. Indirect costs are not directly accounted for and are therefore much more difficult to determine.

As to the purpose of this study, improvements in corrosion detection technology could be expected to decrease direct costs by:

- Decreasing the labor hours for inspection and repair of weapons systems for corrosion
- Reducing the materiel requirements for correction of corrosion damage

- Reducing unnecessary maintenance when it can be shown that such maintenance is not required [i.e., structural tear down and destructive testing]
- Reducing the training requirements and skill level required to perform adequate corrosion maintenance
- and to decrease indirect costs by:
- Decreasing the down time of weapons systems for corrosion maintenance
- Extending the service life of weapons systems by improving the detection and correction of corrosion in its earliest stages
- Simplifying the training (both initial and periodic) of corrosion specialists
- Improving corrosion maintenance policies to more accurately reflect the actual condition of each weapon system.

4.1 Defense

Previous studies have estimated that the total cost of corrosion in the U.S. economy is on the order of 4 percent of Gross Domestic Product. Given that the U.S. has a greater than $7T (trillion) GDP, the impact of corrosion would be approximately $280B. These same studies identified total corrosion costs in the Federal Government sector at about $8B, or approximately 2 percent of the budget. Because the DoD has a higher proportion of equipment and facilities than the typical government agency, it would be reasonable to suggest that at least 3-4 percent of the Defense budget is directly or indirectly influenced by the impact of corrosion on weapons systems, equipment and facilities.

Defense costs also will be influenced by the rate of replacement of weapons systems. Several weapons systems in the U.S. DoD inventory have an average age of more than 30 years, while the average age of land vehicles in the civilian economy is much less. This would indicate that the proportion of expenditures needed to maintain older fleets of vehicles is higher in the defense community than it is in the civilian community, and the cost impact of corrosion is correspondingly higher.

4.1.1 U.S. Defense

Due to the accounting practices in the maintenance area, it is difficult to precisely determine costs of corrosion in defense expenditures. The data are not complete and much of the evidence is anecdotal in nature. However, certain trends are clear and inferences can be made. The U.S. defense establishment annually expends approximately $245B per year. If the defense economy mirrors the overall economy in general and corrosion costs are on the order of 4 percent of the economy, then the total cost of corrosion related activities in DoD would be on the order of $10B, the avoidable costs related to corrosion would be approximately $2.5B per year.

This estimate is supported by other sources. A study sponsored by the Defense Technical Information Center (DTIC) and published in February 1996 came to a similar conclusion. This study, titled "Corrosion in DoD Systems: Data Collection and Analysis (Phase I)," stated that "... the cost estimates for expenses related to corrosion within the DoD alone can reach $10B annually." This study tends to confirm the conclusion reached above, that the total cost impact of corrosion to the DoD is on the order of $10B per year.

There have been bottom-up estimates generated by individual services. A 1990 study by the Air Force identified corrosion related costs, identified by weapon system, at approximately $718M per year. This amounts to about 1 percent of the total Air Force budget for that year. Given that the Army, Navy and the Marine Corps have equally severe corrosion problems, it would be reasonable to conclude that total DoD costs would be approximately 3 times those of the Air Force, or somewhat more than $2B. This estimate is consistent with the "top-down" estimate described above. A recent update to the 1990 Air Force study identifies Fiscal Year 1997 costs at approximately $795M.

The Air Force Corrosion Program Office at the Warner-Robins Air Logistics Center periodically summarizes the identifiable costs of corrosion related maintenance within the U.S. Air Force. For their purposes, corrosion maintenance includes all corrosion treatment, all painting, all protective coating removal and re-application, washing, and inspection for corrosion. Their data include base level maintenance and depot level maintenance. They note that 85 percent of the costs are incurred at the depot level. The most recent study identified 1997 costs of $794,827,154. A similar assessment in 1990 identified costs of $720,457,091. The 1990 cost, escalated by standard methods, would be equivalent to $858,784,857 in 1997 dollars. That the 1997 actual costs are less probably reflect the downsizing of the fleet that has occurred in the intervening seven years as many older, high maintenance cost systems, such as the F-4 and most of the F-111s, have been retired. Table 4.1, at the top of the next column, shows how the costs due to corrosion are distributed.

Table 4-1. U.S. Air Force Total Costs - FY97

Element	Total FY97 $	% of Total
Repair	$ 572,352,704	72
Washing	$ 28,443,783	4
Painting	$ 145,951,530	18
AMARC	$ 4,023,428	1
Vehicles	$ 23,291,759	3
JCN Error Correction	$ 1,207,137	<1
Munitions	$ 6,247,341	<1
Metnav	$ 13,309,471	2
Total	$ 794,827,154	100

Table 4-2 below provides examples of the costs attributable to corrosion for particular weapon systems. These data are based on a 1990 study sponsored by the Air Force Corrosion Program Office.

Note that three systems, the B-52, the C-130 and the KC-135, account for 40 percent of the total of $720M described earlier. It is clear that corrosion costs are greater for larger aircraft and for older aircraft, as one would expect. The reason for the relatively low cost for the B-1B is unclear. Examining the cost changes on a per aircraft basis between 1990 and 1997 provides some interesting results, as seen in Table 4-3, which summarizes for the same example set of aircraft.

Certain figures above stand out. It is illuminating to note that the costs per aircraft for some, but not all, have increased substantially. The reasons for this are probably many. The basing of A-10 aircraft at western desert bases would decrease costs. Improvement of the cost accounting may account for both positive and negative changes. What is most clear, however, is that the cost per aircraft for most types, and especially for large aircraft, has increased dramatically in the past 7 years when these studies were conducted. The general trend, as would be expected, is that as aircraft age, the relative cost of maintenance and repair attributable to corrosion increases significantly. In 1990, the average cost per aircraft was $62,611. In 1997, the average cost was $104,872, an increase of 59 percent. These data suggest that corrosion costs per aircraft have been increasing at an average annual rate of 6.8 percent, substantially greater than the overall rate of inflation.

Corrosion costs in the U.S. Navy (including the U.S. Marine Corps) are not as thoroughly documented. However, certain studies give interesting insights into the overall cost impact of corrosion from several different aspects. The previously mentioned DTIC study included the H-46 helicopter aircraft as a case study. Annual

Table 4-2. Example U.S. Air Force Costs by Weapon System.

Weapon System	Total Cost ($M - 1990)	Cost Per Aircraft ($K)
A-10 Attack	$ 21.5	$ 41.0
B-1 Bomber	$ 1.1	$ 14.0
B-52 Bomber	$ 80.3	$352.2
[illegible]	[illegible]	[illegible].0
[illegible]	[illegible]	[illegible].3
KC-135 Tanker	$ 95.3	$147.9
[illegible] Transport	[illegible]	[illegible].2
F-15 Fighter	$ 19.6	$ 26.1
F-16 Fighter	[illegible]	$ 11.3

Table 4-3. Changes in Cost Per Aircraft, 1990-1997.

Weapon System	Cost Per Aircraft (1990 $, K)	Cost Per Aircraft (1997 $, K)	Percent Change, 1990 - 1997
A-10 Attack	$ 41.0	$ 11.5	-72%
B-1 Bomber	$ 14.0	$ 77.1	+451%
B-52 Bomber	$352.2	$420.7	+19%
C-5 Transport	$136.0	$830.1	+510%
C-130 Transport	$224.3	$ 72.6	-68%
KC-135 Tanker	$147.9	$341.5	+131%
C-141 Transport	$249.2	$466.3	+87%
F-15 Fighter	$ 26.1	$ 39.6	+52%
F-16 Fighter	$ 11.3	$ 10.4	-8%
Fleet Average	$ 66.1	$104.9	+59%

corrosion costs were divided into direct costs and safety costs, a breakout not available elsewhere. Direct costs for a fleet of 325 airframes were identified as approximately $135M per year, or $420K per aircraft per year. This is substantially more than the cost for any single U.S. Air Force type/fleet of aircraft. Since 1980, the safety costs of H-46 mishaps where corrosion was either a direct cause factor or a probable cause factor (mishaps that include 11 fatalities, 7 lost aircraft and 25 damaged aircraft) total approximately $140M. We note here that the average age of the H-46 fleet is over 32 years with plans to keep the aircraft in service until the year 2015.

US Army costs attributable to corrosion are also not well recorded. However, a 1986 study undertaken by the U.S. Army Materials Technology Laboratory, the results of which appear in Table 4.4, is illuminating. This study examined the corrosion-related costs from 1985 through 1986 on the five-ton, 800-series truck, of which 17,396 had been procured at that time. The size of this fleet should be a good indication of costs in similar ground vehicles. This study included the cost of downtime, a cost element not considered elsewhere but real nonetheless. The cost of downtime is reflected, at least in part, by the requirement to procure extra quantities of vehicles in order to provide a minimum number of combat-ready vehicles at any one time. This is an example of the force structure discussion earlier. This study found that the average cost per year for parts, labor, replacement and downtime for this fleet of trucks was $7.8M. This amounted to $453 per truck per year. These dollar figures are in 1986 dollars.

These data are only for the U.S. Army fleet of 5-ton trucks. When one considers all the other land vehicles, aircraft and even boats in the U.S. Army inventory, the cost impact of corrosion is much larger. How much larger cannot be precisely determined from the data currently available.

4.1.2 Canadian Defense Costs

The 1997 defense budget of Canada is approximately $7.1B (US dollars). Using the same heuristic as developed in paragraph 4.1 above, the total cost impact of corrosion on the Canadian defense budget would be approximately $284M. The direct cost of corrosion related maintenance, repair and replacement activities would be on the order of $70M (USD). Using the same estimating procedure, the 1998 cost of corrosion-related activities would be approximately $67M (USD), based on a slightly reduced budget.

4.1.3 Australian Defense Costs

The 1997 defense budget of Australia is approximately $7.8B (US dollars). Using the same heuristic as developed in paragraph 4.1 above, the total cost impact of corrosion on the Australian defense budget would be roughly $312M. The direct cost of corrosion related maintenance, repair and replacement activities would be on the order of $78M (USD). Using the same estimating procedure, the 1998 cost of corrosion-related activities would be approximately $81M (USD) based on a small increase in the budget.

The Corrosion Prevention Centre of Australia, Inc. (CPC), cites a 1983 report (entitled "Corrosion in Australia: The Report of the Australian National Centre for Corrosion Prevention and Control Feasibility Study") that concluded that the avoidable cost of corrosion in Australia was "around $2 Billion in 1982 A$." The CPC also estimates that the total cost of corrosion is about 3 times the avoidable cost. The CPC suggests that an alternative estimate is that the total cost of corrosion is around 4 percent of GNP. Based on a 1997 GDP of $405B, the total cost of corrosion to the Australian economy would be on the order of $16B while the avoidable costs would be approximately $4B. Applying that same proportion to the Australian Defence Budget yields a direct cost of corrosion (to the defense establishment) of approximately $78M.

4.1.4 Summary

Table 4-4. Total Corrosion Costs, U.S. Army 800-Series Trucks.

Year	Parts/Labor/ Downtime Per Truck	Estimated Number of 5-ton Trucks	Total
1986	$ 381.37	47,000	$ 17,924,390
1985	$ 367.77	47,000	$ 17,285,190

Combined, the defense establishments of the three NATIBO sponsor countries expend on the order of $2.1B per year on corrosion related activities and equipment. These costs could be reduced with better NDE/NDI and corrosion detection technology, and productivity improvements in the maintenance areas. The magnitude of these expenditures would make the area of corrosion detection, characterization, and prevention a tempting target for future R&D.

4.2 Commercial

It has been estimated that corrosion of metals costs the United States economy almost $300B per year. Approximately one-third of these costs could be reduced by broader application of corrosion resistant materials and the application of best corrosion-related technical practices. A smaller but not insubstantial portion would be impacted by the application of improved corrosion detection technologies.

The original study by Batelle, based on an elaborate model of more than 130 economic sectors, found that in 1975, metallic corrosion cost the U.S. $82B, or 4.9 percent of its Gross National Product. It was also found that 60 percent of that cost was unavoidable. The remaining $33B (40 percent) was incurred by failure to use the best practices then known. These were referred to as avoidable costs.

In a 1995 update to the original study, the panel estimated that avoidable corrosion costs were now 35 percent of the total of nearly $300B but still accounted for over $100B per year. This figure represents a cost to the economy that may be reduced by a broader application of corrosion-resistant materials, improvements in corrosion prevention practices, and benefits from investment in corrosion related research.

The commercial sector costs of corrosion are particularly relevant to this study. For example, these costs include a tremendous amount of national infrastructure in roads, bridges, and utility systems managed by literally thousands of governments and corporations. Costs and investments on the purely commercial side will have clear economic incentives. Costs and investments on the governmental side will have the added complexity of political and tax revenue implications.

4.3 Summary

The cost impact of corrosion is substantial and difficult to quantify. The costs that can be avoided by the deployment of improved corrosion detection technology cannot be precisely determined but are a significant portion of the total. While cost is a major factor in making decisions regarding investments in the corrosion detection technology area, other factors bear on these decisions as well. These factors include the confidence level in the safety and effectiveness of mission critical systems and those components in which their failure could cause serious injury or loss of life.

Improved corrosion detection could increase maintenance costs earlier on in the life cycle of a system, but in all likelihood would contribute to the reduced life cycle cost of maintaining the system in mission readiness state in the course of its service life. Currently, some amount of corrosion damage in weapons systems goes undetected. If better or broader application of technology finds more corrosion earlier on, then corrosion control and prevention measures can be deployed at that stage. Thus, more extensive corrosion damage would be avoided and the extension of service life of a system could be realized. Other positives associated with such an increase would include a higher degree of confidence in the structural integrity (and therefore safety, reliability and longer useful life) of fielded systems.

As the force structure ages (i.e., the average age of fielded systems, however measured), the question becomes one of investment in technologies, equipment, facilities, training and personnel that will help to assure that the force structure remains militarily effective. In many cases, the option to replace entire items does not exist. We cannot replace a retired aircraft with new production if that system is no longer in production. In this instance, extraordinary investment may be required to keep the system in the active inventory while replacement systems are developed and deployed.

While the annual cost of corrosion is interesting, the more relevant question would be, “What is the appropriate level of future investment in corrosion detection technology to help assure the future safety and reliability of the planned operational force structure?” This question should be answered in the form of bottom-up budget requests generated by the logistics communities of the individual Services in light of established military requirements to field safe and effective systems for some prescribed period of time. More specifically for the purposes of this NATIBO-sponsored study, the question becomes: “What corrosion detection technology could be advanced in the near term that would have a significant impact on reducing the impact of corrosion on military and commercial systems?”

5. Corrosion Detection Technologies Research and Application Activities

5.1 Introduction

The following sections describe some of the corrosion detection technology research and application activities going on within the U.S., Canadian and Australian defense sector as well as within other government organizations. Commercial sector activities and academic institution activities are also documented. This list is not intended to be all-inclusive but provide a snapshot of some of the major developments that are occurring.

5.2 Defense Sponsored Activities

The military is considered the primary corrosion detection technology driver. This is due in part to the fact that military systems typically are fielded longer, have higher cycle rates and operate in more corrosive environments than commercial systems. And with the continual decline in defense spending, the service life for defense systems will be extended even longer with a consequent focus on reducing maintenance costs for these existing systems.

5.2.1 U.S. Activities

Corrosion is considered to be the number one cost driver in life cycle costs of DoD weapon systems. Throughout the DoD, corrosion is regarded as less of a safety or technical issue but rather more of an economic issue. This is because the corrosion problems encountered by the military in their defense systems has been detected and repaired before it could become a safety problem. Currently, corrosion prevention is a higher priority within the military sector.

Technology has been identified as one of the primary mean of reducing the impact of corrosion on DoD weapon systems. One way is to implement more corrosion resistant materials into the defense systems. This could be accomplished by making materials more corrosion resistant by using corrosion inhibitors, surface treatments, and coatings. Implementing a decision making aid would also be useful and provide a systematic way to model the long-term corrosion performance of various materials and structures in order to determine the optimal corrosion prevention and control program for new weapon systems during the acquisition cycle and throughout the service life of the system.

The other way in which technology could be employed to combat the effects of corrosion in systems is to aid maintenance personnel in locating corrosion sites and providing them with optimal solutions to correcting the problems. The DoD S&T community is researching a number of different technologies to achieve these goals.

5.2.1.1 U.S. Air Force

Like the other Services, the Air Force budget to build new defense systems has been reduced and, in response, the Air Force is looking for ways to extend the service life of their existing aircraft in order to meet mission demands. The U.S. Air Force has many old (20 to 35+ years) aircraft that are the backbone of the total operational force. All of these older aircraft have encountered, or can be expected to encounter, aging problems such as fatigue cracking, stress corrosion cracking, corrosion, and wear. Extending the service life and use of these aircraft has resulted in increased maintenance and repair costs due to structural cracking and corrosion problems.

In the late 1950s, the Air Force started to develop an engineering process for systematically controlling the causes of fatigue failure of its aircraft structure. The process was institutionalized as the aircraft structural integrity program (ASIP) in 1958. As a result of a F-111 accident and C-5A wing cracking problems in the late 1960s and early 1970s, the Air Force's ASIP process was extensively modified. Changes were put into effect to control aircraft fatigue cracking, by requiring systematic damage tolerance assessments, whereby the designs account for the presence of preexisting cracks. The design assumed that flaws, defects, and material anomalies could be present at the time of manufacturing and/or immediately after in-service inspections, and that if these cracks grew, these cracks would never reach a size which would jeopardize aircraft safety. The ASIP process ensures that fatigue cracking is controlled throughout the operational life of the aircraft.

In the Air Force, each aircraft (weapon system) has a force structural management plan (FSMP), which was required as part of the ASIP process. The aircraft's FSMP was based on a durability and damage tolerant assessment (DADTA) of the airframe subjected to anticipated operational service and anticipated damage scenarios. This plan guides the inspection, assessment, repair, and maintenance of the airframe according to how the aircraft is being operated. Between 1975 and 1990, the Air Force spent approximately 1 million man hours conducting DADTAs on its aircraft and updating their FSMPs. Updating the FSMP reestablishes the remaining service life of the structure (in terms of expected operations) and forecasts the expected structural maintenance costs associated with this service life goal. It is the responsibility of the major operating commands (MAJCOMs) and aircraft weapon system program office (SPO) to manage this part of the process.

Through the Aircraft Structural Integrity Program and through durability and damage tolerance assessments of older aircraft, the Air Force has identified many potential problems and developed individual tracking programs and structural maintenance plans. However, most of the effects of corrosion are not reflected in aircraft structural integrity models, even though corrosion is one of the most costly maintenance problems for Air Force aging aircraft.

The Air Force's R&D community is responsible for supporting this engineering and management process by improving the technology products and delivering these in a form which facilitates their application by the sustainment community user. One such R&D product being researched is an inexpensive, user-friendly nondestructive inspection system which has wide ranging capability for detecting subsurface (hidden) cracking or corrosion damage.

Extensive interactions between the Air Force R&D and sustainment communities are required to establish the class of sustainment problems which are causing safety and economic concerns. As technology products are defined in response to these needs, the R&D community is working together with the users in establishing the specific requirements for acceptance by the sustainment community.

Military fleet operators have traditionally depended on corrosion prevention as a means of dealing with potential corrosion problems. However, the Air Force, faced with the reality of extended life requirements for their aircraft, is finding significant levels of hidden corrosion. Also, the extent of corrosion damage among similar aircraft can vary widely, due to the different environmental exposure the aircraft have been subjected to and the level and type of maintenance that the aircraft have received. The Air Force is actively researching the best strategy for mitigating the effects of hidden (and possibly widespread) corrosion on the continuing safe operating life of their aircraft.

One of the Air Force's primary R&D goals is to reduce operations and maintenance costs of Air Force weapons via enhanced NDI/E technology. The USAF is considered to have the largest corrosion detection technology development program among the three Services. For over 25 years, the Air Force has maintained a formal fleetwide NDE/I monitoring program as part of its Aircraft Structural Integrity Program (ASIP). The established Air Force NDE/I research and development program is coordinated with both the Air Force System Program Offices (SPO) and ALC technology personnel and aerospace industry technology representatives in order to help assure that capabilities match requirements to the extent possible.

At present, the Air Force relies primarily on visual inspection techniques to uncover corrosion damage. Eddy current (EC) and ultrasonic (UT) methods are the main means used in current practice to detect small cracks nondestructively in aircraft structural members, with radiographic (RT), fluorescent liquid penetrant (FPI) and magnetic particle (MP) methods being employed for more specialized inspections. However, the Air Force believes there remain a number of NDE/I technology improvements needed to keep pace with continually advancing military mission/commercial flight operations and vehicle technology changes. Two damage scenarios indigenous to aging aircraft require significant NDE/I advances in the near term: (a) hidden corrosion detection, imaging and characterization and (b) widespread fatigue damage/cracking detection and quantification. Another key logistics need cited by the Air Force is rapid NDI for advanced composites with complex shapes and densities. The Air Force is looking to improve existing technologies and to develop new technologies to detect these potential failure-causing defects.

5.2.1.1.1 Air Force Office of Scientific Research

The Air Force Office of Scientific Research (AFOSR) manages the Air Force's basic research program. AFOSR initiated a program in the early 1990s in the area of detection and prevention of corrosion in aging aircraft. Their objectives were to:

- Develop a science base necessary for practical NDE instruments capable of detecting hidden corrosion with high accuracy, sensitivity and versatility
- Understand the fundamental chemistry of corrosion
- Develop models of corrosion initiation and propagation
- Develop mathematical models of impedance imaging, and
- Perform controlled experiments which determine the effect of selected parameters on the corrosion process.

The AFOSR funded a number of University Research Initiatives in this area, including the following:

- Iowa State University - Nondestructive detection and characterization of corrosion in aircraft. Their objectives were to develop pulsed eddy-current methods to detect hidden corrosion at joints in the skins of transport aircraft and develop energy-resolved x-ray techniques for complex composite structures in high-performance aircraft.
- Lehigh University - Corrosion and fatigue of aluminum alloys: chemistry, micromechanics and reliability. Their goals were to develop a basic mechanistic understanding of material degradation processes and formulate mechanistically-based probability models for reliability assessments.
- SUNY at Stony Brook - NDE of corrosion and fatigue by laser speckle sensor and laser moiré. They were tasked to perform basic research that would lead to the development of two new NDE tools for the detection of corrosion-based degradation.
- University of Chicago - Scanning tunneling microscopy studies of the morphology and kinetic pathways of corrosion reactions of stressed materials. Their role was to develop an understanding of materials corrosion, with emphasis on the role of surface chemical reactions and atomic-level microstructures, and to study the effect of stress on reactivity of materials and the role of surface defects on oxidation reactions.
- University of Connecticut - Experimental and theoretical aspects of corrosion detection and prevention. The university's objectives were to investigate initiation and growth kinetics of corrosion using electrochemical impedance spectroscopy and study x-ray computed tomography for NDE.
- University of Delaware - NDE of corrosion-damaged structures. The university applied the electrical impedance tomography to corrosion detection and monitoring.
- Vanderbilt University - Fretting corrosion in airframe riveted and pinned connections. They assessed the contribution of fretting to the corrosive deterioration of riveted and pinned connections.
- Wayne State University - Thermal Wave Imaging for NDE of hidden corrosion in aircraft components. Wayne State developed thermal wave IR NDE instrumentation capable of detecting hidden corrosion.

Most of these efforts have been completed and new programs were started in FY 97 as part of the Third Millennium Initiative. These new programs include investigating development of pitting corrosion in aluminum alloys, performing fundamental research to characterize and analyze widespread fatigue damage, and investigating and demonstrating innovative NDE/I techniques that have the potential to produce significantly higher defect detection and characterization accuracy and reliability for detection of corrosion and small fatigue cracks.

5.2.1.1.2 USAF Wright Laboratory Materials Directorate, Wright-Patterson AFB

The USAF Wright Laboratory manages the Air Force's applied research and advanced development program in many aeronautical-related technologies. The Air Force's R&D thrust supporting the structural integrity program is to determine the impact of corrosion damage on the integrity of an airframe. The research scientists noted that, unfortunately, corrosion takes many forms that could impact structural integrity in different ways. And for each form of corrosion damage (uniform, exfoliation, pitting, crevice, intergranular, stress corrosion cracking, etc.), a structural model of the corrosion damage needs to be created to accurately assess its effect on fatigue life and/or residual strength.

In most cases, structural models describe the effect of geometric changes caused by the corrosion, and the structural engineer can easily evaluate the effects. But in some cases, corrosion can substantially lower the structure's resistance to the development of new cracks, and this effect is not always easy to accurately model. For many of the older aircraft, being able to anticipate the development of maintenance causing events with some degree of certainty is a major requirement for the system program offices. The problem with stress corrosion cracking of the thicker components manufactured from older 7000 series aluminum alloys has been a pervasive hidden corrosion problem, causing unanticipated major expenses and substantial downtime for aircraft in depot maintenance due to limited spares stocked.

Wright Lab representatives stated that the Air Force's research and development efforts support: (1) developing what the upper limits of corrosion damage can be before this damage leads to a safety problem, (2) developing structural metrics for corrosion that are used to measure the rates of corrosion for specific types of corrosion damage, and (3) providing a tool set that can be used, in conjunction with the parallel NDE work, to determine maintenance strategies for dealing with corrosion present in the airframe.

The researchers pointed out that highly capable nondestructive evaluation and inspection (NDE/I) methodologies and processes are an enabling tool in the life cycle management of aircraft systems for detection and characterization of defects, flaws or anomalies. They contended that, while the current state-of-the-art portrays significant advances in recent years, major capability improvements still must follow in order to satisfy operational requirements.

Their goals in regard to this encompass:

1. Developing advanced nondestructive evaluation/inspection (NDE/I) systems and methodologies for aging aircraft which have the following characteristics:
   - Improved **sensitivity** for detecting damage
     - Hidden corrosion damage such as in structural interfaces, including around fastener holes
     - Cracking damage such as small, tight cracks and multiple cracking
   - **Accuracy** (improved POD/CL) - smaller margins of error, repeatable and consistent equipment (through design improvements, better calibration capabilities, etc.) resulting in lower false call rates, less required operator intervention, maximized Probability of Detection/Confidence Levels
   - **Speed of application** - faster setup and scan rates without significant loss of fidelity, optimum automation, optimum portability/maneuverability, optimum ruggedness
   - **Data flow management** - high rate, high fidelity data acquisition, and processing, data fusion, interpretative analysis and archiving capabilities
   - **Operator interfaces** - optimized for ease of handling, controlling, instructing, interpretation; optimum incorporation of automation
   - **Equipment versatility** for detecting multiple damage types - emphasis on developing/designing multifunction NDE/I systems (exemplified by the AF MAUS III ultrasonic-eddy current scanning system) to facilitate efficient inspection modality changeovers, reduce individual item inventories, yield greater cost benefits and operating efficiencies
   - Reduced
     - System cost and cost of operation (overall cost of inspection)
     - System complexity
     - System size and weight
   - Validated/demonstrated in aircraft environment

2. Increasing Modularity of NDI Systems
   - Develop NDE/I systems which have efficient modular elements for maximizing and standardizing common features such as:
     - Image enhancement and display
     - Data fusion and data archival
     - Diagnostics and interfaces with diagnostic tools
     - Sensor technologies
     - Automation/motion control
3. Reducing the Cost to Inspect Aircraft
   - Systematically reduce the cost of inspections by focusing on
     - Economical inspection processes such as more efficient scan plans, interactive process diagnostics,

modular system maintenance procedures

- Enhanced training for inspectors
- Simplified and standardized calibration procedures

- Minimization of repeat inspections through increased detection sensitivity and reproducibility features
- Evolving of more affordable NDE/I processes (i.e., filmless radiography)
- Accelerated system demonstration and validation processes.

The Air Force's R&D strategy is to have nondestructive evaluation/inspection methodologies and procedures that provide reliable defect/flaw/damage detection with the maximum affordable sensitivity, accuracy and speed to support Air Force missions. The current aging aircraft-related NDE/I R&D program focusing on improved detection of hidden corrosion and small cracks is planned to produce, demonstrate and transition required advancements to meet specific Air Force customer-identified needs.

This program also has connectivity with germane FAA and NASA efforts so as to maximize technology development coordination and transfer.

Their goal is to have NDE/I that not only supports fleet management and airworthiness assurance programs but also provides essential detection capability data to structural integrity methodologies that predict structural life and determine structural maintenance, inspection and repair requirements, schedules and cost as well as evaluate maintenance and repair strategies. The current aging aircraft-related NDE/I R&D program focuses on detection/characterization of cracks smaller than those that would lead to the onset of widespread fatigue damage (WFD), when multi-site and multi-element damage (MSD and MED) scenarios exist, and 2) detection/characterization of hidden corrosion prior to reaching the maximum limits set by structural integrity as well as economic models.

To achieve these goals, the Air Force intends to make maximum use out of new innovations and advances in sensor, imaging, image enhancement, simulation, model-based defect/flaw/damage signal processing and decision, and ultrahigh rate data management technologies from all fields of science. Where appropriate, they will emphasize incorporation of modular NDE/I process and system elements in new/improved designs in order to optimize versatility/interchangeability and maintainability/supportability; increase standardization of equipment, procedures, calibration, etc.; and reduce acquisition and operating costs. Demonstrations and validations of new technology developments will be conducted, as appropriate, in aircraft maintenance/testing settings and environments in order to duplicate operational conditions to the maximum extent possible. These will include Air Logistic Centers, commercial operator beta-site test locations, the FAA Airworthiness Assurance Nondestructive Inspection Validation Center (AANC) and available OEM facilities.

Currently, Air Force programs are emphasizing low frequency EC process development for interior layer cracks (the lower the frequency, the deeper the penetration) since the electromagnetic fields are much less affected by interfaces (such as in lap joints and stack-ups) than are ultrasonic signals. The Air Force considers higher sensitivity EC probe designs, refined signal processing and more rapid scanning methods and equipment key improvement areas.

The detection of hidden corrosion in aircraft structures with standard NDE/I methods has been investigated by all agencies for a number of years with historically limited success. Recently, increased emphasis has and is being placed on the more promising of the investigated methods such as improved ultrasonic, eddy current, thermographic, and optical techniques; specialized digital x-ray (RT); and development and demonstration of in-situ embedded sensors (e.g., optical fibers, galvanic bi-metallic), etc. In addition, the use of EC with improved imaging capabilities is being studied for applicability. Meanwhile, new fundamental investigations are underway/planned by the Air Force to again seek/identify other potential corrosion detection/characterization methodologies that may apply. Related work is ongoing to more precisely and quantitatively define corrosion damage areas to help refine nondestructive detection and imaging processes and to track corrosion progression rates nondestructively, thereby providing essential data for life prediction models. Studies will continue to seek new/modified NDE/I methods that yield reliable signals from very early stage defects/flaws and that also provide more finely resolved larger flaws.

The Air Force's goal is to optimize NDE/I processes for speed and minimized costs in order to meet operational schedules and budgets. Their future plans include studying advanced intelligent sensor technology (both military and commercial), selected and integrated into state of the art NDE/I instrumentation designs and interfaces with limited access inspection sites to yield significantly increased detection accuracy, sensitivity and consistency. Concentration will be placed on detection of nascent defects/flaws to produce reliable data to support more accurate structural integrity assessments. Studies will continue to seek new/modified NDE/I methods that yield signals from very early stage defects/flaws and that also provide more finely resolved larger flaws. Advances in probability of detection (POD) determination models and methodologies will be developed, demonstrated and validated using accurate, validated aircraft inspection data to yield more precise estimates of structural damage growth rates, life estimates and maintenance strategies.

The Air Force intends to develop faster, more robust NDE/I data acquisition, model-based analysis, signal and decision processing and archiving from new state-of-the-art, human computer interface techniques, data management advances, and the like, to support significantly faster inspection processes. Advanced automation and motion control technology will be coupled optimally to higher accuracy state-of-the-art NDE/I systems targeted to produce high inspection scanning rates over large structures capable of a higher defect/flaw/ damage detection (POD) rate that is cost effective.

Integration of advanced NDE/I processes into a Condition Based Maintenance (CBM) system prototype will be developed and demonstrated comprehensively, including definition of the effects, limits and potential of the key components of the inspection process on system optimization and POD. State-of-the-art visualization technology, exemplified by that from virtual reality developments, will be studied to evaluate the potential of applications to the design and refinement of advanced NDE/I processes and techniques and NDE/I operator training and to measure the effect on NDE/I POD. They also intend to focus on advanced development of accurate, reliable, minimum-cost NDE/I process and instrument/equipment designs, through the adaptation and application of state of the art virtual prototyping technology, with operating properties that promote high POD levels.

In an effort to reduce operation cost (an estimated savings of over $1M per year) and reduce hazardous chemical handling and disposal costs at Air Force Air Logistics Centers and field depots, Wright Laboratory has initiated a research effort into replacing their conventional X-ray inspection methods with filmless radiography for aerospace applications. This effort is evaluating the feasibility of using a filmless radiography system with digital storage capability for aerospace structures and transitioning it to Air Logistics Centers.

5.2.1.1.3 U.S. Air Force Corrosion Program Office, Warner Robins AFB

The Corrosion Program Office is a subdivision of the Air Force Air Materiel Command. The office was created for the purpose of ensuring that the Air Force has a viable program to prevent, detect, and control corrosion and minimize the impact of corrosion on Air Force systems (Air Force Instruction 21-105). Other responsibilities include extending the service life of Air Force systems and impacting the acquisition process for new Air Force systems.

The office was established in 1969 with the publication of Air Force Regulation 400-44. This program was centered at the Air Material Area in Mobile. When the Air Material Area in Mobile was closed, the office was moved to Warner Robins Air Material Area in Georgia. The first annual Corrosion Managers' Conference was held in 1969, and the first Corrosion Summary was issued in February 1972. In October 1979, Warner Robins Air Logistics Center (WRALC) was officially tasked with managing the Air Force Corrosion Program. In October of 1995, the Corrosion Program Office was organizationally realigned as an operating location under Wright Laboratories. The Office consists of both civilian and military personnel as well as specialized labs for corrosion research.

Specific engineering functions accomplished by this office are tri-service technical liaison/support, technology insertion, new technology demonstration/ validation at ALC/field units, engineering/technical consultation and corrosion prevention and control policy establishment. Activities of the Air Force Corrosion Program Office include the following:

- New Materials and Processes Technology Insertion Projects
- Corrosion effects on aging aircraft
- Cost of Corrosion Study
- Aircraft Depaint/Cleaning Projects
- New Weapon Systems Support

- Classified Systems Support
- Thermoplastic Power
- Coatings
- Metal Arc Spraying
- Avionics Corrosion
- Hazardous Waste Reduction/NASA/ DOD/ EPA
- Corrosion Training and Education
- Materials Evaluation.

The Corrosion Program Office is separate and distinct from the NDI Program Office at Kelly AFB in San Antonio, TX and the Aging Aircraft Program Office at Wright-Patterson AFB, though they do coordinate on issues of common interest.

An important corrosion issue raised by the Corrosion Program Office engineers and technicians group was that 90 percent of corrosion prevention is applied on the outer surfaces of aircraft, as opposed to the more structurally important interior of the aircraft. One preventive measure implemented as a result of Corrosion Program Office analysis has been the application of a glossy white polyurethane coating underneath all latrines and galleys. Another issue raised by the group was the inconsistent use of sealants by OEMs on rivet joints.

5.2.1.1.4 Aging Aircraft Office

The Aging Aircraft Program Office was established by the Air Force Materiel Command in 1996 to transition technologies from laboratory research and commercial technology development to the Air Logistics Centers that will address the needs of aging aircraft. The mission of the Aging Aircraft Program Office is to work within and outside the Air Force to transition technologies that will extend the lives and reduce the costs of operating and maintaining aging aircraft systems. The program is targeted towards maintaining airframe integrity and emphasizes developing cross-cutting solutions that will benefit multiple aging aircraft systems. The projects funded by this program will address critical needs of the aging fleet such as corrosion, structural integrity and improved non-destructive inspection techniques. As an agent for technology transition, the program office serves as a link between the R&D community and the sustainment community.

The program office sponsored several projects in FY97, utilizing funds provided by HQ AMC and HQ AFMC, that were geared towards hidden corrosion detection. One project made some improvements to the D-Sight system and validated the improved system. D-Sight, which utilizes a dual pass light reflection method, is of particular interest for inspecting lap joints. Another project is evaluating, improving, and validating a C-scan eddy current system (Zetec MIZ 22 coupled with the Krautkramer Branson ANDSCAN). The final FY97 project involved improving and evaluating the Mobile Automated Scanner (MAUS) system, which can be used for a variety of inspections including disbonds, delaminations and corrosion detection. One of the significant improvements made to the MAUS system was a movable track system to semi-automate the inspection process.

In FY98, the program office will be funding some additional work on the D-Sight system, as well as a new effort to evaluate thermography and dripless bubbler technologies as means to detect hidden corrosion in the vicinity of wing skin fasteners.

5.2.1.1.5 Sacramento Air Logistics Center, McClellan AFB

McClellan employs the following corrosion detection technologies in their inspection of defense systems, primarily aircraft:

- Ultrasonics
- N-ray
- X-ray
- Eddy current
- Magnetic particle
- Laser ultrasonics.

McClellan AFB has two neutron radiography systems. One is stationary, designed to do component parts within four bays. The second is a maneuverable system designed to inspect components while still attached to the aircraft.

At the heart of the state-of-the-art stationary neutron radiography system is the newest research reactor in the U.S. The facility was developed to detect low level corrosion and hidden defects in aircraft structures using neutron radiography. The radiography system can accommodate parts to 34 feel long, 12 feet high and up to 6000 pounds in weight. The center's data systems are designed to provide on-line and off-line tracking of critical components and data reduction for trend analysis. Film radiography systems are also available which can detect extremely low levels of hydrogen and surface corrosion. The facility's real time radiography system has the capability to image dynamic events such as data for egress and hydraulic systems, explosive charges, and oil fill levels, respectively.

The maneuverable N-ray system consists of a hangar enclosed gantry robot with a work envelope of 84 feet wide by 85 feet diameter by 25 feet high. It is the only one of its size in the world, capable of scanning an entire aircraft. The six-axis robot is capable of moving the neutron source along a preprogrammed inspection path to inspect the entire aircraft once it is positioned in the hangar. This method of inspection is capable of detecting moisture in areas where normal inspection methods would fail without extensive disassemble.

The inspector controls the operation from a remote control station and can stop the inspection process at any time to perform specific functions such as zoom and search of a selected location. If interrupted, the system is capable of picking up the previous inspection point within a .025 inch radius.

The following aircraft have used this system: F-111, F-15, the Navy's F-14 Tomcat, the Army's AH-64 Apache Helicopter, the Canadian CF-18, and the Australian F-111C and G models.

McClellan also has a maneuverable, real-time x-ray system which improves performance of x-ray of composite materials in assembled aircraft while providing information not available from other inspection processes. The system supports real-time x-ray aircraft inspection using a robot-mounted system. The system is 77 feet wide be 90 feet diameter and 25 feet high, and has a 420 kV and 160 kV x-ray system mounted on a large gantry robot which is installed in a specially constructed, shielded aircraft hangar. This system is used to check wings and other structural components for fatigue cracks, internal damage to hinges, and frame members. Bonded honeycomb components are checked for core damage and water/corrosion. Outputs from this x-ray inspection system include structural and bonded integrity-defect data, photovideotape graphs recorded data, corrosion-moisture detection location, and crack-debond detection and location. A Canadian CF-18 was sent to the ALC for a full N-ray and X-ray evaluation in 1996.

5.2.1.1.6 Oklahoma City Air Logistics Center, Tinker AFB

The Oklahoma City Air Logistics Center is researching existing and emerging NDE/NDT techniques for aging aircraft through its CORAL REACH program. In conjunction with ARINC and Boeing, the researchers have invasively disassembled a complete KC-135 aircraft. The corrosion found on all structural members was documented. In the course of this investigation, the researchers found corrosion in many areas that are hidden and/or inaccessible even during depot overhaul and therefore are missed by current visual inspection.

As a result of this project, the researchers embarked on an effort to evaluate, prototype and transition state-of-the art NDI systems to C/KC-135 PDM for hidden corrosion detection in fuselage lap joints and around wing skin fasteners. They have completed four comprehensive evaluations of commercial off-the-shelf equipment. No equipment was found suitable to detect intergranular corrosion around wing skin fasteners. The group is currently studying NDI equipment that would detect corrosion around these wing skin fasteners and is in the process of transitioning the MAUS III /IV technology into their inspection procedures.

The ALC is also working with Boeing, ALCOA, the University of Utah, and Wright Labs to determine fatigue crack growth rates in lab grown corroded C/KC-135 structural materials. The resulting fatigue crack growth data will be used in C/KC-135 structural life assessments to account for corrosion effects. To date, tests were completed on 2024-T3/T4 and 7075-T6 material with light to moderate corrosion. These tests showed some increase in crack growth rate compared to uncorroded, but the team believes extensive tests with specimens exhibiting more severe corrosion are needed.

They have conducted fatigue testing and analysis of C/KC-135 fuselage lap joints and upper wing skin panels with precorrosion in order to use the resulting fatigue life data as a gross estimate of the effects of corrosion on fatigue life. In addition, the ALC is involved in corrosion growth rate studies to determine how fast corrosion grows on/in C/KC-135 aircraft structure at different geographical operating locations.

The ALC is also in the process of evaluating the effectiveness of externally applied corrosion prevention compounds/inhibitors in reducing or eliminating corrosion on C/KC-135 aircraft. This work is being done in conjunction with Wright Labs and UDRI. If some of these corrosion preventative measures prove feasible, field applications and exposure evaluations will be made.

The researchers are working with NASA Langley and Wright Labs to determine the effects of active corrosion, prior corrosion damage, corrosion by-products and corrosive environments on fatigue crack nucleation and fatigue crack growth rate of C/KC-135 structural materials.

Together with the FAA, they are conducting full-scale testing of C/KC-135/707 generic fuselage panels with natural prior corrosion damage in hidden and inaccessible areas to determine the interactions between corrosion and fatigue and the effects on structural life.

In conjunction with the University of Oklahoma, the ALC is going to conduct testing and analysis of the C/KC-135 structural components with prior corrosion. They want to compare this data with previous results of uncorroded and lab grown corroded specimens.

They have completed work on a corrosion characterization and comparison mapping project, providing a visual representation of the location and severity of corrosion found during aircraft disassembly and inspection overlaid with existing ASIP points. This data will help identify locations with potential fatigue-corrosion interaction.

The ALC has also finished testing and analysis of precorroded C/KC-135 structural materials to determine the static strength and fracture toughness compared to uncorroded materials.

Currently underway is work with Boeing to conduct corrosion fatigue crack growth testing in a corrosion environment to help determine the effects of such environments on fatigue crack growth. They are also working jointly to test pre-corroded fastener hole multi site damage in an attempt to gauge pre-corroded fatigue crack growth and residual strength of KC-135 aircraft materials with fastener holes. In addition, they are working together on designing, developing, and building a prototype of the Stratotanker Condition Analysis and Logistics Evaluation (SCALE) system engineering tool. The system will be able to collect, document and analyze KC-135 corrosion discrepancies/information for all the structure by tail number and for the entire fleet. It will include graphically enhanced displays, logical and physical models, data entries by input, scans, digital photos and NDI output.

5.2.1.2 U.S. Navy

The Navy has the largest monetary investment in corrosion research. They are also considered to have the best corrosion maintenance and training practices.

Naval systems encounter a wide range of corrosion problems. In trying to fix these corrosion problems, the Navy needs to overcome some unique hurdles due to the severe environment and lack of conveniences that are available to land-based systems. These include dealing with limited maintenance capability and space, the inability to wash their aircraft as frequently as needed, and the lack of contractor support for rework during deployment.

The Navy is focused on three general application areas: ships/submarines; aircraft/weapons; and general corrosion. The highest priority NAVSEA and NAVAIR corrosion concerns are tanks/voids, insulated piping, valves, and hidden aircraft corrosion. These projects are managed by the Office of Naval Research.

The Navy adopted a Condition Based Maintenance (CBM) ACI five year Science and Technology program in 1996 which is managed by the Office of Naval Research. The goal of this program is to identify, develop and demonstrate affordable and robust CBM enabling capabilities to help lower costs of operating and maintaining the fleet. One of the four main thrusts of this program is corrosion detection/prevention.

The Navy is in the process of establishing an Aging Aircraft Group and hopes to work closely with the Air Force on their Aging Aircraft Program.

5.2.1.2.1 Office of Naval Research

As mentioned above, ONR serves as the overall manager for the CBM ACI S&T program within the Navy. In addition to managing the projects highlighted below being conducted by various Navy organizations, ONR has funded Framatome Technologies to address the feasibility of using encircling eddy current to detect changes in pipewall thickness due to corrosion without removing insulation. This is being evaluated as a fast-transition technology for cupro-nickel firemains.

ONR has also funded Texas Research Institute to study the potential of using guided ultrasonic waves to accomplish this same objective. TRI is in the process of developing a pre-production prototype. ONR envisions that this technique, if proven viable, may become the main technique for detecting corroded regions in pipes without removing insulation, replacing all other techniques including those employing eddy currents. Unlike the eddy current technique, which is not suitable for ferromagnetic materials such as steels, the guided wave technique is applicable to all metallic materials.

5.2.1.2.2 Naval Research Laboratory

NRL is currently investigating in-situ detection of changes in the potential of cathodically protected tanks/voids and correlating potential changes with deterioration of the protective coating. Corrosion found in painted ballast tanks is associated primarily with reduced paint thickness over weld spatter and at sharp corners. NRL is researching different remote monitoring technologies for corrosion detection on the ballast of ships and submarines. Part of the program research being carried out is to determine whether the state of the corroding tank can be monitored by monitoring electrochemical parameters such as the corrosion potential, and to develop a correlation between the measured potentials and the condition of the tank. If successful, this study would serve as the technology base for developing tank monitoring procedures for the fleets.

Since the ballast tanks in the more modern ships contain zinc anodes, a change in corrosion potential with paint degradation is expected. For the parts of the tank not covered by water (roof and upper portions of walls), the Navy is considering whether to develop a monitoring technology using galvanic sensors embedded in the paint at the substrate/paint interface.

5.2.1.2.3 Carderock Division, Naval Surface Warfare Center (CDNSWC) - Philadelphia

The CDNSWC team addresses all surface and subsurface corrosion issues and is a one-stop shop for research, development, test and implementation of equipment, techniques and training to the fleet. Because Navy maintenance funding has decreased, CDNSWC strives to be innovative and find ways to streamline the process. Their goals are to increase ship system equipment reliability, reduce costs of repairs and replacements, provide accurate material condition assessment, utilize a variety of technologies, transfer inspection responsibilities for technologies to the Fleet, and oversee Fleet maintenance.

This Nondestructive Test and Evaluation (NDT&E) group is responsible for assessing government and commercial advances in NDT&E technology, investigating high cost maintenance problems, initiating NDT&E system joint developmental efforts, validating NDT&E systems' performance in Fleet applications, and developing Fleet inspection procedures. To this end, this group has developed specific use of inspection technologies in the areas of acoustic emissions, eddy current, fiber-optics, infrared thermography, laser optics, ultrasonics, and magnetic flux leakage.

CDNSWC Philadelphia's developmental work is primarily directed toward finding a cost effective solution to operational maintenance problems for ships or submarines. However, the technology is not limited and can be applied to multiple applications in other government activities as well as the private sector. They have accomplished some innovative things, taking projects from the basic research stage through the implementation stage. Currently, they are concentrating on shortening delivery time to the Fleet through the use of commercial-off-the-shelf (COTS) equipment, where possible.

In some instances, it used to take the Navy seven to ten years from initial concept development through to delivery of a prototype Navy system. Now, since they are moving more towards commercial technology development, this lead time has been drastically shortened. Some of the more complex Navy/commercial developments can take three to five years. If the technology already exists, a performance specification can be written to tailor the commercial system to Navy application within one to two years. And if a commer-cial NDT&E technology to the application already exists which the Navy can capitalize upon, the time to procure the COTS system can be from one to twelve months. With equipment that this group maintains, inspections an be performed on call.

The inspection technologies that this team uses include acoustic emission, eddy current (for condensers), electro-optics, fiber optics, remotely operated vehicles, infrared thermo-graphy, laser optics, ultrasonics, laser shearography, magnetic flux leakage, and guided wave ultrasonics. Ship systems supported by NDT&E inspections include, but are not limited to, main boilers, auxiliary boilers, propulsion shafting, submarine mast fairings, submarine tiles, ventilation systems, elevator wire rope, gun barrels, piping and tubing systems, main condensers, auxiliary condensers, tanks and voids, HP air flasks, incinerator stacks, and composite structures.

Main focus areas of this team have been the in-place inspection of tubing, piping and hardware such as wire rope. They have introduced COTS equipment which have resulted in great savings.

This activity has a number of unique inventions that could prove to have great potential for expanding into both the commercial and other military sectors. One specific area for consideration is in the magnetic flux leakage technology (a derivative of eddy current technology) they developed to inspect for corrosion of wire rope found on aircraft carrier elevators. They use this technology to determine any anomalies present on the surface or under the surface of wire rope. Through use of this technology, the team hopes to be able to extend the current five year requirement for rope replacement. Applications are extensive in the mining, elevator, construction and ski industries as well as the navies and port facilities around the world.

Another possible dual use area is in their continued work on guided wave ultrasonics, which use an array of transducers. This technology will be used to measure wall thickness and cracks over long runs of high pressure piping under insulation in ships and submarines without having to remove the insulation. Texas Research Institute is working with them in this area.

CDNSWC Philadelphia is examining the feasibility of using acoustic emissions, and has started using shear wave ultrasonics for HP air flask/LP air receiver recertifications. Acoustic emission is used extensively in the commercial world for railroad cars and tankers. They are teaming with Physical Acoustics Corporation in Princeton, NJ who have already provided them with prototype equipment for this program. The benefit of these technologies is that they do not have to cut the ship open to inspect, thus saving time and money. It is projected that replacing hydrostatic/volumetric methods for recertification with shear wave ultrasonics will save the Navy in excess of $1M per aircraft carrier and $3M per submarine.

They are also using ultrasonic technology for the inspection of composite materials. Multiple equipments and structural areas of ships and submarine are being replaced with composite materials. Small boats in the Navy, Army and private sector are made with composite hulls. This group is using ultrasonic inspection techniques for defect detection and sizing, and damage assessment and quality assurance of repairs. Also, they have sued ultrasonics in the inspection of HMMWVs for the U.S. Marines.

This unit has developed a number of robotic, remote visual inspection systems that use standard techniques to suit specific inspection needs. One of these is a Remotely Operated Vehicle for Verification and Retrieval (ROVVER). This device, for example, allows for the remote inspection of exhaust stacks from the top, through the ship, to the engine. Another is a miniature robotic component that can be used for examining any four inch by four inch area. Other applications include piping systems, propulsion shafts, gas turbine intake stacks and incinerator exhaust stacks. Co-developed with private industry, it increases Navy inspection capabilities while decreasing inspection costs.

CDNSWC co-developed a laser optic tubing inspection system in conjunction with Quest Integrated, Inc. to inspect internal surfaces of tubing and piping for pitting and cracking. It has been used in many applications, including the inspection of Army tank gun barrels. These systems are used for inspection on main propulsion boilers and condensers and have been distributed for Fleet use. The savings to date realized by the Navy is $10M.

5.2.1.2.4 Naval Surface Warfare Center, Carderock Division – Bethesda

Within the Metals Department of the NSWC, there is a Corrosion Branch (613) that conducts research into the corrosion problems of the Navy. This branch is organized to address three separate technology areas – corrosion engineering and design analysis, corrosion science and coatings, and high temperature corrosion and advanced ceramic materials. The first two concentrate mainly on immersion splash and spray atmospheric marine corrosion.

The Corrosion Branch is involved in the following corrosion issues:

- Ship and submarine HME system corrosion problems
- System and component corrosion design analysis
- USMC vehicle corrosion control
- Waster sleeve corrosion for aircraft carriers
- AC and DC electrochemical testing
- Corrosion rate measurement and prediction
- Materials selection
- Corrosion failure analysis
- Cathodic protection system design and analysis
- Seawater and marine atmospheric corrosion testing
- Full or scale model seawater system and component testing
- Organic coating inspection and performance evaluation
- Corrosion modelling (computer and physical)
- Organic and metal matrix composite corrosion testing and analysis
- High temperature corrosion
- Corrosion control.

Some of the corrosion problems that they are addressing are submarine shaft seal corrosion problems and solutions, crevice corrosion causes and countermeasures, galvanic corrosion of mixed metal systems, seawater and atmospheric corrosion behavior of a broad spectrum of ferrous and non-ferrous alloys, and metal matrix composite corrosion. The NSWC is exploring electro-chemical impedance spectroscopy methods and applications to help detect the extent of the corrosion problems.

Their facilities include an electrochemical test lab, a stress-corrosion cracking test lab, a high temperature corrosion lab, computer workstations and networking to a supercomputer. In addition, they have three seawater and marine atmospheric corrosion test sites – LaQue Center for Corrosion Technology at Wrightsville Beach, NC; CDNWEC in Fort Lauderdale, FL; and NRL in Key West, FL.

5.2.1.2.5 Naval Air Systems Command (NAVAIR)

NAVAIR is spending approximately $1B annually on expenses incurred on maintenance and repair due to corrosion. NAVAIR researchers estimated that NAVAIR could achieve a 25 percent savings battling their corrosion problems by widespread adoption of existing technologies. They believe that aircraft maintenance could be reduced if they had an early warning system for hidden corrosion. With such a system, NAVAIR could effectively transition to condition based maintenance rather than time based maintenance, fixing components only when it was needed. But first, NAVAIR personnel stated that they must have in place a technology that provides them with a high degree of confidence in the data.

At the moment, NAVAIR has three levels of maintenance: 1) on the carrier, 2) intermediate level, and 3) depot level. NAVAIR scientists asserted that if work is conducted at the first two levels, then there is no need to have to bring the component to the depot level. The depot level should be considered a last resort.

NAVAIR's work in the area of corrosion detection sensor technologies employs several different approaches which are summarized below:

Fiber Optic - This program involves embedding very fine fiber optic strands in one continuous length under the protective coatings. The strands are burned with a laser to provide a series of graduations, all of which are different. The limitation here is that the graduations must be very sharp in the fiber. Depending on the degree of corrosion on the surface of the fiber, an interference pattern is produced which can identify the amount of corrosion and the location is known as the graduations generate a unique pattern. The installed position of the strand and its complement of graduations is known. Research is being conducted under a SBIR program by Physical Optics in California, in conjunction with Boeing Aircraft, which is very interested. The present limitation of this technique is the sharpness of gratings and the amount of light that reflects back for discrimination.

Galvanic Sensors - These sensors are constructed by electrodeposition and vapor disposition to form thin films. The sensors are self-contained with a data-logger and appropriate cathode and anode components. The sensor must be hard wired to a datalogger and polled by a central computer either in an onboard or offboard situation. The closer the gap between the electrode elements, the greater the sensitivity. The opportunity to vary the degree of corrosion measured is available upon manufacture as changing the sensor materials and the gap between the elements will result in greater or lessor initial and subsequent current flow growth with time. Sensor miniaturization and the radio transmission of corrosion current signals are the areas of current research activity, as is the conceptual evaluation of aluminum-ion sensitive paint compounds. Limitations to these sensors are the need to hardwire each sensor in an aircraft, which would add a fair amount of weight, and that the lifespan of these sensors is short. Four Coast Guard H-65 helicopters are flying with these types of sensors installed. A coulomb plot will allow for a measure of material loss based on the faraday equation. This test program has been expanded to include the Marine H-53, P-3, H-60 and F/A -18 test aircraft. The Australians and New Zealand Air Force have initiated fleet tests of these sensors. Another portion of this program supports the development of an ultrasonic guided wave probe at Penn State. The probe, which uses both longitudinal and transverse waves, will be able to detect wall thinning and delamination due to corrosion in aircraft.

Corrosion Microsensor - The thin film corrosion sensor technology has been taken further by adding an antennae, power supply, transmitter and memory to enable autonomous remote sensing. The limitation at the moment is the thin film battery necessary to power the unit over time. This technology is still in the early research stages.

Smart Coatings - The principle behind this process is that ions produced by corrosion will combine with this coating material, which will then make the coating especially visible under UV light. The basic problem with this technique is in the control to make exact homogeneous multi-ion paints. Work is continuing in this area.

Standing Wave Sensor - The NAWC has a contract in place to develop a prototype and demonstrate the utility in 1999 for this oblique angle ultrasonic transducer that can be used to measure the location and degree of corrosion. The technique requires a lot of power to be pumped into the structure, which could cause other problems. Thus, the results from this trial are needed before any further judgments relative to future utility can be made.

5.2.1.2.6 US Navy Mid-Atlantic Regional Maintenance Facility, Norfolk, VA

The U.S. Navy Mid-Atlantic Regional Maintenance Facility, located at the Norfolk Naval Shipyard, replaced the Naval Air Rework Facility (NARF) during one of the earlier base re-alignments. The facility is considered an intermediate maintenance facility. As stated previously, the U.S. Navy has three levels of maintenance: (1) organizational, (2) intermediate, and (3) depot. Organizational level maintenance is performed as needed while systems are on-station. Intermediate level maintenance is performed as needed when systems are in port, and is usually more extensive than organizational maintenance. Depot level maintenance is the most extensive level of maintenance, being typically comprised of scheduled major overhaul and repair.

This facility is the cognizant field activity for the EA-6B, and C-2/E-2 support aircraft. They also have experience maintaining F-14 fighters and F-18 attack aircraft that are stationed at Ocean Naval Air Station in Virginia Beach. Since the re-alignment, their responsibilities also now include maintenance on the aluminum superstructures of destroyers and fast frigates. The facility is expanding its responsibility even further to provide maintenance to anybody and any system in any of the services who require NDE, trying to compete with other depots and air logistics centers for maintenance dollars.

The NDI group at the facility is composed of three engineers. Many uniformed maintenance personnel support the group. Their goal is to inspect and fix whatever maintenance problems confront them as quickly and efficiently as possible in support of the Navy's readiness goals.

The basic NDE techniques they use are visual, ultrasonics, and eddy current. Visual techniques are used all of the time; ultrasonics and eddy current are used to further inspect questionable areas, if required. Other techniques are used only for very special circumstances.

The NDE staff stated that they typically do not see problems in lap joints of Navy aircraft. Particular problems they encounter are exposed antenna attachment points, electrical connections, and control surfaces. Recurring problems are usually referred to design teams to see if there is a redesign or retrofit that can help alleviate the problem.

One of the special circumstances they have been dealing with is corrosion in the aluminum honeycomb core of the wings and control surfaces of F-18 aircraft. The basic techniques are not as useful for these components. For these problems, the engineers have found that X-ray radiography and neutron radiography are more useful techniques. They tend to like X-ray radiography better because it's cheaper than neutron radiography and because they have to ship components to McClellan AFB in Sacramento in order to utilize neutron radiography.

5.2.1.2.7 Jacksonville Naval Aviation Depot

The Jacksonville NADEP provides depot level maintenance for P-3, S-3, EA-6B, and E-6 support aircraft, F-14 fighters, and F-18 attack aircraft. The NADEP also services TF34 and J52 jet engines. The emphasis during depot maintenance of these systems is on corrosion detection and prevention. Corrosion inspections are conducted to better understand trouble spots on each aircraft or engine. A typical corrosion inspection for a P-3 takes 30 days.

The predominant technique used to inspect for corrosion at the NADEP is visual. NDE techniques are used to supplement the visual inspections and for particularly tough inspection areas. NDE technologies being used by the engineers at the NADEP are liquid penetrant, eddy current, ultrasonics, magnetic particle, x-ray radiography, and computed tomography. Thermography is rarely used. The engineers are not big proponents of neutron radiography. They understand that it is very sensitive to hydrogen, and thus water, which may cause corrosion, but the cost of implementation is prohibitive.

In the area of corrosion prevention, the NDI team discussed a number of techniques that they think hold great promise. Exterior corrosion problems could be alleviated by washing down the aircraft after each mission. This would remove any salt or other corrosive from the surface of the aircraft. Dehumidification or forced air storage shelters for aircraft should be used to keep them free of moisture. They also believed this could be further enhanced by requiring future aircraft to be designed with air "flow-thrus" in the body of the aircraft to reduce the amount of trapped moisture. Lastly, they discussed the increased use of corrosive preventative coatings. The engineers at the NADEP stated they are currently testing a product called "Dinol" that is used extensively by the Australians on all of their aircraft with very good results.

5.2.1.2.8 North Island, NAVAIR

North Island does major, depot-level aircraft overhauls lasting from 6 months to 1 year in duration. It is similar to the NADEP at Jacksonville, in that it works on F/A-18, E-2, C-2, F-14 and S-3 aircraft. Their focus in the area of corrosion is on maintenance-type prevention using new sealants. They use standard visual, ultrasonic, eddy current and x-ray techniques for corrosion detection. The NDE specialists stated that the E-2 and C-2 airframes are the Navy's biggest problems, due to their age. The S-3s have problems with corrosion, but this is primarily caused by the aircraft's design and is being corrected as the airframes undergo re-work. All F/A-18s receive an annual visual inspection by field teams sent out from North Island. The Navy uses 52-day inspections (primarily visual) at the organizational level to look for corrosion in the field and that the intermediate level of maintenance uses eddy current and ultrasonic techniques.

5.2.1.2.9 Pearl Harbor Naval Shipyard (PHNSY), Pearl Harbor, HI

The PHNSY personnel indicated that one of their primary corrosion problems was with bronze bearing shells, located under the main propulsion shaft on ships, that often corrode badly due to their frequent immersion in seawater. The machining needed to cut out any corrosion is expensive to perform. The use of galvanic straps has mitigated, but not eliminated, the problem. While any corrosion is detected visually (using boroscopes), this still requires removal of rubber bearing elements. Then once these are replaced, it often is found that the receiving area also has corroded, a problem which often is not/can not be recognized until the first repair is made, adding a further cost. The bearing shell corrosion problems have been seen only in warm water climates.

Another significant problem the PHNSY team has encountered is corrosion and rotting of rubber on board naval vessels, especially on submarines. Large pieces of equipment are often mounted on resilient rubber mounts in order to reduce emitted noise. If visual inspection determines that the mounts have swollen, they are replaced. However, it is not known if the mounts can fail without swelling and there is no way to test to see if non-swollen mounts have failed. For instance, it is not possible to determine aboard ship whether a mount is compressed because it is under load or because it has failed.

The representatives also mentioned that corrosion and the condition of air intakes is critical. These intakes gather fresh air and feed it to the ship's power turbines. Due to the salt-laden nature of the maritime air which is ingested, the intakes are subject to corrosion. The attendees did not know what other technologies might be appropriate, but estimated that 99 percent of the inspections performed at present in the fleet on these intake valves are performed visually. They also commented that aluminum forms a self-sealing oxidation layer. Thus, it may be impossible to avoid the formation of some oxidation on its surface.

The representatives commented that in the Navy's environment as a whole, but especially in the submarine world, there is an operational aspect to the cost of corrosion: it can contribute to an increase in emitted noise, reducing the operational effectiveness and survivability potential of the vessel.

On the structural side, most NDI is performed visually, especially in otherwise inaccessible areas. Often, these inspections occur at sea. In fact, accessibility limits the areas where even visual searches can be performed, since often access to even one side of a structure or piece of equipment is difficult. In addition, often the surface preparation required to perform an efficient NDT effort is so extensive that it is not feasible to perform the test/inspection. A specific example cited was that of condenser tubes, for which reliable methods of inspection (eddy current) exist, but for which the preparation is very time-consuming. Consequently, in many cases, often only a general idea of the material thickness remaining in an area undergoing inspection is available in an area of general pitting. Eddy current is used to test/inspect tubing aboard ships, radiography is used to check pipes (it was stated that safety considerations are not as great a concern here), and visual inspections are used on hulls.

One representative stated that there is no such thing as a non-visual non-destructive test of the glass-reinforced plastic used in sonar systems since the material "breaks apart."

One major impediment to maximizing the benefits gained from the inspections which are performed is that often Shipyard personnel do not have the basic information/specification on the piece of equipment or material which is being tested. They often are told by the OEMs that the details of the equipment which is undergoing tests are proprietary, even though the Government usually purchases and should receive engineering drawings for use in the maintenance and repair of the equipment at the time of its procurement. This problem is especially prevalent in the surface craft community.

Again in the area of structures, and especially submarines, it was said that most of the materials being dealt with in the Navy community are thick, and the view of the participants was that proper installation and preservation will prevent corrosion. Thus, they do not view external corrosion as a safety/structural problem (as the air community does) and see no need for special NDI equipment to detect/combat it. If an area of a hull (even a submarine hull) is corroded extensively, it can merely be cut out and replaced. Cutting through hulls is, in fact, a standard procedure, since it frequently is done to gain access to equipment in interior compartments which can be reached in no other way. It often is not even necessary to put the ship in drydock to perform such repairs, although submarines generally are repaired in drydock.

The Shipyard is able to buy its own NDI equipment out of its own budget, so if a new piece of equipment/technology can be justified, it can be purchased. The representatives were asked about their ability to introduce new NDI technologies into use at the Shipyard. They are not subjected to the same constraints as the aircraft industry, where the FAA and OEMs often restrict the use of new technologies to perform corrosion detection for safety or potential liability reasons. Instead, since the Shipyard operates on limited funds, the cost-effectiveness of any new system must be demonstrated if it is to be procured and used. Any new system must be inexpensive enough to be affordable in terms of both procurement and operator training costs.

5.2.1.3 U.S. Army

In the corrosion arena, the Army has placed most of its emphasis on corrosion prevention technologies rather than corrosion detection technologies. The Tank-Automotive and Armaments Command (TACOM) was directed by the Army Materiel Command to develop a Corrosion Prevention and Control Program to address the concerns for Army weapon system corrosion.

Part of the impetus behind this program was the serious corrosion problems affecting the U. S. Army Pacific fleet. The fleet was unable to maintain the vehicles without frequent replacement of exterior items. Vehicles were succumbing to rust and needing to be replaced within 15 years of service life. The Army estimates that the Pacific Fleet has to spend approximately $4M per year on vehicle corrosion control and prevention in order to keep the fleet mission ready. The Pacific Fleet has embarked on a rustproofing/painting program to extend the life of the current fleet by five years.

The Picatinny Arsenal is spearheading the CPC effort for TACOM. The objectives of this program are to decrease life-cycle costs, increase Army readiness by reducing equipment down time, and reduce the maintenance burden being placed on diminishing active and reserve work force resources. The CPC program has empowered Corrosion Integrated Product Teams at all AMC Subcommands whose efforts are coordinated by an AMC Corrosion Abatement Team, chaired by the AMC Corrosion Manager. A major focus of the program is on policy issues to ensure that the most appropriate and economical corrosion control technologies are included in all weapon system designs, and that CPC is part of the materiel release process for new acquisition and rebuild programs. Its goal is to ensure that AR and DoD policy places the responsibility for user's cost of ownership with each Weapon System Manager/PM/PEO throughout the operational phase.

To address the science and technology issues, a two-pronged attack is being implemented: 1) identify, test and implement the latest CPC state-of-the-art practices available in industry, and 2) develop, verify and implement new technologies to reduce corrosion in new and fielded systems.

Finding noninvasive ways to detect hidden corrosion is part of the Army CPC plan. The Army is studying new technologies that are less manpower intensive than those used in the past, with a focus on automating the decision making process. Sensor technology is one of the major Science and Technology R&D areas of the program, particularly for use in locations requiring major disassembly or destructive disassembly for inspection.

5.2.1.3.1 U.S. Army Research Laboratory (ARL), Metals Research Branch

The Metals Research Branch of the Army Research Laboratory is the primary research arm in the Army concentrating on the Army's corrosion problem. Their main focus is on corrosion prevention through coatings.

However, ARL has studied a number of the different technologies that we are addressing in this study for corrosion detection. The lab, though, has examined these technologies more for use at the manufacturing level and/or to inspect production line tools for quality measurement. The techniques are the same but the setup and utility are different.

NDT developments that ARL is pursuing include detecting stress fatigue cracking/stress corrosion using acoustic emission technologies. This entails picking up acoustic emissions from samples while it is stress corroding.

ARL is also developing electrochemical impedance spectroscopy techniques to measure the first beginnings of coating deterioration. This technology is not easily adapted to aircraft because the inspectors would not be able to ascertain what is happening at the rivets.

X-ray images are being investigated using computer topography to develop 3-D images that neural networks can analyze for fault detection. One application this is being used for is for inspecting artillery fuses.

Ultrasonic C-scan transducer developments are being researched that would allow explosive armor to be characterized initially and then tracked over time on a vehicle to determine its protection capability. ARL has two emergent tanks for scan analysis.

In the acoustics arena, ARL is working with a Chicago company, SANTEC Corporation, which is developing a ”2X2” sensor that will provide a one shot C-scan equivalent representation of both flat surfaces and around shapes. This shows great promise for armored vehicles.

In the visual domain, the focus of the work is to develop neural networks for an auto analysis of digitized video. To do this, however, destructive tests are required to train the networks. The advantage to this technology is that you will not have to train people for repetitive inspections. The potential application to corrosion detection is evident but off in the future.

ARL also has eddy current and thermography capabilities. They have not done any research in the eddy current area for a few years. ARL uses the thermography laboratory at the University of Delaware.

5.2.1.3.2 Army Research Laboratory (ARL), Vehicle Technology Center

ARL has an office with five NDE technology researchers in the same building as the NASA NDE researchers as a result of government consolidation. They are working on a number of joint NDE research efforts with NASA Langley researchers (see NASA Langley writeup).

5.2.1.3.3 Army Aviation Missile Command, Depot Maintenance Engineering Team

The Depot Maintenance Engineering Team is responsible for all engineering in support of Army aviation maintenance. They are the lead organization responsible for reviewing corrosion prevention and control for aircraft. There are approximately 30 engineers on this team. One of their major programs is conducting an Airframe Condition Evaluation (ACE) annually. This involves sending teams of inspectors to go out and examine aircraft for indicators of wear and tear, among other things. The objective of this program is to prioritize aircraft for overhaul, in a move towards overhauling aircraft based on condition based maintenance rather than at set intervals. The team recently created additional points to add to their checklist to look for corrosion indicators. They work in coordination with the other Services, sharing data on H-60 helicopters.

5.2.1.3.4 U.S. Army Pacific, Ft. Shafter, HI

The Science Advisor for USARPAC noted that the most pervasive and expensive problem in the Pacific is corrosion. The 25ID(L) spent $11.6M, FY79 - FY84, to repair corrosion on 1,919 vehicles. The current program (FY96 - FY98) will spend $5.9M to repair corrosion on 3,700 vehicles. And USARHAW still has 1800+ pieces of equipment in need of corrosion repair.

She noted that the solution is multi-faceted:

- ground vehicles and aircraft must be designed with corrosion resistant materials and runoff should be encouraged or areas sealed to prevent entry of seawater;
- equipment shipped overseas should be sprayed with a rust inhibitor prior to shipment;
- expensive equipment should be stored in dehumidified shelters or expensive electronic sections of vehicles/aircraft should be dehumidified separately;
- corrosion prevention must be given high priority in maintenance programs by providing necessary tools, training, and time.

All of these - design, materials, preventive measures, storage, and proper maintenance - must be undertaken to alleviate this pervasive problem.

The SA has been continuing discussions with TACOM PMs, requesting the corrosion issue be a strong influence on future upgrades and requesting the application of a rust inhibitor to new equipment prior to shipment. SA has drafted a letter from LTG Steele, CG, USARPAC, to MG Beauchamp, CG, TACOM, requesting Carwell Rust Inhibitor be applied to all ground vehicles sent to USARPAC. Carwell has been proven to be effective in absorbing moisture and providing a protective coating against corrosion without adversely affecting the CARC paint. It is one of the five anti-corrosion products which successfully passed the Fielded Fleet Corrosion Control Program conducted by Materials Modification Inc. and reported in July 1997. The five products reduced mean time to repair (MTR) by at least 30 percent.

A two-and-a- half week Corrosion Prevention and Control (CPC) demonstration and course will be held 27 April - 8 May for welders and motor pool personnel at the 25ID(L). 9thRSC, HiARNG, and USARJ personnel will be included. A vacublaster and Sulzer Metco Flame Spray equipment will be delivered to DOL Shop 5, 25ID(L). TARDEC will provide a welding review and certification. The vendors of the various products will teach grit blasting; and the application of Sulzer Metco flame spray, Zingametall, Ziebart, and Carwell. Mr. Howard Miyamoto, Industrial Hygiene, will address issues associated with the touchup application of CARC paint. TARDEC is funding the welding review; AMC FAST funded the equipment and some of the training.

The Science Advisor provided an overview of the status of various systems:

- GROUND VEHICLES: Upgrades including better corrosion-resistant materials (galvanized GP90, stainless steel, aluminum) and designs to discourage entrapment/encourage runoff are coming or are planned for various ground vehicles from TACOM.
- FMTV: COL Dobeck, PM-FMTV, will have the Carwell Rust Inhibitor applied to all 1196 FMTVs to be shipped to USARPAC in FY98 and FY99; these vehicles will have the advantage of upgrades ($2500 per vehicle) geared to corrosion prevention, the funding for which was obtained by COL Dobeck, Oct 96.
- HEMTT: USARPAC will benefit from the many changes to the HEMTT over the last 10-15 years - welding changes, drainage tubes instead of trapping of water in earlier designs - in the FY98 delivery of 14 HEMTTs. PM-HTV is considering an Engineering Change Proposal (ECP) to provide galvanized cabs, dielectric coatings for electronics and stainless steel tubing.which could enhance future HEMTT procurements.
- PALLETIZED LOADING SYSTEM (PLS): PM-HTV will coat the PLS-1075s coming to USARPAC with zinc chromate primer at a cost of $6K apiece.
- M129 TRAILERS: PM-TAWS is planning to replace the 17 M129 trailers at USARPAC with aluminum trailers.
- 1022A1 DOLLY SETS: ESCO has provided pre-galvanized or hot dip galvanized steel components as well as corrosion resistant hardware in the dolly sets just received by USARPAC.
- ROTORBLADE AIRCRAFT: USARPAC has recently received 32 Blackhawks (UH60L) made by Sikorsky. The 25ID(L) has an effective Corrosion Prevention and Control program; a contractor, LMI, is the second line of defense in corrosion after the unit. The unit takes advantage of a corrosion prevention class provided by the Navy at Barber's Point. None of the aircraft is 'stored'. Sikorsky has an active Corrosion Prevention and Control (CPAC) group, Team Hawk (a quad service) and sponsors Users' Conferences geared for maintenance officers and chaired by the PM. Recommendations are provided as to treatments, assembly, and testing of corrosion-prone areas and a tri-service corrosion manual for field commanders has been developed. AMCOM recommends a zinc chromate spray for corrosion problems.

Maj Chiles, Deputy Support Operations Officer, 45CSG, has developed a Corrosion Prevention and Control Plan which has been approved by BG Campbell, Deputy Commander Support, 25ID(L). SA plans to work with COL Thompson, Commander, 45CSG, and Maj Chiles in building justification for funding of sorely needed vehicle wash facilities at Schofield Barracks and the Pohakuloa Training Area on the Big Island where 25ID(L) conducts much of its training. SA also plans to consider a mix of equipment at 25ID(L) in determining the equipment for which dehumidified storage would be justified. The Science Advisor noted that effective, long-term maintenance is the last, but most important piece of the Corrosion Prevention and Control Program. She asserted that, without it, vehicle redesigns and use of better corrosion-resistant materials will have been for naught.

5.2.2 Marine Corps

As with the other Services, corrosion is a major concern of the Marine Corps. During the Desert Storm build-up, Camp Pendleton identified major environmental compliance issues surrounding Chemical Agent Resistant Coating (CARC) application. Assets returned from SWA highlighted the corrosion problems in the Marine Corps.

The Marine Corps procures most tactical ground equipment through other Services. For example, wheeled vehicles, tanks and engineering equipment (i.e., air conditioners, generators, water purification equipment, etc.) are procured by the Army. Additionally, Marine Corps equipment is transported by ship, and operated in coastal areas, jungles and deserts. This contributes to a severe corrosion environment. As a result, incorporating Marine Corps corrosion requirements requires extensive coordination, in addition to identifying corrosion requirements.

Within the corrosion arena, the Marine Corps' major emphasis is on corrosion prevention and control and they have a program in place to address these issues. The Marine Corps Corrosion Prevention and Control (CPAC) program was formally established by MCO 4790.18 dated 20 June 1994. The order provides policy for the management and execution of the Marine Corps CPAC program, placing management responsibilities at Marine Corps Systems Command (MARCORSYSCOM), Quantico, Virginia, with policy and oversight responsibilities residing at Headquarters, United States Marine Corps. The two primary elements of the program are preventive corrosion control and corrective corrosion control. Preventive measures include acquisition support and technology insertion. Acquisition efforts focus on incorporation of adequate corrosion control measures during the design and production phase. Technology insertion involves the evaluation of commercial products for applicability to Marine Corps tactical ground and ground support equipment. Part of this effort entails evaluating maintenance procedures and recommending changes.

As the Marine Corps prepares to enter the next century, many factors will impact the Marine Corps' ability to maintain a combat ready posture. One area that can benefit from technology and a joint service partnership is corrosion. The Marine Corps has developed a Plan of Action and Milestones as their strategy for the future. This strategy focuses on product and process improvement, training and education, partnerships with other Services and private industry, and other futuristic initiatives. Their underlying intent is to reduce or eliminate duplication of corrosion prevention efforts within the Department of Defense and have laid the groundwork through much interaction with acquisition agencies and groups such as NACE and the Tri-Service Conference on Corrosion. Their vision is for an integrated corrosion control working group at the highest level to address the problems of today and prevent the consequences of tomorrow.

The first effort pursued by the Marine Corps CPAC program was fielding a replacement for CARC. CARC gives Marine Corps equipment its camouflage pattern but environmental restrictions in Southern California limit the amount that can be applied. Headquarters Marine Corps directed that an alternative be found. Extensive testing resulted in a coating that met all camouflage requirements but was not resistant to absorption of chemical agents. This coating, now in use throughout the Marine Corps, is referred to as Waterborne Camouflage Coating (WBCC). It is the precursor of the Waterborne CARC being developed by the Tri-Service SERDP effort.

A major effort to incorporate corrosion requirements into acquisition documents has been initiated. Acquisition reform has mandated a fresh approach to procurement practices within DoD. No longer can MIL-Specs and Standards be used at will. Corrosion requirements must be translated into performance language. Basically, the Services must tell a prime contractor what is required, not how to meet the requirement. As a result, corrosion requirements must be identified in terms of operational environment and required useful life. Tests to verify conformance may still be invoked. Generic wording for all acquisition documents required by DoD 5000 is being developed by a team composed of corrosion and acquisition personnel. Tailoring will be done for specific programs.

The Marine Corps is comparing accelerated test data from GM 9540P/B and ASTM G85 and B117 to marine atmospheric performance of metals and coatings. The objective is to identify the best method to verify conformance of a product to performance specifications.

The Marine Corps is currently evaluating corrosion improvements for many Marine Corps vehicles. Material substitutions for exhaust systems, fuel and brake lines and head lamp assemblies for HMMWVs and 5-ton trucks are being evaluated in marine atmosphere and field tests. Thermal spray aluminum is being evaluated for specific failure points on both vehicles, such as hard top latch, rear corner panels, door frames and posts and roof gutters on HMMWV and cab floor, hood cowl and tool boxes on 5-ton truck. Thermal spray plastic was applied to 5-ton battery boxes. Tests evaluating additives to washdown water and crevice coatings were also initiated.

Corrosion engineering support to Program Managers within MARCORSYSCOM is a major emphasis of the Marine Corps program. While life cycle cost data to support corrosion upgrades is difficult to obtain, the corrosion related maintenance burden is significant enough to justify the improvements. This effort includes design analysis, material and coating selection, evaluation of fleet condition, source selection criteria, and environmental and maintenance impacts. This work is done in coordination with other Services.

Environmental compliance issues plague most Marine Corps locations. Efforts to facilitate organizational maintenance prompted evaluations of surface preparation equipment and surface tolerant coatings. Other efforts to evaluate underbody coatings are underway. These efforts support fielded equipment and can be incorporated into new acquisition initiatives.

Controlled humidity preservation of equipment is being pursued for fielded equipment to isolate the equipment from its environment.

A USMC Corrosion Control Web Site is being developed to encourage information exchange within DoD. This web site will provide information on the Marine Corps corrosion program and provide access to test data.

5.2.3 Canadian DND Activities

The Canadian Department of National Defence (DND) has several different departments and laboratories researching corrosion detection and corrosion prevention technologies. These groups are extremely effective in coordinating their research activities. Most R&D efforts are handled at AVRD and NDHQ. Applications are then developed and tested at ATESS. Those applications which are proven effective are then put into use in the field at area facilities and wing engineering maintenance centers.

A predominant focus of their research is on corrosion prevention and detection in aircraft. The Air Vehicle Research Detachment/Structural and Materials Group oversees R&D in these areas.

5.2.3.1 Air Vehicle Research Detachment

The Air Vehicle Research Detachment (AVRD) is a CRAD organization formed with the goal of providing a focus for, and delivering, air vehicle research and development. One of their R&D thrust areas is the Air Vehicles Thrust, which is aimed at reducing the costs of DND aircraft operations while maintaining or improving airworthiness standards. A large portion of the structures and materials activities are conducted under contract by the National Research Council/Institute for Aerospace Research as one large project under this thrust. Many projects are also initiated in collaboration with the NRC/IAR. The AVRD houses an NDT laboratory with state-of-the-art eddy current, ultrasonic and real-time radiographic equipment in addition to an enhanced visual D-Sight system. Most in-house activities focus on the detection of hidden corrosion and cracks under fasteners.

The AVRD and the NRC/IAR/SML are investigating technologies and advanced materials for improved corrosion resistance in aging aircraft. Both organizations are also researching a wide range of techniques to non-destructively inspect high priority components and address recurrent structures and materials problems.

AVRD cited six examples to highlight the increasing age of the air fleet which are presented in Table 5-1. AVRD believes that the primary corrosion problems in the fleet stem from the use of 7075-T6 aluminum aircraft structures, particularly the Hercules and Aurora fleets. The harsh environments in which these aircraft operate also is a large contributor to the corrosion problems.

AVRD and NRC/IAR/SML are researching the entire spectrum of NDT techniques for corrosion detection. Researchers at NRC/IAR, with early funding support from AVRD, developed the “D-Sight” technique with Diffracto. They are continuing to work to optimize the technique. They claim that D-Sight can now detect 3 percent material loss. They have two current ongoing contracts related to D-Sight with U.S. Air Force OEMs, one of which is with Northrop Grumman in Long Beach, CA. They are also researching advanced optical, eddy current, guided wave ultrasonics, and real-time x-ray techniques.

Table 5-1. The Aging Canadian Forces Air Fleet.

Aircraft	Aircraft Age	Projected Retirement Date
CT "T" Birds	45 years old	2005
CT114 Tutors	34 years old	2015
CC130 Hercules	33 years old	2010
CP140 Auroras	18 years old	2010
CF18 Hornets	15 years old	2010
CH 124 Sea Kings 35	years old	2005

AVRD is collaborating with QETE, the Royal Military College (RMC) and the Aerospace and Telecommunications Engineering Support Squadron (ATESS) to solve its CF-18 rudder and aileron water ingress problem. The goal of this collaborative effort is to quantify how much corrosion is too much or, stated another way, what is the corrosion threshold at which the CF-18 fleet can still operate effectively.

The program directors at AVRD have underway a project performed at Royal Military College on a knowledge based system, which will make corrosion maintenance information more complete and easily retrievable as well as allow the integration of data from various sources, including that from NDT and future on-line monitoring sensors. This information system will aid structural integrity managers making airworthiness decisions and rationalizing maintenance inspections related to corrosion damage.

They have also undertaken a corrosion surveillance project to reduce maintenance costs by optimizing corrosion prevention actions and inspection schedules. This includes data from environmental sensors and on-board optical sensors to monitor corrosion activity.

Other advanced NDT technologies being investigated in-house by AVRS personnel are pulsed eddy current, dual frequency eddy current scanning, and enhanced imaging methods in ultrasonics. Collaborative projects are also in place with NRC/IAR and IMI to investigate air coupled ultrasonics and laser ultrasonics for hidden corrosion detection.

5.2.3.2 Institute for Aeropsace Research (IAR), National Research Council Canada

The NRCC/IAR has an NDI laboratory with state-of-the-art eddy current, ultrasonic and real-time radiographic equipment in addition to an enhanced visual D Sight and Edge of Light (EOL) systems. In-house activities focus on the detection of hidden corrosion, cracks, defects in composite structures and disbonds in bonded joints. The NRCC/IAR is investigating technologies and advanced materials and processes for improved corrosion resistance in aging aircraft. NRCC/IAR is also researching a wide range of techniques to non-destructively inspect high priority components and address recurrent structures and materials problems, inspection reliability assessment as well as NDI signal processing, pattern recognition and neural networks.

Researchers at the NRCC/IAR helped Diffracto Limited develop the D Sight technique for aircraft NDI with funding from DND/AVRD, Transport Canada, FAA and USAF. Work is continuing to work to optimize the technique and to develop quantification capabilities. that the NRCC/IAR has demonstrated that D Sight can reliably detect 3 percent material loss in lap joints. Collaboration continues between DND/AVRD (located in the NRCC/IAR building) regarding research of the entire spectrum of NDT techniques for corrosion detection. The NRCC/IAR is also researching advanced optical Edge of Light (EOL), eddy current, guided wave ultrasonics, air-coupled ultrasonics, and real-time x-ray techniques. Collaborative projects are also in place with Industrial Materials Institute (IMI) of NRCC to investigate laser ultrasonics for hidden corrosion detection in lap joints and exfoliation under faster heads in thick section structures. Naturally and artificially exfoliated specimens (using an NRCC/IAR developed process) are included in this project. This project is partly sponsored by DND /AVRD.

The NRCC/IAR has developed one of the largest Aging Aircraft Specimen Libraries. Over 300 fuselage and wing sections have been collected from decommissioned aircraft (Boeing 707, 727,737 and 747, Douglas DC-9 and DC-10, Lockheed L1011, Bombardier CL-600). These specimens have been inspected with various NDI systems and the data is entered into a database along with AutoCAD drawings. Many specimens contain natural corrosion and cracks. Some have been artificially corroded using an SMPL developed process. The specimens are used by the NRCC/IAR and other organizations to develop NDI systems. For example, including SANDIA Labs who have contracted NRCC/IAR to supply specimens for their corrosion NDI validation work (FAA AANC) and several European Laboratories have also contracted the NRCC/IAR for similar services.

The NRCC/IAR is being supported by AVRD to develop a capability to perform data fusion on a wide variety of NDT techniques. Currently, D Sight and EOL inspections of lap splice joints have been interpreted by data fusion processes on a computer, and research is being carried out in fusion of D Sight/EOL with pulsed eddy current inspections of airframe components.

The NRCC/IAR has current ongoing contracts related to corrosion-fatigue with DND, USAF and OEMs. One of the key aspects of these projects is the development of corrosion metrics using various NDI systems.

5.2.3.3 Quality Engineering Test Establishment (QETE)

The role of the Quality Engineering Test Establishment (QETE) is to work with the various research organizations in Canada to develop efficient and effective techniques for Canadian Forces maintenance detachments in the field.

The primary effort ongoing in the corrosion detection/NDT area at QETE concerns an ongoing examination of water ingress into the composite Al honeycomb structure of CF-18 rudders and ailerons. Upon examining the issue closely, QETE engineers found that 65 percent of CF-18 rudders and ailerons were experiencing some quantity of water ingress that was leading to corrosion in the aluminum honeycomb structures. When QETE consulted with the U.S. Navy about the problem, they discovered that the U.S. Navy simply scraps any rudder or aileron that is found with water ingress. The Canadian Forces, however, does not have the resources to replace every rudder and aileron that experiences water ingress.

In order to address the problem, QETE engineers have initiated an effort to try and quantify how much water ingress, and therefore how much corrosion, is too much. They are testing sample CF-18 damaged rudders and ailerons using through-transmission ultrasonics and X-ray radiography. The QETE engineers consider that neutron radiography and thermography provide them with a good representation of the amount of water in the structures.

5.2.3.4 Aerospace and Telecommunications Engineering Support Squadron (ATESS)

The mission of the Aerospace and Telecommunications Engineering Support Squadron (ATESS) at CFB Trenton is to provide critical aerospace and telecommunications engineering, specialized training and production in response to ongoing maintenance, installations and urgent operational requirements. ATESS has an annual operating budget of $15M.

NDT is one of ATESS' many capabilities, in that they are responsible for the actual development of NDT techniques that are implemented in the field. ATESS inspection technicians utilize both basic and advanced NDT methods. The basic NDT methods used by ATESS inspection technicians are:

- Liquid penetrant inspection (LPI)
- Magnetic particle inspection (MPI)
- Ultrasonic inspection
- Eddy current inspection
- X-ray and gamma ray radiography.

The advanced NDT methods used by ATESS inspection technicians are:

- Robotics scanning system
- Diffracto D-Sight
- X-Ray film digitizer
- Shearography
- Thermography
- Optical prism system
- Multi-directional MPI system.

In regards to thermography, rather than having a pulsed thermography system such as the system being developed by Wayne State University and Thermal Wave Imaging, ATESS instead uses a portable hand-held heater as the heat source. They use a similar infrared camera.

5.2.4 Australian DoD Activities

The major Australian DoD research arm involved in studying corrosion detection technologies is the Defence Science and Technology Office. The Office has a number of divisions addressing different corrosion issues and technologies to employ to detect and correct corrosion. There is a high level of coordination between these divisions. A predominant focus of their work is on aging aircraft as well. A summary of the current R&D activities is provided in the following sections.

5.2.4.1 Defence Science and Technology Office (DSTO)

The role of the Aircraft Corrosion Control, Maritime Platforms Division, is to help the Australian Defence Forces (ADF) control and prevent corrosion in Fixed and rotary wing aircraft and ships. The Aircraft Corrosion Control, Maritime Platforms Division consists of 12 - 15 researchers. Their work is sponsored by the RAAF (which covers Army needs) and the RAN.

Australia flies a number of older aircraft and has found that corrosion is a major driver of aircraft lifetime, overtaking fatigue cracking. One DSTO representative estimated that the cost of corrosion in Australia runs to $25M - $30M AUD per year (scaling off the 1990 USAF study).

AMRL controls the total value of their study program, but decides on the projects studied in consultation with the RAAF and RAN. Ten percent of their budget is devoted to enabling R&D projects. One ongoing project is to implement corrosion databases to quantify whether their work is impacting corrosion. However, they admitted that in the past funding was hard to generate for the types of projects performed by this group, but this is changing.

The division conducts research over a broad front. The first is environmental characterization. That is, AMRL's job is to characterize and monitor the operational environment of the aircraft, including the environment/climate at the RAAF bases, since the aircraft spend 90 percent of the time on the ground. This characterization includes the development of sensors and monitors for use inside the aircraft, to monitor both the environment and corrosion growth. An example is in the tail of the P-3 near the rudder torque tube. Sensors placed here ensure that when the environment becomes "aggressive," the contaminants present will be known. This type of monitoring is to be expanded to other sites within the P-3. The sensor used is based on a galvanic pile, and includes a self-contained, battery-powered (with a 2-month lifetime) chip. Other sensors will be placed in F-111s, but will use a linear polar design to measure corrosion rates *in situ*, allowing AMRL to choose better coatings.

A second area of interest is corrosion prevention. This includes the testing (but not the research and development into) paints, sealants, new alloys, and CPC-free solvents.

Another area of interest is corrosion control. Here, AMRL tries to detect, size and watch the growth of corrosion, removing it only when necessary. This covers three specific sub-areas. The first is the study of corrosion prevention compounds. Here, compound life is key, so that determination of the best means to apply them is essential. A second corrosion control sub-area is aircraft washing in which the careful choice of detergents which clean, inhibit corrosion, and leave little residue is being examined. The third sub-area is dehumidification. This is attempted wherever and whenever possible. The DSTO representatives mentioned that while 501 Wing at Amberley (see 5.2.4.4) is unaware of this effort, the flight line personnel in operational squadrons know of it and attempt to place dehumidifiers near each parking point on the flight line. In addition, the F-111Gs recently received from the USAF which are to be kept in storage will be kept in dehumidified spaces. Such dehumidification facilities cost only $5K - $10K AUD per unit.

AMRL also studies the interaction of corrosion and fatigue. Their belief is that if they are going to leave corrosion in place to monitor its growth and impact, they must know how it interacts with stress loading, especially on plane surfaces and at fastener holes.

The Aeronautical and Maritime Research Laboratory is also involved in eddy current research. The NDE Research group is primarily focussed on the research on the mainstream ultrasonic and eddy current techniques to quantify corrosion and cracking in RAAF aircraft and Navy ships and submarines. The group also has specialist expertise in a range of acoustic and electromagnetic techniques. The NDE research group has a wide-ranging international collaboration program on defence related NDT, especially with the USA, Canada and UK under The Technical Co-operation Program. A second AMRL group focuses on applied development and performs inspections. A representative from this group stated that AMRL introduced NDI into the RAAF about 20-30 years ago. Nationally the Commonwealth Science and Industrial Research Organization (CSIRO, an analog to Canada's National Research Council) and the Australian Nuclear Science and Technology Organization also performs some NDI research, but it is not focused on corrosion.

The Laboratory uses eddy current because it is a mainstream technique that is good for detecting metal loss (while it also detects everything else). In addition, it works in the presence of sealants and air gaps. The lab devotes approximately one man-year annually to eddy current work, attempting to find ways to detect corrosion earlier, discriminate it from other defects, and quantify the damage it causes. They are trying to establish, in laboratory conditions, the minimum amount of corrosion which is detectable by eddy current techniques. To date, they have gotten to 0.5 percent equivalent thickness loss (the losses were not uniform) in 0.5 mm thick plates of 2024 aluminum. They also have looked at the use of eddy current to detect losses in dual-layer panels. Here they have established a threshold below 20 percent loss in the second layer for 1 mm thick 2024 aluminum.

When queried whether once their eddy current techniques were moved from the laboratory, how they would discriminate whether the signal they had detected was corrosion or something else, they stated that they would use a scanning system (such as the ANDSCAN from Krautkramer) which would allow the eye and brain of the technician/user to correlate the findings and separate corrosion from stiffeners or rivet holes.

One scientist admitted that the use of eddy current in thicker structures is more of a problem since penetration is difficult. Here they use pulsed or transient eddy current techniques. He has examined these techniques to detect material loss in multiple sheets of 0.9 mm thick aluminum alloy, using long period/delayed returns to make the measurements. They have shown that the transient eddy current technique is able to quantify the total percentage material loss in a multilayer structure, whilst simultaneously discriminating signals due to actual material loss from unwanted signals due to variations in the air gaps between the layers or changes in the probe liftoff. However, the theory is not fully developed for more complicated structures and work on identifying the relevant relations is underway.

AMRL is also conducting research in ultrasonics, both laser- and piezoelectric-based. Their work concentrates on using ultrasonic techniques to detect early stages of corrosion hidden underneath the top layer of a multi-layered aircraft structure. They employ lamb wave technology to look at attenuation of these waves caused by the existence of corrosion byproducts between two externally mounted transducers. The amplitude of lamb waves decreases with corrosion layer thickness before the corrosion results in significant pitting. Thus, their work focuses on measuring the thickness of the corrosion layer, rather than on measuring the loss of good material, as in eddy current techniques, and is a promising tool for early detection rather than quantification of corrosion.

The NDE researcher involved in the lab's ultrasonic work stated that this single-layer technique has potential but that sensitivity and ultrasonic transducer frequency depends on skin thickness, and presence of paint (or other) layers. Difficulties arise if the skin thickness tapers or if the number of coats of paint change within an inspection area, and separate monitoring of these parameters would be necessary for practical application of the technique. They have been able to detect down to 10 percent (50 microns) corrosion product thickness relating to 1 percent (5 microns) material thickness loss on a 0.5 mm thick plate. They also have been able to detect down to 10 percent corrosion on a 1.0 mm thick plate, or 100 microns of corrosion product, so clearly the technique loses sensitivity as plate thickness increases. In addition, they have been able to separate the transducers by only 40 mm on painted surfaces and 60-100 mm on unpainted surfaces, limiting the large-area scanning capabilities of the technique to date.

This Lamb-wave work is now in the reporting stage and present active corrosion-related research is presently concentrated on the detection of moisture and disbonds in honeycomb structure. The techniques being evaluated for this purpose in the NDE research areas are more quantitative use of the Bondmaster (linked to ANDSCAN for 2-D data presentation for ease of interpretation), acousto-ultrasonics and Airbus Elasticity checker.

They plan to examine the use of ultrasonics in honeycomb structures in the next phase of their analysis.

The division representatives stated that they see no real impediment to the introduction of new NDI technologies. Once AMRL (the R&D support laboratory) can convince the Services of the value of a new technology, it can be introduced and used. Thus, AMRL has a strong input to the ADF.

The DSTO representatives from the Fatigue and Fracture Detection and Assessment Section, Aeronautical and Maritime Research Laboratory also discussed their corrosion sensing work. The goal here is to detect corrosion as early as possible, especially in corrosion-prone areas of aircraft. They are examining the use of installed sensors, such as fiber optic sensors embedded in the sealant of lap joints. They are searching compounds for a fiber coating which will allow them to use fluorescence to detect corrosion at the lowest possible limit of detection. At present, they have gotten to 0.2 ppm of corrosion. Essentially, they exploit the propensity of evanescent radiation to escape from the core of an optical fiber by attaching a strobing light source to one end of an embedded fiber and a sensor to the other. The team de-clads the fiber in the potential area of corrosion, recoating it with a special coating that fluoresces in the presence of corrosion products. When the fluorescent light re-enters the fiber, it can be detected downstream.

In addition, they are examining the use of sheets of conducting polymers to inspect hidden joints inside airframes, relying on a change in the properties of the polymer to reveal corrosion or water contamination. For example, if moisture ingresses near the polymer sheet, a measurable decrease in the conduction of the sheet will occur or the polymer might change color. The latter can be incorporated into clear sealants around fasteners: if the sealant breaks down, the color change can be seen by a simple visual inspection. One representative noted that Dr. Agarwala of NAWC is doing similar work with chemicals in paint coatings.

The Fatigue and Fracture Detection and Assessment Group discussed their work in the NDI of honeycomb structures, including failure analysis, accident investigations and fatigue research. They take an engineering approach to fatigue analysis, considering the materials involved, and use NDI for their studies. They also provide consultant support to the RAAF, both in satisfying longer term research needs and by writing procedures.

They stated that the structural integrity aspect of corrosion is a big issue at present. While there is a need to both stop corrosion and control it, it also is important to assess the short-term criticality of any corrosion that has been detected to an aircraft's structural integrity. Thus, they feel their work has more practical applications and is less physics-based and research-oriented than the work done in other areas of AMRL. They focus on real aircraft components and near-term solutions. For example, they are studying failure and cracking problems experienced in F/A-18 trailing edge flaps. Their lab does develop some technology: they developed depth C-scan techniques to examine impact damage to composite structures on the F/A-18. However, since they have had some bad experiences in the area of technology transfer and commercialization, they never went any farther with the technology and did not attempt to develop it to a point to which it could be deployed to a RAAF unit.

The Ship Structures and Materials Division (SSMD), Aeronautical and Maritime Research Laboratory, is examining the use of electro-chemistry for corrosion detection. The goal of their work is to measure the corrosion itself or the presence of the aggressive chemical species which cause corrosion. They use a galvanic sensor to detect moisture but interpreting this data and correlating it to the rate of induced corrosion is key. To do this, they use airframe materials as their sensors, and are conducting tests to force corrosion to occur so that they can measure the resultant changes to current and resistance. It is hoped that this will allow potential corrosion to be detected before it can begin. The division's second area of study is to use changes in electro-chemical impedance to check the integrity of coatings. Each pinhole-sized breach of a coating reduces the impedance of that coating. That property can be used to monitor the condition of the coating. They are targeting their work to the areas around fasteners.

Representatives of the Airframes and Engineering Division (AED) then talked about their work providing NDI support to the RAAF. They do not devote much study to examining classic corrosion of lap joints, preferring to look at the implications of corrosion on the structural integrity of an aircraft. They mentioned the use of thermography to examine F-111 overwing fairings and accident investigations. The AED has two thermography systems, one operating in the 3 -5 micron band and the other in the 8 -12 micron band.

The AED representatives stated that in P-3C elevator skins, the 10 percent acceptable corrosion threshold is OEM-mandated. They said second layer corrosion is the hardest NDI problem. Their lab has looked at acoustic emission techniques, but have not had consistently successful results, so they are placing more emphasis on thermography now. Eddy current techniques are used for countersunk fasteners with very small holes.

Their first work on composites involved flash thermography. Image enhancement techniques were employed to bring out more detail and even heating pads were used to get thermographic images through the composite honeycomb.

NDI of the honeycomb structure of the F-111 also is of great interest, especially life extension of the existing structure. One AED representative said the aluminum core with aluminum skin honeycomb structure of the F-111 made thermography difficult since there is no change in resistance between the core and the skin. (In contrast, he said the F/A-18 has a composite over a phenolic core). He mentioned that dual-band infra-red techniques might help here. He is evaluating the value of thermal tomography and the Galileo high resolution system for examining honeycomb structures.

The AED representative said that problems with honeycomb structures include water ingress, corrosion, skin/core disbond/degradation and problems with the node bonds. Potential NDI methods used to study these problems include conventional NDI methods (such as ultrasonics, eddy current, radiography, dye penetrants, et al.), thermography, ComScan (Compton backscatter x-ray), neutron radiography (but only over small areas), D-Sight and advanced ultrasonics.

He mentioned that work is being done by CSIRO at Lindfield (near Sydney) under contract with Boeing looking at aluminum core/composite skin honeycomb and traveling waves to scan over the surface of the test article; this method can pick up disbonds on both sides of the skin and can identify on which side the problem occurs.

He said the honeycomb structures experience the three types of problems also discussed at RAAF Amberley (see Section 5.2.4.4): skin-core disbond, node bond failures (the separation of the nodes in the honeycomb), and fillet bond failures. The latter is the greatest problem, since it is hard to detect these failures, they can be critical (there is at least one case of the in-flight loss of a control surface made of honeycomb), access to many problem areas is difficult, it is believed that some of the panels which could suffer from this problem may have no margin of safety/tolerance for this type of failure, and it is impossible to replace some/many of the affected structures since they are integral to the aircraft. His lab and others are "throwing everything at them [i.e., the failure modes] that we can think of."

He then discussed ComScan techniques developed by Philips Company. Philips has a system available commercially at a cost of about $900K AUD, but it requires a large number of detectors if it is to be fast enough to be useful in a practical environment. ComScan techniques can give depth information; however, a new detection head (and re-scanning of an area) is needed for each target depth in the test article. Access to only one side of the structure is needed, but the hardware must be located close to the surface and the size of the head prohibits access to tight spaces and big protrusions on the surface itself force too much lift off. Benefits of ComScan include its capability to provide large area, non-contact scanning, its single-sided nature, its non-reliance on film, and its capability to permit 3-dimensional reconstruction (as many as 22 separate depth slices have been produced). However, it is expensive, has only limited penetration capability (since it relies on detection of backscatter radiation), its resolution decreases as penetration increases, and it presents an ionizing radiation hazard.

In summary, the AED representative agreed that there are no magic bullets in the area of NDI of honeycomb structures. He sees the possibilities for some short-term incremental advances in the areas of small-size ultrasonics probes, use of eddy current in rivet holes, and better penetrant/etchant methods. In the long term, he sees potential benefits from/uses of Compton scatter imaging, pulsed eddy current, non-contact ultrasonics and thermography for simple geometries. He personally is going to pursue thermography.

In a final note, the scientist discussed corrosion problems in helicopters and their rotors. While he is aware that there are problems with these structures, he personally does not study them in his lab since visual inspection and replacement is used to handle any/all problems in the field. For example, the rotors are discarded so frequently for other reasons (for example, H-60 Blackhawk rotors are pressurized and once the pressure is lost – indicating the possible existence of a crack – the blade is discarded), that corrosion rarely is a problem. He also mentioned that since the RAAF relies on OEM specifications, AMRL only sees out-of-the-ordinary problems.

Regarding information availability, one DSTO representative mentioned that none of the research/papers get to Australia, and especially to the RAAF bases.

One representative said that he believed the USN at Jacksonville records all corrosion information for its P-3s and that the USAF records similar data for its aircraft at Warner-Robbins AFB. He indicated that the RAAF at Edinburgh in South Australia does keep information on corrosion work costs as well.

A representative commented that he believes there is economic incentive for the military to improve its ability to detect corrosion. He asserted that it is cheaper to fix it if it is detected early.

5.2.4.2 RAAF Richmond

RAAF Richmond is responsible for the depot-level maintenance of Australia's P-3 and C-130 aircraft, as well as a small number of Boeing 707s used for VIP travel.

The major techniques used in their work are eddy current and ultrasonics, using equipment such as the Panametric Epoch III, Zetec MIZ-22 and Elotest B1 equipment. Richmond has no imaging equipment, performs no fusion of data from multiple technologies, and does not use thermography. It does have an x-ray facility. Ultrasonic techniques are used for corrosion detection, but only for single layer corrosion. RAAF personnel said that, with the digital ultrasonic equipment used at Richmond, the extent of corrosion is sometimes overestimated due to ringing in the probe. Eddy current is used primarily to detect structural defects/cracks (especially after grinding out corrosion), but is also used extensively for corrosion detection in holes.

Hawker Pacific performs contract maintenance of the P-3 aircraft for both Australia and New Zealand at Richmond. Work for the RNZAF focused on wing replacement due to fatigue and horizontal stabilizer corrosion in the 7075-T6 aluminum used in that structure. RAAF has had to refurbish a number of engine nacelles on the New Zealand aircraft, due to the greater weight of that aircraft (compared to the Australian variants). New Zealand's P-3s were experiencing more problems with corrosion than were Australia's. In fact, while it is not official policy, the life of RNZAF P-3 wings are limited by corrosion rather than fatigue.

The RAAF P-3s have experienced significant corrosion problems in the past but many of these problems are now being managed by the application of water displacing chemical preservatives to passivate the corrosion. One of the problem areas has been in the aft wing spar. Hawker Pacific uses eddy current and ultrasonics to examine every fastener in the spar caps, requiring a huge expenditure of man-hours. Hawker Pacific personnel were unaware of any realistic robotic means to perform these inspections, given the complexity of the structures inspected.

Little work has been done so far on composite patches on the Australian P-3s. Bonded metal repairs have been used on C-130 stabilizers and, while only in the early check-out stage, seem to be performing well.

Squadron personnel pointed out that they believed the 10 percent "rule of thumb" threshold for repairing a corroded body part was inappropriate because any "acceptable" level of corrosion would depend on both the stresses and the original thickness (i.e., the degree of over-engineering) of the panel/ body part in question.

5.2.4.3 Tactical Fighter Logistics Management (TFLM) Squadron, RAAF Williamtown

RAAF Williamtown is the home base of 71 F/A-18 aircraft (with an average age of 10 years) assigned to three flying squadrons. These squadrons are supported by the 481 Squadron, a maintenance squadron/facility also located at Williamtown. The TFLM Squadron is the engineering authority for F/A-18 maintenance, managing repairs, acting as a central logistics facility, and approving and promulgating maintenance procedures.

All maintenance at Williamtown is done by RAAF personnel (either in the flying squadrons or in the 481 Squadron) and all was classified as being operational-level maintenance. This includes an R-2 servicing of the aircraft which is performed every 250 flight hours (approximately 18 - 24 months) and which takes 30 - 40 days. (Each flying squadron does six R-2 inspections per year, while 481 Squadron does 12 annually).

RAAF Wiliamtown has considerable NDI equipment (ultrasonic, radiography, magnetic particle, eddy current) which is mainly applied for crack detection in metallic components and comosite monitoring. At present, visual inspections are the "primary" corrosion detection technique used by the TFLM Squadron, although 481 Squadron does also carryout some eddy current work for corrosion. Visual searches also are used to search for impact damage in composite structures.

Williamtown's F/A-18s have experienced surface corrosion due to its near-sea location. While some corrosion problems have been seen in fastener holes, it rarely has extended deep into the surface. Although it was stated that the emphasis placed on corrosion detection has dropped off in the last several years, whenever corrosion is detected, operating procedures mandate that it must be removed. However, it is not clear that all the corrosion found is reported to the TFLM Squadron: despite the length of the R-2 inspection, it was admitted that the aircraft occasionally complete the inspection/scheduled maintenance without the elimination of all corrosion, due to the push to move the aircraft through the inspection. Grinding is used to remove identified corrosion.

The R-2 procedure sees metal corrosion as well as the delamination of the aircraft's carbon composite structure. A future NDI survey is planned for the honeycomb structure.

RAAF personnel stated that they were not confident that they were finding all the corrosion resident in their aircraft. It was mentioned that the Canadians have subjected 15 - 20 of their F/A-18s to an aircraft structural integrity (ASI) inspection, while the Australians have performed only one. A study was done to justify depot servicing to check for corrosion, but it was found to be too costly ($20M AUD per aircraft) to be cost-effective. This was particularly the case given that other nations (e.g., the U.S. Navy) operate their F-18s in much more rugged conditions than Australia and international cooperative programs routinely five Australia advance notice of likely corrosion locations in the R-18s.

RAAF personnel stated that one of the major requirements which is currently being addressed is for a data handling/recording/storage system to identify and map out corrosion "hot spots" and to manage the information on where corrosion is likely to be found on the airframe. Since it is expected that Australia will maintain its F/A-18s in service until at least 2020 - 2025, corrosion detection was viewed as a concern of increasing importance, although it was admitted that no real corrective program for corrosion presently exists. However, plans are in place for a "bird bath" system to improve aircraft washing and consideration is being given to increased use of WDCPs. At present, the preventative measure taken include: 1) washing the aircraft every 60 days, although this was admitted not to be frequent enough; 2) use of WDCPs (e.g., LPS-2 and -3); 3) removal of EMI dissimilar material connections; and 4) use of improved paint (semi-gloss vice matt, although it was stated that the aircraft have not been painted as often as would be liked).

They also stated that it would be very desirable to detect corrosion without the need to dismantle significant parts of the aircraft (a major driver of the $20M AUD/aircraft cost of a depot-level corrosion detection regime). In this context, external or one-sided corrosion detection sensors would be of maximum desirability.

RAAF personnel pointed out that the 10 percent "rule" is not generally applied. Instead, more interest is placed on the criticality of the specific component and on how much material is left in a corroded area, rather than on how much has been lost. The desire for a corrosion monitoring and reporting system to map problem areas was repeated, so that the loop can be closed on the problem and the prevention of corrosion (e.g., the WDCPs) can be attempted, instead of just reacting to its presence.

Williamtown RAAF personnel demonstrated the use of "metallic rubber" to check for internal cracks and corrosion. This is a rubberized compound drawn by a magnetic field into the internal surfaces of a component being tested. When dried and extracted, a simple visual inspection of the "mold" permits the detection of cracks and corrosion. The material is manufactured by Dynamold, Inc. of Fort Worth, TX, and has a NSN code number assigned. They indicated that it is not appropriate for use in aluminum structures.

5.2.4.4 RAAF Amberley, Queensland

RAAF Amberley is the home of 501 Wing, which is responsible for performing depot-level maintenance on all of Australia's (and now the world's) F-111, relying on the original equipment manufacturers (OEM), but modifying the OEM procedures for local conditions. Routine maintenance at 501 Wing is now being part-civilianized in an effort to cut costs.

Amberley is also the home of Australia's Non-Destructive Inspection Standards Laboratory (NDISL). This group has a low budget and a small NDI team. This team trains and reviews RAAF inspection personnel for all RAAF bases and also trains defence staff from Southeast Asia. They make their own reference standard pieces to check their NDI equipment and to train inspection personnel. This team is also responsible for writing NDI procedures for RAAF aircraft maintenance.

Visual inspection is the primary corrosion detection technique used at Amberley. However, the NDISL had just received a new NDI instrument, a Sonic Bondmaster. This uses lower frequency ultrasonics to check for disbonds, and is useful in finding crushed core or water intrusion in honeycomb structures. Other techniques used include X-rays, ultrasonics, eddy current inspection and magnetic rubber inspection.

At the F-111 maintenance facility, staff assigned to maintain those aircraft stated that Australia is now the world's sole user of the aging F-111. The 22 original Australian F-111Cs average 25 years of service; the 16 F-111Gs recently received from the USAF are somewhat younger. All are expected to remain in service for another 25 to 30 years.

The NDI lab primarily inspects control surfaces (honeycomb structures/panels). All other corrosion inspection is performed via visual means, and corrosion is treated on the spot by grinding/rubbing it out, often by hand. In fact, it was stated that a major means of detecting corrosion in body panels was to conduct a tap test in which maintenance personnel crawl over the aircraft tapping it with hammers to detect (aurally) areas for more detailed subsequent testing. Such a manual test takes from 5 to 6 days of effort by multiple personnel to complete.

Steel structures on the aircraft can be inspected using magnetic rubber (discussed previously) to find defects on the order of .010 - .020 cm in size. Radiography is used, but it was stated that it is not good at finding early corrosion and the parts/aircraft being inspected must be moved to a separate facility. Thermography had been used with only limited success: the available equipment is old and past failures/inadequacies have limited its acceptance and use.

Personnel stated that stress corrosion is a big problem with these aircraft, especially on the floor trusses of the crew module. These trusses are difficult to reach and inspect, requiring the removal of the crew seats and other equipment. Boron patches have been used to make required repairs. In addition, the splice joint on the overwing fairing has been "letting go." The D6 steel honeycomb generally has not presented as large a corrosion problem as had been feared (given USAF experience with the aircraft), despite the relatively humid and tropical climate of Amberley. Problems have arisen where the cadmium plating has been chipped off, however. In addition, the D6 steel has experienced cracking problems, mostly in the wing carriage boxes.

The F-111 possesses many skin-to-honeycomb contact areas and staff pointed out that many of these areas are not or can not be inspected. Problems have been seen on the dorsal surfaces of the aircraft (where maintenance personnel tend to walk), but rarely are these areas inspected by anything other than the previously mentioned tap test. They also mentioned that the smoke from the starter carts has corroded the doors near the engine starter ports. Corrosion has been detected on the bulkhead behind the radar dish, and is removed by hand buffing. The forward equipment bay doors also experience corrosion, and not just at the hinges.

The depot personnel mentioned that corrosion in the engine intakes is being seen with more frequency. Some believe that this has been maintenance-induced, i.e., that the act of stripping the paint off the inlets to search for and remove corrosion has induced the problem to grow in magnitude, since more corrosion was seen with each stripping and inspection. The response has been to cease the stripping of the paint in the engine intakes. This would appear to be a ripe opportunity for the use of non-visual NDI techniques to search for corrosion beneath the non-removed paint in this area.

No use is made of WDCPs at Amberley. Only WD-40 (a water displacement formulation) is used as a lubricant. Machine oil is sprayed into finger tanks (which are no longer used to carry fuel on the Australian aircraft) to act as a corrosion preventative.

A major inspection of the aircraft, called an R-5, is performed every 2,000 flight hours, or approximately every 7 years. This inspection takes from 30 - 40 weeks; the duration is dictated by the availability of spares.

Data is collected pertaining to the maintenance performed on each aircraft, but none is related explicitly to the cost of detecting and eliminating or preventing corrosion. It was estimated that from 30 to 40 percent of the work performed on the F-111s is corrosion removal.

Depot personnel discussed Fillet Bond and Node Bond Problems in Bonded Panels (particularly honeycomb structures). Three types of problems have been seen in honeycomb structures. The first is skin-to-core disbonding, a standard problem in which, as its name implies, an aircraft's skin panels separate from the honeycomb structure beneath them. This problem can be relatively easy to detect with such simple NDI techniques as a tap test.

The second is fillet bond failure, which is interfacial failure between the honeycomb core and the adhesive. The problem is difficult to detect. With aluminum or graphite skins, common tap tests are inadequate (since loads and stresses on the panels often change when the aircraft is on the ground vice in flight), and even ultrasonic techniques are somewhat ineffective (although thermography might work). In addition, large areas often need to be checked: in one example, staff stated that the problem area was 20 times larger than the size of the problem which had been identified originally by a tap test.

Fillet bond failures can result in a great loss of structural strength. They are almost invariably associated with moisture intrusion, caused by problems such as failed sealant at fasteners, disbonds, or defective (usually injection) repairs. It also is suspected that water may be migrating through graphite seams. While corrosion is often present, it is not the cause of the failures. When the failures get bad enough, the skin surface of the affected area can (and has) blown off in flight. These types of failures have been seen in F/A -18A to D aircraft with F/A-18D models less than five years old, and in the F-111. Representatives stated that even the Airbus 320, with its phenolic core honeycomb, has experienced these problems.

The third type of failure is node bond failure, in which the bond which is supposed to keep together the cell walls of the honeycomb itself falls apart. This type of failure, while easily detected by x-rays, is generally found only during repair of the structure for other reasons. In fact, while it is generally caused by the elevated temperatures used during other repair/curing procedures, this type of failure may occur at a location away from the site of the repair which caused it. Node bond failures can result in a core cell peel strength loss of up to 90 percent.

Depot representatives also stated that the F-111 horizontal stabilizer has been a problem. If/when the Sacramento Air Logistics Center closes, Australia, which plans to keep their F-111s operational until at least 2020, may find it difficult/impossible to repair those structures.

Depot representatives stated that the maintenance procedures promulgated by 501 Wing take what the OEM recommends and, whenever they are found to be wanting, tailors them for the local/Australian situation. They noted that 501 Wing has the authority to make decisions on the need to procure a new piece of NDI equipment, based on needs expressed by the flying squadrons. However, since funding is always a problem, whenever they develop/get a new procedure to perform, they try to build around and employ an existing piece of NDI equipment. In the instances when money becomes available due to the cancellation of other projects, 501 Wing can buy new equipment with those funds. However, even when 501 Wing can procure new NDI systems, training on their use is difficult to get (due to Australia's distance from the manufacturers) and then it is difficult to find the funding to travel and use the equipment at any location other than Amberley. Thus, it is difficult to "buy and try" a new system.

The depot representatives could not think of a corrosion-caused failure. Whereas the F-111s used a great deal of sealant on their panel joints, the newer helicopters in the Australian inventory were manufactured using dry joints, and have experienced many corrosion problems. Because of this, corrosion is receiving more attention now than it has in the past.

5.3 Department of Transportation

The Department of Transportation is involved in a number of different R&D programs for detecting corrosion in aircraft. The following paragraphs highlight some of their activities in this area.

5.3.1 FAA Technical Center

The FAA Technical Center initiated a program in inspection system research in 1990 as part of the National Aging Aircraft Research Program. That program was designed to implement National Traffic Safety Board recommendations in report AAR 89/03, which recommended that the FAA perform research to support the deployment of more capable inspection systems with less sensitivity to human inadequacies. Government and industry oversight of inspection research further recommended that the FAA establish a validation center to ensure the reliability of new technology being introduced into the maintenance environment. To accomplish this, the FAA set up the Center for Aviation System Reliability (CASR) at Iowa State University to oversee inspection system development and the Aging Aircraft Nondestructive Inspection System Validation Center at Sandia National to conduct inspection system validations. The FAA does not conduct any research in-house.

Like the U.S. Air Force, the FAA does not consider corrosion a safety issue. They do not consider corrosion a problem. Rather, they define it more as a cost issue.

The performance standards that the FAA is trying to achieve are:

- Detection of 0.025 inch crack emanating from the shank of a counter sunk rivet hole in 40 mil fuselage skins
- Detection of 0.050 inch crack emanating from the shank of a rivet hole in the second and third layers of fuselage skins (40-60 mills below surface)
- Detection of a 0.100 inch crack under 0.500 inches of aluminum wing skin
- Reliable detection and mapping of corrosion thinning to five percent material loss
- Reliable detection of one square inch disbonds in composites up to five layers from the inspection surface.

The FAA works with CASR to develop new maintenance procedures where the emerging technologies that complement the medium to heavy airline inspections are given their first exposure for potential use by an airline. The new technology or technique then becomes an issue for the airlines to either convince and/or pay for the manufacturer to authorize the technology. This is because the manufacturer ultimately carries the liability. The manufacturer takes an existing service bulletin and submits literature on the technology along with service literature. The FAA then reviews this application and, if approved, issues an AD. Oftentimes, operators request an alternate means of compliance that applies only to that operator. This alternate can be granted in a shorter period of time.

FAA representatives stated that airlines primarily rely on visual inspections, believing that there is always some sort of visual indicator of corrosion and that, once discovered, then needs to be inspected further to determine the extent of the problem. The FAA representatives stated that the ultrasonics techniques are not that popular with the airline industry due to the requirement for a water medium to couple the article and the transducer. He noted that the FAA is most interested in the scanned pulsed eddy current techniques and they have a parallel effort to the USAF in this area. The FAA feels that this technique has much to offer in its specific area of interest - the detailed inspection or point detection of corrosion in a small area.

The FAA representatives pointed out that the FAA's mandate is not directive by nature and thus, they will not impose corrosion detection techniques and equipment on either the airlines or the manufacturers. Instead, they encourage the airlines to follow whatever guidance the OEM s dictate regarding maintenance. As is currently done, the individual airlines will continue to work with the manufacturers to employ equipment and techniques which prove cost effective and which meet the inspection needs in achieving compliance.

The FAA's inspection system development work embodies several related efforts to advance flaw detection technology:

- Crack Detection: To improve the sensitivity and reliability of techniques to detect and characterize small, inter-layer, and obscured cracks characteristic of widespread fatigue damage. Technologies currently of interest to the FAA include laser ultrasonics, pulsed eddy current, superconducting quantum interference devices (SQUID), ultrasonic pulse compression, energy sensitive X-ray for engine case inspection, dual probe ultrasonics, electromagnetic acoustic transducers, and advanced electromagnetic sensors for widespread fatigue damage assessment, and an advanced penetrant inspection technology.
- Corrosion Detection: To develop non-invasive techniques to detect and characterize disbonding and understrength bonds in skin splices. Technologies of current interest for verifying bond integrity include thermography, low frequency ultrasonic scanning, air coupled ultrasonics, and capacitive array sensors (for inspection of composites). Corrosion detection technologies of interest include magneto-optic eddy current imaging (MOI), pulsed eddy current, D-Sight, and portable low-radiation hazard, real-time x-ray.
- Robotics and Automation: To enhance the capability and reliability of inspection systems by developing faster, more accurate means of deploying the probes and interpreting probe signals. Technologies of current interest include

signal processing for sliding and rotating eddy current probes, self-focusing ultrasonics, and signal processing for ultrasonic billet inspection.

The technologies that the FAA has and is studying and the programs they have in place to conduct this research is highlighted in the following paragraphs.

One of the FAA sponsored programs is to provide new technology for crack detection based on non-contact generation and detection of high frequency ultrasound. The Sagnac interferometer for ultrasound measurements has been developed. A fully featured interferometer will be tested on rough aircraft surfaces under field conditions. CASR is working on the development of this prototype.

The FAA has also sponsored CASR to develop pulsed eddy current inspection techniques to detect and characterize small fatigue cracks in layered joints. This task builds on a swept-frequency device developed at ISU that can determine the location of corrosion loss, thickness of both outer and inner layers of skin, and separation between the two layers. The technology has been licensed by Sierra Matrix.

In addition, CASR is working on developing scanned eddy current methods to detect and characterize corrosion and corrosion related cracking in lap joints, quantitatively determining metal skin thickness loss. A laboratory pulsed eddy current device has been developed and a second generation prototype has been designed. This project will further develop and integrate pulsed eddy current technology into a portable scanning instrument.

SQM Technology is working with CASR on another eddy current technology project to extend this technology to deep inspection for hidden flaws. They plan to build a prototype superconducting quantum interference device (SQUID) for deep pulsed eddy current inspection of thick wing structures by January 1999.

CASR, in conjunction with Northwestern University, is also working to develop a dual probe ultrasonics system for the detection and characterization of fatigue and stress corrosion cracks in multi-layered structures. At this time, the DC-9 T-Cap applications is complete, has been approved and is being applied by at least three airlines. Validation efforts are underway for the DC-9 Wing Rear Spar Aft Flange and the DC-10 No. 2 Engine Pylon Spar Cap Strap in cooperation with Northwest Airlines and McDonnell Douglas.

CASR is working on the development of a portable low-radiation hazard X-ray system capable of providing enhanced real-time X-ray images coupled with a detailed quantitative measure of material thickness and the presence of corrosion at selected points of interest. They plan to complete the experimental characterization of the diffraction effects in samples supplied by Pratt and Whitney and Boeing using the germanium or the CdTeZn detector and develop specifications for the system.

CASR has contracted with Wayne State University to provide thermal wave imaging technology for rapid integrity assessment of adhesively bonded aircraft structures with emphasis on detecting corrosion and disbonding in multi-layer joints. To date, the pulse-echo thermal wave inspection system has been demonstrated in the laboratory, during field trials at Northwest Airlines, and in conjunction with an USAF corrosion detection program. Several tests have also been conducted at the AANC and a reduced size imaging system has been developed. They are working on an advanced prototype that will offer more practical use with little or no aircraft preparation required.

This technology also has strong USAF sponsorship. NASA Langley is interested in this technology as well. NASA is funding Bell Scientific in the area of algorithm development at the Lawrence Livermore Laboratory to help refine this current technology process.

CASR is also exploring the feasibility, applicability, development, and improvement of air-coupled ultrasonic inspection methods for defect detection in typical aircraft geometries, particularly concentrating on composite materials and composite joints. McDonnell Douglas has interest in this technology and has supplied coupons to be tested.

In addition, CASR has just started exploring applications of novel electromagnetic inspection methods based on rapid-scan, staring/focusing capacitive array sensors to NDE and NDI of composite materials. A feasibility study is underway.

CASR is concentrating resources on developing a low frequency immersion quality ultrasonic scanning method using a dripless bubbler to detect corrosion and disbonds in adhesively bonded structures. The dripless bubbler was demonstrated at the AANC in April and November 1994. The system was tested in February 1995 during Tinker AFB tests. Sierra Matrix licensed the technology in 1996 and is actively developing a commercial system.

CASR is in the process of developing a simplified version of a new ultrasonic technique to detect small cracks, high density inclusions, hard interstitial defects, and stress-induced porosity by using adaptive time-delay focusing of either the original signal or the time reversed scattered signal. The second generation field prototype with surface and lamb wave capability is scheduled to by completed by November 1997 with validation forecast to be completed by mid-year 1998.

CASR has also funded the Canadian company, Diffracto, in conjunction with Transport Canada and NRC, to develop a prototype D-Sight system for rapid surface corrosion assessment. A second generation prototype was completed in 1995.

CASR has been assessing the reliability of representative and critical visual inspection activities to identify and assess some of the more important factors effecting such activities. The experimental trials are now complete. They have produced quantitative results on the probability of different flaw/defect types and sizes, inter-inspector reliability, and an estimate of inspector characteristics included in the design. Also documented are qualitative results comparing experimental "typical" situation with inspectors' usual working context, rank ordering and weighing the importance of performance influencing factors (including time factors) and classifying errors.

Mature technologies are transitioned to a validation and final development phase under the FAA's inspection reliability and validation program. In regards to technology transfer initiatives, the FAA is accomplishing this through a process of application oriented systems development, system validation, and information dissemination, culminating in licenses and commercialization partnerships. For example, in August 1996, CASR signed a licensing agreement with a manufacturer of inspection equipment for two CASR developed technologies: a pulsed eddy current device and an advanced ultrasonic inspection system.

Working together with the AANC, CASR has successfully transitioned a new inspection technology to industry. CASR developed a prototype ultrasonic device, which was validated at AANC. It has been specified in a McDonnell Douglas Service Bulletin as an alternate inspection technique for the DC-9 wing box T-cap inspection for mandated corrosion detection inspection. The new technique will save over 700 man-hours per inspection compared to the current inspection method. It also requires less disassembly of the aircraft part to conduct the inspection, thus resulting in less chance of ancillary damage during the disassembly and reassembly if no corrosion is detected.

Even though the work the FAA has done is extensive, the FAA representatives pointed out that the development of new technologies that the airlines need will likely come from the DoD. The FAA has no real power in directing or changing inspection procedures. They noted that there is no real incentive for the airlines to implement inspection techniques that reduce inspection times. This is because the airlines have scheduled times at which they bring their aircrafts in for medium and heavy checks. To shorten the timeframe for the maintenance function will not change how early these aircraft get released because of the other processes that are conducted during that time. These other processes take a given amount of time to perform and no quicker way to perform these other procedures is foreseen in the near future.

5.3.2 FAA Airworthiness Assurance NDI Validation Center (AANC)

The Airworthiness Assurance Nondestructive Inspection Validation Center (AANC) was founded by the FAA in response to the Aviation Safety Research act of 1988, which mandates that the FAA carry out research and develop technologies to help the aviation industry to 1) better predict the effects of design, maintenance, testing, wear and fatigue in the life of an aircraft; 2) develop methods for improving aircraft maintenance technology and practices including nondestructive inspections; and 3) expand general long range research activities applicable to aviation systems. The AANC validates NDI technology, assesses the reliability of NDI applications, provides quantitative reliability data on the field application of inspection and repair technologies, and performs other projects to support the FAA and aviation industry. Prior to its inception, there was no formal process for validating NDI technologies.

Sandia National Laboratories was funded by the FAA in August 1991 to establish the Validation Center at Albuquerque International Airport. The center is located in a 24,000 spare foot hangar at the west end of the airport.

A 27-year-old Boeing 737 aircraft was acquired as a test bed in October 1992 and the Center began operating in February 1993. McDonnell Douglas DC9 fuselage sections were acquired in 1993. The U.S. Coast Guard donated a Falcon HU25A aircraft to the center in June 1994. The center acquired a Fairchild Metro II commuter aircraft in 1995 as well. In addition, the AANC has a large collection of aircraft structural test specimens with characterized flaws, some cut from aircraft and others built to aircraft structural specifications with built-in flaws.

AANC's original mandate was to validate inspection technologies for aging aircraft applications. That validation process involves the assessment of the reliability of inspection systems (including human factors) and an estimation of the cost effectiveness of those technologies. It assists developers with analysis and provides cost benefit feedback relative to time taken for sample analysis versus false alarm rate. Since its inception, the scope of AANC activities has broadened to include activities in structural integrity analysis, repair assessment, and composite structure assessment.

The FAA's National Aging Aircraft Research Program is concerned that the increasing age of aircraft and the corresponding increase in inspection and inspection frequency could result in the reduced reliability of safety related inspections. The FAA is examining technologies having less susceptibility to human and environmental factors to offset the increasing inspection burden and reduce possible collateral damage associated with disassembly, reassembly, and modification of airplane structures.

FAA representatives have cited as a concern that in today's competitive environment, many aircraft operators feel compelled to maintain older inspection systems rather than invest in new systems and training. The FAA believes that, without intervention, the potential exists for technologies to remain "on the shelf" because operators cannot afford the time and resources to pursue validation and reliability assessments necessary to assure themselves, aircraft manufacturers, and regulatory authorities of the applicability of those technologies. The AANC addresses this issue. To date, the AANC has conducted well over 100 demonstrations of emerging technologies.

As a result of the validation process, if the AANC discovers that a particular system is both capable and reliable, the FAA will allow its utilization as an alternate means of compliance for certain FAA Airworthiness Directives. These directives often originally require significant disassembly and inspection or modification of the structure.

When an airline operator or maintenance facility wants the FAA to certify a technology as an alternate means of compliance, they must first demonstrate the technology to the FAA. The FAA then adopts and approves the technology. Often, the airlines go to regional FAA officers for certification of new technologies. In fact, over time, regional offices have been considered to be specialized in certain areas, such as commuters, helicopters or engines.

In citing accomplishments to date, the FAA representatives listed the following corrosion detection technology developments:

DC-9 Tee Cap Inspection - the AANC worked with McDonnell Douglas Aircraft, Northwest Airlines, and SAIC Ultra Image to validate an ultrasonic inspection technique developed by Northwestern University for the detection of corrosion and cracks in the DC-9 wing box tee cap. The technique, which has been written into a service bulletin revision, improves inspection area coverage by 2 to 1 and inspection time by a factor of at least 10 to 1.

Ultrasonic/eddy current scanner survey - the AANC evaluated representative ultrasonic and eddy current scanner systems for use on aircraft by demonstrating systems on test specimens and full-scale aircraft.

Some other activities currently in progress (with industry or outside participants) include a visual inspection reliability experiment with assessment of visual aids (ATA Inspection Network), DC9 wing box inspection alternate means of compliance (Northwest Airlines, McDonnell Douglas, Northwestern University), halon bottle inspection (American Airlines), multi-layer airframe crack detection reliability experiment (Boeing), boron-epoxy structural reinforcement (Delta, Lockheed, Textron Specialty Materials, Robins AFB), and small crack detection reliability experiment (Boeing, Technical Oversight Group on Aging Aircraft).

5.3.3 U.S. Coast Guard

As with the DoD, the Coast Guard is concerned with maintaining and operating aircraft in an extremely corrosive environment. Their aircraft are flying well into their design life as well and hence, the Coast Guard is concerned with reducing corrosion degradation. Corrosion is a fleetwide problem that is exhibited in all Coast Guard aircraft. The Coast Guard has developed a Process Guide to provide guidance for managing an effective Aeronautical Engineering Corrosion Control Program. This guide establishes policies to reduce the impact of corrosion deterioration on aircraft, components, and support equipment; providing guidance for a written air station corrosion control plan, and ensuring that future systems are designed to be corrosion resistant.

The Coast Guard has a Corrosion Prevention Advisory Board that provides recommendations to the Chief, Aeronautical Engineering division regarding policy and oversight of the Coast Guard corrosion prevention and control program. In addition, the CPAB advises the Commanding Officer, Aircraft Repair and Supply Center, of process improvements to enhance corrosion prevention and control at AR and SC.

The Aircraft Repair and Supply Center, Engineering Division, Corrosion Control and Reliability Centered Maintenance Division, is working in conjunction with NAVAIR on their thin film galvanic sensor research for in situ corrosion monitoring. They have outfitted several H-65 helicopters with these sensors in an effort to gather data on the levels of corrosion experienced in these aircraft. With this data, they hope to be able to move towards condition based maintenance of their aircraft.

The sensor consists of gold and cadmium plated on a Kapton film with carefully space gaps. Wires lead to the data acquisition system. When conditions provide enough conductivity between the metal, a small corrosion current is developed which is measured by a Zero Resistance Ammeter. Up to eight channels can be monitored. Some are for the corrosion sensors; two are for temperature/humidity probes. The data can be downloaded to obtain a measure of the corrosivity of the atmosphere in which the sensor is placed.

This project is being conducted as part of the Site Specific Aircraft Corrosion program. Sensors were placed on two aircraft at each of two air stations: Corpus Christi and Detroit. These stations represent the extremes of corrosive and least corrosive atmospheres. By installing these corrosion monitoring units at the air stations, they hope to be able to attribute that portion of the corrosion due to the flight profile and that due to the geographical location. If the results reflect distinct differences between the two air stations, the team believes the data will enable PDM cycles to be selected on the basis of corrosion potential at each location, i.e., prolonging the interval for those aircraft less at risk.

5.4 NASA Sponsored Activities

NASA has a number of distinct corrosion problem areas where they are concentrating much of their NDE R&D work. NASA Langley deals mainly in studying ways to detect and deal with corrosion under a thin layer of aluminum through its Aging Aircraft program and coordinates extensively with the Air Force through its Aging Aircraft initiatives. The Kennedy Space Center research work, on the other hand, is aimed at studying corrosion of various space systems and concentrates a lot of its energy in dealing with corrosion found under relatively thick aluminum and in between the tiles and the aluminum layer of spacecraft.

5.4.1 NASA Langley Research Center

The Nondestructive Evaluation Sciences Branch at NASA Langley Research Center (LaRC) is one of the major drivers of NASA's NDE research program. The program focuses on maintaining an NDE science base core, developing new technologies for the Agency, and transferring problem solutions to customers. The LaRC NDE research program is concentrated in two Offices - Safety and Mission Quality (Code Q) and Aeronautics, Exploration and Technology (Code R), covering applications primarily for Space Operations/Transportation System (spacecraft integrity), Subsonic and Hypersonic Aeronautics (aircraft integrity).

NASA Langley Research Center is the central focal point for the NASA sponsored Aging Aircraft Program and is working with U.S. Air Force NDE researchers at Wright-Patterson AFB on the Air Force Structural Integrity Program. The NASA Aging Aircraft Program is a $45M program (total) that has been ongoing for seven years.

The general areas in which NASA Langley NDE researchers are conducting research are thermography, ultrasonics, and eddy current. All principal investigators at NASA Langley performing the research in these areas are NASA employees, of which there about 15. NASA NDE researchers have patents in thermography and ultrasonics.

Specific technologies being researched at NASA Langley include understanding the physics of thermography and ultrasonic techniques, and optimizing the techniques for technology transfer. The researchers believe that thermography is the best technique for the overall scan of large areas such as the surface of aircraft. They consider it a relatively quick technique, taking eight hours to scan an entire B-737 aircraft. The researchers also believe that ultrasonics and eddy current are the best techniques for "point" inspections. Ultrasonics can detect material loss as low as 3 percent; eddy current can detect material loss as low as 5 percent.

NASA staff stated that automation can also help reduce costs and the time to perform corrosion inspections. NASA has sponsored an SBIR for a robotic crawler that can access hard to reach areas of aircraft.

5.4.2 Jet Propulsion Laboratory

The JPL NDE and Advanced Actuators (NDE-AA) Lab was established in May 1991. The JPL NDE Lab supports the JPL's materials and structures NDE requirements, particularly space-flight hardware. The Lab is involved with research and development to allow:

- Detection and characterization of defects
- Determination of material properties
- Sensors for in-process and in-service monitoring
- Characterization of actuators and sensors at controlled conditions

The NDE-AA Lab current research areas include:

- Aging Aircraft NDE - Ultrasonic detection and characterization of damage to metallic structures and degradation in composite materials. This effort is sponsored by AFOSR and is a subcontract with the University of Texas at El Paso (UTEP) The leaky Lamb wave (LLW) method is being investigated as a tool for defect detection and characterization as well as material properties determination. Laser induced plate waves are being studied to develop a method of performing rapid couplant-free ultrasonic NDE. Also, Intelligent NDE techniques are being explored (including sensor data fusion) as a means of in-service corrosion monitoring.
- Multifunctional Automated Crawling System (MACS) - MACS is a multifunction automated crawling system (MACS) designed and fabricated to carry miniature instrumentation to perform a wide variety of inspection tasks while attached to the surface of the structure of interest. The immediate application of MACS is aircraft inspection and various inspection modules can be used for this purpose. MACS employs ultrasonic motors for mobility and suction cups for surface adherence. MACS has two legs for linear motion and a rotation element for turning, enabling any simultaneous combination of motion from linear to rotation about a central axis. The use of ultrasonic motors, composite materials construction, miniature computer and video cameras enables a small, light weight crawling system with an effective carrying capability ratio of about 1:10. MACS I is 11x19 inches and, in its MACS II new design, MACS II, the size is reduced to 10x10 inch.

The target application of the MACS was the inspection of the exterior of the C-5 aircraft. Currently, there are large areas of the aircraft that are difficult to reach by a person because these places are very high up on the aircraft (such as the upper areas of the fuselage and the tail section). MACS will be able to crawl across an aircraft carrying NDE sensors on a pre-programmed path, performing autonomous tests (with the use of built-in artificial intelligence) and sending data (at present via an umbilical cord, but eventually by radio) back to a computer for storage and later analysis. These images and sensor data would be sent back to an operator who could be at the base of the aircraft, in a local control room, or potentially anywhere in the world. This program is sponsored by the Robotics and Automation Center of Excellence (RACE), Kelly AFB, San Antonio, TX. The JPL's NDE & AA Group leader foresees a potential combination with the MAUS, which was developed by Boeing/McDonnell-Douglas to perform autonomous, multi-mode NDE tasks.

The PC technology can provide a model for smart mobile platforms that uses the MACS technology, namely establishing an equivalent to the motherboard. The availability of such a platform will offer the NDE industry a basis to develop miniature plug-in instruments. Robotic inspection instrumentation is a multidisciplinary field and the ability to specialize in specific areas of the required components will lead to innovative miniature plug-ins with limited resources. This can be similar to the development of such PC products as the modem and many other boards.

The JPL's NDE&AA Group leader stated that he has a concept jointly with the University of New Mexico for a "snake" robot, so-called boro-robot. Such a robot can be used to access hidden areas through small openings in aerospace structures to conduct inspection and maintenance tasks. This concept takes advantage of the JPL telerobotic technology and can be constructed of multiple elements that emulates a snake in its dexterity. Each element of the boro-robot is made of three inter-crossed miniature struts and three independent linear actuators. The struts support and vibrationally stabilize the boro-robot structure and the actuators assure the manipulation capability and dexterity. Without disassembly, a boro-robot would enable to inspect and maintain aircraft engines, fuel tanks and other hidden areas of aircraft structures. As an inspection system, it can be developed to carry CCD for visual tests, fiber optics for transmission of laser pulses to induce ultrasonic test, eddy-current probes for crack detection around fasteners and many other sensors.

The JPL NDE&AA Lab is spinning-off its technology to medical diagnostics and treatment applications, under NIH sponsored tasks as well as noninvasive geophysical probing of terrestrial and planetary ground surfaces, under NASA tasks. The scientists of this lab are working in cooperation with various universities (including UCLA, UTEP and UNM), industry and NASA centers to develop the necessary technologies. Because of their work in the area of actuators, such as ultrasonic motors and electroactive polymer muscles, and robotics the JPL NDE lab has been renamed to include advanced actuators in its title.

5.4.3 NASA Kennedy Space Center

The instrumentation engineers at the NASA Kennedy Space Center (KSC) who work in the Special Development Laboratory (SDL) provide direct technical and operational R&D support to all NASA Program Offices at NASA Johnson Space Center in Houston, TX. These include the Space Shuttle Program Office and the Space Station Program Office. One component of this R&D support is the NDI/NDE of space qualified components such as the reusable solid rocket boosters used by the Space Shuttle.

Regarding NDI/NDE for corrosion, the engineers pointed out that they consider some of their major corrosion problems to be with components such as the Shuttle Solid Rocket Boosters that are re-used after their recovery from the salt water environment of the ocean. However, this belief is not held by NASA Headquarters, and thus, funding for R&D on NDI/NDE for corrosion is close to nonexistent.

Despite this lack of funding, the engineers at KSC have developed NDE techniques to solve recurring problems. SDL engineers, for instance, are using thermography to inspect for disbonds in the aluminum honeycomb structure of the rudder speed brake on the shuttle. They consulted with NASA Langley when fabricating the system. The technique is also being used to inspect the Shuttle payload bay doors. The technique can fully scan one door in about a day.

The engineers also are researching development of a scanning eddy current microscope. Since funding is limited, they are designing and fabricating it from components purchased at local hardware stores.

5.5 Department of Energy (DOE)

The DOE has sponsored a number of research activities into enhancing NDE technologies. Their research is cited in the following paragraphs.

5.5.1 Lawrence Livermore National Laboratory

Lawrence Livermore National Laboratory (LLNL) employs 20- 24 people in the area of NDE, and does about $1M -$2M of work annually in the area. Their goal in the NDE thrust area is to support initiatives that advance inspection science and technology and look to provide cutting-edge technologies that show promise for inspection tools three to five years in the future. LLNL does research in the areas of dual-band infrared, radiography, and ultrasonics. LLNL also does some work in x-ray computed tomography and acoustic emissions, and is beginning to work with lasers.

Most of the research conducted at LLNL is in the area of thermography, with a focus on the examination of aging nuclear weapons. For their work, corrosion is not as much an issue as is chemical change. At present, about 50 percent of their work focuses on nuclear weapons, a reduction from previous years. The Lab also has worked with the FAA on aging aircraft (receiving about $800K over 5 years), the auto industry on metal matrix composites, the California Department of Water Resources on dams (receiving about $1M), and the Federal Highway Department, attempting to detect cracks in bridge decks (receiving about $800K over 3-4 years). They have also worked with Boeing on composite durability for a high-speed civil transport aircraft (a large, multi-year effort). Specifically, they are trying to accelerate the aging of composites, and then test them with NDE techniques, and to report their findings to the FAA.

LLNL's work in radiography is not directed toward corrosion detection per se, but rather toward new developments in electronic imaging and image intensifiers. New work is being done in the area of amorphous silicon arrays for use in lower dose x-ray imaging using 8" by 8" flat panel imagers (from Xerox) which are not susceptible to radiation damage. While standard radiography is sensitive down to a material loss level of 2 percent, they believe their electronic imaging techniques will be sensitive down to 1 percent. Much work is also being directed toward computerized tomography, but they recognize that this technique is relatively slow, and hence is better used during production than for postproduction work in the field. They also are working on x-ray backscatter imaging (i.e., one-sided x-ray imaging), based on a technology from Phillips, which produces a map/scanned image by imaging a 2” wide swath which moves at 4” per minute in a raster scan pattern. This technique is currently used by the Canadian Air Force.

There also is a group at LLNL that has worked with embedded electro-chemical sensors to search for corrosion products.

LLNL is pushing toward using data fusion techniques to combine the results of ultrasonic, radiography and computerized tomography to enhance detection. Since all data collection is computerized and sent to a central computer, the possibility of fusing exists and they consider that the payoffs offered by this data fusion may be great.

LLNL also does all types of traditional ultrasonic work, including C-scans and B-scans, using two large tanks to examine, for example, lap joints and welds. They have experience in the testing/evaluation of a wide variety of materials, including steel, composites and ceramics, and excel in the area of signal processing (specifically in the use of neural nets to classify defects and extract information) and high resolution imaging. They have built a number of prototype scanners for commercial customers, such as the auto manufacturers, and work with vendors to commercialize their (LLNL’s) designs.

LLNL also has worked with the Department of Water Resources (examining dam tendons, which are 40’ by 1” pipes embedded in concrete within the dams and their floodgates). Most of their research in this area involves laser generation and detection of ultrasound, including a 4-year, $1M IRAD program. While this is not as sensitive as piezo-electric ultrasound, they have worked with Johns Hopkins to do model-based signal processing schemes to increase sensitivity. Recently, they have worked on a DOE project on process control to listen with an acoustic sensor (specifically an interferometer beam) to judge the status of a laser cut being made through a material. The ultrasonics group is more focused on the application of technology for DOE than pure research, especially on the use of fiber optics to permit laser ultrasonics to be performed while positioning the lasers outside of hostile environments.

LLNL uses IR tomography to quantify corrosion damage, and can detect differences in thickness of less than 10 percent. LLNL researchers have pioneered the use of dual-band IR (DBIR) imaging, working in the 3-5 and 8-12 micron bands. Flash lamps are used as the heating source. Their DBIR tomographic (DBIR-CT) technique gives three-dimensional, NDE, pulsed-IR thermal images, in which the thermal excitation provides depth information, while the use of tomographic mapping techniques eliminates deep clutter. (In fact, the researchers mentioned that they have worked on algorithms to distinguish sealant globs from actual corrosion between the layers of a structure.) The technique creates background-corrected thermal maps, and can detect/depict flaws in three dimensions, depicting flaw size and its estimated depth even in multi-layer structures. DBIR-CT thus permits the detection of low levels of corrosion; provides corrosion defect maps in three dimensions; and results in a lessened for exploratory, destructive testing. The technique was developed originally for use in aquifer detection, then was transferred to land mine detection, and now has been applied to the detection of aircraft defects and corrosion.

LLNL is moving into the area of thermal inertial maps, which will permit the tagging and removal of foreign material clutter (both shallow sealants and deep, interior insulation) from the images produced by the DBIR techniques. The researchers indicated that they can also do crack detection, but admitted that this work was at a very early experimental stage and the ultrasound techniques remain superior. They claim to be able to calibrate metal loss at the five percent level with few or no false calls.

5.5.2 Lawrence Berkeley National Laboratory

LBNL currently does little work directly related to corrosion detection technologies per se, but is heavily involved in developing NDE/NDI technologies that could have potential for detecting corrosion in defense systems. The Engineering Division does electronic instrumentation and detection technology, most of which is nuclear related, and includes x-ray diffraction. The Mechanical Engineering Department designs and builds particle accelerators and their related detectors. Many of the Lab's personnel are dual-hatted as professors at Cal-Berkeley.

LBNL has been researching NDE acoustic wave technology, particularly laser vibrometry, for the auto industry, with a focus on adhesively bonded joints in lightweight materials (such as aluminum). The auto industry has traditionally used steel components, welding and destructive testing, but has been moving to the use of aluminum/composites, bonding techniques, and NDE. LBNL researchers are exploring non-contact, fast/real-time, reliable, on-line NDE techniques and the sensor development for them. They are examining using higher frequencies (with the drawback of limited penetration) to detect smaller defects; in increasing spatial resolution, requiring more time per measurement and more measurements; and in global excitation.

LBNL began by looking at bonded T-joints in aluminum plates, exciting the plate and using a laser vibrometer to scan the length of the joint to see if they could get recognizable, localized resonances at a defect. This technique is fairly sensitive, but, since it requires access to the joint, not entirely satisfactory. They are now looking at shooting transient waves across the joint and trying to get back projections from any defects. Their work also includes looking at composite plates, using higher frequencies (with their admittedly limited penetration) to cover as much surface area as possible. While this is sensitive to defects, the mode shapes of the returned signals vary with the frequency of the waves being used, potentially confusing the results. The scientists are also working on non-contact scanning data acquisition.

In the future, the LBNL personnel hope to expand this work to consider the test and analysis of structural members; the development of excitation sources and sensors; an analytical model; and robotics and control systems for the development of scanning heads. This work has been accomplished for the Office of Transportation Technology over the past 14 months. It is a small-scale project in a new field for LBNL.

LBNL has done extensive work in the testing of energy efficient windows in a climate lab, using an IR camera for surface temperature readings. Their experiment most closely related to the area of corrosion detection involved placing a strip of heaters on one side of a plate connected by a lap joint to another plate. An IR scanner and sensor is placed on the other side of the joint to detect temperature differences caused by debonds/defects. This could be applicable to corrosion detection since corroded areas have a higher thermal resistance than non-corroded areas, but requires access to both sides of a joint.

5.6 Department of Commerce/NIST

To help U.S. industries avoid the negative impact of corrosion, NIST and the National Association of Corrosion Engineers (NACE) joined together to form the NACE-NIST Corrosion Data Program. The objective of this program is to use the latest advances in information science and technology to provide industry with convenient and reliable information on materials performance and corrosion control. Working with experts from industry, NACE-NIST knowledge engineers work to develop expert systems, databases, and modeling programs that are distributed to industry to help avoid corrosion failures. The overriding goal of the CDP is to enhance the cost effective practice of corrosion prevention by collecting, organizing, evaluating and disseminating, in computerized form, corrosion and materials performance information.

Researchers at NIST are also working to develop improved laboratory and field techniques for measuring and monitoring the chemical reactions that degrade the performance of materials in service. NIST's Materials Performance Group focuses on mechanical properties, deformation processing and fracture, and on the effects of corrosion on metals performance. The Group's primary mission is to assist U.S. industry in these areas through the traditional NIST activities of measurement science and test methodology, standards, data, and metals characterization. One of their current thrusts is on developing reliable data on materials performance and corrosion control. NIST researchers were instrumental in the development of transient and static electrochemical techniques for assessing corrosion reactions such as potentiodynamic polarization, electrochemical noise, ac impedance, and in-situ ellipsometry. Also, NIST researchers have developed methods for measuring the corrosion of metals in field conditions, such as steel in soil and sea-water, electric utility lines in soil, and of steel in concrete. Currently, NIST researchers are working on in-situ monitoring of electrochemical conditions and using the information obtained from electrochemical measurements to predict the performance of materials in service.

5.7 Commercially Sponsored Activities

There are a number of ongoing R&D activities in the corrosion detection technologies arena, primarily driven by the need for improved capabilities to detect hidden corrosion in aircraft. Some of the major activities are documented in the following paragraphs.

5.7.1 ARINC

ARINC has worked closely with the Oklahoma City Air Logistics Center on investigating technologies that can detect corrosion in aircraft lap joints and upper wing skins. The work has been conducted in three phases.

During the first phase, conducted between 1991 and 1993, ARINC investigated commercial-off-the-shelf (COTS) equipment that could adequately scan the lap joints and wing surfaces for corrosion. The result of the first phase was a determination that no COTS equipment existed to detect corrosion in upper wing skins. COTS eddy current equipment did exist for lap joints.

Phase two of the effort consisted of investigations of emerging technologies to detect corrosion in upper wing skins. This was completed in November 1995. A number of promising technologies were identified, primary among them ultrasonics. Based upon the phase two results, ARINC is now working on phase three, with goals to 1) develop and prototype a single system to scan wing skins and fasteners for corrosion, and 2) optimize COTS products for lap joint corrosion detection.

5.7.2 Boeing Information, Space and Defense Systems, Phantom Works, Seattle Materials and Processes (M&P) NDE Group

The Boeing Seattle M&P NDE group has concentrated on NDE data processing, developing engineering solutions to materials evaluation, and developing advanced sensors. Their mission is to reduce the costs and technical risk of developing and evaluating hardware by applying advanced physics principles to materials evaluation. Currently, the group is composed of 4 Ph.D. scientists, 2 engineers, and 1 technician. Some of the test capabilities available in-house are an industrial X-ray computed tomography facility, a microfocus X-ray computed tomography facility, full waveform ultrasonics, eddy current, portable NDE equipment and a radiation effects laboratory. When bidding contracts, they act as a clearinghouse for the company, integrating the best technologies into the proposal.

This group uses current state-of-the-art equipment where possible and develops new approaches when available equipment proves inadequate. Table 5-2 describes Boeing R&D contracts as of March, 1997.

The Seattle M&P NDE team estimated that the microfocus computed tomography equipment purchased in 1993 has already paid for itself in reduced manpower required for failure analysis and in improved quality of data. The NDE Data Fusion Workstation is being used extensively on a wide range of Boeing products because it significantly reduces the time to develop a new NDE data application, and because it presents the information in a highly compressed visual format that makes it much easier for the evaluator to comprehend. In regards to achieving higher fidelity, which will lead to fewer false calls, they are working on improvements to shearography, interactive multimedia computer based training (IMCBT) and NDE for low observables. The shearography and IMCBT tasks will be completed in 1998. A prototype handheld infrared directional reflectometer for evaluating infrared LO surfaces has been built and tested, and two more are being

Table 5-2. Current Boeing Defense and Space Group R&D Aging Aircraft Contracts.

Contract Name	NDE Value $K	Funding Agency	Task(s) Description
Novel NDE for Corrosion Detection	$737	WL/MLLP	-Atmospheric Neutron Radiography -Fiber Optic Corrosion Detector -Neutron Activation
Failure Analysis, Shearography and Training (FASR)	$676	WL/MLLP	-CT for failure analysis -Shearography improvements to simplify interpretation by enhancing postprocess image data -Interactive multimedia computer based training for NDE
NDE Data Fusion	$951	WL/MLLP	NDE Data Fusion Workstation combining multi-mode NDE data to reduce ambiguity
NDE technology for LO airframe structures	$440	WL/MLLP	Handheld IR directional reflectometer
Enhanced laser generated ultrasound	$603	WL/MLLP	Evaluate laser ultrasound system at Sacramento ALC
Stripping, repaint of E-3 radomes	$80	ESC	Paint thickness mapping using ultrasonic microscope
New E-3 radomes	$60	ESC	Paint thickness mapping
E767 (Japanese AWACS)	$40	JASDF	Paint thickness mapping
Optical fiber based NDI system for aging structures	$200	ARPA	Low observable corrosion sensor using handheld directional reflectometer

fabricated for delivery to the Air Force.

Recent examples of applications of advanced NDE to Boeing programs include the following:

- Transferred synthetic aperture processing of ultrasonic microscope data to the Operations organization.
- Developed ultrasonic method to measure paint thickness on AWACS radome (estimated savings of > 8 man years)
- Used CT data to calculate the area of complex parts for production plating operation (estimated savings of $500K/year)
- Developed precision electrical bonding/grounding meter for commercial aircraft production, which is now in use.
  - Measures very low impedances
  - 1/6 the weight of previous meter
- Refined eddy current based fiber weight sensor which measures electrical impedance of carbon fiber prepreg to obtain the aerial density of the fiber. This equipment greatly reduces the cost of measuring resin to fiber ratios compared to solvent extraction methods.

Boeing has completed the evaluation of three novel NDE techniques to detect corrosion on aircraft under contract from the Air Force Research Laboratories (AFRL). These three techniques are; atmospheric neutron radiography, embedded fiberoptic corrosion sensor, and neutron activation.

In atmospheric neutron radiography, the use of naturally occurring neutrons in the upper atmosphere was examined as a possible way of imaging corrosion. A neutron beam which closely approximates the atmospheric spectrum was used to simulate several years of flight exposure, and insufficient image contrast was found in the exposed image recording materials. Boeing concluded that the atmospheric neutron radiography technique was not feasible.

The fiber optic corrosion sensor relied on etching of aluminum plated onto a bare fiber core sensor to change the amplitude of the optical transmission through the sensor region as the aluminum plating corroded to indicate the presence of corrosion. While the technique worked as predicted when a bare sensor was subject to corrosion, its performance was very erratic and the fiber was prone to breakage when mounted on a piece of corroding aluminum. Boeing concluded the technique was too high risk to warrant further development.

The neutron activation technique exploits the fact that short half life isotopes are produced when a part is exposed to a short burst of neutrons. Each isotope produces a family of gamma decay photons which have characteristic energies as they decay. These photons can be detected and sorted by energy, allowing assessment of the elemental composition of the part being evaluated. For this application, Boeing used the oxygen in the corrosion products was the element for detection. In a laboratory environment, aluminum hydroxide equivalent to a thickness of 0.003 inch spread over a one square inch area in the presence of aluminum metal was reliably detected. Based on these results, Boeing concluded that this technique warranted further development, which has occurred under

Boeing internal funding to aimed at detecting shell inclusions in titanium castings.

Under contact from AFRL, Boeing is evaluating the Laser Ultrasound Inspection System (LUIS) at McCellan AFB in Sacramento. The purpose of this contract is to gain experience with this technology, document lessons learned for future ALC equipment acquisitions, and project future enhancements to existing equipment. One of the key conclusions from this study was that laser based ultrasonics (LBU) has a major advantage over conventional ultrasonics when scanning a part in a region where the outer surface has a sharp radius. On flat or gently curved outer surfaces, conventional ultrasonic techniques in general achieve better performance as measured by cost, throughput, and data quality. Since conventional ultrasonic techniques are relatively mature and LBU techniques are still evolving rapidly, these conclusions should be considered as a current assessment, not a final conclusion.

5.7.3 C. W. Pope & Associates Pty. Ltd.

C. W. Pope, a commercial NDT and materials testing company with 115 employees, is one of the major naval contracting NDT companies in Australia, doing substantial NDT for the Australian Navy in the Newcastle dockyard.

Company representatives highlighted three specific areas of company expertise:

- Standard pulse echo ultrasonics for far-side corrosion testing in ship structures
- Standard pulse echo ultrasonics for use in the petrochemical industry, to examine insulated pipelines while the pipe is still on-line
- NDT for aircraft frames and corrosion in tubing, especially in helicopters. (Since many of the structures here are on the order of only 1 mm thick, they believe real-time x-rays may let them look through the tubing to examine both the internal and external structures. They can examine a helicopter in a single day, taking 25 frames).

Radiography and ultrasonics are their traditional NDE methods. Real-time radiography technology is a key area for the company, since down-time and environmental issues are driving the commercial power industry in Australia, and this technology allows the company to provide improved information to their customers in a shorter time, improving return on investment.

Pope also has begun in association with an English firm, AEA Sonomative, that has developed software to tie a pulse echo ultrasonics probe to other software that will produce graphic images. They are beginning to use B-scan techniques (as a new way to present data, i.e., in cross-sectional view). This has been used on storage tank floor and piping inspections. They also are using magnetic flux leakage techniques, although they admit that this is less viable in aluminum structures. Finally, they do some thermography, although they have not used it for fatigue testing or corrosion detection.

The mainstay of Pope’s R&D group is the use of electro-magnetic acoustic trans-ducer (EMAT) technology for NDE. This produces sound waves in materials using an electric coil and magnets, sending energy along a surface to an area(s) to which normal access may not be possible. This was first used to detect stress corrosion cracking in natural gas pipelines, but company representatives indicated it also can be used to detect corrosion. However, they pointed out that the equipment required is big and bulky, and must be included in part of the "pig" that goes down the tube, performing the inspection. The technology was developed by Rockwell in the 1960s for missiles. It provides good depth/penetration capability and needs no couplant, but sensitivity of the technique always has been a problem.

They stated that research people in NDT all over the world are moving toward EMAT, but that Pope is already using it in the field. Pope has received the largest grant which the American Gas Association has ever sent outside the U.S. to explore this technology. Others working in this field include Babcock and Wilcox and NASA.

Characteristics and constraints of EMAT technology include:

- It is dry, needing no couplant
- It provides a macro inspection technique for large surfaces/areas, and in all but "weird" geometries, micro inspections can be performed
- Direct physical contact is not necessary, so it can be used through paint or other surface coverings
- It is not important which side of the surface the defect is on (i.e., whether the defect is on the same or opposite side of the transducer is irrelevant)
- It has a low false call rate (reliability in the "high 90s")
- It sends out a parallel beam, vice the expanding beam produced by ultrasonic techniques
- With proper processing, a 3-dimensional wire diagram of the results can be produced
- However, size can be difficult to estimate
- The item being inspected must have a minimum internal diameter of a "few inches" and a "fist-sized" external diameter, otherwise resolution is lost.

A real-world example of the use of EMAT technology is in the inspection of ship fire extinguisher systems. Use of EMAT techniques could cut the time needed to inspect these systems to a fraction of the huge amount needed by more traditional manual ultrasonic techniques.

Pope generally gets paid by the man-hour and that they essentially have no competition in the fields in which they work. Thus, they have no incentive to incorporate new technologies into their repertoire if those technologies reduce the cost which they can bill to their customers, especially to the government.

5.7.4 Diffracto Limited

Diffracto Limited is a small, high-tech firm that markets D Sight aircraft inspection, (DAIS 250C, DAIS250CV), an enhanced visual, rapid scan inspection system designed for corrosion detection along lap joints and surface distortions in the uppermost layer of the surface. This technology magnifies surface curvature changes, such as pillowing or bulging between rivets, to the exterior skin of the aircraft, making them readily apparent. The system is encased into a movable sensor, which is placed directly onto the surface of the aircraft.

The D Sight technology is described as a dual light pass retro-reflection technique.

This technology uses a CCD camera, a white light source mounted slightly below the camera lens, and a retro-reflective screen. A surface targeted for D Sight inspection is either reflective or made reflective with an environmentally friendly highlighting fluid. Light from a source is directed to the inspected surface (primary signal), reflected to a retro-reflective screen and back to the inspected surface (secondary signal). The retro-reflective screen, covered with multifarious silvered glass beads, returns a corrupted pattern of light to the inspection surface; not a perfectly mirrored light pattern of the primary signal. The resulting superimposition of the two light patterns creates the D Sight effect that is captured by a CCD video camera positioned slightly above the light source. The image from the retroreflector is seen through the surface near the local curvature distortions as bright and dark gray-scale variations. It is the nature, size orientation and contrast of these intensity variations that determines the extent of the surface deformation and ultimately the corrosion level.

A software program has been established to both provide a baseline aircraft grid and map the inspection carried out relative to inspection criteria established in the planning process. Large surface areas of aircraft can be mapped quickly with problem areas identified for more detailed inspection using a more traditional method like eddy current or ultrasound. It can also be used to monitor corrosion growth by comparing previous images to present images and calculating the difference. In addition, the system also has capabilities to determine impact damage and de-bonds on composite surfaces.

Initial research using D Sight as an inspection technology in the aerospace industry was funded by the Structures, Materials and Propulsion Laboratory of the Institute for Aerospace Research (IAR), under the auspices of the National Research Council Canada (NRCC). D Sight for aerospace continues to be explored by several government agencies within Canada and the US, as well as in Europe.

Diffracto is developing a scanner that uses Diffracto's patented D Sight technology for the detection of corrosion in lap splices. The goal of this R&D initiative is to produce enhanced visual D Sight images from a lightweight, low cost device that can be used by one operator and provides limited data storage capability. The scanner development phase is scheduled to be completed by April 1998. The project is Phase IV of a larger program that saw the development of the DAIS using a full view application of D Sight. This phase of the program is being funded jointly by the Transportation Development Centre of Transport Canada and Diffracto. The TDC funding level is 70 percent. Earlier phases of the program included funding by the DND, FAA, U.S. Air Force and the NRCC, with the FAA contributing the largest share of the funding via an international agreement.

The D Sight technology also is used for the detection of impact damage and delaminations/ disbonds in composites as well as any other topological surface anomaly. Other applications include automotive applications for the inspection of Class “A” surfaces. For instance, the system is panned to be used to detect small defects on a premium vehicle of a large automotive company prior to the application of paint.

5.7.5 Engineering Testing and Research Services (ETRS)

ETRS is an applications-oriented Australian commercial consulting firm. ETRS has a network of 16 offices, making it the largest single supplier of NDI services in Australia.

The company is accredited with ISO 9001 and has approvals for corrosion survey of hull structures with DNV, Lloyds, ABS and Bureau Veritas. ETRS also has CASA certificate approval for NDI as well as having approval from commercial aircraft manufacturers such as Hamilton Standard, Lear jet and many commercial small operators.

ETRS is heavily involved in corrosion failure assessments and suitability of materials for various environments, especially offshore marine structures. Radiography, eddy current and ultrasonics are being used extensively to assist in the monitoring of corrosion of piping, pressure equipment and marine structure. Ultrasonics is used with interface triggering for oxide thickness measurements. B-scan ultrasonic techniques are sued for the cross-sectional presentation of rear-wall corrosion on storage tanks and pressure vessels, detected by standard pulse echo techniques.

The company’s application of corrosion techniques are used in several areas, including:

- High temperature electro-chemistry, looking at ways to inhibit/reduce corrosion of electrodes caused by the extremely caustic fluids used in aluminum plants
- Electro-chemical power source performance evaluation, assessing how corrosion of battery plates affected performance in telecommunications and military systems
- Sacrificial anode performance in gypsum/bentonite backfill media
- Exfoliation corrosion of high-strength Al-Mg alloys, such as used in high-speed catamarans and other applications in the shipping industry
- Anti-foulants for aluminum-hulled ships (copper-based formulations)
- Filiform corrosion (in automotive, marine and aerospace applications).

5.7.6 McDonnell Douglas Corporation (Now a wholly owned susidiary of The Boeing Company)

The McDonnell Douglas Phantom Works is very active in NDE R&D and has a number of laboratories and functional groups that support this line of research. Some of the NDE methods currently under development for corrosion detection are multi-modal, large area scanning, nuclear magnetic resonance, and computed radiography. From 1992-1997, the company has dedicated significant resources to corrosion detection development, broken down into the following development stages and percentage breakouts (see Table 5-3).

McDonnell Douglas currently markets their Mobile Automated Scanner (MAUS), a portable C-scan inspection system that integrates several traditional inspection modes into a single package. Its capabilities include pulse-echo ultrasonics, ultrasonic resonance, and eddy current. The multi-modal approach allows inspection of a variety of structure types, including composite metallic and bonded assemblies. This system is used in a variety of manufacturing and aircraft maintenance environments for quality inspections, damage assessment, repair evaluation, and aging structural evaluation programs. The MAUS is hand held and moves along a surface on rubber wheels coupled to an encoder that translates position information to c-scan format. The system also has data formatting and archiving capabilities.

The equipment is portable and easy to set up, and can quickly inspect large structures. Scan speeds of up to 400 square feet an hour can be achieved.

The MAUS system was developed under a 1991 USAF contract as part of the "Large Area Composite Inspection System" program. It was developed primarily for scanning large composite structures such as those found on the B-2 and C-17 aircraft. Using a vacuum-assisted scanning track, the MAUS has been used to scan the DC-10 crown skin for cracks. The inspection was accomplished in 4 hours, compared with the 100 hours required for an equivalent inspection using radiography. This technique has been particularly useful for examining corrosion in fuselage lap joints, such as those found on the KC-135 aircraft.

MAUS development continues under a USAF ManTech project to further develop the system to incorporate additional bond testing capabilities and PC-based software. Other goals are to conduct additional field evaluations and incorporate change requests from these evaluations, investigate battery power alternatives, and deliver a field hardened prototype.

McDonnell Douglas currently has over 30 systems in the field. The USAF has

Table 5-3. McDonnell Douglas Corrosion Detection R&D Funding Profile.

Method Development Stage	Funding Percentage (%)
Basic Research	2
Exploratory Development	17
Applications Development	7
Full Scale Development	35
Technology Implementation	39

MAUS III systems at McClellan AFB, Tinker AFB, Hill AFB, Charleston, Warner-Robins AFB, Kelly AFB, and the Air Force Research Laboratory. The Navy has systems at NAWC Patuxent River and at NADEP Cherry Point. Within industry, systems have been procured by major aerospace companies in the U.S. On the international front, the Royal Air Force (UK) has acquired one system.

McDonnell Douglas is also developing Nuclear Magnetic Resonance technology to determine the presence of incipient corrosion under coatings. The concept is to pulse the surface with a tuned RF pulse in the presence of a magnetic field and measure the resonant frequencies that result. This technique has demonstrated good detection capability for corrosion under paints and sealants and moisture detection under thermal tiles on the space shuttle.

Another corrosion detection technology area that McDonnell Douglas is pursuing is computed x-ray radiography. Basically, this technique deals with exposing a phosphor coated image plate to x-rays and analyzing the reaction of the phosphors with radiation. The image plate reader then captures the data, which is saved in a digital file and transferred to a data review station for interpretation on a high resolution monitor. This technology is being evaluated as a replacement for film due to its excellent contrast sensitivity. Economic benefits may also be realized through elimination of film.

5.7.7 PRI Instrumentation, Inc.

Physical Research, Inc. (PRI) was founded in 1980 and is based in Torrance, CA. The company receives about $1M annually in sales and has had over 200 contracts during its lifetime. The company has expertise in electronics (especially high speed analog to digital converters) and NDE (the company manufactures the Magneto-Optic/Eddy Current Imager (MOI) device, the first one of which was shipped in 1992). PRI is responsible for the R&D aspects of the MOI product. Its subsidiary, PRI Instrumentation, Inc., which has the MOI as its sole product, is responsible for product commercialization.

PRI's MOI device exploits a principle discovered 150 years ago by Faraday when he observed that when plane polarized light is passed through glass in a direction parallel to an applied magnetic field, the plane of the polarization is rotated. The device provides a NDT system for inspecting ferrous and non-ferrous conducting materials and can detect the magnetic fields associated with both surface and subsurface defects (both cracks and corrosion). The depth of penetration is dependent on the material being tested and the frequency used (which can range from 1.5 to 100 KHz). The lower the frequency, the deeper the penetration for a given material, with depths of 0.015" to 0.12" achievable in 7075-T73 aluminum. The MOI produces a direct, analog image of the defect and projects that image on a head-mounted display, while having the capability to simultaneously send data to a computer for storage and later analysis and/or to a videotape machine. The entire system consists of a 6" x 8" x 14" control unit, a 3-lb. handset that is used to perform the actual scanning of the surface being examined, and a headset. The system costs under $30K per unit.

The MOI allows rapid inspection of large areas for defects. For example, it was stated that the inspection time for a B-52 can be reduced from 38 - 40 hours to 3 hours. The MOI permits reliable inspection through both paint and decals (reducing, for example, inspection times for Tower Air from 2500 hours to 84 hours), and, since its displayed results are easy to interpret, requires minimal operator training. It has been approved by, among others, Boeing for use in fatigue crack detection on all models of its aircraft; the Air Force on B-52s and KC-135s, with the C-5 in evaluation; and the Navy on C-2s and E-2s.

The latest versions of the MOI rely on sheet current induction, removing the requirement to rotate the unit 90° to eliminate the chance that a crack is parallel to the eddy current field. PRI claims that earlier versions were about as reliable as standard eddy current devices, while the latest model (with the sheet current induction) is better. Although current models can be used on slightly concave surfaces (as long as lift-off is not excessive), a version (called the Rotomag) is in development which will have feet tailored for pipes, power plant turbine blades, and other curved surfaces. Also in development is a palm-top version (smaller configuration) with a CCD camera.

PRI representatives said that the MOI has a unique capability to detect cracks in dimpled countersinks. Its display allows the user to see the fields which look like the crack/corroded area. It has the advantage that minimal signal processing is needed, as opposed to standard eddy current devices, which require heavy use of signal processing techniques.

Although it originally was used, and primarily was approved, for crack inspection, the MOI technology is now recognized as a useful detection tool for corrosion. Its use in this area has been approved by Gulfstream and is being evaluated at Tinker AFB and by United Airlines. PRI researchers believe that it could (with processing) generate contour pictures of any corrosion. The scanning movement required for use of the unit helps to pinpoint corrosion. It also has proven useful in finding defects in spot welds such as were used on the KC-135 and the A-10.

5.7.8 Southwest Research Institute

SwRI NDE&T researchers have developed two technologies they researched specifically for corrosion detection: (1) magnetostrictive sensors (MsS), and (2) orthogond axis eddy current imaging. Currently the MsS technique is used strictly to detect corrosion in steel pipelines. The technology consists of electrically inducing an elastic mechanical wave along the longitudinal axis of a pipe and then detecting the characteristics of the wave (e.g., amplitude, wavelength, frequency) both before and after the wave travels the length of the pipe. Reflected signals can indicate defects such as corrosion in the pipe. A key feature of this technology is that it allows inspection of long lengths of pipe from one access point. Funding for the technique was originally provided by the Federal Highway Administration and the Gas Research Institute. SwRI is presently looking for other sponsors to continue development of the technique.

SwRI has worked with E-Systems to research the use of their orthogond axis probe technique to detect corrosion in aircraft. The orthogonal axis probe provides greater sensitivity then conventional probes by using transmitter and receiver coils that are located together but oriented differently to avoid electromagetic coupling to each other. This configuration significantly reduces the probe's sensitivity to liftoff variations. The research with E-Systems consisted of analyzing aluminum skin structures on Navy P-3 and RC-135 aircraft. No follow-on research occurred with E-Systems.

5.7.9 Thermal Wave Imaging, Inc.

TWI is a small business incorporated in 1992 that employs eight people. It is dedicated to the development and commercialization of infrared thermal wave imaging technology that was initially developed at Wayne State University. The company licenses Wayne State's intellectual property and has expanded on this patented technology. TWI currently has patents related to thermal wave imaging data interpretation and the application of heat through flash lamps and reflectors to area surfaces. They have other patents pending.

Thermal wave imaging is a pulsed - 5 milliseconds - system that can operate on a midwave 3 to 5 micron infrared band or longwave 8 to 12 micron infrared band. The thermal pulses traverse through objects, reflect off subsurface defects, and then return to the surface as thermal wave "echoes." This technique allows for an accurate measure of material thickness differences. The spatial resolution is inversely porportional to thickness (or depth) so the technique works best on shallow defects. The detectors can be composed of either indium antimonide or platinum silicide. The IR detector is prepacked and the system is built around the camera (TWI works with all the major camera companies on this.) The system does not need to be cooled. The TWI representatives estimated that their system can cover approximately one square foot every 15-30 seconds. They consider this technology as complementary to such point measurement techniques as ultrasound and eddy current by providing non-contact, wide area coverage within a few seconds.

In 1993, TWI introduced EchoTherm - an integrated system for IR NDE of subsurface defects. It analyzes the thermal behavior of the sample in response to a controlled heat pulse and is touted as being easily interpretable, highly repeatable and immune to variations in ambient conditions. The system consists of a pulsed heat source (typically, high-power photographic flash lamps), an IR video camera, and image processing hardware and software controlled by a personal computer. It is fully digital and includes PCI-based image acquisition hardware; a Windows based software program for data analysis; flash lamps and optics for maximum uniformity, minimum afterglow and short duration; a programmable flash power supply; and a portable Pentium computer. EchoTherm is configured for either laboratory or field use and is compatible with all leading IR focal plane array cameras.

TWI representatives cited that the benefits of the TWI technology include its ability to scan a wide area quickly and provide fast, quantitatively defined feedback with minimal operator interpretation. They stated that it is easier to interpret than techniques based on optical interference methods. Thermal wave imaging measures the time at which things occurred and not the amplitude as opposed to conventional thermography where only the surface temperature of the part is measured. It can be employed on aluminum, plastics, steel, and composites like graphite epoxy. It is less effective when dealing with highly insulating materials like rubber or glass.

There are, however, a few limitations. Images created by defects deep below the surface tend to blur. When testing highly reflective metals, operators will have to coat surfaces with water-soluble solutions to help absorb the IR light and provide better emissivity for the cameras.

The cost of the TWI system is $110K per system - $60K for the camera and $50K for the other components. The TWI system uses COTS products whenever possible and they have built the system with open architectures so that if one module changes, the whole system does not need to be scrapped.

TWI has R&D contracts/testing with or systems in place at the Navy, NASA, Boeing, Lockheed Martin, Harvard University, GM and Ford. Several TWI customers, including Boeing, Lockheed Martin, and General Electric, have bought multiple systems.

TWI has two SBIRs with the Navy through the NAWC. One involves reducing the current TWI system to a handheld unit by minimizing the power requirements for the shipboard system. The other entails developing an integrated ultrasound IR system using an ultrasound or eddy current probe on the IR picture for use in defining depth measurements and material loss in composites. TWI's NASA work deals with assessing composite material delamination/ impact damage. Boeing employs four TWI systems for commercial applications, mainly dealing with detecting adhesive bonding and corrosion in metals and composites. Ford and GM use these systems for testing in the production process.

The TWI representatives foresee the biggest market for their technology in the commercial and military aircraft industry. Other applications the company hopes will develop into a big market is automated inspection facilities and petrochemical pipeline inspection.

As to potential new customers, TWI believes that many of the largest composite manufactuers are looking to replace half of their imaging ultrasound systems with new technology.

5.7.10 Tektrend International

Tektrend is a Canadian commercial company that designs and manufactures custom NDE equipment for government and commercial clients. It is a small company, employing 25 people, of which 20 are engineers, scientists, and technicians.

Tektrend's business is divided between manufacturing and R&D. Manufacturing comprises 70 percent of the business, R&D 30 percent. Saleswise, 90 percent of Tektrend's sales are to U.S. commercial and government entities; 10 to 15 percent of sales are to the U.S. and Canadian military. Most of Tektrend's manufacturing and R&D, 75-80 percent, is focused on ultrasonic products. The remaining 20 percent-25 percent is comprised of manufacturing and R&D of acoustic emission, eddy current, and radiography products.

Tektrend sells a wide range of products. They sell a hand-held 2-axis ultrasonic tester that costs $48K. They also sell 6-axis desktop and 9-axis floor model ultrasonic testers that range in price from $50K to $250K. The costs of these systems include training and software installation. One other important ultrasonic product developed by Tektrend is an automated pressure hull intelligent ultrasonic inspection system for submarines in drydock. Equipment is custom built to fit the client's needs and include industrial manufacturing systems.

One R&D area that the company is concentrating on is electromagnetic acoustic transducers (EMATs). Their researchers believe that recent developments by Tektrend and others in this area could revolutionize ultrasonics. Up until the present, EMATs have been very costly. Tektrend and others are bringing down cost by reducing the size and using atate-of-the-art magnet and electronics.

5.7.11 TPL, Inc.

TPL is a small business headquartered in Albuquerque, New Mexico whose areas of product development include electromagnetic sensors, electrical impedance spectrometers, (EIS), and real-time digital x-radiography systems.

Their EIS product line, dubbed "Dielectroscope" is used for characterization of heat damage in composites, for evaluation of protective coatings such as paint on ship hulls and for detection and characterization of moisture in composites.

They have developed a suite of magnetometer-based NDE sensors, called Advanced Penetrating Electromagnetic Technology (APET), which have much improved low-frequency response compared with conventional coil-based eddy current systems. These sensors are used to detect and image deeply buried cracks and corrosion in conductive materials.

TPL's real-time, digital x-radioscopy program is based on a high frame-rate, large area (8.5"x11"), radiation hard imaging array. The system offers high spatial resolution and a dynamic range (depth) exceeding that of film. As a result, there is no need to "bracket" an exposure range. The system is currently being applied to NDE, tomography-based coordinate measurement and medical applications.

5.7.12 Utex Scientific Instruments

Utex is a Canadian commercial company that designs and manufactures custom high resolution ultrasonic NDE equipment, and develops "NDE Workstation" software to combine and display results from a multitude of NDE technologies, either separately or simultaneously. It is a small company, employing 10 people.

Utex incorporated in 1991 and has R&D and marketing departments. Approximately 60 percent of Utex's revenues are spent on R&D related activities. All manufacturing of the ultrasonic instruments is outsourced. 70-80 percent of Utex's sales are exports to either the U.S. or European countries. Utex has no current funding from DND or the U.S. DoD.

Utex makes two different Ultrasonic Pulser Receivers, the UT320 and the UT340. The receivers are designed to be high resolution in both power and frequency. Table 5-4 indicates some of the current users of Utex's pulser receivers. Most of the users of Utex products also employ the Utex "Winspect" software.

Winspect has become the de facto standard "NDE Workstation" software, currently holding 50 percent of the market. The software is completely independent of the type of NDE technique used. Utex was the first NDE software vendor to convert entirely to the Windows operating system.

Utex has been selling Winspect since 1995. When first released, it was targeted primarily at the research market to gauge what needed to be improved. Since then, they have marketed Winspect heavily to aircraft OEMs. They are currently working with Lockheed Martin, McDonnell Douglas, Northrop Grumman, and Boeing. In fact, Winspect has been designed to interface with the McDonnell Douglas MAUS NDE device. Utex has also begun marketing Winspect to the pipeline industry.

Table 5-4. Some Users of Utex Pulser Receivers.

AECL Chalk River Labs	NASA Lewis Research Center
College of William and Mary	National Research Council Canada
Electricite de France	Ontario Hydro
Electricity Corporation of New Zealand	Pacific Gas and Electric
Imperial College of Science, Technology and Medicine	Pratt & Whitney Canada
Iowa State University	Southwest Research Institute
Los Alamos National Laboratory	Wright Patterson AFB

Utex is currently developing NDE databases to store historical NDE data. Utex believes that Winspect is several years away from being a true data fusion engine, which is one of the ultimate goals for the software.

Utex has also developed Imagine3D ultrasonic simulation software, which is also becoming an industry standard.

5.8 Commercial Airline Activities

The following paragraphs highlight some of the ongoing commercial airline activities in regards to corrosion detection and maintenance. These writeups are intended as a representative sample of the industry, not all inclusive. Since 1975, corrosion has been a contributing factor in at least 687 commercial aircraft accidents/incidents, resulting in the loss of 87 aircraft and 81 lives.

5.8.1 Aloha Airlines

Aloha Airlines representatives stated that they follow the procedures of Boeing's Corrosion Prevention and Control Program, which is outlined in Airworthiness Directive 90-25-01. The basic elements of the program are inspection of primary structures; initial and repeat inspection intervals based on calendar time rather than flight hours; maintenance such as cleaning, inspection, rework, and corrosion prevention treatments; and periodic adjustments to the program in order to maintain a corrosion severity of Level I. Aloha Airlines inspectors are trained at and largely depend upon visual inspection as their primary mode for inspecting for corrosion.

5.8.2 Air Canada - Dorval

Air Canada is the largest Canadian airline. The Dorval Airport location in

Montreal is the site of a large Air Canada maintenance facility. Like all Canadian airlines, Air Canada is regulated by Transport Canada, the Canadian equivalent of the U.S. Federal Aviation Administration (FAA). The use of NDT techniques in the performance of routine maintenance on Air Canada's passenger aircraft is one of the areas regulated by Transport Canada. For the most part, visual techniques are the primary techniques required by Transport Canada. Therefore, those are the techniques most widely utilized by Air Canada. They have the capability to do eddy current and ultrasonic inspections, but not on a large scale. The Air Canada engineers felt that the economics of airline maintenance does not justify the use of other NDT techniques. They also stated, though, that they do not break out corrosion costs separately so could not quantify what corrosion maintenance is currently costing.

5.8.3 Northwest Airlines, Minneapolis, Minnesota

Northwest Airlines primarily relies on visual inspection when conducting inspections for corrosion detection. They have, however, been very active in testing new/enhanced corrosion detection technologies and view thermography as a technology that shows real promise and could offer potential large savings to the airline.

Northwest Airlines NDE professionals asserted that the airline problem is driven by both the physics of corrosion and the directives of the FAA. For example, the corrosion AD requires that any corrosion detected during visual inspection be repaired before returning the aircraft to service. It does not specify an allowable degree of material loss or involvement. NDE inspection of fuselage lap splice repairs establishes a 10 percent material loss threshold for repair. Thus, on one hand, an airline may not want to know about corrosion losses of less than 10 percent because that leads to unnecessary repairs. On the other hand, it has to know when 10 percent has been exceeded. This logically leads to an accuracy requirement in sensing technology on the order of 1 or 2 percent.

The airlines use structural repair manual limits to establish three levels of corrosion. Level One is within SRM limits and can be repaired using cleanup methods. Level Two is a higher degree of material loss that requires repair or replacement of the offending parts. Level Three is a serious material loss that affects the structural integrity, and therefore the safety, of the aircraft. It is at Level Three that notification of the OEM and the FAA would be required. The airlines distinguish between primary and secondary structures in dealing with corrosion repair. For example, the areas around lavatories and in bilges are routinely examined and treated as normal maintenance. The involvement of spars, attach fittings and landing gear would be much more serious.

The experience at NW highlights the complexity of the corrosion problem. In many cases, repair of corrosion seems to increase the rate at which it returns and grows, suggesting that the cure can be worse than the disease. A significant need expressed was that of understanding and tracking the rate of corrosion growth to establish better inspection and repair intervals. There was consensus that corrosion removal generates some unknowns, particularly regarding fatigue life and future tendency to corrode in the repaired area. They stated that the scientific understanding of corrosion is not as complete, nor is corrosion as well modeled, as is crack growth and fracture mechanics. The interactions between fatigue and corrosion are not well understood. This interaction is exhibited in stress corrosion particularly.

The airline maintenance is treated primarily in economic terms within the overall safety guidelines. As it happens, aircraft are retired for several different reasons. In some cases, retirement is driven by the engines and in others, by the airframe. New aircraft are delivered with a design lifetime. This lifetime is often doubled or tripled as various modifications and improvements are made. It is not unusual for a fleet aircraft to be in its second or third lifetime (based on the original design). Thus it is essential to track and understand the maintenance and overhaul history of every aircraft on an individual basis. The airline representatives stated that the airlines freely share this sort of maintenance information with each other.

Northwest representatives noted that they must justify investment in costly corrosion detection tools, as any unscheduled or unplanned maintenance has a direct impact on operations. They pointed out that airlines must adhere to safety guidlines but should also avoid flight delays and cancellations.

5.8.4 Qantas Airways

Visual techniques are still the major corrosion/defect detection means employed by Qantas. Qantas representatives stated that they believe it is "hard to beat" human inspectors. They did note that too little consideration is given to in-service corrosion issues during the design stages of an air transport's life. The 10 percent 'threshold' is employed only if the OEM reduces permissible tolerances: the representatives pointed out that they "see no use" for it unless degradations of greater than 10 percent are legitimate problems. Qantas works under Australia's Civil Aviation Safety Authority (CASA) certification program, which follows Boeing's Corrosion Prevention and Control Program (CPCP). Qantas has a good relationship with Boeing, so they feel they can suggest changes in their corrosion detection procedures as necessary.

Corrosion inspections are normally done when the aircraft undergoes a check visit. Thus, corrosion control is tied to chronological time vice flight hours or operational use. In general, the entire aircraft is not inspected. Rather, attention is focused on known trouble points. In essence, they look for corrosion where the OEM tells them to inspect. Qantas personnel stated that even tap tests are sufficient in certain areas where they are known to be adequate, and that anyone can do such a test at any time without needing specialized equipment or trained personnel. If corrosion is detected, it is dealt with immediately. However, if the corrosion is found at the end of the inspection and is not deemed so bad as to be a safety concern, elimination of the corrosion might be delayed until the next inspection. They stated that corrosion is at least "made safe" when it is found.

Qantas personnel expressed satisfaction with the process used at Qantas, feeling that all detected corrosion is removed and that Qantas's corrosion prevention program is working well. However the representatives feel intergranular corrosion is not well detected by non-visual NDT technologies, leaving much of the detection effort to the eyeballs of their engineers who do visual inspections. They did say that second layer corrosion is a problem, since they are limited in what they can see/detect and what they can do about it once detected. The Qantas representatives believe far side corrosion can be resolved, but that second layer is more difficult.

There was some debate about whether corrosion returns faster once it has been repaired. One representative asserted that it depends on the nature of the repairs: shoddy repairs do cause more problems than they eliminate, but corroded areas which are treated and sealed correctly will not cause subsequent problems. The need for corrosion prevention also was emphasized.

Qantas representatives stressed that their NDI branch is not an R&D organization. While the airline may have some facilities, they have neither the inclination nor the mandate to perform R&D-type operations due to the cost involved. The OEMs also have a say in the R&D process, either accepting or rejecting new NDT schemes.

The return on investment (ROI) of the NDI group is important, and the period over which they must show a return is shrinking, being about 12 months now. Thus, while the staff can see the benefit of scanning systems, they cannot justify their purchase at this time. The NDI group representatives also stated that maintenance organizations are always asked to minimize expenditures: from the point of view of management, spending money to put video screens in every seatback may be more desirable than spending it to improve maintenance equipment.

Qantas representatives stated that Ansett Airlines (a domestic competitor) uses Airbus aircraft which have experienced a great deal of water-caused delamination of the composite materials used in the aircraft. Thermography was used to detect these problems. Ansett monitors the problem, but does not fix it unless necessary.

The airline’s use of radiography has been limited by a number of factors. The primary one is environmental issues. Radiography is not very ‘green’, due to the radiation itself, the heavy metals on the film and the noxious solvents required. However, the staff admitted that radiographic film and images are the standard against which all other imaging systems are compared and that people like to see a hard copy of results.

They feel that the sensors used in thermographic systems are getting better now and Qantas is considering acquiring an infrared capability within the next year.

As an aside, Qantas representatives stated that the CASA (Australia’s equivalent to the FAA) has lost its NDT capability completely, as its remaining engineers have little or no expertise in NDT. Even accident investigations are performed commercially in Australia.

The representatives feel that corrosion detection should consist of three parts: a broad scan, a supplementary analysis to quantify the extent of a problem, and an engineering approach to marry the corrosion detection effort into the aircraft’s maintenance plan. They believe composites may be over-inspected just because of the unfamiliarity of the airlines with that material.

Qantas used to keep its planes for 20,000 flight hours and then sold them. Now, some of the airframes in their fleet have accumulated over three times that amount of flight time. While Qantas flies in a relatively benign environment (long flights without a lot of frequent landings and takeoffs), the extended use of their aircraft into what previously would have been considered to be their third or later design lives has heightened their awareness to and concern with the effect of corrosion on those structures.

5.9 University/Academic Research Activities

5.9.1 Carnegie Mellon Research Institute

The FAA has funded this institute to develop an aircraft inspection robot called the Automated Nondestructive Inspector (ANDI). This robot, when completed, will be able to walk over, under and around aircraft fuselage attached by suction cups on its seven feet. It will be able to carry out optical inspections as well as eddy current and ultrasonic inspections. A prototype was tested at USAir's maintenance facilities.

5.9.2 College of William and Mary, Department of Applied Science

The Department of Applied Science (AS) at the College of William and Mary has a number of ongoing NDE Ph.D. research projects, including:

- Lamb Wave Tomography

Research Partner: Physical Sciences, Inc. (funded in part by ONR)

- Photo and Thermo-elastic NDE

Research Partner: Stress Photonics, Inc.

- Thermographic Penetrant NDT

Research Partner: NAWC/AD

- Laser Ultrasonic NDE

Research Partner: NASA NESB

- Thermography and IR Microscopy

Research Partner: Stress Photonics, Inc.

- Large Ultrasonic Phased Arrays

Research Partner: NASA NESB.

In addition, the Department of AS is researching numerical and analytical modeling techniques for all NDE methods, and is investigating using neural networks, fuzzy logic, and expert systems to process NDE test data.

The College of William and Mary staff believe the ultrasonic lamb wave technique can have applicability for detecting corrosion damage though they consider this technique to be at least one year away from commercialization.

5.9.3 Iowa Sate University, Center for Nondestructive Evaluation

As mention earlier, the FAA has set up the Center for Aviation System Reliability (CASR) at Iowa State University to oversee inspection system development. Their research programs are described in the FAA section.

Iowa State University also is the parent organization for the Institute for Physical Research and Technology, under which resides the Center for NDE. The researchers at the institute are generally not full time professors but, rather, full time researchers. The technical staff is both full time and some part time students from the university. The institute has existed since 1984, has approximately 100 total staff, and has an annual budget of approximately $8M per year. There are 22 sponsoring organizations, including the National Science Foundation, the FAA and NIST.

One of their main areas of research is in the eddy current technology. Their research is focused on the control of the probe through a computer controlled scanning system and the processing of the data to generate C-scan (color "3-D") images of the structure being examined. With this approach, the researchers are able to analyze material loss on the back side of the top layer, the top side of the bottom layer, and the bottom side of the bottom layer, subject to the usual limitations of an eddy current system. They are not working specifically on multiple frequency scanning at this point. The goals of the system they are developing are that the system be inexpensive, portable, light weight, and provide quantitative results. Their prototype system, using a ruggedized 486 portable computer, displays corrosion loss both by surface and by depth. Test specimens run from 0 to 30 percent material loss with an accuracy within a few percent.

The Iowa State researchers are also working on a low energy, energy dispersive approach to X-ray radiography. Again, their focus is on the computer processing of the real-time data. Their approach is analogous to color photography as opposed to B&W. The researchers foresee this technology as leading to both the characterization of corrosion and, perhaps more importantly, the validation of other techniques that would be more efficient and less expensive. Because they are dealing with low energy X-rays, they perceive the shielding problem as minor compared to current industry standard systems.

Another technology they are developing is the Dripless Bubbler system designed to employ ultrasonic sensors in areas and locations that are otherwise very awkward or impossible due to the need to employ a coupling fluid between the probe and the surface to be inspected. This device surrounds the probe with water contained by concentric brushes (rings of bristles). Water is pumped into the cavity by a pneumatic pump and removed by a vacuum system. Thus, this device can operate on vertical and curved surfaces and works best inverted as on the underside of wings. This system is able to display C-scan and B-scan side-by-side as a means to distinguish between de-bond and corrosion. The focus of this research is the manipulation of the probe and the associated data processing . The payoff will be more rapid surveys of complex areas subject to the limitations of the sensing technology.

Iowa State also houses the newly formed Aging Aircraft Center of Excellence (AACE), an FAA sponsored industry/ academia consortium that is now focused on advanced materials, landing gear, and crash worthiness. It is an outgrowth from the previously mentioned Center for Aviation System Reliability, also at Iowa State. The AACE has corresponding responsibilities to the AANC and the Engine Titanium Consortium (ETC), also sponsored by the FAA. Because this center is new, no specific results can be cited as of yet. The AACE is emblematic of the concentration of FAA sponsored research activities at Iowa State University.

5.9.4 Johns Hopkins Laboratory

The Johns Hopkins Center for Nondestructive Evaluation was established in 1984 as an interdivisional, cross-disciplinary program of research and instruction in nondestructive evaluation and measurement science and technology.

5.9.5 Royal Military College

The Royal Military College (RMC) in Kingston, Canada performs scientific and technical research to support Canadian Forces. RMC collaborates with all research organizations within DND and provides research opportunities for scientific and technical personnel.

RMC has instituted a Unified Corrosion Control and Preventative Maintenance Program. The program has three major components:

- Predictive Modeling
- On-board monitoring
- Rationalization.

The rationalization thrust is comprised of an Information Processing subcomponent and includes the development of a design tool RMC calls MSG-3.

RMC personnel are focusing on on-board monitoring and information processing projects. In the area of on-board monitoring, RMC has two ongoing research projects: (1) Aircraft Corrosion Surveillance, and (2) Development of On-Board Corrosion Sensors. In the latter project, RMC is working with Patuxent River Naval Air Warfare Center and Australian researchers via a TTCP researching imbedded electrochemical sensors. As part of the thrust area, though, RMC is also researching the following types of potential on-board corrosion sensors:

- Electrical resistance
- Linear polarization resistance
- Zero resistance ammetry
- Potentiodynamic polarization
- Electrochemical impedance spectroscopy
- Electrochemical noise.

In the information processing area, RMC personnel are working on a project entitled "Knowledge Based System for Monitoring Corrosion in Aircraft." In this effort, RMC is designing an information architecture that will include historical maintenance databases that they hope will ultimately be capable of fusing and displaying inspection results from numerous NDT techniques simultaneously.

The RMC neutron radiography facility has been used on a collaborative effort with QETE to inspect the composite control surfaces of CF-18s. Currently, it takes seven to eight days to inspect one-half of the surfaces on a CF-18 using neutron radiography. RMC's goal is to optimize the system and drop the inspection time in half.

5.9.6 UCLA

UCLA researchers are studying the characteristics of materials degradation due to corrosion and fatigue in aerospace and aircraft structures, specifically aluminum alloys and advanced composites. The research is supported by the AFOSR and ONR. They have examined crack initiation in aluminum plates with multiple holes and pits in order to be able to quantify the degree of corrosion in a structure.

The UCLA researchers focus is on ultrasonics. They have developed a guided wave based technique to determine the presence of hidden flaws in aluminum lap splice joints, and the stiffness degradation of composites subject to fatigue loading.

UCLA is currently developing a technique to detect the presence of very small crack-like defects in structural components using an active method involving the initiation of cracks. In addition, the UCLA researchers are examining laser shock peening to prevent corrosion, using a layer to shock the surface of an object to improve its corrosion resistance. This work is still in the preliminary R&D stage. UCLA will test the shocked samples for fatigue.

5.9.7 University of Dayton Research Institute

The University of Dayton Research Institute (UDRI) is currently conducting a program entitled "Automated Corrosion Detection Process/System for Cost-Effective Maintainability." The program is issued through Warner Robins AFB, and monitored by the NDE Branch of the Air Force Research Laboratory at Wright-Patterson AFB. The purpose of the program is to develop and apply new corrosion detection technologies and couple these with automation technology to provide significant maintainability improvement of the C/KC-135 or similar type aircraft through:

- Accurate corrosion detection at less than ten-percent thickness loss
- Reduced person-hours to effect corrosion inspections through automation
- Reduced aircraft flow time
- Efficient discrimination through data fusion techniques
- Accurate reproducibility of inspections from aircraft to aircraft through inspection system reproducibility.

There are several tasks on this program. UDRI is developing a formalized approach to corrosion detection technology assessment. This includes definitions of corrosion metrics, specimen designs, NDE output, and analysis methodologies. Several different specimen designs are being considered. Specimens will be both real aircraft lap joints and doubler sections and engineered panels with various configurations and profiles of thickness loss and corrosion by-products.

UDRI is also optimizing via subcontract several NDE technologies including thermography, radiography, ultrasonic and eddy current inspection methods. After optimization, each technology will be evaluated according to the technology assessment methodology described above. Corrosion detection technologies either developed or advanced by NASA Langley Research Center will also be investigated.

An analysis is being conducted in parallel with this effort in which various automation concepts are being studied for inclusion in the program. The analysis is based upon inputs from several vendors, and examines the feasibility of the various automation concepts including implementation, cost and risk issues. After this evaluation and analysis phase, one or more NDE technologies will be selected for inclusion in the integration phase of the program, in which the NDE system will be integrated with a selected automation concept and a central controller. The resultant prototype will then be demonstrated in an inspection of aircraft structures on a KC-135 tail section.

UDRI is also identifying the data necessary to provide clear, accurate and complete corrosion inspection results. If more than one NDE technology is chosen for integration into the system, then a data fusion environment will be required to efficiently provide the necessary information to the maintainer. UDRI is developing this data fusion environment and will demonstrate the results as part of the system demonstration described above.

UDRI will also be developing procedures for quantifying the reproducibility of inspection results and certifying inspection reliability results. These procedures will then be used to characterize the corrosion inspection system being developed on this program.

UDRI has also conducted an NDE requirements survey addressing different types of damage and structural and maintenance characteristics. This study has surveyed USAF System Program Managers and other government and aerospace individuals and organizations. The results will be summarized in a report to the government.

5.9.8 University of Pennsylvania

The focus of the UPenn program has been on defining the corrosion fatigue mechanism on aircraft aluminum alloys. The ethos of the program is that corrosion and fatigue are not separable but part of the same mechanism. Both aircraft manufacture and aircraft design contribute to whether the craft is susceptible to stress corrosion/corrosion fatigue or not. The University has embarked on a program to develop an electrochemical fatigue sensor for the U.S. Air Force.

5.9.9 University of Washington

The Applied Physics Laboratory is a research unit of the College of Ocean and Fishery Sciences at the University of Washington. It employs approximately 250 science/engineering professionals and support staff in six departments.

The Ocean Engineering Department is the main department dealing with the issue of corrosion, primarily in the area of marine corrosion. They have done a lot of work involving shipboard sonars and are currently working on corrosion resistance testing of underwater fiber optic cables, CHT tank inspection, and wall corrosion detection. The UW group provides corrosion monitoring instrumentation that can be used on tanks, vessels, and pipelines.

The department's main source of funding is the Navy through a NAVSEA omnibus contract. Their main sponsor is ONR, largely through their Ocean Sciences Directorate. Total program size is approximately $25M.

5.9.10 Wayne State University

Dr. Robert Thomas, along with Dr. Lawrence Favro, two professors of Wayne State University, invented and patented the thermal wave imaging technology. This thermal wave imaging technology is a hand held inspection technique that quantifies information on corrosion and operates using a focal plane array camera with a 3 to 5 micron band infrared wave band. The technology is considered especially effective when dealing with a single skin or working on wing fasteners. The system measures material loss and lap-splice corrosion as well as indicating de-bonds in composite materials. Thermal wave imaging can do multiple layers if there is a sealant between layers but is best when used on the first layer. It is a lot more trouble to work with when inspecting lap splices.

The camera of the Wayne State system weighs seven to ten pounds and it is estimated that inspectors could inspect the entire belly of an aircraft in one day. The real time-consuming aspect to the technology is in the recharging of the flash lamps. The University is working on improving this aspect.

Wayne State has received funding from the FAA Airworthiness Assurance Center at Sandia and the Air Force Office of Scientific Research. The university's ongoing research involves examining improvements in cameras, power supplies, and software algorithms.

5.10 Summary

There are a number of different research and development activities ongoing in the field of corrosion detection technologies. A major thrust of the research being conducted is for detecting hidden corrosion in aircraft. The defense departments are the leaders in pursuing technology developments, driven by their need to extend the service life of their current defense systems while reducing maintenance costs due to the decline in defense budgets. Much of the funding for academic research in this area is provided by the defense departments.

6. Corrosion Detection Technologies Industry Demographics

Although a few simple industrial applications of nondestructive testing (NDT) began to emerge decades before World War II (primarily x-radiography), most of the modern techniques (e.g., ultrasonics, fluorescent liquid penetrant, eddy current, computed tomography, etc.) have been invented/developed since the 1940s and 1950s. Application of nondestructive inspection (NDI) processes to aerospace materials, structures and vehicle systems began to accelerate in the 1960s and 1970s with the emergence of new aircraft structures design philosophies (both commercial and military) to control fatigue cracking, including early nondestructive crack detection. The state-of-the-art advances that have evolved over the last 25 years (particularly the last five to ten years) have provided a strong base for many important inspection processes that are helping to support safe and reliable fleet operations.

Corrosion detection is one small niche market of the NDE/NDT industry. NDE/NDT equipment suppliers and service providers are not dependent upon the corrosion detection market for their livelihood. In fact, the NDE/NDT end user industries run the gamut, including defense aerospace, commercial aerospace, automotive, shipbuilding, chemical/ petrochemical, construction infrastructure, electronics/electrical, energy (utilities), ordnance, and railroad. The following subsections highlight the major equipment suppliers and the industry outlook for each of these technology areas.

6.1 Visual

Visual inspection is the inspection method most widely used to inspect for corrosion. Maintenance inspectors predominantly rely on visual inspections - approximately 80-90 percent of the time - to uncover corrosion problems. Though this typically entails an inspector with a flashlight, there are many advanced optical pieces of equipment to conduct a more sophisticated inspection, including flexible fiberscopes and rigid borescopes, video probes, inspection crawlers and robots, fiber optic sensors, and laser shearography.

There are over 50 companies that offer this type of equipment to the North American market, a market valued at over $200M.

6.1.1 Equipment Providers

Fiberscopes and borescopes are the largest product sector in this technology area and are used in the inspection of engines and airframes. They are considered a subsector of the medical endoscope market, a market that is expanding due to the increased use of non-invasive techniques in medicine. Because of this, the advances made in the medical arena profit the industrial market.

Flexible fiberscopes use a bundle of optical fibers to show an image from an inspection area to the user's eye or to a camera. This type of equipment contains an eyepiece, an insertion tube, a bending section, and a distal tip. They range in price from $2K to $10K, depending on the degree of sophistication and manipulation required.

Rigid borescopes work in much the same way as flexible fiberscopes in that they both rely on a fiber-optic bundle to illuminate remote spaces. What distinguishes the two is that borescopes convey an image by a series of lenses in a rigid tube vice a bundle of optical fibers. And, borescopes require a straight line of access.

Many suppliers of fiberscopes also supply borescopes. The major fiberscope/ borescope supplier is Olympus. Other suppliers are Machida, Instrument Technology, Richard Wolf, Circon ACMI, Schott Fiber Optics, and Lenox Instrument. Most of these companies are foreign owned, though many do some sort of assembly and/or manufacturing in the U.S. to be able to bid on government contracts.

Video probes use a miniature video camera at the end of a cable to conduct inspections. Welch Allyn is the leading supplier and first introduced the device to industry in the 1980s. Other suppliers include Olympus, Visual Inspection Technologies, Instrument Technology, and Fibertron.

Diffracto holds the patent on D-Sight. The company has delivered 10 D-Sight Aircraft Inspection Systems (DAIS) to customers in North America and Europe.

Equipment suppliers of robots and crawlers have concentrated most of their marketing on uses in hazardous waste inspection, nuclear power plants, offshore oil platforms, power plant inspections, and sewer inspections. The main use of this type of equipment is for inspection of pipelines. Suppliers include REMOTEC, Benthos, Visual Inspection Technologies, PLS International, CTS Power Services, Racal Survey, Cues, RS Technical Services, and Pearpoint.

Laser shearography has been used to inspect engines and airframes of aircraft. Most often this technique is used to inspect composite materials for voids, delaminations, and unbonds. Laser Technology dominates the laser shearography market. They hold key patents in this area and have primarily focused on the inspection of composite parts of military aircraft, though crossover applications into commercial aircraft, medical implants, and other components are anticipated.

The major suppliers of remote video microscopes are Japanese. The two key players are Moritex and Keyence. One of the few North American companies involved in the field is Infinity Photo-Optical.

Remotely operated vehicles are used in nuclear power plants and offshore drilling platform inspection. Most are controlled via an attached cable. Prices on these systems range from $20K to $200K. Equipment suppliers include R.O.V. Technologies, Benthos, International Submarine Engineering, and Deep Ocean Engineering.

6.1.2 Industry Outlook

Visual/optical methods are extensively used in jet engine inspection, which makes them particularly sensitive to DoD aerospace shipments. This market area is expected to continue to decline as budget cutbacks ensue. Military aerospace product exports have also declined. And, with the decline in the DoD aircraft force structure, this will also contribute to a decreasing number of jet aircraft and engines needing to be inspected.

NASA, on the other hand, is looking to expand its use of optical inspection, and place less emphasis on their magnetic particle and liquid penetrant testing. This is due to concerns about disposing of liquid wastes and eliminating the use of chlorofluorocarbons used in pre-cleaning steps. The environmental cleanup of weapons facilities has actually increased the demand for inspection robots and crawlers.

The commercial aircraft industry has been a growth market for visual inspection technologies, though this industry has declined slightly in recent years. And, with air carriers consolidating, many have combined their maintenance depot operations and hence have a surplus of optical equipment.

As the aerospace industry continues to use more composite materials, the need to inspect multi-layer laminated structures will increase. This will likely prove to be a growth market for remote video microscopes, which are used to inspect airframes and airfoil surfaces for corrosion as well as inspecting composite parts for impact damage.

The shipbuilding industry is on the decline, as is the budget for repair/ modernization of existing ships.

The automotive industry will continue to be a growth market for the visual inspection technologies. The Big Three use remote optical inspection on their production line, and with the increased emphasis on quality and reduction of defects, the techniques will be used even more extensively.

The chemical/petrochemical industry is also a huge market for remote optical inspection technologies. These techniques are used extensively at plants to inspect inside tanks, structures and piping. Pipe crawlers having vision capability combined with ultrasonic capabilities are in high demand. Remote optical vehicles are being used more frequently to inspect underwater pipelines and platforms. This is due in part to advances that have been made at LLNL to overcome the attenuation limitations encountered with flood lamps.

The electronics industry will also prove to be an expanding market for visual inspection capabilities such as remote video microscopes and microboroscopes. These techniques are used to inspect such components as electronic assemblies and computer disk drives.

Another growth industry is utilities where remote optical inspection techniques, such as video probes and remotely operated vehicles, are predominant.

As advances are made in the field of visual inspection technologies, the market for these technologies is expected to expand as these technologies become more commonly accepted and can be demonstrated to save time and minimize risk.

6.2 Eddy Current

Testing using eddy currents began in the 1930s. This technology is usually used in the inspection of metals but can be applied to any conducting sample. Eddy current testing is used for in-line production testing of metal bar, tubing and wire; in-service maintenance inspection of components in the field and in re-work facilities; and gauging the thickness of layers. Most military depots have this capability, and it is quite commonly used in the inspection of aircraft.

6.2.1 Equipment Suppliers

There are a handful of major suppliers. Zetec is considered the largest supplier and primarily focuses on the nuclear steam generator, aerospace and automotive markets. Magnetic Analysis is in the tube, bar and wire production inspection area. Foerster, a subsidiary of the German company Institut Dr. Foerster, deals in the tube-bar and wire inspection; aerospace and automotive fields. This company has a marketing agreement with UniWest to sell its equipment to the aerospace industry. Other suppliers include the following:

- Stavely – aersospace
- K.J. Law – automotive
- Hocking (based in the UK with its equipment distributed in the U.S. exclusively by Krautkramer Bransom) – aerospace and automotive
- UniWest- aerospace.

6.2.2 Industry Outlook

For years, the industrial base for this technology area consisted of small companies. Several of these companies were acquired by larger companies as they thrived. But, because the outlook for this technology is not considered high-growth, some of the large companies who made these earlier acquisitions have divested themselves of this business area.

Because the eddy current users demand a high level of support, overseas companies have had to establish a North American subsidiary to gain market share. Many are actively pursuing export markets due to sluggish domestic sales. Recent advancements have made the eddy current equipment less dependent on operator interpretation and, thus, more amenable to automated testing.

Eddy current technologies are an established process control method in a number of industries and are displacing other NDT methods in a number of areas due to environmental concerns. The technology is also used extensively in maintenance inspections of aircraft, pipelines, and chemical process plants, among other areas.

One potential growth area for eddy current technologies is with NASA, which is evaluating replacing its penetrant inspection with eddy current testing. The inspection of airbag components is also considered an expanding market as is the automotive industry, which uses eddy current extensively for numerous applications. The chemical/ petrochemical industry is another major end-user of eddy current testing especially for testing tubing for wall thinning. Eddy current inspection will continue to play a crucial role in the in-process inspection of milled components, such as wires, tubes and bars. It is also critical in the high speed inspection of ammunition and grenades for cracks and corrosion. And this technology plays a major role in a number of coating and finishing industries.

The utility industry could prove to be another significant market for eddy current equipment providers. Electric utilities are increasing their level of NDT inspection due to regulatory changes that are forcing the industry to restructure in a new competitive environment. The increased competition is causing the utilities to look to ways to extend power plant service intervals and slash operating budgets. The industry is targeting faster, more efficient ways to conduct inspections. The nuclear power industry is also stepping up its NDE inspections due to safety considerations in their aging facilities. In addition, eddy current technologies are the primary inspection technique of steam generator tubing in pressurized water reactors.

6.2.3 Ultrasonics

The testing of the propagation of sound in solids dates back to 1808. The invention of the ultrasonic reflectoscope in 1940 led to the development of modern ultrasonic NDE equipment. The base consisted of small companies, several of which were acquired by larger companies as the market for these products grew. Ultrasonic technologies are used in flaw detectors, thickness gauges, and bond testers.

6.2.3.1 Equipment Providers

McDonnell Aircraft, a unit of McDonnell Douglas (now Boeing), is a major supplier of ultrasonic scanning systems. The company markets the MAUS system and mainly focuses on the aerospace sector. One area of concentration is on composite aircraft structures. Other major suppliers include:

- Panametrics – aerospace, microelectronics
- ABB Amdata – power plants
- Sonix – acoustic microscopy for microelectronic/materials applications
- Tecrad - power plants

- IRT (an Israeli company) – aerospace, utilities
- SAIC Ultra Image (incorporates IRT electronics and scanners into its product line) – aerospace, ships, subs, utilities, and petrochemical
- Sonoscan – acoustic microscopy for microelectronic/materials applications
- Tektrend (Canadian company) – aerospace, utilities, research into new techniques (e.g., guided wave ultrasonics).

Major suppliers of ultrasonic instruments and transducers for flaw detectors and thickness gauges are Krautkramer Branson (owned by Emerson Electric), Panametrics, Staveley, ABB Amdata, NDT Systems, and StressTel (owned by Emerson Electric).

6.2.3.2 Industry Outlook

This technology is presently not considered a high-growth industry, which has led to the divestiture of some of these earlier acquisitions. As with eddy current providers, sluggish domestic markets have led suppliers to pursue exports. Recent advancements have made the equipment less dependent on operator interpretation and more amenable to automated testing. Because this technology area is electronics-based, advancements and price/performance improvements in microelectronics and computer technology enhance the state-of-the-art of this technology.

Several industries are now using ultrasonics in process control. The technology is also used extensively in maintenance inspections of aircraft, pipelines, chemical process plants, and power plants, among other areas. As is the case with eddy current technologies, ultrasonic technology is displacing other NDT methods in a number of areas due to environmental concerns.

Within the large ultrasonic systems market, a shakeup has occurred with LK Tool, Rolls –Royce MatEval and NDT Systems withdrawing from the North American market and Automated Inspection Technologies folding. There are a number of reasons for this upheaval: 1) the companies could not reduce their costs and remain profitable due to the high investment and fixed costs incurred, 2) the reduction in military aircraft procurement, 3) the slow-down in aircraft orders, and 4) the huge upfront capital investment required from buyers, causing them to hesitate on making acquisitions of this nature.

The aircraft industry is considered an ex- market for ultrasonics due to its increased use of composites. And, the Air Force continues to use ultrasonic testing in its Retirement for Cause program to inspect jet engine parts for cracks. The Air Force also continues to use large ultrasonic systems for maintenance inspection of aging aircraft. As proven at the FAA's National Aging Aircraft Center, ultrasonics can now be used in the maintenance inspection of tee-caps.

Ultrasonic systems also play a major role in the inspection of high-space equipment, especially since the Challenger spacecraft tragedy. These systems are used extensively to inspect rocket motors (previously only inspected by radiography) and propellant liners.

In the automotive arena, the inspection of airbag inflators is considered to be an area of business expansion for ultrasonic systems. Ultrasonic systems are being used more frequently in the area of process control in high-volume batch processes, particularly for flaw detection, fluid level measurement, and thickness measurement. It is used for tire inspections as well.

Ultrasonic systems are used extensively in the chemical and petrochemical industry, especially to inspect tubing wall thickness. New uses for ultrasonic systems are beginning to be developed in the utilities industry, especially in regards to steam generator testing. Mobile ultrasonic units are also finding niches in the nuclear power plant industry inspecting for intergranular cracking.

These systems also have a market in the metals industry where they are used to inspect pipes and tubing coming off the production lines for flaws and thickness.

Ultrasonic testing is used to inspect rail sections during the manufacturing process as well as for maintenance on the railbed. This technology is also being researched for the inspection of railroad wheel rims. At present, approximately one million wheels are replaced annually in North America as part of routine maintenance. These replacements could be avoided by the use of stepped up ultrasonic inspections measuring for residual stress.

6.2.4 Radiography

Radiography is the first method of internal visualization to be adapted to NDE in the 1930s. Film based radiography equipment and film are considered mature products, making it difficult for suppliers to develop niche markets since buyers treat the products as commodities rather than unique devices. The primary radiographic market is medical. This technology is in direct competition with advancing ultrasonic and eddy current technologies.

6.2.4.1 Equipment Providers

The number of major radiographic film suppliers has decreased from four to three – Agfa, Fuji, and Kodak. Competition is fierce among the remaining film suppliers targeting a shrinking market.

Major X-ray equipment suppliers are Lorad, Pantak, Philips, Seifert, Andrex, and Bateau.

Suppliers of real-time radiography systems are Nicolet Imaging Systems (the leader), LumenX, Philips, FeinFocus, NDT Marketing, Lixi, Glenbrook Technologies, CR Technologies, SAIC, and Lockheed Martin.

Major suppliers of computed tomography systems are:

- Hewlett-Packard – electronics
- ARACOR – rocket motor inspections
- Scientific Measurement Systems – industrial applications
- Bio-Imaging Research – flaw detection.

6.2.4.2 Industry Outlook

The film-based market has been under pressure from military cutbacks and corporate restructurings. Competition has also increased in the early 1990s when surplus radiography equipment became available and competed with new equipment. Film use is declining with the emergence of real-time radiography and user concern with the environmental impacts of film processing. In addition, this technology area also must compete against continual advancements in the field of eddy current and ultrasonic technologies.

The non-film based radiography market has also declined due to military cutbacks, which has lessened the demand for aerospace and ordnance inspection. Suppliers have branched out to other commercial markets such as the automotive and electronics industry to shore up their marketplace stance. The development of portable radioscopic systems has opened up the technology for use in field inspections of pipelines and aircraft. And new applications in process control are emerging. This technology is being continually enhanced due to advances being made in the area of digital electronics and computers.

The computed tomography market has also suffered due to military cutbacks, as well as commercial customers' desire for lower prices and faster performance. The Navy has purchased six systems for the inspection of their Trident II missiles, though future procurements are not anticipated in the near future. Hill Air Force Base also procured a number of systems for the inspection of rocket motors, but again, the need in the near future for more systems is considered limited. The decline in defense procurements has led CT suppliers to develop new CT products for the commercial market, mainly for use in the production process. These systems are considerably smaller than the large DoD systems and, hence, sold at a much reduced cost ($500K as compared to multi-million dollar). Emerging applications for computed tomography systems include metrology, reverse engineering, and rapid prototyping.

Film radiography continues to be used in routine inspections of metal parts in military aircraft and missiles. However, film radiography has suffered a decline in other aspects of military aircraft inspection, such as inspection of wing fuel tanks of military cargo aircraft. The military is now using eddy current testing to find cracks in weep holes of these fuel tanks.

There is some question about what will happen to the Sacramento Air Logistics Center's radioscopic system upon the closing of McClellan AFB in 1998. It is expected that this $12M system will either be sold to a private operator or maintained by the Air Force at some other locations.

Commercial aircraft inspection during the manufacturing process is a huge market area for radiographic testing. The trend in in-service inspections of commercial aircraft is toward use of advanced nondestructive inspection technologies, such as computed radiography systems. On the other hand, the use of film radiography for in-service inspections is declining.

Film radiography still has a niche market in the inspection of warheads where this technology can be applied to inaccessible locations that cannot use real time systems. Real time radiography systems are used quite extensively for inspecting large ordnance such as artillery shells. And, with the end of the cold war, an increased need for these systems has occurred to provide for the safe disassembly of warheads. Neutron radiography is used to examine ordnance devices containing hydrogenous explosive or propellant in closed metal casing.

Film radiography is used in the shipbuilding area for a number of applications involving the inspection of inaccessible components of ships and submarines.

In the automotive arena, the inspection of airbag components is considered to be an area of business expansion for radiography. Radiography also is used extensively in the inspection of production castings.

The electronics market is a major business base for real-time radiography techniques. It is used in the inspection of surface mounts, multi-layer circuit boards, and semiconductor packaging. Film radiography is also still being used for such applications as failure analysis.

Film radiography is used in utilities for weld inspection and corrosion monitoring, among other applications. Considering the aging of the nuclear power plants and the restructuring and increased competition in the electric utility industry, stepped up inspections of these systems are anticipated.

The metals industry is another major marketplace for radiography systems. Inspections include pipes, tubing, and welds, to name a few components.

The railroad industry continues to be a major market area for radiography systems in regards to the inspection of railbeds and railroad tank cars. Though film radiography is primarily used, the industry is examining filmless radiography for its potential to reduce costs and environmental concerns.

Another anticipated growth market for radiography systems is in the medical field, inspecting such medical devices as artificial hearts, implants, and pacemakers during the assembly process.

6.2.5 Thermography

A thermography system will generally consist of heat sources (lamps or flash lamps), heat measurement devices (infrared cameras), and image/data processing and analysis equipment. Thermography as an inspection technology compares known images of non-damaged structure with images of the inspected structure to identify areas requiring further, more quantitative examination.

6.2.5.1 Equipment Suppliers

The industrial base for thermography consists of camera suppliers, system integrators and service providers. The largest DoD/DND suppliers of infrared systems are Lockheed Martin, Texas Instruments, and Hughes. At present, they are not focusing on the NDE market; however, should the NDE market develop, they will in all likelihood play a more prominent role.

The primary suppliers of cameras are Amerber Electronics (a subsidiary of Raytheon), Cincinnati Electronics, Mitsubishi, and Inframetrics. Current system integrators are Bales Scientific, EG&G Hudson, and Graseby Infrared.

Thermal Wave Imaging and Wayne State University are primary service providers attempting to create a market for thermal techniques for NDE. They hold most of the patents for the pulsed thermal imaging technique.

6.2.5.2 Industry Outlook

Thermography suppliers are not dependent upon the NDE/NDT sector. Other major markets for this technology are predictive maintenance, quality and process control, R&D, night vision, law enforcement, aircraft landing guidance, and biomedical and automobile drivers' aids. Expansion of the thermography market is somewhat hampered by its high equipment prices, lack of user training, and need for well-defined, established procedures. Although, the decrease in prices of focal plane arrays is expected to help expand use of thermography into other market areas.

6.3 Summary

The industry outlook for each of these technologies varies as does the industrial base supporting development of them, though none of these technologies is dependent upon the corrosion detection technologies field for its livelihood. However, the NDE/NDT equipment suppliers are very amenable to custom adapting their equipment for specific applications for a fee.

The industrial base for visual, ultrasonic, and eddy current equipment is relatively stable.

The base for film-based radiography equipment has been dealt some setbacks in recent years as film use is on the decline with the emergence of real-time radiography, military cutbacks, and user concern with environmental impacts of film processing. The number of major radiographic film suppliers has decreased from four to three, with competition fierce among those remaining fighting for market share in an ever shrinking market.

Non-film based radiography suppliers market is in a state of flux. The market for radioscopy systems has declined due to military cutbacks. However, in response to this, suppliers have branched out to other commercial markets such as the automotive and the electronics industries to shore up their marketplace stance. And, with the development of portable radioscopic systems, new uses for this technology have opened up, such as in-field inspections of pipelines and aircraft.

The number of thermographic equipment and service providers is expanding from a handful to a larger number as the technology matures.

7. Conclusions Regarding Facilitators Enabling More Widespread Use of Corrosion Detection Technologies

The following sections describe the facilitators in place to enable further widespread use of corrosion detection technologies that we have described throughout the course of this report. The facilitators are not intended to be all-inclusive but rather pinpoint the most prominent ones we identified through this study.

7.1 Heightened Awareness

Due to the 1988 Aloha Airlines incident and the Military Forces' need to extend the service life of military systems three to four times their original design life, there is heightened awareness to the issue of corrosion and how it is a key contributor to system failures and a driving factor in terms of safety, downtime and costs. The FAA has put in place a number of policy directives aimed at the early detection and correction of corrosion problems. The Military Forces have all stepped up efforts to prevent and control corrosion and are keenly aware that in order to meet their readiness goals, they need to effectively detect and reduce the effect of corrosion on their defense systems. This need has been underscored by shrinking defense budgets, reduced procurements of new equipment, and increased reliance on modifications and upgrades to current systems. Corrosion has been cited as one of the largest cost drivers effecting life cycle costs.

7.2 Established Working Groups

There are a number of established associations and working groups addressing the issue of corrosion, both within North America and internationally. These include the National Association of Corrosion Engineers, the Nondestructive Testing Information Analysis Center, and the Canadian Nondestructive Testing Association. The U.S., Canadian and Australian Governments also coordinate on their research into the field of corrosion detection technologies via the Corrosion Sub-Panel of the Technology Panel for Advanced Materials (part of Project Reliance).

The DoD, FAA and NASA have all established Aging Aircraft Programs to address corrosion issues. Similar research is being conducted in Canada by their National Research Council, and in Australia by their Defence Science and Technology Office. And, the Military Services have put in place corrosion prevention and control programs. One of the goals of these programs is to adopt techniques that will enable more efficient and cost-effective maintenance inspections with fewer personnel.

A history of informal/formal technical interactions, information exchanges and cooperation exists between the DoD, FAA and NASA NDE/I programs. An example of cooperation among federal agencies (of which 14 participated including the AF, FAA and NASA) is the inter-government-agency working group on NDE/I, sponsored by the White House Office of Technology Policy (OSTP), Committee on Materials (COMMAT), to facilitate exchange of NDE/I R&D results and promote joint planning.

In addition, each of the Services conducts regular meetings to address corrosion issues. There have also been a number of coordinated meetings amongst and between the U.S. Services, including the Joint Service Working Group on Corrosion, as well as with NASA and the FAA.

7.3 New Emphasis on Cost Effectiveness/Condition Based Maintenance

As a cost savings strategy and to eliminate the need for unnecessary maintenance, the Services are moving away from routine maintenance where components are replaced based upon length of time in service rather then real need. They are instituting programs where components are replaced based on their condition rather than to conform to a given time-in-service. This move to condition based maintenance will provide incentives to employ newer, more efficient corrosion detection techniques so that personnel will be better able to pinpoint the extent of their corrosion problems and its effect on the structural integrity of the system.

8. Conclusions Regarding Barriers Affecting the Widespread Adoption of Corrosion Detection Technologies

8.1 General Barriers

There are several barriers to the wider appreciation of both the cost and importance of corrosion in military systems and wider support of R&D that will mitigate against the effects of corrosion. Only recently has the FAA sponsored an Aging Aircraft Program to address many of these concerns.

Similarly, the U.S. Air Force has recently increased the emphasis on these problems by establishing an Aging Aircraft and Systems Office in the Aeronautical Systems Center at Wright-Patterson AFB, Ohio. However, other general barriers to widespread adoption of corrosion detection technologies still exist.

8.1.1 Data Not Readily Available

While collecting data for this study, we discovered that recently published NDE/NDT and corrosion detection reports are not showing up in DTIC, Dialog and other literature searches. Most of the publications that are in these databases are dated. Also, in trying to gain data from the depot/field level in regard to maintenance and failure analysis and the role of corrosion in the need to repair and replace parts, it became apparent that this type of information is not easily obtainable and, hence, is not given the visibility it needs at different levels to ensure that these recurring corrosion problems are effectively communicated and that procedures are put in place to rectify the situation. This was true also in the case of trying to quantify the cost of corrosion to defense systems. There is no uniform equation or standard economic developed of the elements for determining the corrosion costs (though Warner Robins has released a 1998 report that breaks these elements down for aircraft). In a recent development, Tinker Air Force Base has just initiated (late 1997) a project to establish an Aging Aircraft database.

8.1.2 Research Is Dispersed

There are a number of different research organizations conducting studies in the area of corrosion detection technologies. However, these groups are widely dispersed within DoD, DND, and the Australian DoD, reducing the visibility of the work being performed. Until recently, there was not a great deal of coordination in the U.S. between these different groups, especially outside of their respective Services though more coordination has been initiated between these groups as of late. The Canadian and Australian organizations are more effective in communicating their research results within their countries, however all three countries could benefit by increased coordination and sharing of findings between their research communities. And, there appears to be a disconnect between the operators and the R&D community. The R&D community is focusing on 6.1 and 6.2 research whereas the operators are conducting program specific research, and there does not seem to be effective communication occurring between the different groups.

8.2 Technology Barriers

As described earlier, corrosion is itself a complex phenomenon involving the interaction of several different physical processes. This complexity is the basis for the wide array of technologies that are employed to detect and characterize corrosion. As would be expected, the technologies vary widely in reliability, accuracy, effectiveness and affordability. This section discusses the major barriers to quantitative improvements in the state of the technology.

8.2.1 Need for Newer Techniques Not Widely Recognized

The general impression that was formed through the numerous site visits conducted by the research team was that most users are satisfied with current techniques. Commercial users are wont to invest in additional CD technology that cannot be clearly justified in economic terms. Overall, they are satisfied that current technologies and techniques have served to prevent catastrophic losses. They are not informed as to the potential for reduced maintenance and repair costs that could be realized through improved corrosion detection technologies and techniques. There is agreement that the direct and indirect costs of corrosion are substantial; there is not agreement that these costs can be substantially reduced through further investment in corrosion detection and quantification technologies and tools.

8.2.2 NDE/NDT Technologies Developed for Applications Other Than Corrosion

The first concern of structural and materials engineering has been the detection and characterization of defects that can be adequately modeled and therefore predicted; i.e., cracks. NDE/NDT technologies have evolved to support the science of fracture mechanics, a discipline that is now highly developed and quite reliable in predicting the life of complex structures in known cyclic loading environments. These technologies, notably eddy current and ultrasonic, have proven useful for detecting and characterizing the material loss caused by corrosion. However, this is after the fact. The difficulty, and near impossibility, of predicting corrosion has pointed the work in detection technologies more toward detection of cracks than detection of material loss due to corrosion. The fact that corrosion is caused by many interacting processes contributes to this situation.

8.2.3 Efficiency/Reliability of Newer Techniques and Cost/Benefits Not Well Established

The transition of a new technology from laboratory to field application is difficult. The government has been able to invest in some of the more sophisticated technologies (such as neutron radiography) that would be beyond the reach of commercial enterprises, airlines for example. Typically, a new technology that has been developed in a laboratory is commercialized by a small company, often a start-up. Basically, the marketplace determines the success or failure of a particular technology through customer determination of the cost-effectiveness of each new offering. Without some history that would support improved cost-effectiveness, a new technology or technique faces a large hurdle to implementation on a wide basis.

8.2.4 Safety Concerns About Radiography Techniques

Although radiography is perhaps the most precise of the corrosion detection, and especially corrosion quantification, technologies, it presents the most serious hazard to the users. Indeed, in many jurisdictions radiographic facilities and operators are required to be licensed. Field operation of x-ray equipment requires that personnel be kept at some distance from the radiation sources. The emphasis on worker safety and concerns for liability judgments serve to impede the wider implementation of radiographic techniques.

8.2.5 Thermography Perceived as Not Effective or Reliable

Thermography depends on operator interpretation of how an image of the structure in question differs from an image of a perfect or, at least, acceptable, structure. Thus, for every image produced there must be a means to compare that image against that of a similar undamaged structure. Combined with the fact that thermographic images are somewhat "fuzzy" compared to other imaging techniques (visual, radiographic, etc.), many users remain skeptical of the precision and reliability of thermography as a corrosion detection technology. This is due to the fact that thermographic images are captured by IR cameras that are made up of an array of detectors, each detector contributing one pixel to the overall picture. Thus, IR cameras have much lower resolution than visual photographic processes (in much the same way that a photograph has much better resolution than a television image).

8.2.6 Human Factors Limitations

Much of the work in inspecting for corrosion is repetitive and, in a word, tedious. For example, inspecting 25,000 rivets and fasteners on an aircraft using an eddy current probe can be a mind-numbing experience. Take into account that much of the work is done in awkward locations and sometimes under adverse environmental conditions (darkness, cold, etc.) Added together, the problem of inspection for corrosion goes well beyond that of just the technology of the sensing device and the processing of the information. It must include an array of human factors that will limit the overall effectiveness of the inspection process.

8.3 Policy/Fiscal Barriers

8.3.1 Cost of Corrosion Difficult to Calculate

Determining the costs of corrosion in the life cycle of a system is difficult to calculate. There currently is no baseline for this type of measurement and no good cost data at present. Hence, the costs of corrosion are not considered upfront in the acquisition cycle since no benchmark for measuring the impact of corrosion has been established. In addition, an effective cost/benefit analysis of the cost savings generated by implementing a corrosion detection technology is difficult to quantify.

8.3.2 Commercial Airlines/Military Have No Economic Incentive to Improve Probability of Detecting More Corrosion

There is a paradox here in that detection of more corrosion means that more repair work must be done, and that will increase maintenance costs. This is because the FAA and military maintenance guidelines are relatively narrow. These guidelines say, in essence, that any corrosion detected must be corrected. The goal of the airlines, then, is to maintain each aircraft at an adequate level while expending no more in maintenance funds than is necessary. Perhaps the most attractive economic incentive to the commercial airlines would be improving the productivity of the inspection process, thereby reducing the cost of maintenance, assuming that that can be done without compromising the safety or the service life of the aircraft. With regards to the military, employing new technologies cost money and, with the airlines, this cost must be weighed against the return on investment to the facility. Without quantitative cost data to support a decision to invest in new technologies, most of the actual users would not incur such an expense at the depot level.

8.3.3 Cumbersome, Lengthy Process for Emerging Techniques to Gain Wide Acceptance/FAA-OEM Approval

Currently, Service Bulletins are developed by the Original Equipment Manufacturers (OEMs) to deal with specific maintenance problems. The FAA may issue Airworthiness Directives (ADs) to deal with problems of a more urgent nature. Service Bulletins receive FAA approval before issuance. Airline maintenance operations may implement the Service Bulletin through an Alternate Means of Compliance (AMC). While the AMC is valid for the developing airline, it is not useable by another maintenance organization. In their quest to control costs, airlines seek lower cost alternatives to mandated inspection and repair requirements. The approval process for an AMC is lengthy and expensive. Thus, any new technology that has promise to improve the inspection process and the productivity of the maintenance operation faces a not inconsequential approval cycle before it is generally accepted in the customer community.

8.3.4 Increased Training Requirements for Technicians to Use Different Technologies

Every different corrosion detection technology will entail different training requirements. Eddy current and ultrasonic sensors produce displays that require a high degree of sophistication to properly interpret. Improved processing of newer techniques, such as stepped pulsed eddy current, provide c-scan images that are much more intuitive but still require expert interpretation, especially in determining when a particular threshold has been exceeded and some expensive repair process is required. The range of technologies also expands the knowledge required to interpret the results. Thus, for a technician to be considered fully qualified in all areas necessary to perform a complete corrosion inspection, many more skills are required than before. Coupled with this is the fact that the number of trained NDT inspectors is dwindling due to base closures and consolidations and turnover at the maintenance level. Hence, the Services are experiencing a loss of corporate memory through retirement of key personnel.

9. Recommendations of The National Research Council

The National Research Council, in 1997, published the report of a study, titled "Aging of U.S. Air Force Aircraft." This study examines the entire range of topics affecting the useful life of aircraft, including overloading, fatigue cracking, and corrosion. The recommendations from this study relative to corrosion detection technologies are highly relevant and illuminating, and apply to other services and other vehicles as well. The study recommendations for near-term research and development of corrosion detection and NDE technologies are summarized here:

<u>Recommendation 19</u> (Regarding Corrosion and Stress Corrosion Cracking). Evaluate and implement methods to provide earlier detection of corrosion. Examples of specific tasks include:

- Investigation of environmental sensors to allow aircraft maintenance organizations to anticipate when conditions are likely to lead to corrosion

- Evaluation of the applicability of the (US) Navy's condition-based maintenance program to (US) Air Force needs
- Development of techniques to locate, monitor, and characterize defects and chemical and physical heterogenenity within coatings.
- Development of techniques to locate, monitor, and characterize defects and chemical and physical heterogenenity within coatings.

Recommendation 30 (Regarding Nondestructive Evaluation and Maintenance Technology). Apply automation and data processing and data analysis technologies to augment NDE tools to perform rapid, wide-area inspections. Examples of specific technologies that should be investigated include:

- Effective automation of inspections and data collection equipment
- Imaging technology for improved data analysis and interpretation
- Data integration for different test methods for more complete and quantitative interpretation of the measurements
- Scanning and automated inspection facilities, especially for ultrasonic and eddy current methods
- Supportable instrumentation and equipment packaging that is convenient for the operator and can survive the depot environment
- Effective and focused engineering of field equipment capable of reproducing laboratory and production test performances.

The study identified critical NDE inspection needs for aging aircraft. The NDE inspection needs specifically related to corrosion and not related to fatigue and cracking are summarized in Table 9-1.

These recommendations tend to support the conclusions and recommendations made independently in the NATIBO study reported herein.

10. Recommendations

Table 9-1. Critical Corrosion NDE Inspection Needs for Aging Aircraft.

Critical Need	Candidate NDE Methods	Potential Techniques
Hidden corrosion	Electromagnetic	Pulsed eddy current Multifrequency eddy current SQUID technology Eddy current
	Thermal	Time-resolved thermography
	Radiography	Energy-sensitive detectors Microfocus real-time radiography Neutron
	Ultrasonic	Bubbler/scanning methods
	Optical	Boroscope
Corrosion in multi- layer structures	Electromagnetic	Pulsed eddy current Multifrequency eddy current
	Radiography	Real-time imaging In-motion film
	Ultrasonic	Scanning (if gaps can be bridged)
Stress corrosion cracking in thick sections	Ultrasonic	Pulse echo Scanning

10.1 Request the Corrosion Sub-Panel of TPAM Perform Added Coordination Activities

To ensure the widespread dissemination of published reports on corrosion and that information regarding corrosion detection techniques, advances, and implementation are effectively coordinated throughout the NDE/NDI community, the Corrosion Sub-Panel of TPAM should be approached about taking on the responsibility of:

- Coordinating and promoting inter-action between the Services and identifying common problems
- Establishing a central repository of reports and other corrosion related information
- Improving report distribution
- Pooling information on system failures/corrosion problem areas
- Establishing a Point of Contact database of technology experts (placed online and updated annually) so that timely consultation on specific corrosion related issues can be achieved.

If buy-in to these coordination activities is achieved, perhaps this panel could enlist the aid of the NTIAC to support these efforts.

10.2 Appoint Recognized Champions to Push for Corrosion Agenda and New/Higher Fidelity Techniques

To ensure that the entirety of system life cycle costs are considered in the procurement process, identify and enlist military champions to "market" the savings to Programs/Program Managers from 1) building into the design of the system protective measures to protect against corrosion and 2) including processes for detecting corrosion problems early in a system's life cycle.

Additionally, the logistics community should be made aware of the importance of corrosion prevention and corrosion control in planning for the life cycle support of systems and in developing R&D requirements for extending the life cycle of weapon systems. These champions could emphasize the importance of considering corrosion costs as an independent variable for determining life cycle costs and push for establishing benchmarks for measuring the impact of corrosion on the service life of a system. In order to better define these costs, the champions could recommend that economic models be developed that address the costs of corrosion in the life cycle of the system and address the savings realized by planning for corrosion detection upfront and detecting corrosion early on in the system's maintenance life. In addition, these champions could strive to establish an integrated approach to tackling corrosion issues, ensuring that Integrated Product Teams consisting of structural engineers, NDE/NDI personnel and researchers address these issues in a joint fashion.

10.3 Target Insertion/Demonstration Program

In order to demonstrate the benefits derived from employing a certain corrosion detection technology(s), a widely applicable, high payoff, dual use insertion/demonstration program would be an ideal mechanism. Such an insertion/demonstration program would have to substantially meet the criteria described in Section 1 earlier, i.e., a potentially powerful technology that has dual-use application, can be supported by the industrial base, and for which there is a window of opportunity to mature.

A candidate for an insertion/ demonstration program might be multi-sensor and multiple data fusion, incorporating automation/robotics as deemed feasible. These suggestions support the findings of the National Research Council, and have met with widespread backing from the members of the NDE/NDI community. Industry and government input would need to be solicited to develop a DoD/DND/Australian-specific program that involves the fusing of as many NDE techniques as possible. Researchers, developers and end-users would participate in the identification and selection process.

10.4 Streamline Process for Inserting Newer Techniques into OEM Maintenance Procedures

The feedback from the research community through the OEMs back to the users and operators of the systems should be shortened. It should be possible to incentivize this process to reward improvements that can enhance system reliability and extend the life of a system while reducing the cost of inspection and repair. The use of electronic updates to inspection and repair manuals can reduce the administrative delay.

10.5 Increase Collaboration between the Military Departments and University NDE/NDT Departments on Training

Training is usually an afterthought following the development of new inspection technologies and tools. It should be possible to procure integrated training along with any new inspection tools. Such training would be essential until each using organization was able to develop a core of expertise and thereby be able to conduct their own training programs.

Appendix A
Acronyms

Acronyms

AACE	Aging Aircraft Center of Excellence
AANC	Airworthiness Assurance Nondestructive Inspection Validation Center
ACE	Airframe Condition Evaluation
AD	Airworthiness Directive
AED	Airframes and Engineering Divison
AFB	Air Force Base
AFOSR	Air Force Office of Scientific Research
ALC	Air Logistics Center
AMC	Alternate Means of Compliance
AMC	Army Materiel Command
ANDI	Automated Nondestructive Inspector
AR	Army Regulation
ARL	Army Research Laboratory
ASIP	Aircraft Structural Integrity Program
ATESS	Aerospace and Telecommunications Engineering Support Squadron
AUSS-V	Automated Ultrasonic Scanning System - Generation Five
AVRD	Air Vehicle Research Detachment
CARC	Chemical Agent Resistant Coating
CASA	Civil Aviation Safety Authority
CASR	Center for Aviation System Reliability
CBI	Compton Backscatter
CBM	Condition Based Maintenance
CCD	Charge Coupled Device
CDP	Corrosion Data Program
CFB	Canadian Forces Base
COTS	Commercial-Off-The-Shelf
CPAB	Corrosion Prevention Advisory Board
CPC	Corrosion Prevention and Control
CSIRO	Commonwealth Science and Industrial Research Organization
CT	Computed Tomography
DADTA	Durability and Damage Tolerant Assessment
DBIR	Dual Band Infrared
DBIR CT	Dual Band Infrared Computed Tomography
DND	Department of National Defence
DOC	Department of Commerce
DoD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation

DSTO	Defense Science and Technology Office
DTIC	Defense Technical Information Center
EC	Eddy Current
EIS	Electrochemical Impedance Spectroscopy
EMAT	Electro-Magnetic Acoustic Transducer
ETRS	Engineering Testing and Research Services
FAA	Federal Aviation Administration
FMTV	Family of Medium Tactical Vehicles
FPI	Fluorescent Liquid Penetrant
FSMP	Force Structural Management Plan
GDP	Gross Domestic Product
HFEC	High Frequency Eddy Current
IAR	Insitute for Aerospace Research
IMI	Industrial Materials Institute
IR	Infrared Red
JPL	Jet Propulsion Laboratory
KSC	Kennedy Space Center
LBL	Lawrence Berkeley Laboratory
LFEC	Low Frequency Eddy Current
LLNL	Lawrence Livermore National Laboratory
LPI	Liquid Penetrant Inspection
LUS	Laser Based Ultrasound
MACS	Multifunctional Automated Crawling System
MAJCOM	Major Operating Command
MARCORSYSCOM	Marine Corps Systems Command
MAUS	Mobile Automated Scanner
MCT	Microfocus Computed Tomography
MED	Multi-Element Damage
MOI	Magneto-Optic Imaging
MP	Magnetic Particle
NACE	National Assocation of Corrosion Engineers
NADEP	Naval Aviation Depot
NASA	National Aeronautical and Space Administration
NATIBO	North American Technology and Industrial Base Organization
NAVAIR	Naval Air Systems Command
NAWC	Naval Air Warfare Center
NDE	Nondestructive Evaluation
NDI	Nondestructive Inspection
NDISL	Non-Destructive Inspection Standards Laboratoy
NDT	Nondestructive Testing
NRCC	National Research Council Canada
NRL	Naval Research Laboratory
NSWC	Naval Surface Warfare Center

NTIAC	Nondestructive Testing Information Analysis Center
OEM	Original Equipment Manufacturer
PHNSY	Pearl Harbor Naval Shipyard
PM	Program Manager
POD/CL	Probability of Detection/Confidence Level
PRI	Physical Research Instrumentation, Inc.
QETE	Quality Engineering Test Establishment
R&D	Research and Development
RMC	Royal Military College
ROI	Return on Investment
ROV	Remorely Operated Vehicle
RT	Radiography
S&T	Science and Technology
SBIR	Small Business Innovative Research
SDL	Special Development Laboratory
SML	Structures and Materials Laboratory
SPO	System Program Office
SQUID	Superconducting Quantum Interference Device
SSMD	Ship Structures and Materials Division
SwRI	Southwest Research Institute
TACOM	Tank Automotive Command
TDC	Transportation Development Centre
TFLM	Tactical Fighter Logistics Squadron
TPAM	Technology Panel for Advanced Material
TWI	Thermal Wave Imaging
UDRI	University of Dayton Research Institute
USAF	United States Air Force
USMC	United States Marine Corps
UT	Ultrasonic
WBCC	Waterbourne Camoflauge Coating
WDCP	Water Displacing Chemical Prservatives
WFD	Widespread Fatigue Damage

Appendix B
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135	Spencer, Floyd, and Donald Schurman	Reliability Assessment at Airline Inspection Facilities. Volume III: Results of an Eddy Current Inspection Reliability Experiment	DOT/FAA/CT-92-12, III
136	Sridhar, Narasi and Darrell Dunn	In-Situ Study of Salt Film Stability in Corroding Pits by Raman Spectroscopy (Information Slide)	Provided by Southwest Research Institute
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139	Thompson, R.B.	Laboratory Nondestructive Evaluation Technology for Materials Characterization	Journal of Nondestructive Evaluation, Vol. 15, Nos. 3/4
140	TPL, inc.	Nondestructive Evaluation (includes TPL, inc. product guides)	Provided by TPL, Inc.
141	Truchetet, Fred, et.al.	Automatic Surface Inspection of Metal Tubes by Artificial Vision	Materials Evaluation
142	Tullmin, M., P.R. Roberge and M.A. Little	Aircraft Corrosion Surveillance in the Military	NACE Corrosion/97 Paper No. 527
143	Tullmin, M., P.R. Roberge and M.A. Little	Sensors for Aircraft Corrosion - Review and Future Developments	NACE Corrosion/97 Paper No. 301
144	Twomey, Michael	Inspection Techniques for Detecting Corrosion Under Insulation	Materials Evaluation
145	Wanhill, R.J.H, and J.J De Luccia	An AGARD-Coordinated Corrosion Fatigue Cooperative Testing Programme	AGARD Report No. 695
146	Wei, Robert P., and Gary Harlow	Corrosion and Corrosion Fatigue of Airframe Materials	DOT/FAA/AR-95/76
147	Weischedel, Herbert R.	The Inspection of Wire Ropes in Service: A Critical Review	Materials Evaluation
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149	Willie, David J. and Frank Karpala	Proactive Aircraft Lap Joint Corrosion Maintenance Scheduling	Airframe Finishing Maintenance and Repair Conference and Exposition. SAE Technical Paper 961247
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152		Detector Handbook	Laser Focus World
153		Dry-Couplant Ultrasonics Eliminates Contamination (Materials Progress Summary)	Advanced Materials & Processes
154		Eddy Current Inspection Evaluated for Aircraft (Materials Progress Summary)	Advanced Materials & Processes
155		Eddy Current Probe Operates During Rolling Operation (Materials Progress Summary)	Advanced Materials & Processes
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157		Heat-Pulse NDT Reveals Fiber Volume Fractions (Materials Progress Summary)	Advanced Materials & Processes
158		Metallic Corrosion Annually Costs U.S. $300 Billion (Materials Progress Summary)	Advanced Materials & Processes
159		NDT of Jet Engines: An Industry Survey. Part One	Materials Evaluation
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161		NDT Systems Combined to Detect Cracks and Flaws (Materials Progress Summary)	Advanced Materials & Processes
162		NTSB Incident Report	WWW Download - http://www.ntsb.gov:80/aviation/DCA/96A036.htm

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163		Product Showcase: Nondestructive Testing Equipment	Advanced Materials & Processes

ID #	Author	Title	Source/Citation
164		Product Spotlight: Acoustic Emission and Vibration	Materials Evaluation
165		Product Spotlight: Eddy Current Testing	Materials Evaluation
166		Product Spotlight: Magnetic Particle and Liquid Penetrant Testing	Materials Evaluation
167		Product Spotlight: NDT of Steel	Materials Evaluation
168		Product Spotlight: Radiography	Materials Evaluation
169		Product Spotlight: Ultrasonic Testing	Materials Evaluation
170		Product Spotlight: Visual and Optical Testing	Materials Evaluation
171		Seek But Don't Destroy	Machine Design
172		Sound Out Cracks in Ceramics and Metals (Materials Progress Summary)	Advanced Materials & Processes
173		Superconducting Tapes Tested Ultrasonically During Heating (Materials Progress Summary)	Advanced Materials & Processes
174		Test Warns of Aircraft Cracks and Corrosion (Materials Progress Summary)	Advanced Materials & Processes
175		X-Ray System Uses Miniprobes to Detect Corrosion in Pipes	Advanced Materials and Processes, P. 13
176		X-Rays, Ultrasound, Optics Generate Maps of Stresses (Materials Progress Summary)	Advanced Materials & Processes

Appendix C
Points of Contact

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