FINAL REPORT

Infrared Reflectance Imaging for Environmentally Friendly Corrosion Inspection Through Organic Coatings

ESTCP Project WP-0407

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John Benfer
John Weir
Dennis Leyble
Brian Pollock
Matthew Campbell
Steven Chu
Nils Fonneland
Mike Miller
NAVAIR ISSC/FRC-SE
NAS Jacksonville

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14. ABSTRACT

This report documents and presents the results and theory of both Infrared Reflectance Imaging Technique (IRRIT) and Blackbody Illumination Methods, which produce high fidelity images of corrosion and other structural defects under coatings. The technology exploits the difference in infrared (IR) reflection properties between corroded and non-corroded metallic surfaces. The IR energy passes directly through the coating and then reflects off the metallic substrate back through the coating and into an IR camera. Since the corroded areas do not reflect the IR energy as well as the non-corroded areas, a picture or image is generated by the IR camera much the same as observing the corrosion under standard visual techniques.

The demonstration and validation measurements at NAVAIR Jacksonville (P-3 Outer Mold Line) and Oklahoma City Air Logistics Center (KC-135 Inner Mold Line and B-52 Inner Mold Line) illustrate clearly that the IRRIT is an improved method of corrosion inspection compared to the current baseline visual inspection method. IRRIT will give an engineering and corrosion control staff the capability to make sound engineering decisions as to whether to remove coatings or not to remove the coatings based on the reliable detection of corrosion through coatings.

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TABLE OF CONTENTS

1. INTRODUCTION 1

1.1 BACKGROUND 1
1.2 OBJECTIVES OF THE DEMONSTRATION 2
1.3 REGULATORY DRIVERS 2
1.4 STAKEHOLDER/END-USER ISSUES 3

2. TECHNOLOGY DESCRIPTION 4

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION 4
2.1.1 Infrared Reflectance Imaging Technique (IRRIT) 4
2.1.2 IR Blackbody Technique 7
2.1.3 IRRIT versus IR Blackbody 7
2.2 PREVIOUS TESTING OF THE TECHNOLOGY 9
2.3 FACTORS AFFECTING COST AND PERFORMANCE 9
2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY 9
2.4.1 Comparison to NDI Technologies 9
2.4.2 Coating System Limiting Factors 11

3. DEMONSTRATION DESIGN 12

3.1 PERFORMANCE OBJECTIVES 12
3.2 SELECTING TEST PLATFORMS/FACILITIES 13
3.2.1 NAVAIR Jacksonville, P-3 OML 13
3.2.2 OC-ALC, KC-135 IML and B-52 IML 14
3.3 TEST PLATFORM/FACILITY HISTORY/CHARACTERISTICS 15
3.3.1 NAVAIR Jacksonville, P-3 OML 15
3.3.2 OC-ALC, KC-135 IML and B-52 IML 16
3.4 PRESENT OPERATIONS 17
3.4.1 NAVAIR Jacksonville, P-3 OML 17
3.4.2 OC-ALC, KC-135 IML and B-52 IML 17
3.5 PRE-DEMONSTRATION TESTING AND ANALYSIS 17
3.5.1 Pre-Demonstration Optimization/Baseline Testing 17
3.5.2 A-10 Mini Demonstration 18
3.5.3 Fort Bragg, NC, Pre-Demonstration Planning 19
3.5.4 US Coast Guard Mini Demonstration 19
3.5.5 Warner Robins Air Logistics Center (WR-ALC), Pre-Demonstration 21
3.5.6 Summation of Pre-Demonstration Testing and Analysis 21
3.6 TESTING AND EVALUATION PLAN 22
3.6.1 Demonstration Set-Up and Start-Up 22
3.6.2 Period of Operation 23
3.6.3 Surface Area Inspected 23
3.6.4 Operating Parameters for the IRRIT 24
3.6.5 Experimental Design 24
3.6.6 Product Testing 32
3.6.7 Demobilization 32
3.7 SELECTION OF ANALYTICAL/TESTING METHODS 33
3.8 SELECTION OF ANALYTICAL/TESTING LABORATORY 33

TABLE OF CONTENTS

4. PERFORMANCE ASSESSMENT 34

4.1 PERFORMANCE CRITERIA 34
4.2 PERFORMANCE CONFIRMATION METHODS 35
4.3 DATA ANALYSIS, INTERPRETATION AND EVALUATION 36
4.3.1 Corrosion Inspection Comparison – NAVAIR Jacksonville, P-3 36
4.3.2 Corrosion Inspection Comparison – OC-ALC, KC-135 and B-52 45
4.3.3 Summation of Dem/Val Results 53

5. COST ASSESSMENT 56

5.1 COST REPORTING 57
5.1.1 Baseline Maintenance Procedure 58
5.1.2 Alternative Scenario Description: Condition-Based Maintenance 59
5.1.3 Maintenance Cycle Extension Scenario 61
5.2 COST ANALYSIS 63
5.2.1 Cost of Demonstration 63
5.2.2 Baseline Cost Analysis 63
5.2.3 Condition-based Maintenance Scenario Cost Analysis 67
5.2.4 Maintenance Cycle Extension Scenario Cost Analysis 73
5.2.5 Scenario-Based EHS Savings 74
5.2.6 Impact of Varying Labor Rate 76
5.2.7 Life Cycle Analysis 79
5.2.8 Inner Mold Line Costs and Savings 81
5.2.9 Cost Analysis Summary 82

6. IMPLEMENTATION ISSUES 84

6.1 ENVIRONMENTAL PERMITS 84
6.2 OTHER REGULATORY ISSUES 84
6.3 END-USER/ORIGINAL EQUIPMENT MANUFACTURER (OEM) ISSUES 84
6.3.1 Interested Customers 85
6.3.2 IRRIT System Modifications 87
6.3.3 Service and Support Package 88

7. REFERENCES 89

8. POINTS OF CONTACT 90

APPENDIX A ANALYTICAL METHODS SUPPORTING THE EXPERIMENTAL DESIGN A-1
APPENDIX B ADDITIONAL PRODUCT TESTING B-1
APPENDIX C IRRIT DEM/VAL QUALITY ASSURANCE/QUALITY CONTROL PLAN C-1
APPENDIX D OPTIMIZATION/BASELINE TEST PLAN D-1
APPENDIX E LABORATORY DATA E-1
APPENDIX F DEM/VAL PLAN DEVIATIONS F-1
APPENDIX G ENDORSEMENT LETTERS G-1
APPENDIX H COST ANALYSIS TOOL H-1
APPENDIX I APPLICABLE UNITED STATES PATENTS AND PATENT APPLICATIONS I-1
APPENDIX J NDI CERTIFICATION J-1
APPENDIX K MID WAVE INFRARED INSPECTION OF CORROSION UNDER PAINTED AIRCRAFT COMPONENTS K-1

TABLE OF CONTENTS

APPENDIX L SUPPLEMENTAL EVALUATION OF ADDITIONAL COMMONLY USED COATINGS L-1

LIST OF FIGURES

Figure 2-1: IRRIT System 4

Figure 2-2: IR Wavelength versus Visible Wavelength 5

Figure 2-3: Visible Image versus IR Image 6

Figure 2-4: IR Reflectance versus IR Blackbody 8

Figure 3-1: Paint Removed from P-3 Aircraft by Chemical Paint Stripping 13

Figure 3-2: Typical KC-135 IML 14

Figure 3-3: A-10 Fuel Cell - IR Images 18

Figure 3-4: Severe Corrosion in A-10 Fuel Cell IML 19

Figure 3-5: USCG HU-25 - IR Images 21

Figure 3-6: IRRIT System Schematic 22

Figure 3-7: Gantt Chart for Navy P-3 OML Dem/Val 23

Figure 3-8: Gantt Chart for USAF KC-135 + B-52 IML Dem/Val 23

Figure 3-9: Areas to be inspected with IRRIT 25

Figure 3-10: Navy P-3 Wing Section inspected with IRRIT 25

Figure 3-11: Navy P-3 Fuselage Section inspected with IRRIT 26

Figure 3-12: Process Stream w/IRRIT Added 29

Figure 3-13: KC-135 IML IRRIT Inspection Area 30

Figure 3-14: B-52 IML Bomb Bay Longeron 31

Figure 3-15: OC-ALC Process Stream with IRRIT Added 32

Figure 4-1: P-3 Tail #912 (Wing Section) - IR Image 41

Figure 4-2: P-3 Tail #912 (Fuselage Section) - IR Image 42

Figure 4-3: P-3 Tail #772 (Wing Section) - IR Image 43

Figure 4-4: Navy P-3 OML Wing Section Corrosion Location Identification 44

Figure 4-5: MilCam used at OC-ALC 46

LIST OF FIGURES

Figure 4-6: IRRIT versus Eddy Current 47

Figure 4-7: False Positive – Location Incorrectly Identified as Corrosion by IRRIT 48

Figure 4-8: Spot welds evident via IRRIT inspection 48

Figure 4-9: B-52 #1 (Longeron Section) - IR Image 52

Figure 4-10: Navy P-3 OML - Accuracy of IRRIT Inspection versus Visual Inspection 53

Figure 4-11: KC-135/B-52 IML - Accuracy of IRRIT Inspection versus Visual Inspection 54

Figure 4-12: Average Accuracy of IRRIT Inspection versus Visual Inspection 55

Figure 5-1: Baseline Maintenance Process 58

Figure 5-2: Percentage of Baseline Labor and Materials Used in Alternatives.....60

Figure 5-3: Annual VOC Emissions for Alternative Scenarios.....74

Figure 5-4: Annual Hexavalent Chromate Use for Alternative Scenarios 75

Figure 5-5: Annual Hazardous Waste Produced in Alternative Scenarios 75

Figure 5-6: Annual Savings vs. Labor Rate.....77

Figure 5-7: Payback Period vs. Labor Rate 78

Figure 5-8: Savings per Aircraft vs. Labor Rate.....79

Figure 5-9: IML Full Strip vs. IRRIT Inspection EHS 82

Figure 6-1: Potential Navy Environmental and Cost Savings 86

Figure 6-2: Potential USAF Environmental and Cost Savings (without APC's/ELT's).....86

Figure 6-3: Potential USAF Environmental and Cost Savings (with APC's/ELT's).....87

Figure 8-1: Organization Chart.....92

LIST OF TABLES

Table 2-1: Cost and Performance Factors....9

Table 2-2: Inspection Method Comparisons....10

Table 2-3: Paint and Coating Systems Tested with IRRIT....11

Table 3-1: Performance Objectives....12

Table 4-1: Performance Criteria....34

Table 4-2: Expected Performance and Performance Confirmation Methods....35

Table 4-3: Inspection Error Contributing Factors (OML)....37

Table 4-4: Navy P-3 Dem/Val Data Points Acquired (Raw Data)....38

Table 4-5: Navy P-3 OML Real-Time Results versus Post-Processing Results....39

Table 4-6: Navy P-3 Dem/Val IRRIT Scan Rates....40

Table 4-7: Inspection Error Contributing Factors (IML)....45

Table 4-8: USAF KC-135 and B-52 IML Dem/Val Data Points Acquired (Raw Data)....49

Table 4-9: USAF KC-135 and B-52 IML Real-Time Results....50

Table 4-10: USAF KC-135 and B-52 Dem/Val IRRIT Scan Rates....51

Table 5-1: Estimated % of A/C Directed Through Four Condition-Based Maintenance Options....61

Table 5-2: Estimated Annual Quantities of Aircraft Stripped....62

Table 5-3: Baseline Labor Requirements....64

Table 5-4: Baseline Materials and Utilities Cost Data and Assumptions....64

Table 5-5: Baseline EHS Cost Data and Assumptions....65

Table 5-6: Total Baseline Strip and Repaint Costs....65

Table 5-7: Baseline VOC Emissions....66

Table 5-8: Baseline Chromate Use....66

Table 5-9: Baseline Costs Per Year....66

Table 5-10: Single IRRIT System Cost....67

LIST OF TABLES

Table 5-11: Alternative Capital & Equipment Maintenance Costs 68

Table 5-12: Condition-Based Maintenance Labor Requirements 68

Table 5-13: Condition-Based Materials and Utilities Cost Data and Assumptions.....69

Table 5-14: Condition-Based EHS Costs 69

Table 5-15: Cost Per Aircraft of Condition-Based Maintenance.....70

Table 5-16: Total Procedure Costs 70

Table 5-17: Capital and Annual Cost of Condition-Based Maintenance 70

Table 5-18: Condition-Based Maintenance Simple Pay-back Period.....71

Table 5-19: VOC Emissions per Aircraft for Condition-Based Processes 71

Table 5-20: Hexavalent Chromium Applied.....72

Table 5-21: Condition-Based EHS Emissions.....72

Table 5-22: Baseline vs. Condition-Based VOC Emissions.....72

Table 5-23: Maintenance Cycle Extension Cost Comparison 73

Table 5-24: Maintenance Cycle Extension Payback Period and EHS Savings 74

Table 5-25: Impact of Labor Rate on Savings for +1 and +2 Year Interval Shift 76

Table 5-26: Impact of Labor Rate on Savings for +3 and +4 Year Interval Shift 77

Table 5-27: 15 Year Life Cycle 80

Table 5-28: NPV, IRR, and Discounted Payback.....80

Table 5-29: One Time Strip, Inspect, and Repaint Coating usage.....81

Table 5-30: Annual VOC and HAP Savings from IRRIT Inspection 82

ACRONYMS

AAB	Aging Aircraft Branch
AFB	Air Force Base
AFRL	Air Force Research Laboratory
ASW	Anti-Submarine Warfare
BB	Blackbody
BUNO	Bureau Number
CAA	Clean Air Act
CBA	Cost Benefit Analysis
COTS	Commercial Off-the-Shelf
CPC	Corrosion Preventative Compound
CSG	Corrosion Steering Group
CTC	Concurrent Technologies Corporation
Dem/Val	Demonstration/Validation
DHR	Directional Hemispherical Reflectance
DIFAR	Directional Frequency and Ranging
DoD	Department of Defense
ECAM	Environmental Cost Analysis Methodology
EHS	Environmental, Health, and Safety
ESTCP	Environmental Security Technology Certification Program
FAA	Federal Aviation Administration
FOV	Field of View
FPA	Focal Plane Array
FST	Field Support Team
FTIR	Fourier Transform Infrared
GFIC	Ground Fault Interrupt Circuit
HAFB	Hill Air Force Base
HAP	Hazardous Air Pollutant
HAZMAT	Hazardous Material
IML	Inner Mold Line
InSb	Indium Antimonide
IPA	Isopropyl Alcohol
IR	Infrared
IRR	Internal Rate of Return
IRRIT	Infrared Reflectance Imaging Technique
JCAA	Joint Council of Aging Aircraft
LPS	Local Process Specification
MAD	Magnetic Anomaly Detection
MOI	Magneto Optic Imaging
MWIR	Mid-Wave Infrared
NAVAIR	Naval Air Systems Command
NAVOSH	Navy Occupational Safety and Health
NDI	Non Destructive Inspection
NEΔT	Noise Equivalent Delta Temperature
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NGC	Northrop Grumman Corporation

ACRONYMS

NPV	Net Present Value
NUC	Non-Uniformity Correction
O&M	Operating and Maintenance
OC-ALC	Oklahoma City Air Logistics Center
OEM	Original Equipment Manufacturer
OML	Outer Mold Line
PC	Personal Computer
PI	Principal Investigator
P2	Pollution Prevention
QM	Quality Manager
RCRA	Resource Conservation Recovery Act
RT	Room Temperature
SERDP	Strategic Environmental Research & Development Program
Sq. ft.	'square foot' or 'square feet'
USAF	United States Air Force
USCG	United States Coast Guard
USN	United States Navy
VOC	Volatile Organic Compounds
WP-AFB	Wright Patterson Air Force Base
WR-ALC	Warner Robins Air Logistics Center
μm	Micrometer

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ABSTRACT

Surface corrosion on aluminum aircraft skins, near joints and around fasteners is often an indicator of buried structural corrosion and cracking. Aircraft paints are routinely removed to reveal the presence of corrosion on the surface of metal structures, and the aircraft is subsequently repainted following repair. This process can be very expensive, time consuming, and results in the generation of air pollution and process waste. A method, other than visual inspection, is needed to detect the early onset of corrosion on metal substrates covered by protective coatings so that aircraft paints do not have to be stripped without cause. By employing non-destructive techniques to inspect the aircraft exterior structure without removing coatings, the amount of stripping and reapplication of coatings that occurs at the military rework facilities can be substantially reduced. It is anticipated that hazardous pollutants will be significantly reduced by eliminating scheduled organic coating removal and moving to a process where IR measurements will be used to determine when and if coating removal is required.

This report documents and presents the results and theory of both Infrared Reflectance Imaging Technique (IRRIT) and Blackbody Illumination Methods, which produce high fidelity images of corrosion and other structural defects under coatings. The technology exploits the difference in infrared (IR) reflection properties between corroded and non-corroded metallic surfaces. Infrared radiation from maintenance facility lights, the sun, or a low-wattage IR heater illuminates the area to be observed. The IR energy passes directly through the coating and then reflects off the metallic substrate back through the coating and into an IR camera. Since the corroded areas do not reflect the IR energy as well as the non-corroded areas, a picture or image is generated by the IR camera much the same as observing the corrosion under standard visual techniques.

The demonstration and validation measurements at NAVAIR Jacksonville (P-3 Outer Mold Line) and Oklahoma City Air Logistics Center (KC-135 Inner Mold Line and B-52 Inner Mold Line) illustrate clearly that the IRRIT is an improved method of corrosion inspection compared to the current baseline visual inspection method. IRRIT will give an engineering and corrosion control staff the capability to make sound engineering decisions as to whether to remove coatings or not to remove the coatings based on the reliable detection of corrosion through coatings. A level of 70-80% accuracy was achieved with the IRRIT while performing in a non-interference role with production. This inspection accuracy rate is significantly higher than the 5-25% accuracy of the visual inspection method. In theory, if the IRRIT user spends significant time scanning and doing the real-time inspection the level of accuracy should be close to 100%.

The cost and environmental benefit criteria for pollution prevention was projected and applied based on actual usage data of materials plus projected waste savings scenarios from the demonstration and validation measurements at NAVAIR Jacksonville and Oklahoma City Air Logistics Center. The study, based upon an aircraft with an estimated 6500 square feet surface area, confirms a potential environmental savings of 300,000 pounds of Volatile Organic Compounds, 2,500 pounds of Chromates, and 1,100,00 pounds of Hazardous Mtaerials can be saved for a fleet of 100 aircraft over a 4 year period. Additionally, labor and material savings of $135,000 per aircraft can be realized.

The detection of corrosion under coatings was initially funded by the Strategic Environmental Research & Development Program (SERDP) under Contract DACA72-99-C-0011 and a follow-on contract was awarded and funded by the Environmental Security Technology Certification Program (ESTCP) for the purpose of eliminating or minimizing pollution from unnecessary paint removal operations on DoD weapons platforms, such as, aircraft.

1. INTRODUCTION

1.1 Background

Prematurely stripping aircraft for corrosion inspection or maintenance purposes causes excess pollution in the form of Hazardous Air Pollutants (HAP), Volatile Organic Compounds (VOC) emissions, Resource Conservation Recovery Act (RCRA) waste, and carcinogenic chromates. Aircraft organic coatings are routinely removed to reveal the presence of corrosion and treat corrosion on the surface of metal structures, and the aircraft is subsequently recoated. This process is expensive, time consuming, and results in the generation of large quantities of waste that must be disposed of appropriately. A method is needed to detect the early onset of corrosion on metal substrates covered by protective coatings so that aircraft coatings do not have to be stripped unnecessarily. By employing nondestructive techniques to inspect the aircraft exterior structure and finish, the amount of unnecessary stripping and reapplication of coatings that occurs during aircraft maintenance can be substantially reduced.

Aircraft rework typically involves the stripping and reapplication of coatings applied to protect aircraft structure. With recent advances in coating technology, new coatings will last beyond the current depot level maintenance cycles of 4-8 years for most military aircraft. It is currently feasible to apply corrosion inhibiting primers that provide excellent adhesion properties and are not intended to be routinely stripped. In addition, it is anticipated that the next generation of cleanable, durable topcoats may remain on the air vehicle for extended periods (10+ years). In the past, stripping of the coatings provided a means to visually inspect the condition of the substrate. As the industry moves toward application of more permanent coatings, it is imperative that alternate inspection techniques be developed which can verify the integrity of the coating system and substrate without relying on coating removal for similar aircraft coating systems.

Over the years, a variety of nondestructive methods have been evaluated for detection of corrosion under paint, but no modern technique has been broadly implemented. One of the limitations of most conventional Non Destructive Inspection (NDI) techniques is their lack of sensitivity to relatively small concentrations of corrosion products at the metal/coating interface. Ultrasonic test and eddy current inspection, two of the most widely used NDI techniques in the Aerospace community, can be used to detect relatively large amounts of material loss due to corrosion, but they do not meet the objective of detecting corrosion under paint in its earliest stages. Another NDI technique, flash thermography, has been shown to be effective for detection of corrosion under paint at early stages, but it is relatively slow, open to operator interpretation, and labor-intensive when compared to Infrared Reflectance Imaging Technique (IRRIT).

The IRRIT approach was successfully developed under a previous Government contract managed by the Strategic Environmental Research and Development Program (SERDP) Project PP-1137 under the Secretary of Defense Office with Northrop Grumman Corporation (NGC) as the prime contractor. The technology exploits the difference in infrared reflection properties between corroded and non-corroded metallic

surfaces. IR radiation from maintenance facility lights, the sun, or a low-wattage IR heater illuminates the area to be observed. The IR passes directly through the coating and then reflects off the metallic substrate back through the coating and into an IR camera. Since the corroded areas do not reflect the IR energy as well as the non-corroded areas, a picture or image is generated by the IR camera much the same as observing the corrosion under standard visual techniques. This technology can be utilized as a tool to more accurately assess aircraft coating system performance for purposes of service life extension and corrosion management. Use of this inspection tool is projected to result in significant DoD (Department of Defense) pollution mitigation.

1.2 Objectives of the Demonstration

The objective of the project was to demonstrate/validate (Dem/Val) the capability of IRRIT to detect corrosion through aircraft coating systems as compared to visual corrosion inspection. Applicable goals of the Dem/Val were as follows:

- Compare IRRIT with current visual inspection techniques to assess corrosion through outer mold line (OML) coatings and gather data at NAVAIR Jacksonville on P-3 aircraft.
- Compare IRRIT with current visual inspection techniques to assess corrosion through inner mold line (IML) coatings and gather data at Oklahoma City Air Logistics Center (OC-ALC) on KC-135 and B-52 aircraft.
- Prove the technique and determine cost/waste reductions from actual depot maintenance operations.
- Show potential reduction in Hazardous Materials (HAZMATs) and VOC emissions.
- Determine the reduction in cost to inspect and repair coatings due to reduction in labor hours and flow/down times.
- Collect and analyze data and develop recommendations for technology transfer.

1.3 Regulatory Drivers

The need to reduce pollution is driven by regulatory issues and government policies. The National Emissions Standard for Hazardous Air Pollutants (NESHAP) has been the principal compliance driver over the last decade for the aerospace industry, in particular NESHAP 40 CFR Part 63. HAZMAT reduction is driven by the Clean Air Act (CAA) and RCRA through Pollution Prevention (P2) efforts. Many P2 projects impact both CAA and RCRA concurrently. Examples are:

- CAA: Solvent substitution replacing high vapor pressure solvents with compliant, lower vapor pressure chemicals, utilizing non-VOC and/or non-HAP solvents and coatings, powder coat applications vs. conventional coating, etc..
- RCRA: Reducing or eliminating toxic/corrosive/flammable/reactive waste streams through material substitution, increasing recycling efforts for solid waste, etc.

Both CAA and RCRA mandate either directly or indirectly that efforts to minimize pollution be instituted. The CAA under the NESHAP 40 CFR Part 63 places such restrictive limits on material use, that when considering the liability of using chemicals

that could potentially be used for non-compliant applications, material substitution has a far greater appeal. When signing a Hazardous Waste Manifest, the generator declares that they have a program in place to reduce the volume and toxicity of waste generated to the degree determined to be economically practical. This minimizes the present and future threat to human health and the environment.

The emission of chromium compounds has been reduced significantly under the NESHAP regulation, which impacts most aircraft maintenance and rework facilities. This regulation limits the amounts of air pollution such as toxic chromate that can be generated for facilities such as NAVAIR Jacksonville and OC-ALC. NAVAIR Jacksonville and OC-ALC follow Title V, which is the Air Operating Permit Issued by State Department Environment of Protection. It is noted that Title V is one (1) of six (6) in the CAA. Additionally many states require active pollution prevention programs with set goals to eliminate pollution from maintenance operations within their states by law. IRRIT will promote the reduction of the above environmental concerns.

1.4 Stakeholder/End-User Issues

The demonstrations validated that the technology can be used to detect corrosion through coatings in a maintenance environment. The IRRIT will ascertain the current condition and integrity of the OML and IML coating systems, for an engineering disposition of required maintenance. It is anticipated this technique will lead to deferred or reduced maintenance, for example interval shift, reduced maintenance by scuff sanding and repainting or spot repair. Stakeholder decision making issues include the ability to use the IRRIT inspection tool for establishing the following:

1. Criteria for stripping and repainting the entire aircraft
2. Criteria for local small spot strip and re-paint
3. Criteria for strip and re-paint of large local areas
4. Criteria for scuff, sand, and prime/topcoat if no corrosion is present under coatings

The affected weapon systems may include the following aircraft:

<u>Exterior Finish System (OML)–</u>

- United States Coast Guard (USCG): All Aircraft
- United States Navy (USN): P-3, E-2, E-6, T-45, C-2, C-9, C-40
- United States Air Force (USAF): E-3, E-8, C-12, C-20, C-21, C-32, C-37, VC-25, All USAF Trainer Aircraft

<u>Interior Finish Systems (i.e., IML, Fuel Cell and Components) –</u>

- USCG: All Aircraft
- USN: All Aircraft
- USAF: All Aircraft

2. TECHNOLOGY DESCRIPTION

2.1 Technology Development and Application

The technology developed in the SERDP Project PP-1137 as described in Section 2.1.1 is the base technology. Figure 2-1 illustrates the IRRIT system.

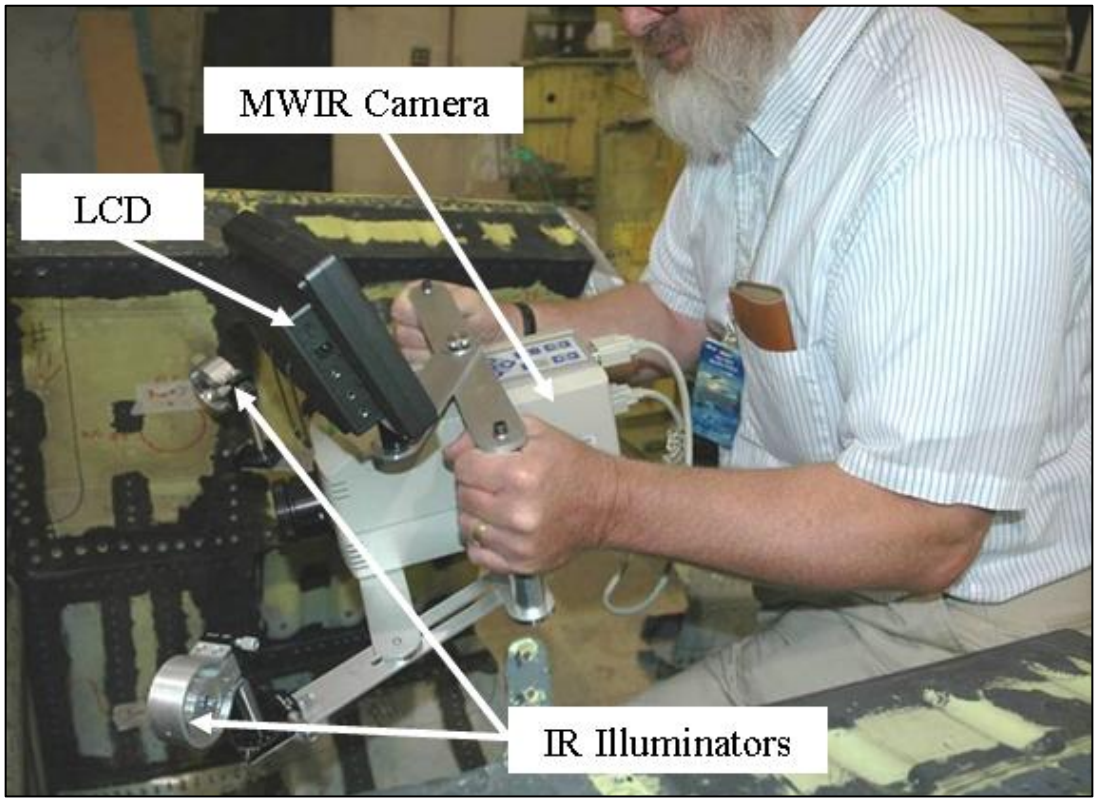


Figure 2-1: IRRIT System

2.1.1 Infrared Reflectance Imaging Technique (IRRIT)

One way to detect corrosion products at the paint/metal interface is to use an optical reflectance probe to detect changes in reflectance as a result of corrosion. Spectral reflectance signatures may be used to detect the presence of various chemical species, including corrosion products. An IR beam must be able to pass through the coating, reflect from the metal surface, and pass back out through the coating. Coatings are normally designed with pigment sizes tailored so that they are opaque in the visible region of the spectrum (0.40 to 0.75 micrometer (μm)), so they preclude using optical techniques in the visible to "see" through the coating to the metal. However, the scattering power of pigments is diminished as the probe wavelength becomes longer. For many coatings, a spectral window opens in the near and mid-wave infrared (MWIR, 3-5 μm) spectral regions. As a result, a correctly adjusted IR camera can simply see through some paints (refer to Figure 2-2).

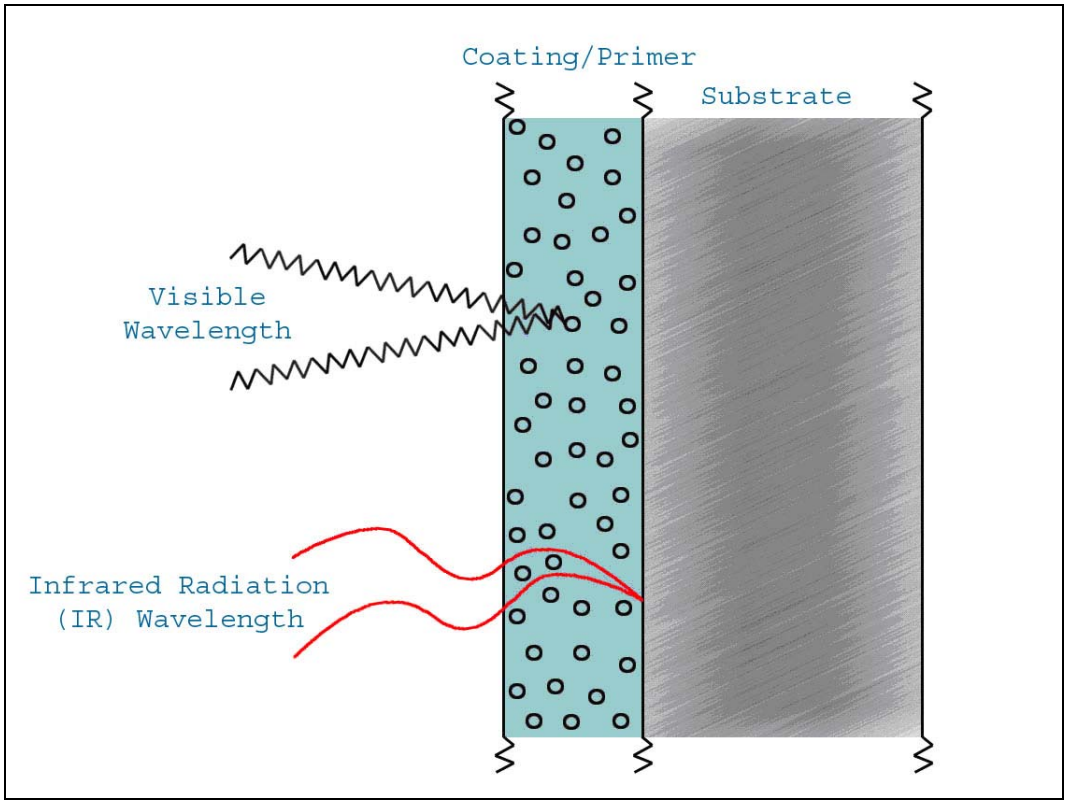


Figure 2-2: IR Wavelength versus Visible Wavelength

The IRRIT concept employs the use of IR focal plane technology coupled to spectral filters to image the reflectance of large areas of an aircraft's structure simultaneously. Sensitive high-resolution IR focal plane cameras are already used to obtain thermal images for use in thermography. IR cameras can be used to create an image showing reflectance variations over a painted aluminum surface. Band pass filters can be selected to match the paint transmission windows based on the spectral database of paints and corrosion of metal surfaces.

Spectral imaging systems can be specially designed from commercial systems. During the SERDP program, these systems were incorporated in a hand-held camera, which produced images that were quickly downloaded to a computer for analysis. A hand-held Merlin® IR Camera (FLIR Systems) system was used to inspect broad areas of an aircraft fuselage, and with a change of lens, it was converted into a low power magnifying system to obtain detailed assessments of corrosion.

There is a significant reduction in reflectance from a corroded substrate. By identifying the ratio of the reflectance spectra of the painted clean aluminum to the spectra of the painted corroded aluminum, a contrast enhancement technique was developed. It was found that the corrosion signature in the paint transmission window can be "seen" through this paint system with this camera. Figure 2-3 illustrates an IR image with corrosion beneath the coating, note the corrosion and how it appears dark.

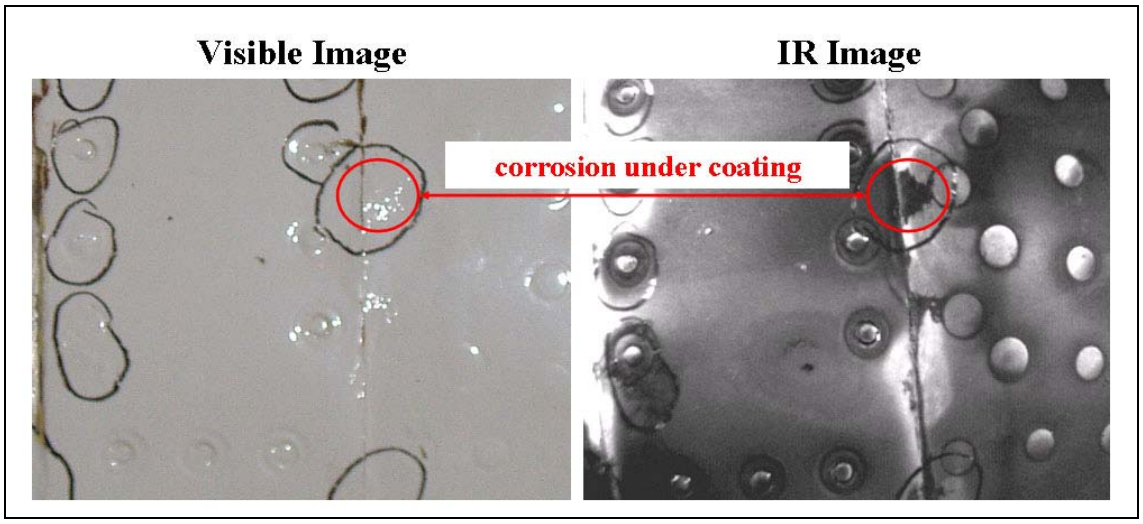


Figure 2-3: Visible Image versus IR Image

Contrast is enhanced by rejecting IR reflection from the paint in the non-transmitting regions. In principle, this is not unlike a technique known as IR reflectography that is used to see the underlying canvas in paintings. However, reflectography uses IR film or low sensitivity near-IR cameras that are inefficient in penetrating the paint. In addition, reflectography is not a multi-spectral technique (no rejection of non-transmitting spectral regions), and it does not have any sensitivity in the mid-IR paint transmission region between 4 and 5 μm. Broadband IR radiation is used to illuminate the painted part. The intensity of the illumination should be sufficient to dominate the parts' natural thermal emission at ambient temperature and in the spectral range of interest. As a result of the investigation into paint and coating IR transmission described above, a spectral filter, preferably cold (77 Kelvin [-321.07ºF/-196ºC], the operating temperature of Indium Antimonide (InSb) Mid-IR camera focal plane), is used to block out all IR light in the non-transmissive regions of the paint. In the non-transmissive regions, light would only be reflected from the upper portion of the paint layer and result in significantly reduced contrast in the final image.

The reasons for the ability of the IR spectral imaging technique to see through layers of paint include a reduction in diffuse scattering at the longer wavelengths, and the high sensitivity and dynamic range of today's commercial IR cameras. Scattering, which is the physical scattering of light by objects or pigments, is significantly reduced when the wavelength is increased by an order of magnitude (0.50 to 5.0 μm). This is because the wavelength becomes much larger than the physical size of the pigment particles. The paint transitions from being a diffuse scatterer in the visible region into a transparent "clear coat" in the mid IR. That is why so much surface detail can be resolved in the images. In addition, these cameras are normally used for thermal imaging where small differences in temperature need to be measured. This translates into a high sensitivity for small differences in reflectance for the spectral imaging technique. For thicker paint coatings with low contrast between corroded and un-corroded areas, there will be a small difference in reflectance in the painted panel between the two areas. A sensitive IR

camera can image a surface with low contrast. High fidelity images of the substrate can be imaged through certain commercial and military paint systems (up to 10 mils) with available commercial MWIR camera systems outfitted with spectral filters.

2.1.2 IR Blackbody Technique

Another technique utilizing the same Merlin® MWIR camera to detect corrosion under coatings involves the use of IR radiation which emanates directly from the part itself without the need of external heaters to provide IR energy. In this case, the IR radiation is emitted from the part's surface in the form of blackbody radiation, which penetrates out through the coating and is imaged by the IR camera. The advantage to the blackbody method is that external illuminators are not needed and that the energy only has to pass through the coating once. The major difference between the two approaches is that the part itself becomes the illuminator. In the case of blackbody radiation, the corrosion actually emits more IR radiation than the uncorroded surface and hence, corrosion shows up as a lighter (hotter) area then the uncorroded area. This is just the opposite from the IR reflectance method that indicates corrosion as a dark area when imaged with the Merlin® MWIR camera.

2.1.3 IRRIT versus IR Blackbody

It is important to understand the image differences between IR reflectance and the blackbody modes. Figure 2-4 (A) is a standard visible light image of a painted corroded aluminum panel illustrating exposed corrosion on the left hand side with the right side being corrosion that has been painted with epoxy primer and gloss urethane color insignia white. The corrosion can not be seen under the coating, except when observed with IR as illustrated in Figure 2-4 (B and C).

Figure 2-4 (B and C) illustrates the primary observable difference between the IR Reflectance and the Blackbody Modes when detected in the Merlin® MWIR camera.

In the reflectance mode, as illustrated in Figure 2-4 (B), the observed corrosion is denoted by the dark areas while in the case of the Blackbody Mode the observed corrosion is white.

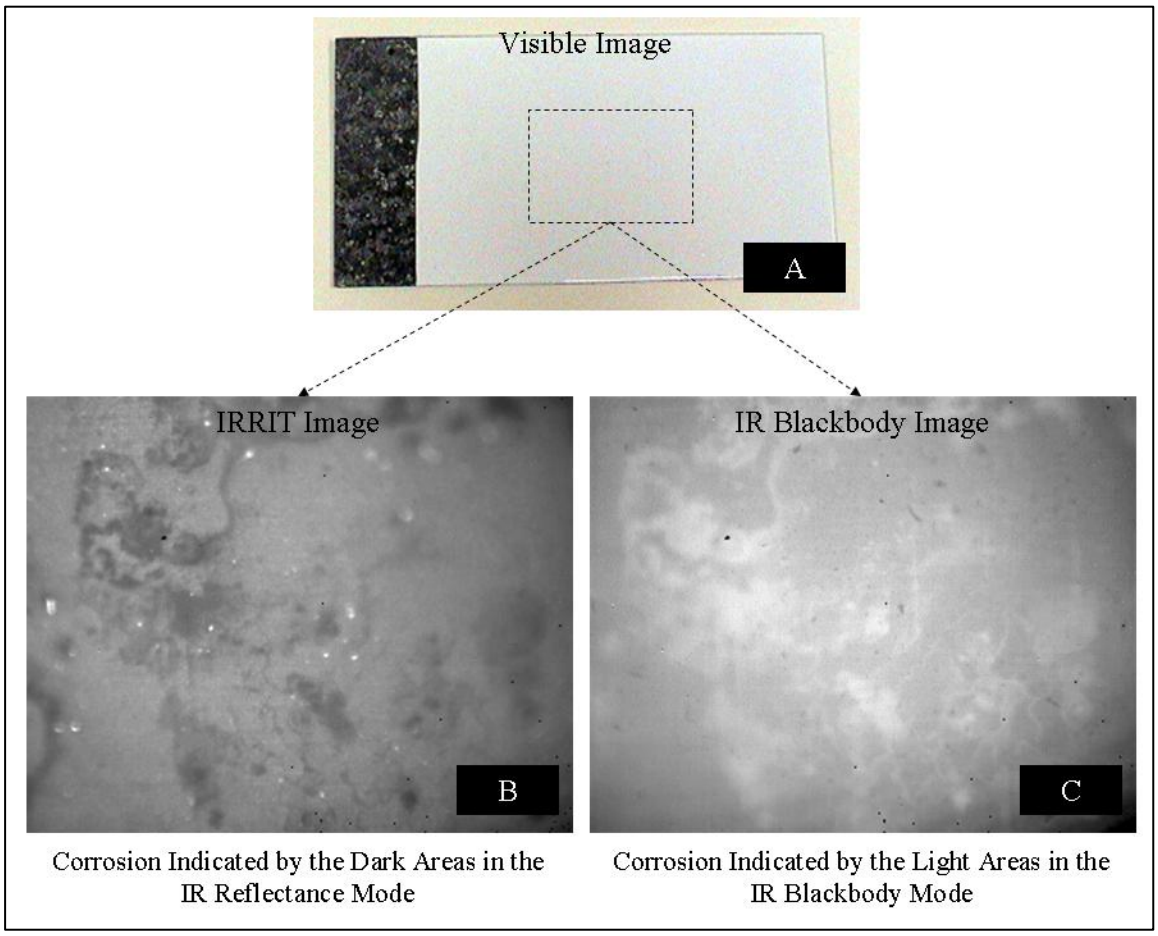


Figure 2-4: IR Reflectance versus IR Blackbody

Comparing both Figure 2-4 (B and C) and superimposing them over each other, it can be clearly seen that the dark patterns match the light corrosion patterns in the respective figures. These facts lead to an interesting possibility that if the IR heat flux of the corroded areas equals the IR heat flux of the non-corroded areas, the corrosion will not be observable and hence the corrosion would not be detected through the coating. In fact, this is a distinct possibility that could be encountered in the field by the camera operator. Such a scenario could occur while using the IR camera system in the IR reflectance mode. For example, a hot metallic aircraft structure would emit IR energy in the blackbody mode with the corrosion appearing light such as in Figure 2-4 (C). If an IR reflectance method using IR illuminators is employed the corrosion will appear dark, as previously demonstrated, provided the corrosion area does not emit more energy than the background in reflection. The potential issue is that if the illuminators do not provide enough IR flux to be reflected from the non-corroded background, this background will appear darker provided the blackbody mode dominates the IR reflectance mode. The corroded area may appear to be the same with respect to the background brightness or the corroded area in the IR reflectance mode would emit energy in the blackbody equal to the energy being reflected by the IR reflectance heaters in the non-corroded area. This would create a condition of zero contrast and hence no corrosion will be observed by the IR

camera operator. This condition is obviously not acceptable with respect to the demonstration and validation of the equipment to the end user. A laboratory study using a controlled temperature protocol was conducted to address this issue and determine the actual parameters required to eliminate this possibility (refer to Appendix E.7). This study concluded that if this scenario was to occur, a solution would be to increase the IR heat flux that is emitted from the IR illuminators, thus overpowering the blackbody effect.

2.2 Previous Testing of the Technology

Significant prior testing of the IRRIT technology occurred under the SERDP Project 1137 by NGC. The testing protocol and results of the testing can be found in the Final Report, "Non Destructive Testing of Corrosion Under Coatings," September 2004.

The objective of SERDP Project 1137 was to research and develop nondestructive inspection techniques to locate hidden corrosion on aircraft surfaces without requiring removal of the coating. The most promising corrosion inspection method studied under the SERDP contract was the IRRIT. The SERDP Project 1137 Final Report describes progress made for years 1999 through 2004 for Corrosion Detection and Standards Development.

2.3 Factors Affecting Cost and Performance

The primary factors that affect cost and performance are listed in Table 2-1, below.

Table 2-1: Cost and Performance Factors

Cost Factors
1. Deferred or reduced magnitude of aircraft corrosion maintenance 2. Environmental, Health, and Safety (EHS) issues (e.g., wastewater, hazardous waste, VOCs, chrome paint use) 3. Capital Costs
Performance Factors
1. Coating type, composition and IR transmission 2. Coating thickness 3. Climate conditions (e.g., temperature, humidity)
Cost and Performance
1. Inspection/Scan rate 2. Detection threshold and sensitivity 3. Labor

2.4 Advantages and Limitations of the Technology

2.4.1 Comparison to NDI Technologies

Some of the advantages and limitations of the IRRIT technology and a comparison between other corrosion inspection techniques are illustrated in Table 2-2. In Table 2-2, IRRIT and the visual inspection alternative (both shaded gray) are the two alternatives directly compared against each other during the Dem/Val. Reviewing the table illustrates

that the IRRIT is competitive with the alternate methods of detecting corrosion under coatings. As described in the comments column, the IRRIT can quickly generate real time images comparable to a visual inspection of a stripped surface. Analysis of the images requires the same skill set as that required for a visual determination of corrosion damage. This differs from most other NDI systems, which produce non-visual data requiring interpretation.

A variety of nondestructive methods have been evaluated for detection of corrosion under paint, but no modern technique has been implemented. One of the limitations of most conventional NDI techniques is their lack of sensitivity to relatively small concentrations of corrosion products at the metal/coating interface. Ultrasonic test and eddy current inspection, two of the most widely used NDI techniques in the aerospace community, can be used to detect relatively large amounts of material loss due to corrosion, but they do not meet the objective of detecting corrosion under paint in its earliest stages.

Table 2-2: Inspection Method Comparisons

Inspection Method	Time to conduct corrosion survey for a 10 ft^2 surface area	Skill Level	System Cost	Near Surface Detection Sensitivity Level	Comments
Ultrasonic	**4 hrs Set up time = 1 hr.**	**High**	**Medium 30K to 100K**	**Low to very poor on surfaces**	**Interpretation Issues**
Eddy Current, Conventional	**1 hr Set up time =0.5 hr.**	**High**	**Medium 45K to 100K**	**Low, but problems with fasteners/joints**	**Interpretation Issues/problems**
MOI (Eddy Current)	**30 min Set up time = 0.5 hr.**	**Med.**	**Low 25K**	**Low**	**Interpretation Issues**
Thermography	**1 hr Set up time = 2 hrs.**	**High/ Med.**	**High 150K+**	**High**	**Images require Interpretation**
X-Ray	**4 hrs Set up time = 2 hrs.**	**High**	**High/Medium 50K to 125K**	**Medium**	**Health Issues Work area must be cleared of personnel**
Microwave	**1 hr Set up time = 0.25 hr.**	**High**	**Low 5K to 10K**	**Medium, but issues with Fasteners / joints**	**Edge Effects, Interpretation Problems**
IR Reflectance (IRRIT)	***15 min Set up time =0.5 hr.***	***Low/ Med.***	***Medium 70K***	***High***	***Real Time Images, Easy to Interpret* Fast***
Visual Inspection	**10 min Set up time < 0.5 hr.**	**Med.**	**Low 5K**	**Medium**	**Interpretation Issues**

*Unique to IRRIT: Lowest projected labor times and rates needed for cost effective corrosion surveys. Easiest technique to interpret because of real time images with highest fidelity of all systems compared. Note: Set up times vary, depending on standards to be checked, equipment warm up, and calibration.

2.4.2 Coating System Limiting Factors

The following table illustrates coating systems that were tested with the IRRIT. In general, MWIR (3-5 micrometers) cameras are capable of imaging through typical organic coatings applied to proper military specification thicknesses. It should be noted that IR transmission is dependent on coating type and thickness. Also, although details are given in Table 2-3 to specific coatings and manufacturers, the IRRIT technology is not limited to these specific products. This table documents what coatings have been tested and either showed MWIR transmission success or failure. Typical aircraft OML and IML coating systems allow significant MWIR transmission. IRRIT failed to image through low IR primer, CARC coatings, polysulfide sealants, and metal filled coatings.

Table 2-3: Paint and Coating Systems Tested with IRRIT

Type	Specification	Color # (FED-STD-595)	Manufacturer	Part #
Pretreatment – Chemical Conversion Coating	MIL-C-81706 Class 1A	Not Applicable	Turco Alumigold or Alodine 600	
CPC	BMS 3-35	Not Applicable	Zip-Chem	Cor-Ban 35
Epoxy Primer	MIL-P-23377 Type I High Solids	Not Applicable	Deft	02-Y-40A
	MIL-P-85582 Type I, Class C1	Not Applicable	Deft	44-GN-7
	MIL-P-85582 Type I, Class N (Candidate)	Not Applicable	Deft	44-GN-098
	MIL-P-85582 Type I, Class C2	Not Applicable	Deft	44-GN-072
	TT-P-2760 Type I Class C	Not Applicable	Deft	09-Y-002
Solvent-Borne Epoxy Primer	MIL-P-23377 Type I Class C	Not Applicable	PRC DeSoto	EEAY051A
Polyurethane Topcoat	MIL-PRF-85285 Type I	Gloss Gray 16440	Hentzen	04644AUX-3
Polyurethane Topcoat	MIL-PRF-85285 Type I	Gloss White 17925	Deft	03-W-127A
High Solids Polyurethane Topcoat	MIL-PRF-85285 Type I	Flat Gray 36293	Deft	03-GY-322
High Solids Epoxy Primer	BMS 10-79	Not Applicable	Akzo Nobel	10P20-44 NSN: AD32-47-300-0354
Polyurethane Topcoat	BAMS565-09 Type I Class A Grade B	Coast Guard Gloss White	Akzo Nobel	Eclipse ECL-G-46 NSN: AD32-47-300-0446
Polyurethane Topcoat	BMS 10-79	Coast Guard Gloss Orange	Akzo Nobel	Eclipse ECL-G-6615 NSN: AD32-47-300-3655
Fluid Resistant Epoxy Topcoat	MIL-PRF-22750	Gloss White 17925	Deft	01-W-081
Fuel Tank Coating	AMS-C-27725	Not Applicable	PRC DeSoto	825X309
APC Polyurethane Topcoat	MIL-PRF-85285 Type I	Flat Gray 36173	Deft	99-GY-001
		Flat Gray 36118	Deft	99-GY-13
		Flat Gray 36375	Deft	99-GY-003
		Gloss White 17925	Deft	99-GY-009
Epoxy Primer	MIL-P-53022B Type I	Not Applicable	Sherwin Williams	E90W201/V93V202
CARC Polyurethane Topcoat	MIL-C-46168 Type IV	Flat Green 34094	Sherwin Williams	F93G27/V93V20
		Flat Black 37030	Sherwin Williams	
	MIL-C-53039A	Flat Green 34094	Sherwin Williams	F93G104
		Flat Black 37030	Sherwin Williams	F93B102
	MIL-C-64159 Type II	Flat Green 34094	Sherwin Williams	F93G504/V93V502
		Flat Black 37030	Sherwin Williams	F93B505/V93V502
Low IR Epoxy Primer	MIL-P-85582 Type II, Class C2	Not Applicable	Deft	44-GN-76
Low Density Epoxy Primer	MIL-P-85582 Type I, Class C2	Not Applicable	Deft	44-GN-36
Polysulfide Sealant	MIL-S-81733 Type III	Not Applicable	PRC DeSoto	

Green Shading = IRRIT had success with this coating when applied up to 2-3 times proper military specification
Orange Shading = IRRIT had success only when this coating applied to proper military specification thickness
Red Shading = IRRIT had no success imaging through coating

3. DEMONSTRATION DESIGN

3.1 Performance Objectives

The main performance objective of this demonstration is to identify corrosion under coatings with the IRRIT technology. The performance objectives for this project can be found in Table 3-1.

Table 3-1: Performance Objectives

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance
Quantitative	1. Product Testing	Higher Level of Accuracy w/IRRIT Regarding Corrosion Detection, as Compared to Visual Inspection.	Performance Criteria Met
Quantitative	2. Hazardous Materials	Projected Reduction of VOC, HAP, and HAZMAT (by deferring maintenance) Pollution Prevention Savings Resulting from Reduced Maintenance	Performance Criteria Met
Quantitative	3. Process Waste	Projected Reduction of VOC, HAP, and HAZMAT (by deferring maintenance) Pollution Prevention Savings Resulting from Reduced Maintenance. No known process waste generated.	Performance Criteria Met
Quantitative	4. Factors Affecting Technology Performance	Scan Rate w/IRRIT will Not Interfere w/Current Maintenance Flow Process (Complimentary Tool to Visual Inspection) Scan Rate of Dem/Val (Surface Area Inspected) Enhanced Condition Based Assessment	Performance Criteria Met

3.2 Selecting Test Platforms/Facilities

Two facilities were chosen to Dem/Val the IRRIT technology. The NAVAIR Jacksonville, FL, facility was chosen to Dem/Val the IRRIT on an aircraft OML. The OC-ALC facility was selected to Dem/Val the IRRIT on an aircraft IML. Army ground vehicles were considered, but were rejected, due to the inability of the IRRIT to image through the Chemical Agent Resistant Coating (CARC) system (refer to Table 2-3 and Appendix E.5).

3.2.1 NAVAIR Jacksonville, P-3 OML

The P-3 aircraft maintained at NAVAIR Jacksonville, FL were selected as the OML is corrosion prone and the IR characteristics of the current paint system lend itself to successful demonstration of the IRRIT. The P-3 operates in a maritime environment that exposes the aircraft to severe corrosive conditions. The aircraft, when not on patrol, are also stationed in a maritime environment. High corrosion areas on the P-3 aircraft were targeted during the Dem/Val based on the past history of P-3 corrosion surveys and maintenance records. The P-3 aircraft uses standard military coatings and finishes.

Corrosion inspection currently consists of visual inspections. Chemical stripping of the aircraft (Figure 3-1) occurs on set intervals regardless of the corrosion findings. It was the goal of this project to demonstrate that the IRRIT can successfully identify the surface condition beneath the paint.

Mr. John Benfer, PI for this ESTCP program is the Senior Corrosion Engineer at NAVAIR Jacksonville. Mr. Paul Kenny, the Senior NDI Engineer at NAVAIR Jacksonville, works with Mr. Benfer in the process of investigating the potential incorporation of IR systems into various NAVAIR process streams.

Figure 3-1: Paint Removed from P-3 Aircraft by Chemical Paint Stripping

3.2.2 OC-ALC, KC-135 IML and B-52 IML

The KC-135 and B-52 aircraft maintained at OC-ALC were selected for a number of reasons, primarily, both models are aging (some aircraft are up to forty years old), aircraft availability, and the opportunity to Dem/Val the IRRIT on IMLs. Since the IRRIT system had already been demonstrated on the exterior of the P-3 aircraft and some limitations were identified with thicker OML coatings, it was decided that IRRIT would next be evaluated on IMLs. IML inspections allowed an additional data set for IRRIT inspections on complex surfaces and geometries. If one can reduce/prevent IML corrosion by early detection then serious structural damage can be potentially avoided. After a preliminary inspection, it was confirmed that the KC-135 IML (refer to Figure 3-2) and B-52 IML were suitable for Dem/Val.

KC-135 and B-52 lead maintenance engineers expressed a high degree of interest in the IRRIT technology due to potential labor and maintenance cost savings. Ms. Hoang Nguyen, the engineer in charge of B-52 maintenance, showed interest due to the fact that areas of the B-52 IML are coated with a chromated primer. Some of these chromated areas have been stripped and replaced during required fleet-wide inspections, which might have been avoided through use of the IRRIT. Mr. Steve West and Mr. Jeff Catron, senior NDI engineers at OC-ALC, also showed interest in the implementation of IR systems, and supported the selection of the KC-135 as a target for the Dem/Val. Currently, the KC-135 IML corrosion inspection technique consists of visual and eddy current inspections of structurally critical areas. Incorporating IRRIT could reduce the amount of paint stripping required.

Figure 3-2: Typical KC-135 IML

3.3 Test Platform/Facility History/Characteristics

A description of the facilities and the platforms selected to Dem/Val the technology are as follows:

3.3.1 NAVAIR Jacksonville, P-3 OML

The facility chosen for the OML Dem/Val was NAVAIR Jacksonville, Florida. Since its establishment in 1940, the production shops have maintained almost every type of Navy aircraft - fighter and attack planes, patrol, antisubmarine, reconnaissance, transport, trainer, special configuration, and helicopters. The overall workload has expanded to include the rework of engines, components and ground support equipment, plus other support functions vital to the Fleet.

Continual change and improvement have characterized the Depot's history. NAVAIR Jacksonville occupies 54 buildings on over 102 acres with several offsite locations as well and returns over $219 million in payroll to the Jacksonville economic community. The Depot is an industrial leader in the region and one of three modern industrial facilities commissioned by the Navy to perform in-depth maintenance, repair, overhaul and modification of fleet aircraft, engines, and aeronautical components. Other Navy depot facilities exist; examples are NAVAIR Cherry Point, NC, and North Island, CA. Similar facilities exist within the Air Force, as well as the Army.

The platform chosen for the OML Dem/Val was the P-3 Orion Aircraft. This aircraft is a four-engine turboprop anti-submarine and maritime surveillance aircraft. The P-3 was originally designed as a land-based, long-range, Anti-Submarine Warfare (ASW) patrol aircraft, the P-3s mission has evolved in the late 1990s and early 21st century to include surveillance of the battle space, either at sea or over land. Its long range and long loiter time have proved to be invaluable assets during *Operation Iraqi Freedom* as it can view the battle space and instantaneously provide that information to ground troops, especially U.S. Marines.

The P-3 has advanced submarine detection sensors such as Directional Frequency and Ranging (DIFAR) sonobuoys and Magnetic Anomaly Detection (MAD) equipment. The avionics system is integrated by a general purpose digital computer that supports all of the tactical displays, monitors and automatically launches ordnance and provides flight information to the pilots. In addition, the system coordinates navigation information and accepts sensor data inputs for tactical display and storage. The P-3 can carry a mixed payload of weapons internally and on wing pylons.

The aircraft is constructed of conventional aluminum typical of structures designed in the 1960's. It consists of 2024-T3 (OML) and 7075-T6 (Wings), and typical aerospace coatings. The overall surface area of the P-3 is approximately 6,500 ft^2. The P-3 fuselage has a radius of 68 inches that begins to taper at Fuselage Station (FS) 901 to a radius of 48 inches at FS 1117. The P-3 OML uses standard coatings consisting of MIL-C-5541 chemical film treatment, MIL-PRF-85582 Type I epoxy primer (Deft Primer Part No. 44-

GN-7), and MIL-PRF-85285 Type I polyurethane topcoat (Hentzen, Federal Standard Color No. 16440).

3.3.2 OC-ALC, KC-135 IML and B-52 IML

The facility chosen for the IML Dem/Val was OC-ALC. OC-ALC, located at Tinker Air Force Base (TAFB), was founded in 1941 (as the Oklahoma City Air Material Area, OC-AMA) when the War Department sought to establish an aircraft maintenance depot in the central U.S. OC-ALC was soon tasked to repair B-17s and B-24 bombers in World War II, and fitted out B-29 bombers. OC-ALC subsequently supported all major conflicts in which the U.S. was engaged. The facility was renamed OC-ALC in 1974.

OC-ALC maintains a wide range of aircraft (over 2000 in a multitude of models) for all U.S. Armed Services. It is the premier aircraft engine maintenance facility in the U.S. Department of Defense, servicing jet engines dating from the Korean War to the most modern stealth aircraft engines and is responsible for managing some 23,000 engines throughout the DoD. Maintenance is not limited to engines – airframe and avionics maintenance are part of OC-ALC's duties. Airframe maintenance, which requires substantial paint stripping for corrosion detection and thus drives IRRIT interest in OC-ALC.

The platforms chosen for the IML Dem/Val were the KC-135 Stratotanker and the B-52 Stratofortress.

The KC-135 Stratotanker, introduced to service in 1956, is based on the Boeing 367-80 prototype (the "Dash-80" that also led to the famous Boeing 707.) The last KC-135 was delivered to USAF service in 1965, indicative of the age of all KC-135s in service. The most notable function of the KC-135 is aerial refueling of other U.S. military aircraft, extending their ranges significantly. However, the KC-135 may also transport up to 83,000 pounds of cargo in its voluminous interior. Through the years, the KC-135 has been altered to do other jobs ranging from flying command post missions (including the EC-135C "Looking Glass") to reconnaissance. Because of the cancellation of the KC-767 program, the KC-135 will remain in service and likely be upgraded in coming decades, making detection of corrosion on these aging airframes more critical.

The B-52 Stratofortress was conceived as an intercontinental bomber and was introduced in 1954. A total of 744 B-52s were built, with the last delivered in 1962, making all B-52s in excess of forty-five years old. Over the years, the B-52s have been modified substantially from their original role as high-altitude nuclear bombers. B-52s can now carry in excess of one hundred conventional bombs, operate at "treetop" in ground-hugging flight, may utilize a wide range of weapons (from simple free-fall bombs to cruise missiles), are the most economical of the U.S.'s heavy bombers, and boast the highest combat readiness rate of U.S. heavy bombers (80% readiness, vs. 57% for the B-1 and 40% for the B-2). For these reasons, the USAF plans to keep the B-52 in service until the year 2040, with associated maintenance concerns for aircraft that will eventually be older than the retirement age of their crews.

The KC-135 IML includes standard aircraft coatings. Consisting of chemical film treatment MIL-C-5541, epoxy primer MIL-PRF-23377, and a corrosion preventative compound (CPC). The B-52 IML bomb bay area includes the same coating system as the KC-135 IML with the addition of MIL-PRF-85285 topcoat.

3.4 Present Operations

Current corrosion inspection processes at NAVAIR Jacksonville and OC-ALC are as follows:

3.4.1 NAVAIR Jacksonville, P-3 OML

Current NAVAIR Jacksonville, operations require the P-3 aircraft to be stripped of organic coating for the purpose of OML corrosion inspections, approximately every 4 years. After coating removal, the OML or exterior of the aircraft is inspected by visual means for corrosion. Corrosion is then removed and then repainted in accordance with the Local Process Specification (LPS 650). Waste streams are summarized in a baseline process flow diagram (refer to Figure 5-1 in Section 5). Refinishing of the P-3 is a major cost driver, which involves material cost, labor costs, and disposal costs associated with the RCRA waste.

3.4.2 OC-ALC, KC-135 IML and B-52 IML

Current OC-ALC operations require the IML of B-52 and KC-135 aircraft to be stripped of coatings on an as-required basis for the purpose of IML corrosion inspections. In the most recent example cited, B-52s bomb bay longerons were stripped of their paint during depot maintenance visits until every B-52 in the fleet had been stripped and inspected. Similarly, 48 KC-135s pass through OC-ALC annually and the IML is selectively stripped in areas requiring maintenance at each induction.

3.5 Pre-Demonstration Testing and Analysis

No current practice can be used to obtain baseline data for rapidly imaging corrosion through paint. Therefore to further define the technology to be demonstrated, optimization/baseline testing (refer to Section 3.5.1), and mini field demonstrations (refer to Sections 3.5.2, 3.5.3, 3.5.4, and 3.5.5) have been accomplished prior to the Dem/Val. Mini field demonstrations were conducted to further refine the technology and the operation of the system. These entailed optimization/baseline testing and taking the camera system into the field to conduct data collection and assessments. The details of these field measurements are contained in Section 3.5.2, 3.5.3, 3.5.4, 3.5.5, and Appendix B. The results of the optimization/baseline testing are summarized in Appendix E.

3.5.1 Pre-Demonstration Optimization/Baseline Testing

A summary of the optimization/baseline testing consists of the following:

- Field of View (FOV) and Resolution Study
- Coating Types and Thicknesses
- Part Contour and Geometry
- Dust, Dirt, Oils/Grease (operational Fluids)

- Illumination Method
- Image Processing
- Ergonomics
- Thickness, Temperature, Illumination and Software

This optimization/baseline test plan has been included as Appendix D. A number of test specimens were created to simulate these potential variables identified above. These test specimens used alloys, surface preparations, and coatings that are representative of the demonstration aircraft. The results of the optimization/baseline testing and laboratory testing can be found in Appendix E. Supplemental evaluation of commonly used aircraft coatings can be found in Appendix L.

3.5.2 A-10 Mini Demonstration

A mini-demonstration was held at Hill Air Force Base (HAFB) in Ogden, UT in March 2005 utilizing the IRRIT. It was shown with this demonstration that corrosion could be detected in areas not readily observable without the aid of this IR inspection tool. Current practice was to visually inspect the coatings for indications of corrosion, prior to rework of the corrosion. It was demonstrated that HAFB had the potential to visually "miss" corrosion not readily observable on the surface of the coating, and in fact this was the case. IR photographs that were taken clearly demonstrated that corrosion was visible under the coating and not on the surface (refer to Figure 3-3). If not properly maintained in a timely manner this would result in additional corrosion and more pollution (refer to Figure 3-4).

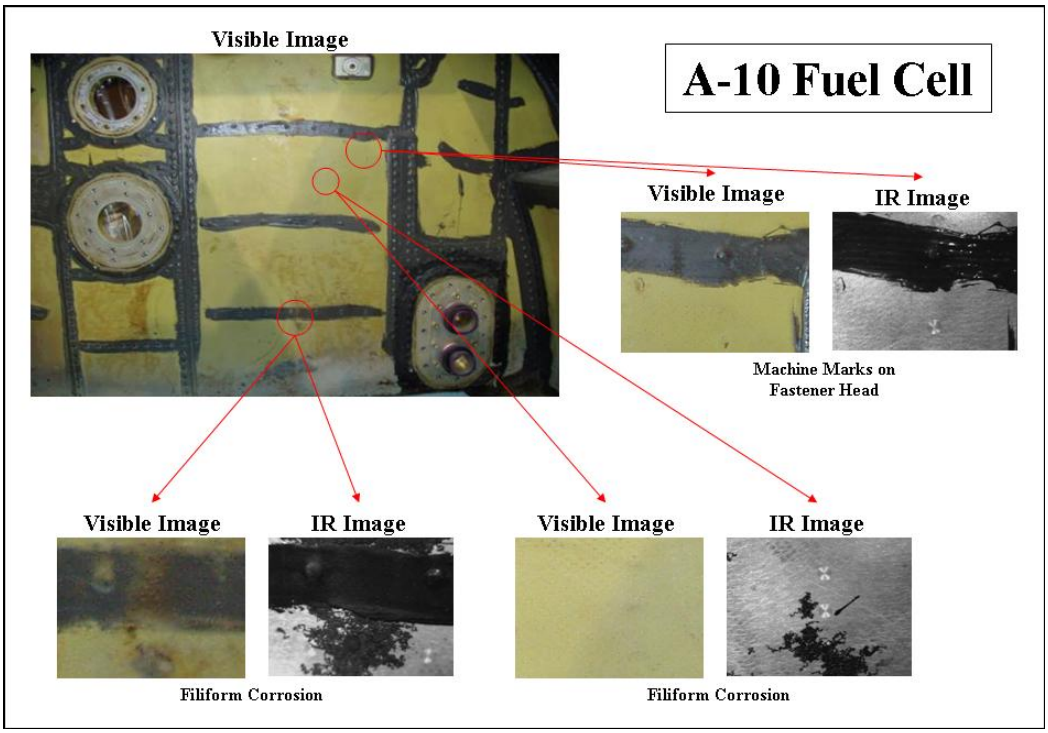


Figure 3-3: A-10 Fuel Cell - IR Images

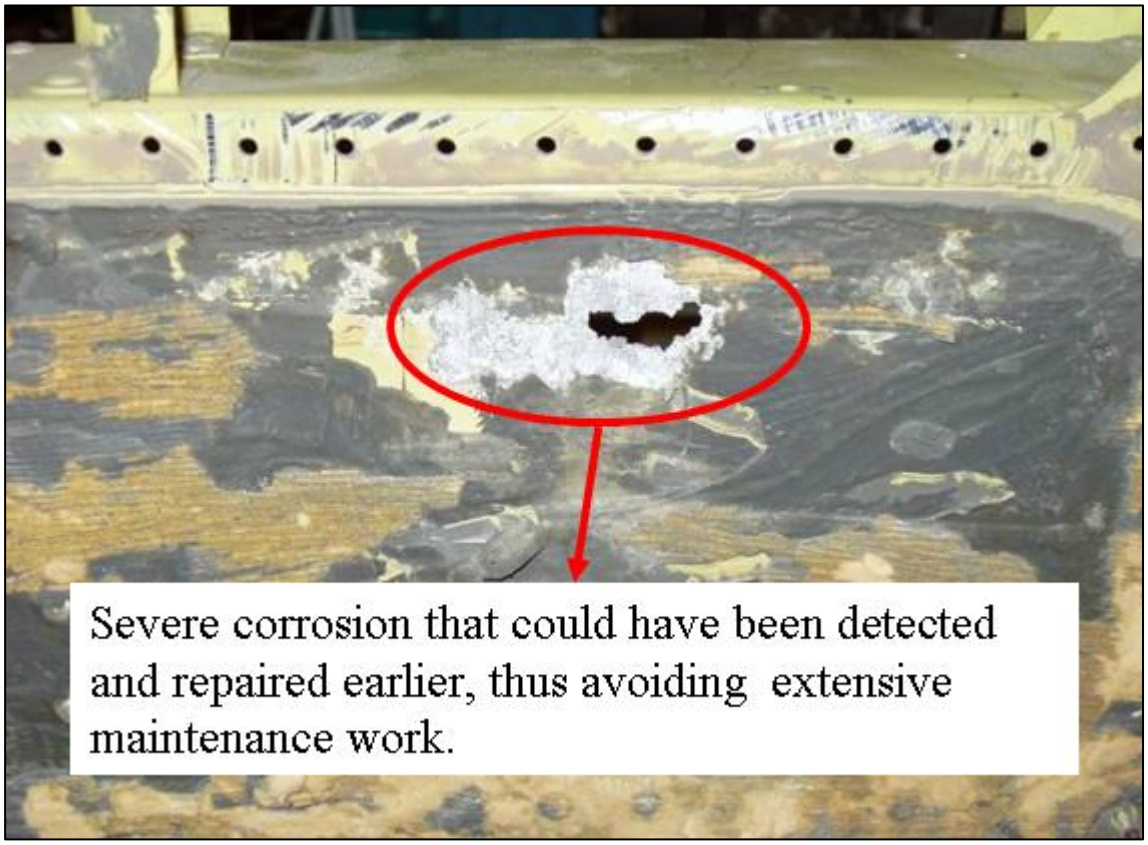


Figure 3-4: Severe Corrosion in A-10 Fuel Cell IML

3.5.3 Fort Bragg, NC, Pre-Demonstration Planning

Two trips were made to the Fort Bragg, NC Army Facility during January and May 2005. These trips explored the potential of doing a Dem/Val at Fort Bragg on Army ground vehicles, Family of Medium Tactical Vehicles (FMTV). However, laboratory testing concluded that the CARC did not allow for sufficient MWIR transmission (refer to Appendix E.5), thus the project was redirected to USAF IML coating systems.

3.5.4 US Coast Guard Mini Demonstration

A mini-demonstration was held at the Sandia Federal Aviation Administration (FAA) NDI Validation Center facility in Albuquerque, NM in July 2005. A US Coast Guard (USCG) aircraft, HU-25 was inspected using the IRRIT system (refer to Figure 3-5).

The USCG Aging Aircraft Branch (AAB) at the Aircraft Repair and Supply Center, Elizabeth City, NC, has been an active participant in a cross service program that includes corrosion detection under aircraft coatings. USCG AAB arranged for a HU-25 aircraft (tail # 2103) to be used for the USCG mini demonstration. The contact at the NDI validation center was Mr. David Moore. The Sandia Facility was tasked to evaluate the paint thickness of aircraft to verify the measurements are representative of USCG

aircraft. The paint thickness of this aircraft was in the medium average range of 8-11 mils with some areas of 6 mils and other areas of 13 mils, but for the most part between 8-11 mils. This aircraft is a good representation of the USCG HU-25 air vehicle fleet. Attendees/participants included Mr. John Benfer (NAVAIR Jacksonville), Mr. John Speers (WP-AFB), Mr. David Allen (ASM Management), Mr. Rusty Waldrop (USCG AAB), and Mr. Sam Benavides (USCG AAB), Mr. John Weir, Mr. Steven Chu, and Mr. Dennis Leyble, all of NGC.

The initial concerns over the ability to detect corrosion under coatings were paint thickness and the ability to detect the reflectance properties of the corrosion with a gloss topcoat applied. High gloss paint degrades the MWIR contrast due to less flux reaching the substrate.

The team detected several areas that appeared with a reflectance signature indicative of surface corrosion. These areas were marked and organized. The marked areas, while painted, demonstrated no signs of visual corrosion indicators. A Sandia representative, Joe Dimambro, performed thermography with the ThermoScope II™ on specific locations previously marked out by the IRRIT scan. Paint stripping and visual inspection of the bare surfaces validated the IRRIT corrosion reports.

The IRRIT demonstrated the ability to detect corrosion under the HU-25 paint scheme of cross section thickness between 8-10 mils. This was successful, despite the relatively thick coatings and glossy paint scheme of the aircraft. The camera was easy to use, lightweight, and demonstrated enhanced capability as compared to visual inspection and flash thermography.

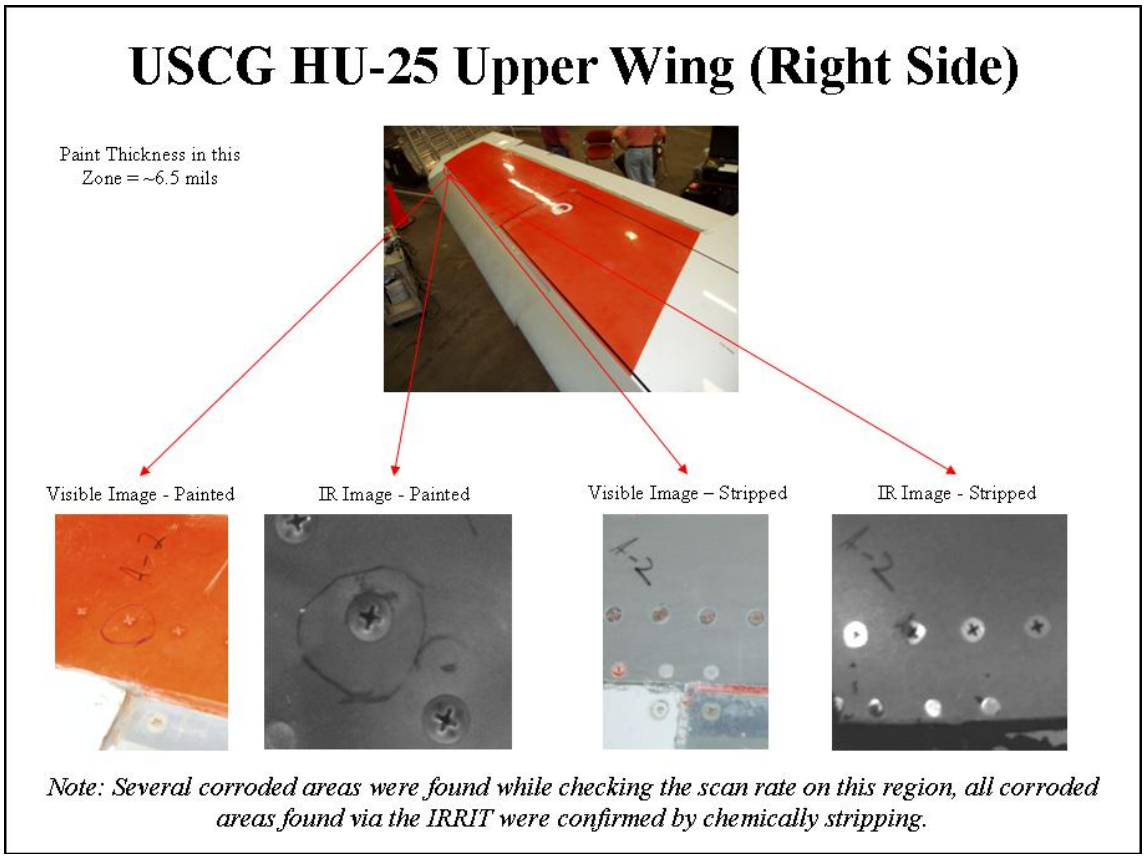


Figure 3-5: USCG HU-25 - IR Images

3.5.5 Warner Robins Air Logistics Center (WR-ALC), Pre-Demonstration

One site visit was made to WR-ALC in October 2005 to explore the potential of doing an additional OML Dem/Val on the C-130 or C-17 aircrafts (refer to Appendix B.2). An IRRIT inspection of selected C-130 and C-17 aircraft at WR-ALC was accomplished. However, the results indicated reduced inspection capability. This reduced capability to image through these coatings may be the result of the type of primer and/or the specific color of topcoat used by the USAF on OML applications as compared to the Navy. This trip resulted in an investigation of free-standing films based on typical USAF OML paint schemes by FTIR transmission analysis.

The FTIR transmission analysis of the free-standing films proved that insufficient MWIR is transmitted through the USAF OML paint schemes (refer to Appendix E.3). This led to redirecting the USAF OML effort to USAF IML at OC-ALC and the feasibility of using the KC-135 IML and B-52 IML as candidate aircraft for IRRIT inspection.

3.5.6 Summation of Pre-Demonstration Testing and Analysis

In summary, the pre-demonstration testing confirmed the ability to effectively use the IRRIT to successfully detect corrosion through typical aircraft coatings. This testing also defined the operating envelope of the IRRIT system primarily related to coating

thickness, color, IR illumination, and transmissibility (refer to Appendix B). The optimization/baseline testing characterized the IRRIT system parameters; whereas the field pre-demonstration visits resolved operational issues. Improvements made during pre-demonstration testing confirmed the system was ready for a depot/production Dem/Val, concurrent with existing production processes.

3.6 Testing and Evaluation Plan

3.6.1 Demonstration Set-Up and Start-Up

The Dem/Vals took place at NAVAIR Jacksonville and OC-ALC. Equipment (refer to Figure 3-6) was manually transported to aircraft depot location, utilizing two travel containers. The IRRIT system was set-up every day (refer to Appendix A for the Merlin® camera procedures) and tested/calibrated to ensure the system was functioning properly prior to use. Calibration involved the use of a "1951 USAF Glass Slide Resolution Target" coated with the same coating system as the P-3 aircraft. This standard ensured the IRRIT system was operating and functioning properly. For safety protection purposes (of equipment and personnel), the system had a surge-protected 110V power and Ground Fault Interrupt Circuit (GFIC). Operation of the IRRIT system and all Dem/Val activities occurred on a non-interference basis.

The IR Merlin® Camera is manufactured and serviced by FLIR/Indigo in Goleta, California. In the unlikely event that the camera was damaged, the camera would have been sent back for repair to FLIR. NGC also had two backup Merlin® cameras and accessories that could have been used to continue the Dem/Val. If the lens of the camera had become dirty or greasy, NGC would clean the lens with Isopropyl Alcohol (IPA) in accordance with FLIR/Indigo recommended procedure for cleaning the lens.

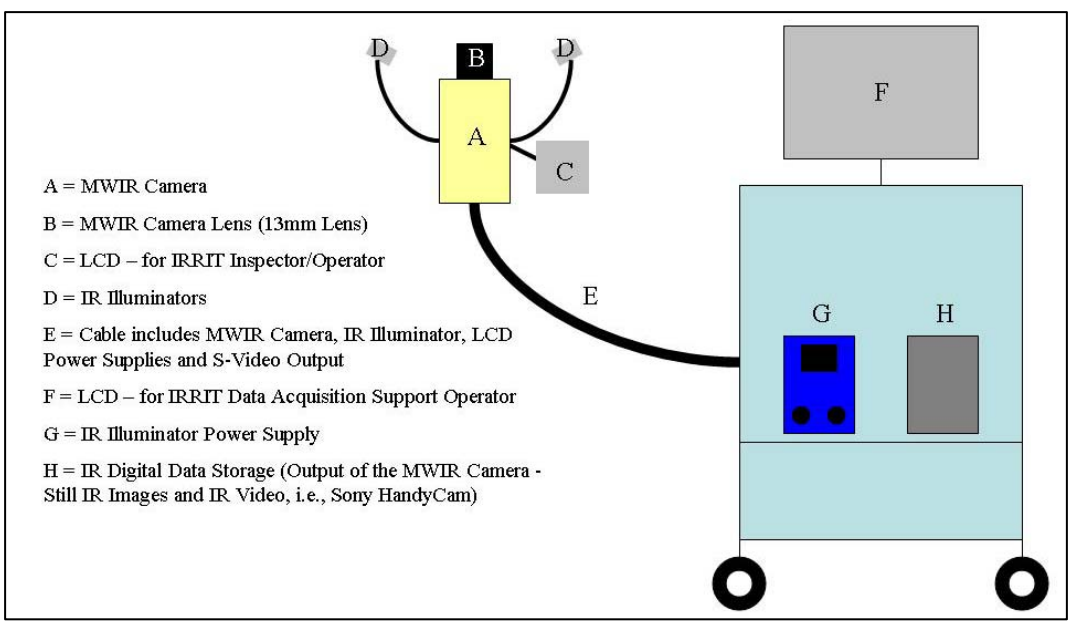


Figure 3-6: IRRIT System Schematic

3.6.2 Period of Operation

The dates and duration of each phase for both the OML and IML Dem/Vals are found in the following Gantt charts.

Task Name	Start	Finish
Navy P-3 Dem/Val: Outer Mold Line (OML)	**Tue 2/7/06**	**Wed 5/10/06**
P-3 "#912" Wing Section (OML): Visual Inspection (Primer + Topcoat)	Tue 2/7/06	Tue 2/7/06
P-3 "#912" Wing Section (OML): IRRIT Inspection (Primer + Topcoat)	Tue 2/7/06	Tue 2/7/06
P-3 "#912" Wing Section (OML): Visual Inspection (Post Chemical Strip)	Fri 2/10/06	Fri 2/10/06
P-3 "#912" Wing Section (OML): IRRIT Inspection (Post Chemical Strip)	Fri 2/10/06	Fri 2/10/06
P-3 "#912" Wing Section (OML): Visual Inspection (Flash Primer)	Mon 5/8/06	Mon 5/8/06
P-3 "#912" Wing Section (OML): IRRIT Inspection (Flash Primer)	Mon 5/8/06	Mon 5/8/06
P-3 "#912" Fuselage Section (OML): Visual Inspection (Primer + Topcoat)	Tue 2/7/06	Tue 2/7/06
P-3 "#912" Fuselage Section (OML): IRRIT Inspection (Primer + Topcoat)	Tue 2/7/06	Tue 2/7/06
P-3 "#912" Fuselage Section (OML): Visual Inspection (Post Chemical Strip)	Fri 2/10/06	Fri 2/10/06
P-3 "#912" Fuselage Section (OML): IRRIT Inspection (Post Chemical Strip)	Fri 2/10/06	Fri 2/10/06
P-3 "#912" Fuselage Section (OML): Visual Inspection (Flash Primer)	Mon 5/8/06	Mon 5/8/06
P-3 "#912" Fuselage Section (OML): IRRIT Inspection (Flash Primer)	Mon 5/8/06	Mon 5/8/06
P-3 "#772" Wing Section (OML): Visual Inspection (Primer + Topcoat)	Sat 5/6/06	Sat 5/6/06
P-3 "#772" Wing Section (OML): IRRIT Inspection (Primer + Topcoat)	Sat 5/6/06	Sat 5/6/06
P-3 "#772" Wing Section (OML): Visual Inspection (Post Chemical Strip)	Wed 5/10/06	Wed 5/10/06
P-3 "#772" Wing Section (OML): IRRIT Inspection (Post Chemical Strip)	Wed 5/10/06	Wed 5/10/06

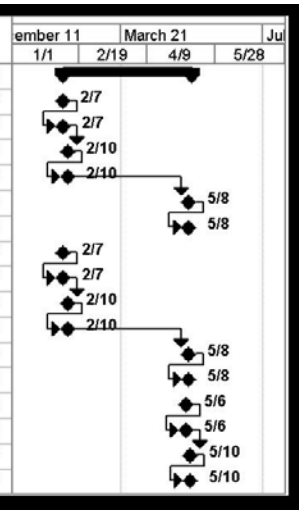


Figure 3-7: Gantt Chart for Navy P-3 OML Dem/Val

Task Name	Start	Finish
USAF KC-135 and B-52 Dem/Val: Inner Mold Line (IML)	**Mon 10/23/06**	**Thu 10/26/06**
KC-135 "#1" Bulkheads (IML): IRRIT Inspection	Mon 10/23/06	Mon 10/23/06
KC-135 "#1" Bulkheads (IML): Spot Strip Localized Areas	Tue 10/24/06	Tue 10/24/06
KC-135 "#1" Bulkheads (IML): Visual Inspection of Localized Areas	Tue 10/24/06	Tue 10/24/06
KC-135 "#2" Bulkheads (IML): IRRIT Inspection	Wed 10/25/06	Wed 10/25/06
KC-135 "#3" Port Wing Spar: IRRIT Inspection	Thu 10/26/06	Thu 10/26/06
B-52 "#1" Bomb Bay Longerons (IML): IRRIT Inspection	Tue 10/24/06	Tue 10/24/06
B-52 "#1" Bomb Bay Longerons (IML): Spot Strip Localized Areas	Wed 10/25/06	Wed 10/25/06
B-52 "#1" Bomb Bay Longerons (IML): Visual Inspection of Localized Areas	Wed 10/25/06	Wed 10/25/06
B-52 "#2" Bomb Bay Longerons (IML): IRRIT Inspection	Wed 10/25/06	Wed 10/25/06
B-52 "#2" Bomb Bay Longerons (IML): Spot Strip Localized Areas	Thu 10/26/06	Thu 10/26/06
B-52 "#2" Bomb Bay Longerons (IML): Visual Inspection of Localized Areas	Thu 10/26/06	Thu 10/26/06

Figure 3-8: Gantt Chart for USAF KC-135 + B-52 IML Dem/Val

3.6.3 Surface Area Inspected

For the Navy OML Dem/Val, a random sampling of two P-3 aircraft with standard paint schemes were used to demonstrate and validate the IRRIT, which resulted in a total of 300 square feet of P-3 surface area inspected with the IRRIT (refer to Appendix F). The 300 square feet encompassed 200 square feet from the first P-3 (Tail # 912, Bureau Number (BUNO) 158912) wing and fuselage sections (100 square feet each), and 100 square feet from the second P-3 (Tail # 772, Bureau Number (BUNO) 162772) wing section only. The areas inspected with the IRRIT system were selected due to the fact that they were historically corrosion prone areas.

For the USAF IML Dem/Val, three KC-135 and two B-52 aircraft were also used to demonstrate and validate the IRRIT, which resulted in approximately 100 square feet total of KC-135 and B-52 surface area inspected with the IRRIT. The KC-135 bulkheads sections were selected to showcase the IRRIT system on IML locations, and the ability to inspect structurally vital components in complex geometry areas. The B-52 longeron sections were inspected with the IRRIT and had previously been stripped and recoated for inspection purposes.

3.6.4 Operating Parameters for the IRRIT

The typical operating parameters were determined by previous optimization/baselining work (refer to Section 3.5). The set-up of the system involved two inspectors. The first operator acted as the IRRIT camera operator, looking for the corrosion, real-time. The second operator monitored the real-time video, equipment and data acquisition.

The IR camera with an internal cooler requires 15-30 minutes of cool down to reach the Focal Plane Array (FPA) operating temperature. Once the camera is cooled, an image appears on the monitor and proper distance for the desired Field of View (FOV) is established. Depending on the temperature of the aircraft surface and the FPA response, the Non Uniformity Correction (NUC) may have to be changed to one appropriate for the conditions encountered. An offset correction will clean up the image. Images will then be acquired from the inspection area of concern. Monitoring of all procedures was accomplished in Quality Assurance Control Plan (refer to Appendix C).

3.6.5 Experimental Design

3.6.5.1 Experimental Design - Navy P-3 OML Dem/Val

During the demonstration process, selected areas on the P-3 painted aircraft were inspected visually and with IRRIT. Corrosion sites were fully documented by indexing the corrosion sites to the engineering drawing location. IR imaging (IRRIT) of the painted section was conducted to locate the sites of corrosion, and IR photographic images were taken for documentation purposes. Following chemical paint stripping, the same area was inspected visually and digital images were recorded. Visual documentation occurred before and after stripping of the coating. A comparison of the marked areas exhibiting signs of corrosion was made between the IRRIT (prior to chemical stripping) and visual inspection method (post chemical stripping) to validate the results. Optimized parameters for the IRRIT were defined and established as a result of the IRRIT Optimization/Baseline testing. This optimization activity was completed prior to the demonstration/validation on the P-3 aircraft. Two (2) operators were used to conduct the IRRIT survey. The IRRIT operator scans the area to be inspected and the support person is responsible for recording and marking the corroded regions with a grease pencil. Details of the designed experiment can be found in the following sections.

The selected areas inspected were representative of the P-3 structures and known to be corrosion prone based on past history with the aircraft. The two high corrosion areas

and critical structural areas were selected on both the wing and fuselage OML (refer to Figure 3-9). The areas inspected were located (or indexed) according to the P-3 structural stations, as defined by the applicable P-3 assembly drawings.

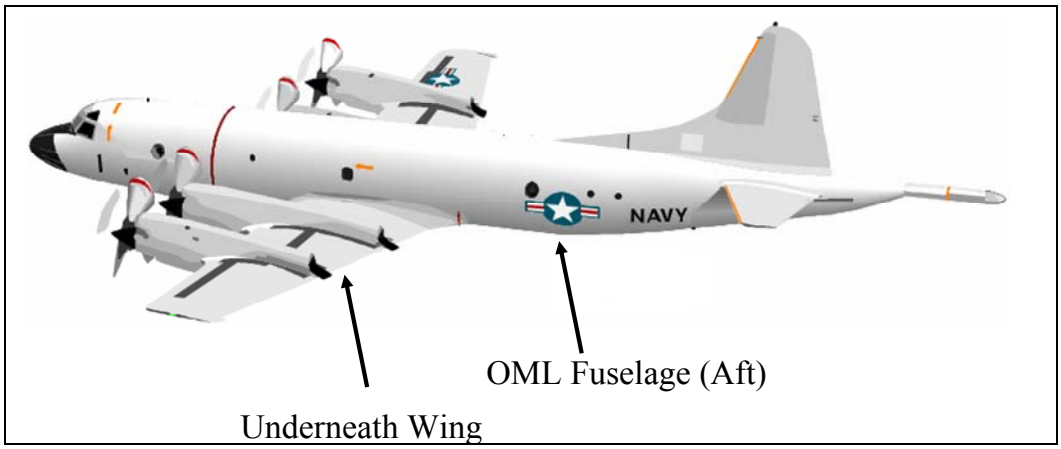


Figure 3-9: Areas to be inspected with IRRIT

The lower section of the inner port wing made from corrosion-prone aluminum alloy 7075-T6 was inspected between the forward and aft spar and Stations 65 and 147 (refer to Figure 3-10).

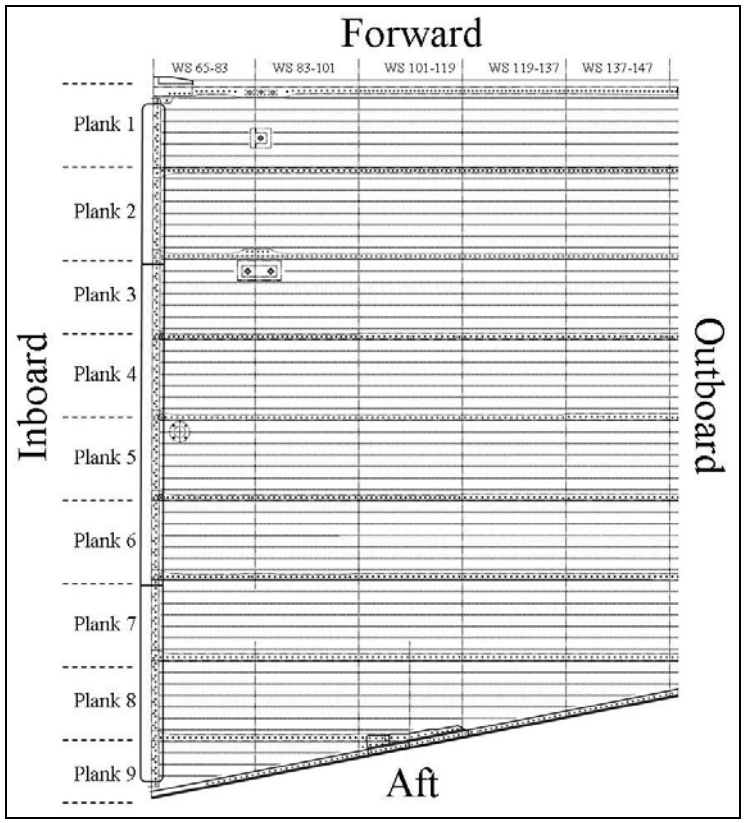


Figure 3-10: Navy P-3 Wing Section inspected with IRRIT

The fuselage section that was inspected (refer to Figure 3-11) is manufactured out of aluminum alloy 2024-T3 and located approximately between Stringers 43 to 46 and Stations 850-1050. The fuselage section is curved and is representative of locations on the fuselage with a fuselage radius of 48 inches to 68 inches, while the underneath section of the wing is mostly topographically flat. The radius section was selected to demonstrate dynamic illumination, orientation of the IR camera and a potential reduced FOV.

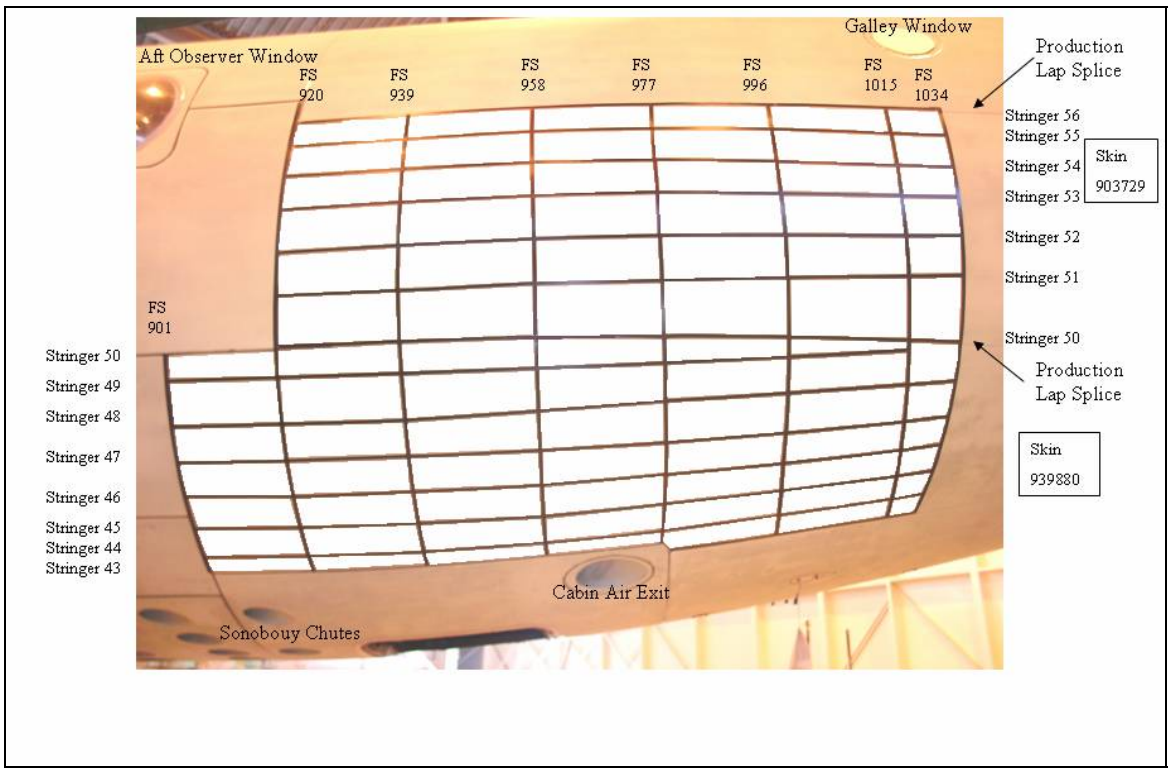


Figure 3-11: Navy P-3 Fuselage Section inspected with IRRIT

IRRIT inspection of the lower wing surface required the orientation of the camera in the vertical position, as opposed to the mostly horizontal position for the fuselage section. The approximate location of these two (2) selected areas can be seen in Figure 3-9. Prior to the corrosion survey, actual locations of these areas to be surveyed were marked or lined out to establish an acceptable FOV for the camera. The locations were approximately 10 feet by 10 feet or 100 square feet total in surface area per location.

The demonstration and validation started off with measuring the coating thickness variations to ensure that the aircraft met the under 10 mils criteria for the inspection to proceed. Note: This was not anticipated to be a problem as the experience with the P-3 by both Northrop Grumman and NAVAIR Jacksonville is that the finish thicknesses have not exceeded these values. The other reason to measure the thickness is to document the thickness of the coatings, so as to demonstrate that the variation of the coating thickness within the 10-mil thickness limit will not adversely effect the interpretation of the detected corrosion or lack of corrosion under the surface. The thickness was recorded at

or near the intersection of all ribs and stringers. This will produce a natural grid for future reference and analysis of the data.

Visual inspections of the two zones were inspected by the NAVAIR Jacksonville Corrosion Control Team. This corrosion inspection was conducted (in accordance with Navy Manual NA 01-1A-509) prior to coating removal. Corrosion sites were numbered and identified by structural location by the NAVAIR personnel, but were not marked on the P-3 structure directly so as not to influence the Northrop Grumman Team who were responsible for the IRRIT inspection of the coated structure. The NAVAIR personnel marked a visual map constructed from either a detailed photograph of the P-3 structure showing Stations and Stringers or a visual map constructed from the engineering drawing from the two selected areas. For example, each corrosion site had the Station number called out in exact inches. The vertical location was called out by stringer location. The closest stringer was measured in inches and the dimensional distance and stringer location were recorded. The exact horizontal locations of the corrosion sites were determined on the side of the fuselage. The location of each corrosion site was by marked by location on the P-3 engineering drawings or detailed photograph of all Stations and Stringers, which were apparent in the photograph.

The stripping of the P-3 aircraft was accomplished in accordance with the current paint removal methods used at NAVAIR Jacksonville, as called for in the LPS 250. Paint stripping was accomplished within Bldg 101S, which is normally used for stripping P-3 aircraft. The stripping was performed by experienced shop 6211 and shop 62711 personnel currently responsible for stripping operations.

A visual inspection of the stripped area to identify actual corrosion sites within the wing and fuselage inspection zones was conducted by both the NAVAIR team and the Northrop Grumman Team. The locations of all visible corrosion sites were documented utilizing P-3 structure as a template. Corrosion sites were numbered, identified by structural location, categorized, visually mapped and photo documented. The corrosion was documented by direct measurement (e.g., length, width, or diameter) and through qualitative assessment of degree of corrosion (e.g., light, moderate and severe). After visual inspection, IR photo documentation were conducted on all corrosion sites detected during the visual inspection of the stripped surface for future comparisons with the (under the coatings) corrosion sites previously detected during the initial IR scan. Corrosion sites detected after the stripping, but not found during the initial IR scan under the coating, were fully documented as to location and marked as missed or failed to detect. Additionally, corrosion sites marked as corrosion sites during the initial IR scan and found to be non-corroded areas (after stripping) were marked as a false positive and numbered. The last two conditions will be considered failures of the IR system to detect the accurate condition of the substrate.

A final corrosion inspection took place after the aircraft had been glass bead peened for corrosion removal plus chemical film treated (Alodine) and flash primed. This thin flash primer acts as a temporary corrosion prevention measure used at NAVAIR

Jacksonville. The inspection procedure was in accordance with the previously described procedures except that the area was not re-stripped and inspected again, as this area was previously stripped as described above. The purpose of this inspection was to determine what the reworked P-3 aircraft looks like under the IRRIT process to assure false positives are better understood, defined and cataloged as potential anomalies such as Alodine staining, peening marks, potential minor and acceptable corrosion damage left after corrosion removal operations, among other miscellaneous anomalies. It must be understood that after the flash priming has been accomplished in the production cycle, the aircraft was assumed to have only acceptable defects on the surface, active corrosion is not present. These under the paint defects were compared and analyzed in accordance with the procedure outlined below. This was considered the last inspection (see Figure 3-12 for the process stream). The final inspection is intended to reduce subsequent inspection interpretation issues and errors (false positives) with aircraft selected for the Dem/Val.

An assessment comparing the number of corrosion sites identified during the visual inspection of the painted surface with the number of corrosion sites identified with the IR inspection of the painted surface was made following demonstration. The number of actual corrosion sites was determined after the areas inspected were stripped. The total percent error (%) was the total number of both the % false positives sites "detected" as a percentage of actual corrosion sites and the total number of sites not detected, as a percentage of sites actually observed (see formula below). This was analyzed from both an estimated total surface area and total number of sites detected perspective. Particular attention was given to false positives, as these indications would possibly result in stripping an aircraft that would normally not have to be stripped in depot operations.

$$\text{Total \% Error} = \left(\frac{\text{Number of False Positives} + \text{Number of Corrosion Sites Not Detected}}{\text{Number of Actual Corrosion Sites}} \right) \times 100$$

An assessment was made comparing the degrees of severity of corrosion sites through qualitative and quantitative ratings of the degree of corrosion. Calculations were made to establish percent error based upon dimensions of the corroded area and rating of severity (e.g. light, moderate, severe). The inspection scan rates were determined and compared with the total % error of detection including false positives for all six (6) selected areas survey areas. This was compared to the scan rate of the visual technique currently used at NAVAIR Jacksonville.

The process stream is summarized in Figure 3-12. Inspection points were selected to validate and document each step. However, actual implementation after Dem/Val would anticipate only one inspection point.

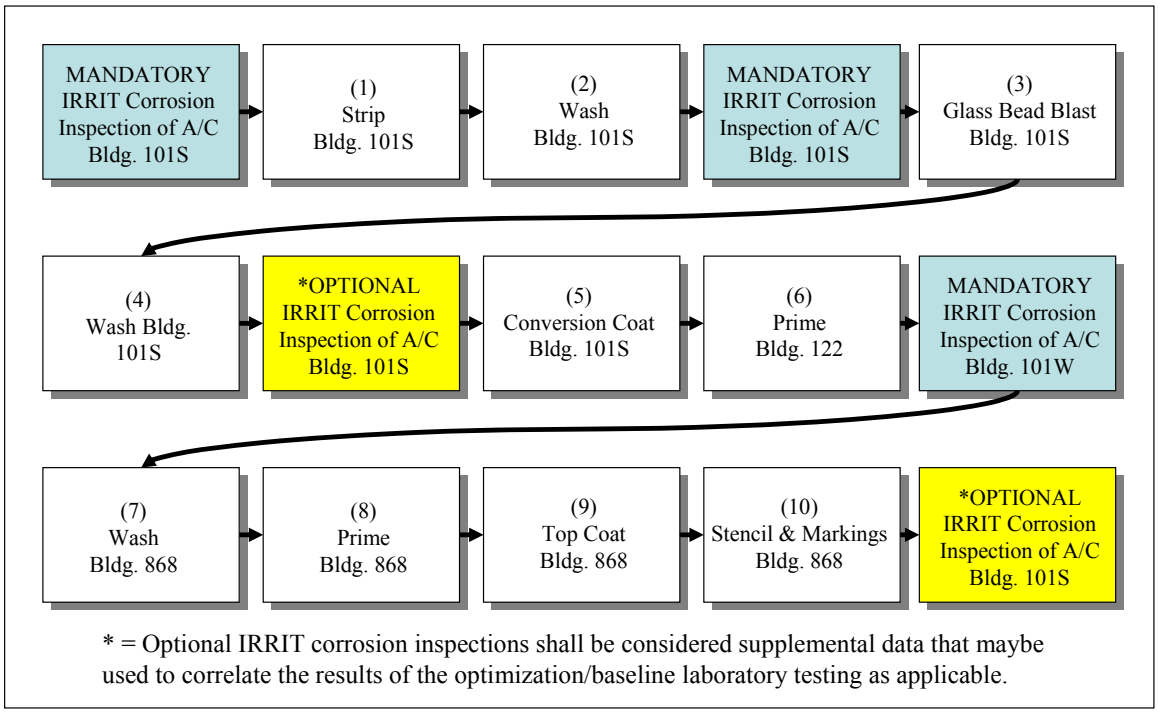


Figure 3-12: Process Stream w/IRRIT Added

3.6.5.2 Experimental Design – USAF KC-135 + B-52 IML Dem/Val

During the demonstration process, selected areas on the subject aircraft were inspected visually and with IRRIT. The process required several hours of access to the areas of interest on each aircraft, which was scheduled to avoid interference with regular maintenance activities. IR imaging (IRRIT) of the painted section was conducted to locate the sites of corrosion, and IR photographic images were taken for documentation purposes. Following chemical paint stripping (by default limited to areas with corrosion detected by IRRIT), the same area was inspected visually and digital images were recorded. Hence, optical documentation occurred before and after stripping of the coating. A comparison of the marked areas exhibiting signs of corrosion was made between the IRRIT (prior to chemical stripping) and visual inspection method (post chemical stripping) to validate the results. Two (2) operators were used to conduct the IRRIT survey. The IRRIT operator scanned the area to be inspected and the support person was responsible for recording and marking the corroded regions with a grease pencil. Details of the Dem/Val procedures can be found in the applicable OC-ALC KC-135 and B-52 Dem/Val Plan.

The primary vehicle of interest was the KC-135, due to the age of the aircraft (the youngest KC-135 was delivered to the USAF in 1965), and the likelihood that it will remain in service for decades more. This age makes detection and repair of corrosion damage critical. KC-135s are also frequently available for inspection, with about 48 passing through the OC-ALC facility annually (roughly 1 aircraft per week). Select areas of two KC-135 aircraft were inspected. The selected areas inspected were corrosion-prone areas of concern to KC-135 maintenance personnel. It was noted that the IML of

the KC-135 was not regularly stripped of paint, so paint stripping will be limited to areas where the IRRIT identifies corrosion. Areas of interest in the KC-135, as illustrated in Figure 3-13, include:

- Fuselage structural frames
- Two wing carry-over frames ("horseshoe fittings")
- Stringer carry-throughs ("splices")

The KC-135 areas of interest were internal structural components. The "horseshoe fittings" are load-bearing members that help distribute loads from one wing to the other, wrapping around the diameter of the fuselage like vertical horseshoes. Several similar structural frames ("formers") had been identified as areas of interest to KC-135 maintenance personnel. Finally, the "carry-throughs" that connect "stringers" (light structural frames running lengthwise inside the skin of the aircraft) through the formers had also been identified as prone to corrosion and cracking. Wing spars were also considered, but preliminary tests during the 19 April 2006 visit to OC-ALC demonstrated that the many hydraulics and secondary structural components made access difficult with the current FLIR camera. The total inspected area would be about 100 square feet per aircraft.

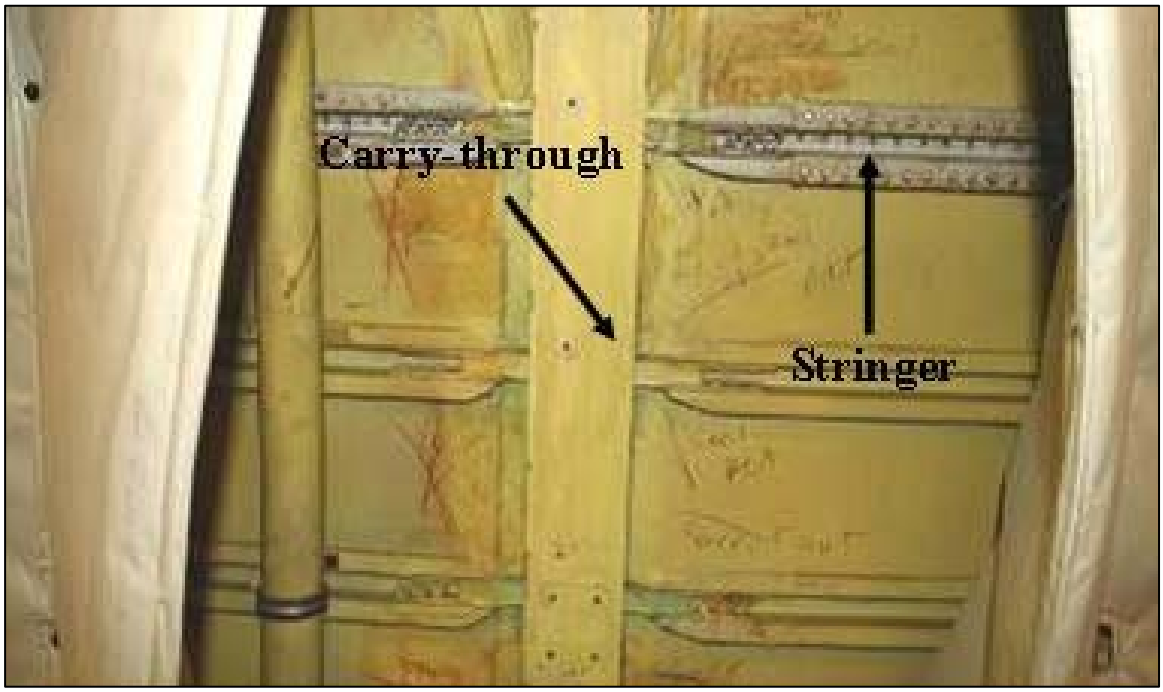


Figure 3-13: KC-135 IML IRRIT Inspection Area

After the successful preliminary camera test, B-52 aircraft were selected for IRRIT inspection. Areas of interest in the B-52, as illustrated in Figure 3-14, include:

- Bomb bay longerons

The B-52 areas of interest were in the bomb bay, partly due to their corrosion issues (they are exposed to outside weather conditions) and partly due to their accessibility and minimal interference with maintenance schedules. Within the bomb bay, the primary target was the longerons (heavy lengthwise structural members) at the bottom sides of the bay. The total inspected area was about 40 square feet or less. Unlike the KC-135 inspections, the longerons have previously been stripped and repainted for corrosion control purposes.

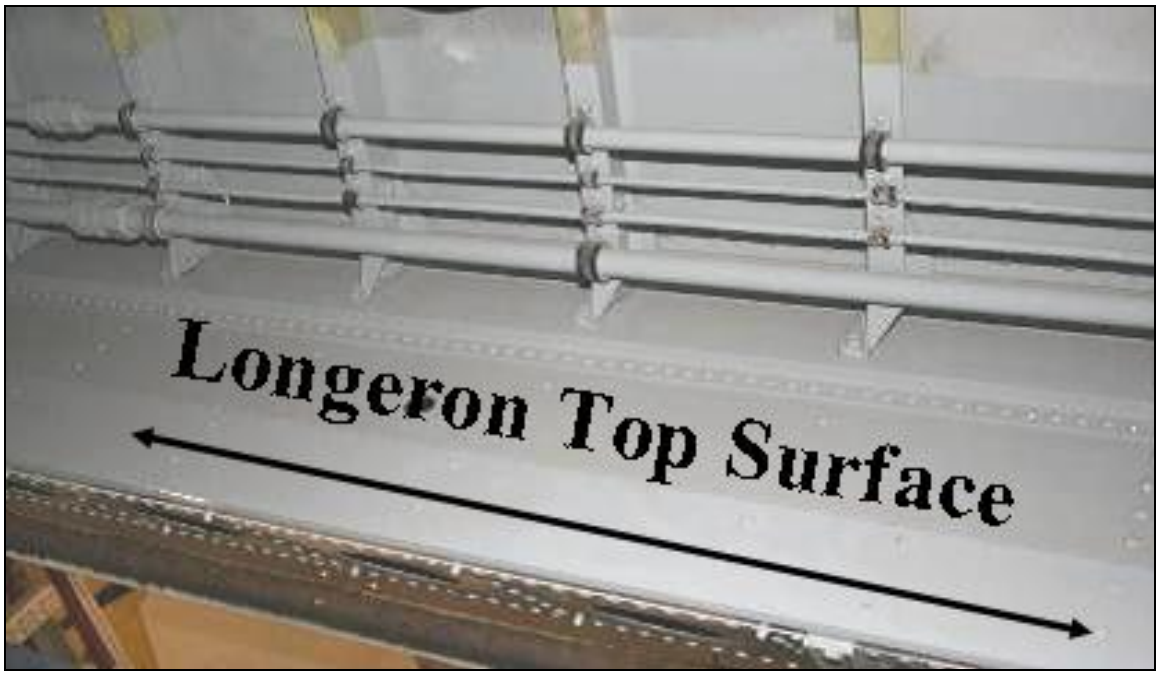


Figure 3-14: B-52 IML Bomb Bay Longeron

The process stream is summarized in Figure 3-15. Inspection points were selected to validate and document each step. However, actual implementation after Dem/Val would anticipate only one inspection point.

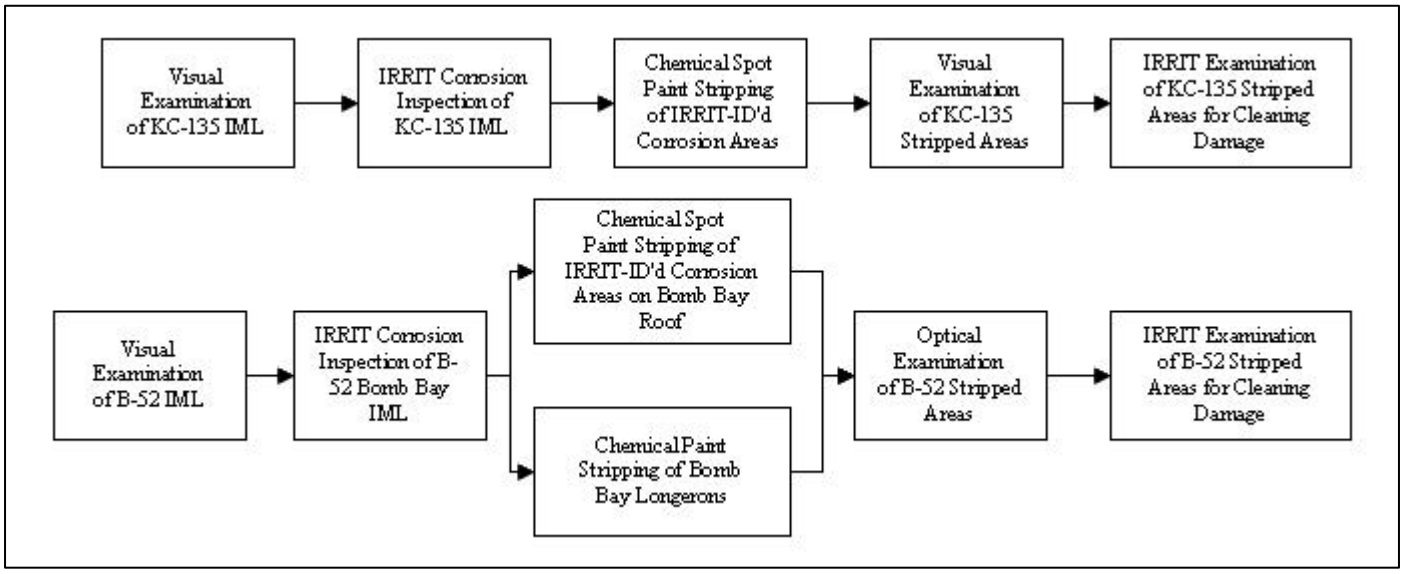


Figure 3-15: OC-ALC Process Stream with IRRIT Added

3.6.6 Product Testing

Product testing for all platforms was accomplished by conducting a corrosion survey utilizing the IRRIT to view potential corrosion sites. The NGC Team was responsible for conducting the IR inspection for corrosion through the coating. A digital video record was made in the IR to continuously monitor the IR survey. The time to conduct this survey was recorded. The IRRIT parameters (distance, NUC camera settings, illumination type, wattage, etc.) selected for the IR camera were determined by an established optimization/baseline test process, prior to the Dem/Val. Corrosion sites were marked on the surface of the painted aircraft and labeled in sequence. In addition, locations of these marked corrosion sites were documented (according to stations/stringer locations designated on aircraft engineering drawings), and digital IR and visible photographs. Post-processing the corrosion data could then be categorized as direct measurements (e.g. length, width, or diameter) and through qualitative assessment of degree of corrosion (e.g. light, moderate, and severe).

In the case of the P-3, additional IR inspections took place to validate maintenance induced anomalies during the corrosion removal process, glass bead peening, etc., did not show up as corrosion indications on the substrate surface under the paint. The reason for this step is to assure that once the aircraft returns to the depot, surface indications were not mistaken for corrosion during future IRRIT corrosion inspections.

3.6.7 Demobilization

The IRRIT was designed to be portable and was easily dismantled and removed after daily use (which took on average less than 15 minutes). A formal demobilization plan was not applicable, due to the portability of the IRRIT.

3.7 Selection of Analytical/Testing Methods

Calibration standards developed through the Optimization/Baseline testing were utilized at the demonstrations to ensure operational performance of the camera. These calibrations standard are defined as a "1951 USAF Glass Slide Resolution Target" coated with epoxy primer (MIL-PRF-85582) and polyurethane topcoat (MIL-PRF-85285) (refer to Appendix E.6). This standard ensured the IRRIT system was operating and functioning properly. These standards were checked at the beginning and end of each day of operation.

3.8 Selection of Analytical/Testing Laboratory

NGC conducted the pre-demonstration and pre-validation testing as required by the Optimization/Baseline Test Plan. NGC personnel operated the camera during the Dem/Val. NGC has extensive experience in previously conducting SERDP and ESTCP testing for detecting corrosion under coatings. No outside laboratories or independent evaluators were required due the fact that cognizant government and *CTC* engineers with expertise in the corrosion control area were utilized on the project team.

4. PERFORMANCE ASSESSMENT

4.1 Performance Criteria

The general performance criteria used to evaluate the IRRIT technology are summarized in Table 4-1. These performance criteria have been categorized as either primary or secondary criteria.

Table 4-1: Performance Criteria

Performance Criteria	Description	Primary or Secondary
Product Testing	IR Camera detection limits, test matrix parameters. Distance from area of inspection. Detects corrosion under coatings prior to stripping. To be verified by visual inspection after stripping operations are complete.	*Primary*
Hazardous Materials	Generation of hazardous waste will be reduced by the introduction of this technology demonstrated by the Cost Benefit Analysis (CBA).	*Primary*
Process Waste	Generation of process waste will be reduced by the introduction this technology demonstrated by the CBA.	*Primary*
Factors Affecting Technology Performance	Inspection environment will determine parameters for technology to operate optimally. Camera settings will be adjusted depending on Ambient temperature/surface temperature. Thickness of coating. Chemical composition of coating system.	*Primary*
Ease of Use	Minimal operator training required – about 4 hours required. Inspectors that normally do visual inspections for corrosion can use this system.	*Secondary*
Reliability	Manufacturer expects at least 8000 hours use before breakdown. No expected breakdown during Dem/Val.	*Secondary*
Versatility	The IRRIT and BB techniques are ideally suited to any platforms (besides P-3) that have coating systems transparent in the 3-5 micrometer range. Besides large areas, additional optics can be employed to inspect parts for, pits, fractures, part ID obscured visibly by the coating.	*Secondary*
Maintenance	Setup, operating, and breakdown procedures can be designed for easy operation. There is minimal maintenance required for the camera.	*Secondary*
Scale-Up Constraints	Depending on the number of cameras employed, an entire aircraft or selected locations can be recorded for future comparisons. Corrosion-prone areas of the aircraft will be inspected first to determine whether or not the balance of the aircraft needs to be inspected. Other equipment will be required to scan the entire structure: Scaffolding will allow access to higher areas. Robotics may also be needed for highly automated scanning.	*Secondary*

4.2 Performance Confirmation Methods

An overview of the results of the testing conducted is presented in Table 4-2.

Table 4-2: Expected Performance and Performance Confirmation Methods

Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual Performance
PRIMARY CRITERIA (Performance Objectives) (Quantitative)			
Product Testing	*Corrosion detection equal to or better than the visual inspection currently utilized after stripping coatings.*	*Visual Records*	*Corrosion detection better than visual inspection (refer to Section 4.3.1)*
Factors Affecting Performance (Pollution Prevention) • temperature of A/C • coating thickness • chemical composition of coating	*Acceptance criteria:* *Range 32-100 deg. ^{o}F* *Not to exceed 10 mils.* *Mil-Spec epoxy and urethane-based*	*Projected by Calculation and Measurement*	*All factors within acceptance criteria range, no negative impact of IRRIT imaging.*
Hazardous Materials	*No hazardous waste is introduced by this technology.*	*Operating experience*	*No hazardous waste was introduced by this technology.*
Process Waste	*No process waste is introduced by this technology.*	*Operating experience*	*No process waste is introduced by this technology.*
SECONDARY PERFORMANCE CRITERIA (Qualitative)			
Ease of Use	*Minimal operator training required – about 4 hours required. Inspectors that normally do visual inspections for corrosion can use this system.*	*Operating experience*	*Rapid acquisition of IRRIT images performed by field engineers and technicians.*
Reliability	*Manufacturer expects at least 8000 hours use before breakdown. No expected breakdown during Dem/Val.*	*Record keeping*	*No reliability issues.*
Versatility	*The IRRIT and BB techniques are ideally suited to any platforms (besides P-3) that have coating systems transparent in the 3-5µm range. Besides large areas, additional optics can be employed to inspect parts for, pits, fractures, part ID obscured visibly by the coating.*	*Operating experience/Assessments*	*Blackbody not suitable for aircraft inspection.*
Maintenance	*Setup, operating, and breakdown procedures can be designed for easy operation. There is minimal maintenance required for the camera.*	*Operating experience/Assessments*	*Minor maintenance required for commercial off-the-shelf (COTS) data cables.*
Scale-Up Constraints	*Depending on the number of cameras employed, an entire aircraft or selected area can be recorded for future comparisons. Corrosion-prone areas of the aircraft will be inspected first to determine whether or not the balance of the aircraft needs to be inspected. Other equipment will be required to scan the entire structure: Scaffolding will allow access to higher areas. Robotics may also be needed for highly automated scanning.*	*Operating experience/Assessments*	*No scale-up constraints.*

4.3 Data Analysis, Interpretation and Evaluation

The following sections (Section 4.3.1 and 4.3.2) describe data reduction, validation and reporting for the Navy OML and OC-ALC IML Dem/Vals respectively.

The Dem/Vals proved the IRRIT as an improved method of corrosion inspection over the current baseline visual inspection method used at the demonstration sites. This new method will give the engineering and corrosion control staff the capability to make sound engineering decisions as to whether to remove coatings or not to remove the coatings based on the reliable detection of corrosion under coatings. Additionally, the CBA criteria for pollution prevention was projected and applied based on actual usage data of materials plus projected waste savings scenarios (refer to Section 5).

4.3.1 Corrosion Inspection Comparison – NAVAIR Jacksonville, P-3

The Navy P-3 OML Dem/Val included the inspection of 2 aircraft (P-3s), consisting of 300 square feet of inspected area. The first aircraft inspected with the IRRIT was P-3 Tail #912, Bureau Number (BUNO) 158912 (200 square feet IRRIT inspected); the second aircraft was P-3 Tail #772, BUNO 162772 (100 square feet IRRIT inspected). During this Dem/Val various data points were acquired, including coating thickness, air (ambient) temperature, aircraft skin/surface temperature, visible images and IR images/video (refer to Table 4-4). The following paragraphs discuss these critical data points.

Coating thickness evaluation allows the IRRIT user to ascertain if the operational parameters of the system are met on selected demonstration aircraft. Based upon FTIR analysis, utilizing samples of various coating thicknesses, the user can determine if the MWIR transmission of the coating is sufficient to allow imaging through the coating system (refer to Table 2-3). Average coating thicknesses that were recorded during the P-3 OML Dem/Val were 0.5 mils (flash primer) to 4 mils (primer and topcoat), which is within the operational parameters of the IRRIT system.

Temperature measurements provide the IRRIT user with information on adjusting the quantity of IR illumination, to maximize image contrast. Improper adjustments of IR illuminators can create a condition of zero contrast, resulting in the inability to locate and image corrosion by the IRRIT operator. Optimization/baseline studies using a controlled temperature protocol were conducted to address this issue and determine the actual parameters required to eliminate this possibility (refer to Appendix E.7). During the OML and IML Dem/Vals, for blackbody imaging method to have worked (based on the MWIR camera and internal camera settings that were utilized) an approximate 10°F temperature differential from the air to aircraft skin temperature would have been required. However, based on the air and substrate temperature data that was recorded at NAVAIR Jacksonville and OC-ALC, IR reflectance (IRRIT) was determined to be the best method for detecting corrosion beneath the coated surface (refer to Table 4-4 and Table 4-8).

Visible images, IR images, and real-time IR video were recorded for documentation and comparison purposes in support of data analysis. A comparison of the

areas exhibiting signs of corrosion under coatings was made between the IRRIT (prior to chemical stripping) and visual inspection method (post chemical stripping). These results were then evaluated in accordance with Table 4-2. Locations within the selected inspection areas indicating corrosion under the coating system were marked for further detailed IR photo-documentation with a grease pencil or chalk. The data evaluation and interpretation consisted of: 1) a quantity of corrosion positively identified; 2) false positives (areas that were incorrectly identified as corrosion); and 3) undetected corrosion (inspection miss). IRRIT images and visible images (digital) with primer and topcoat (P-3 as received) were documented to assess corrosion sites identified during the IRRIT and visible scans, for determination of detection accuracy and condition based assessments.

After detailed visual and IR photo-documentation of the painted surface, the aircraft OML was chemically stripped using standard approved NAVAIR Jacksonville procedures. After chemical stripping, the IR images and visual images were obtained and compared with the coated surface, prior to stripping. The data acquired is summarized in Table 4-5 and Figure 4-1 and Figure 4-2. Finally, an IRRIT inspection after aircraft priming was conducted, to demonstrate the effect of corrosion removal processes was accomplished (refer to Appendix F – Dem/Val Plan Deviations). This data ensured that the surface effect from the glass-bead corrosion removal process is not misinterpreted as corrosion. This step further increased the confidence level, that the substrate surface finish will not be incorrectly identified, as corrosion on future inducted aircraft.

The results of the data concluded that the IRRIT method of corrosion inspection is significantly more accurate than the visual corrosion inspection method (refer to Table 4-5). The IRRIT method located on approximately 74-77% of the actual corrosion real-time, whereas the visual inspection located on approximately 5-12% of the actual corrosion. Post processing of the IRRIT data increased the average value to 79-86%.

It was noted during Dem/Val that the type and size of corrosion (i.e., filiform, general corrosion, etc.) was not a contributing factor in IRRIT inspection error. Post processing the IRRIT data to understand demonstration inspection error identified several contributing factors that may have occurred during the Dem/Val process (refer to Table 4-3).

Table 4-3: Inspection Error Contributing Factors (OML)

Error	Type of Error	Description
#1	Operator Error	IRRIT operator missed the corrosion location(s), but after reviewing IR images or IR video it was determined that the system actually picked it up.
#2	Operator Error	IRRIT operator missed the corrosion location(s) due to MWIR camera auto-gain issue (refer to Appendix E.8 Investigation to Correct Auto-Gain Image Issue), which was later corrected post processing.
#3	Operator Error	IRRIT operator did not scan the inspection zone completely – and since the zone was not scanned via the IRRIT it would have been impossible to identify the corrosion.
#4	System Failure	IRRIT system could not detect corrosion location(s) through coating system. This option did not occur during the Navy P-3 OML Dem/Val.
#5	Operator and System Failure	False Positive - Location incorrectly identified as corrosion through coating.

In theory, if the IRRIT user spends a lot of time scanning and doing the real-time inspection the level of accuracy should be close to 100%. However, due to the time constraints of production and other reasons a level of 74-77% accuracy with the IRRIT, which is still significantly higher than the 5-25% accuracy of the visual inspection method.

Table 4-4: Navy P-3 Dem/Val Data Points Acquired (Raw Data)

Navy P-3 Tail #912	As Received (Primer + Topcoat)							
	P-3 OML Location	Paint Thickness Measurements	Air Temperature Measurements	Aircraft Skin Temperature Measurements	Visible Photos	IR Photos	IR Video (hour:min:sec)	Date Data Acquired
	Wing	26 Measurements (AVG = 2.44 mils)	5 Measurements (AVG = 69.1°F)	4 Measurements (AVG = 70.6°F)	375 Images	201 Images	02:29:09	2/7/2006
	Fuselage	24 Measurements (AVG = 3.07 mils)	3 Measurements (AVG = 70.1°F)	4 Measurements (AVG = 71.9°F)				2/7/2006
	Post Chemical Stripping							
	P-3 OML Location	Paint Thickness Measurements	Air Temperature Measurements	Aircraft Skin Temperature Measurements	Visible Photos	IR Photos	IR Video (hour:min:sec)	Date Data Acquired
	Wing	*Not Required*	2 Measurements (AVG = 64.5°F)	2 Measurements (AVG = 66.8°F)	173 Images	101 Images	01:22:51	2/10/2006
	Fuselage	*Not Required*	1 Measurement (AVG = 71.8°F)	4 Measurements (AVG = 78°F)				2/10/2006
	Flash Primer							
	P-3 OML Location	Paint Thickness Measurements	Air Temperature Measurements	Aircraft Skin Temperature Measurements	Visible Photos	IR Photos	IR Video (hour:min:sec)	Date Data Acquired
	Wing	26 Measurements (AVG = 0.79 mils)	3 Measurements (AVG = 80.5°F)	2 Measurements (AVG = 81.9°F)	60 Images	48 Images	NA	5/8/2006
	Fuselage	9 Measurements (AVG = 0.54 mils)	2 Measurements (AVG = 85.2°F)	1 Measurement (AVG = 84.9°F)				5/8/2006
Navy P-3 Tail #772	As Received (Primer + Topcoat)							
	P-3 OML Location	Paint Thickness Measurements	Air Temperature Measurements	Aircraft Skin Temperature Measurements	Visible Photos	IR Photos	IR Video (hour:min:sec)	Date Data Acquired
	Wing	15 Measurements (AVG = 3.59 mils)	2 Measurements (AVG = 80.1°F)	2 Measurements (AVG = 79.95°F)	136 Images	100 Images	00:50:17	5/6/2006
	Fuselage	*NO MEASUREMENTS TAKEN – REFER TO APPENDIX F (Dem/Val Plan Deviations)*						
	Post Chemical Stripping							
	P-3 OML Location	Paint Thickness Measurements	Air Temperature Measurements	Aircraft Skin Temperature Measurements	Visible Photos	IR Photos	IR Video (hour:min:sec)	Date Data Acquired
	Wing	*Not Required*	2 Measurements (AVG = 78.55°F)	2 Measurements (AVG = 78.7°F)	125 Images	102 Images	NA	5/10/2006
	Fuselage	*NO MEASUREMENTS TAKEN – REFER TO APPENDIX F (Dem/Val Plan Deviations)*						
	Flash Primer							
	P-3 OML Location	Paint Thickness Measurements	Air Temperature Measurements	Aircraft Skin Temperature Measurements	Visible Photos	IR Photos	IR Video (hour:min:sec)	Date Data Acquired
	Wing	*NO MEASUREMENTS TAKEN – REFER TO APPENDIX F (Dem/Val Plan Deviations)*						
	Fuselage	*NO MEASUREMENTS TAKEN – REFER TO APPENDIX F (Dem/Val Plan Deviations)*						

Note: IRRIT Real-Time Accuracy Range = 74-77%
IRRIT Post-Processing Accuracy Range = 79-86%
Visual Accuracy Range = 5-25%

Table 4-5: Navy P-3 OML Real-Time Results versus Post-Processing Results

Navy P-3 Tail #912	Real-Time Results (P-3 OML Wing Section)					
	Inspection Technique	Suspected Areas of Corrosion	False Positives	Misses	Actual Corrosion Sites	% Accuracy
	Visual Inspection Results	10	1	163	172	5%
	IRRIT Inspection Results	128	0	44	172	74%
	Post-Processing Results (P-3 OML Wing Section)					
	Inspection Technique	Suspected Areas of Corrosion	False Positives	Misses	Actual Corrosion Sites	% Accuracy
	Visual Inspection Results	*Visual inspection does not allow for post-processing results.*				
	IRRIT Inspection Results	135	0	37	172	79%
	Real-Time Results (P-3 OML Fuselage Section)					
	Inspection Technique	Suspected Areas of Corrosion	False Positives	Misses	Actual Corrosion Sites	% Accuracy
	Visual Inspection Results	5	0	66	71	7%
	IRRIT Inspection Results	55	0	16	71	77%
	Post-Processing Results (P-3 OML Fuselage Section)					
	Inspection Technique	Suspected Areas of Corrosion	False Positives	Misses	Actual Corrosion Sites	% Accuracy
	Visual Inspection Results	*Visual inspection does not allow for post-processing results.*				
	IRRIT Inspection Results	57	0	14	71	80%
Navy P-3 Tail #772	Real-Time Results (P-3 OML Wing Section)					
	Inspection Technique	Suspected Areas of Corrosion	False Positives	Misses	Actual Corrosion Sites	% Accuracy
	Visual Inspection Results	27	2	74	99	25%
	IRRIT Inspection Results	75	0	24	99	76%
	Post-Processing Results (P-3 OML Wing Section)					
	Inspection Technique	Suspected Areas of Corrosion	False Positives	Misses	Actual Corrosion Sites	% Accuracy
	Visual Inspection Results	*Visual inspection does not allow for post-processing results.*				
	IRRIT Inspection Results	85	0	10	99	86%

Note: Post-processing allows the IRRIT user to review IR images and IR video to identify corrosion locations that may have gone initially undetected during the real-time inspection.

Table 4-6 below illustrates the IRRIT scan rates of the Navy P-3 OML Dem/Val. The total average scan rate was 127 ft²/hour. During the Dem/Val process the scan rate improves as the experience in IRRIT operation and procedures are refined. The Dem/Val process required extensive documentation which reduced the scan rate. Typical field operation of the IRRIT inspection would not require this level of documentation.

Table 4-6: Navy P-3 Dem/Val IRRIT Scan Rates

Navy P-3 Tail #912	As Received (Primer + Topcoat)	
	P-3 OML Location	Scan Rate
	Wing	64 ft²/hour
	Fuselage	73 ft²/hour
	Post Chemical Stripping	
	P-3 OML Location	Scan Rate
	Wing	150 ft²/hour
	Fuselage	207 ft²/hour
	Flash Primer	
	P-3 OML Location	Scan Rate
	Wing	150 ft²/hour
	Fuselage	*Scan Rate Not Recorded*
Navy P-3 Tail #772	As Received (Primer + Topcoat)	
	P-3 OML Location	Scan Rate
	Wing	120 ft²/hour
	Fuselage	*NO MEASUREMENTS TAKEN – REFER TO APPENDIX F (Dem/Val Plan Deviations)*
	Post Chemical Stripping	
	P-3 OML Location	Scan Rate
	Wing	*Scan Rate Not Recorded*
	Fuselage	*NO MEASUREMENTS TAKEN – REFER TO APPENDIX F (Dem/Val Plan Deviations)*
	Flash Primer	
	P-3 OML Location	Scan Rate
	Wing	*NO MEASUREMENTS TAKEN – REFER TO APPENDIX F (Dem/Val Plan Deviations)*
	Fuselage	*NO MEASUREMENTS TAKEN – REFER TO APPENDIX F (Dem/Val Plan Deviations)*

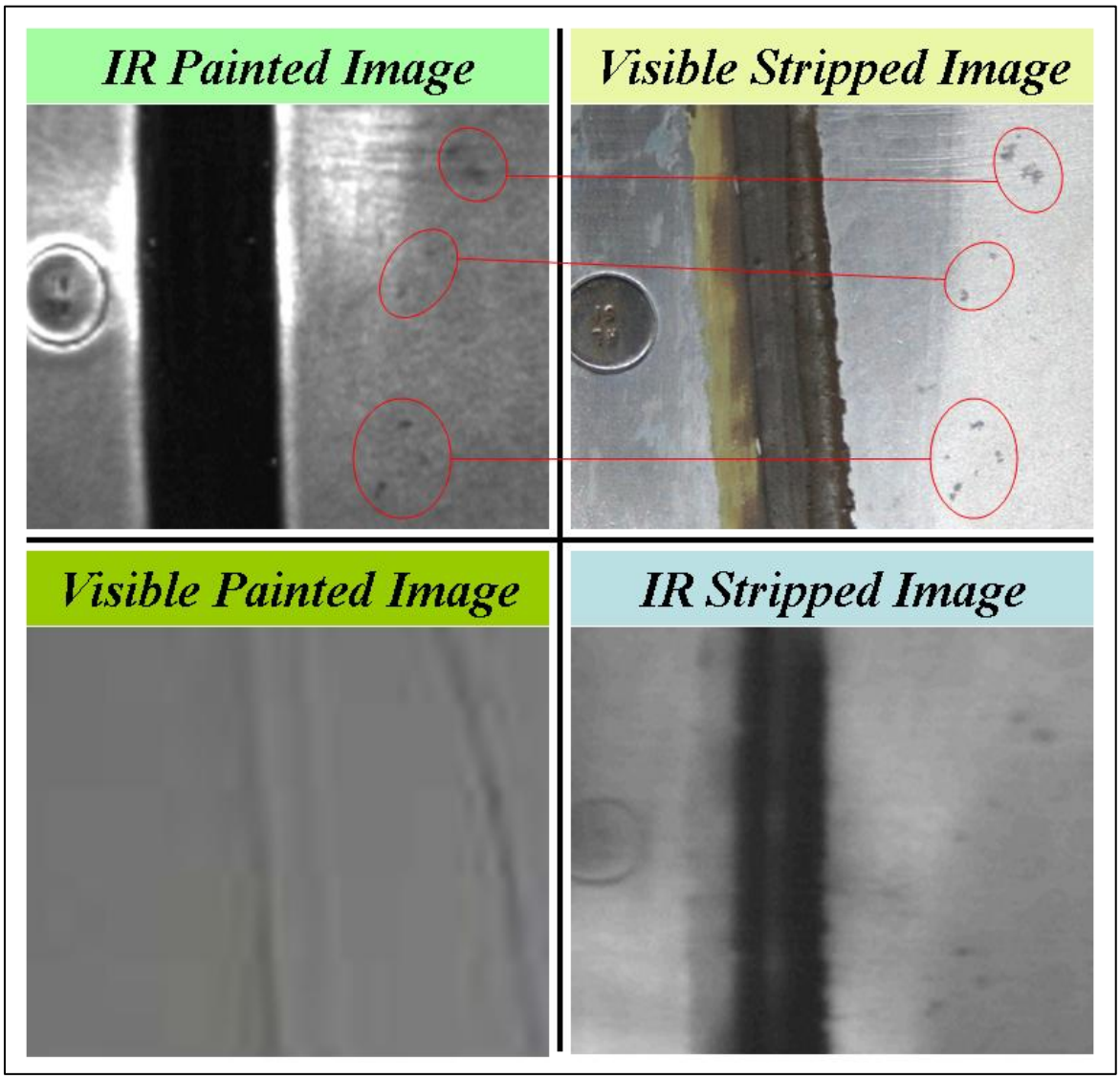


Figure 4-1: P-3 Tail #912 (Wing Section) - IR Image

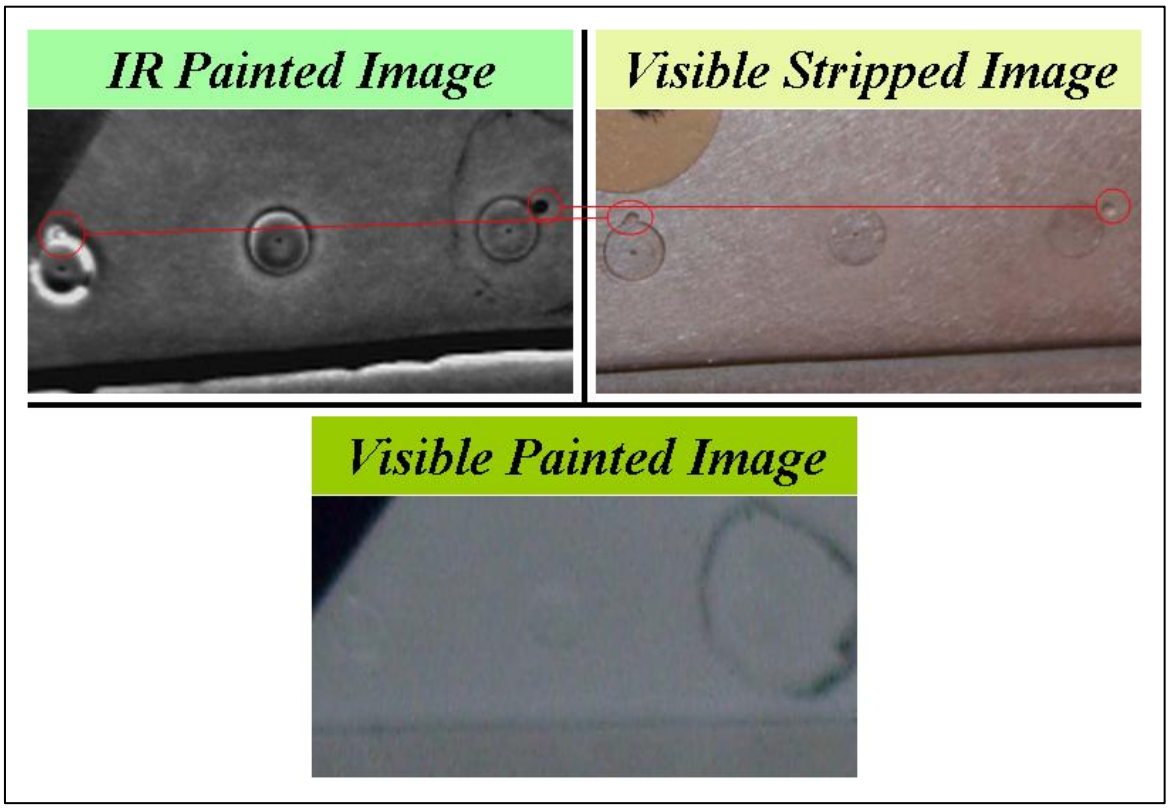


Figure 4-2: P-3 Tail #912 (Fuselage Section) - IR Image

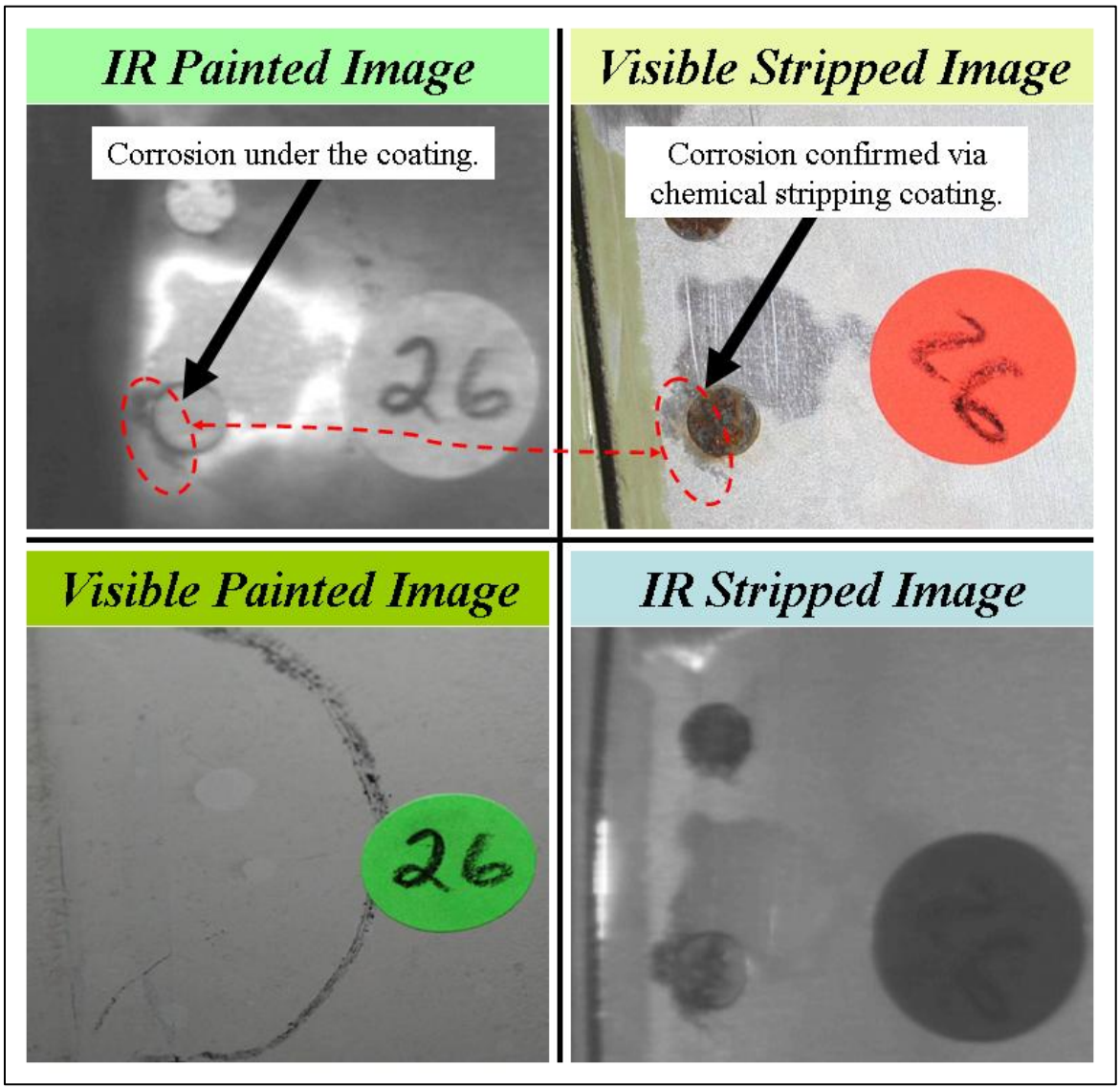


Figure 4-3: P-3 Tail #772 (Wing Section) - IR Image

Figure 4-4 illustrates the corrosion locations that were identified during the Navy P-3 (Tail #772, BUNO 162772) Dem/Val. The note within the figure defines the corrosion location and what method they were found and documented.

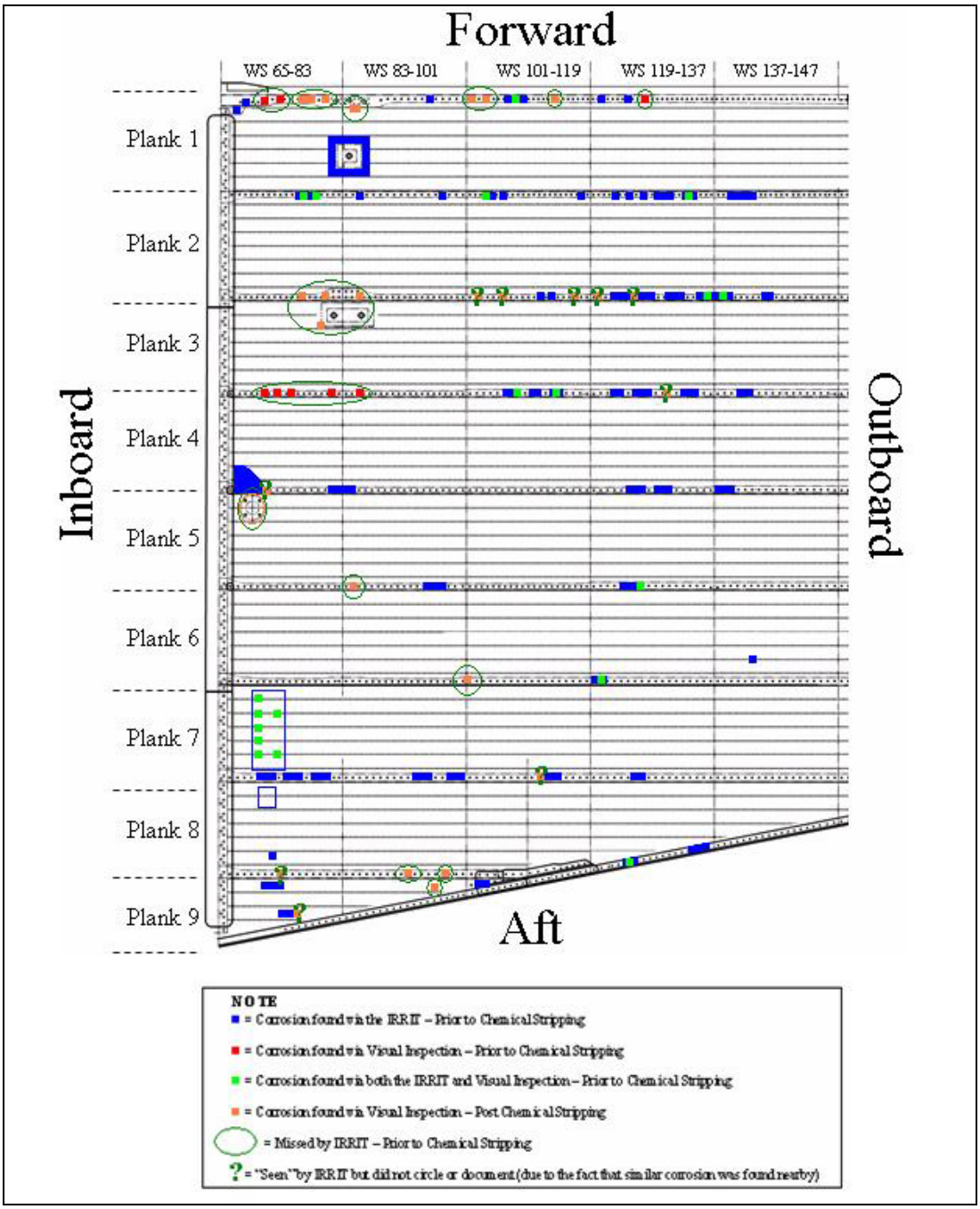


Figure 4-4: Navy P-3 OML Wing Section Corrosion Location Identification

4.3.2 Corrosion Inspection Comparison – OC-ALC, KC-135 and B-52

The USAF KC-135 and B-52 IML Dem/Val included inspection of 5 aircraft, encompassing 3 KC-135s and 2 B-52s. During this Dem/Val various data points were acquired, including coating thickness, air (ambient) temperature, aircraft skin/surface temperature, visible images and IR images/video (refer to Table 4-8 and Table 4-9). The above data points are discussed in detail in Section 4.3.1.

During this Dem/Val suspected corrosion with the IRRIT system was identified, and the corrosion was confirmed by localized paint stripping and visual inspection. The inspection areas in the KC-135 were the fuselage IML (refer to Figure 3-13), wing to fuselage carry-through fittings (refer to Figure 3-13), while the B-52 were truss-shaped longerons in the bomb bay (refer to Figure 3-14). Following IRRIT inspection, the suspected corrosion areas were marked and stripped of paint to allow visual inspection. The visual and IRRIT inspections were compared to determine the performance of the IRRIT inspection. In general, the KC-135s and B-52s did not produce a large number of corrosion locations, and of those found, some were either false positives or were superficial corrosion that was removed during the stripping process (refer to Table 4-7 and Table 4-9).

Table 4-7: Inspection Error Contributing Factors (IML)

Error	Type of Error/Failure	Description
#1	Operator and System Failure	False Positive - Location incorrectly identified as corrosion through coating. In the case of the KC-135, the false positive was due to surface contamination (refer to Figure 4-7)
#2	Dem/Val Procedural Error	Location identified (by IRRIT) as corrosion could not be validated during post strip analysis. In the case of the B-52, the coating removal process included mechanical measures, which may have resulted in inadvertently removing corrosion product (s) (refer to Table 4-9).

During the IRRIT inspection on KC-135 #1, 6 locations were marked to be stripped. Out of these 6 locations, 4 were identified as corrosion and the remaining 2 were identified as spot welds. After chemically stripping the primer, 2 out of the 4 were correctly identified as being corrosion by the IRRIT inspection. The 2 locations that were falsely identified by the IRRIT inspection, turned out to be a visually transparent "waxy substance" on the surface of the primer (see Figure 4-7). Even though this "waxy substance" was visually transparent and could not be seen, it was not transparent in the IR, and thus was confused to be corrosion. Future IRRIT inspections will have to include thoroughly cleaning the surface prior to inspection. The 2 locations that were identified by the IRRIT as spots welds were confirmed via the chemical stripping (see Figure 4-8).

KC-135 #2 during the IRRIT inspection appeared corrosion-free. The entirety of the main cargo door interior surface was inspected in approximately half an hour, with only one suspect corrosion location identified. Bulkheads were also examined with only one more corrosion location identified. Due to the success on B-52 #1 and scheduling pressures, a visual inspection was not conducted on KC-135 #2.

The purpose of the IRRIT inspection on KC-135 #3 was to demonstrate the utility of the new-model IRRIT camera (MilCam) for inspecting the wing spar. This entailed working in a tight space that had prevented IRRIT inspection with the Merlin® MWIR camera. In addition, a technology demonstration was performed for Navy E-6 field engineers located at OC-ALC.

Figure 4-5: MilCam used at OC-ALC

Inspection of B-52 #1's bomb bay longerons yielded a few suspected corrosion locations during IRRIT inspection. Eight corrosion locations were identified. After being stripped of paint, 7 proved to be corrosion. It is suspected that the corrosion was so minor on one of the locations that it was removed during the chemical stripping process.

IRRIT inspection of B-52 #2 revealed 2 suspect corrosion locations on the longerons. Subsequent stripping and inspection showed corrosion at one location. It is suspect that the corrosion was so minor on the other location that it was removed during the chemical stripping process.

The IRRIT inspection process performed acceptably on the B-52 IML with no significant inspection performance impacts due to complex geometry (found in KC-135 IML). Based on the IML Dem/Val results, future IRRIT inspections will require the removal (dry-wiping) of surface contamination, known to be problematic in IR (i.e., dirt, dust, oil, grease, etc.), prior to inspection (refer to Figure 4-7). Early detection of corrosion allows the user to minimize or prevent structural damage and pollution prevention through the use of the IRRIT (refer to Figure 3-4). IRRIT inspection process provides improved sensitivity for detection of surface corrosion as compared to standard eddy current and visual inspection methods utilized at OC-ALC (refer to Figure 4-6).

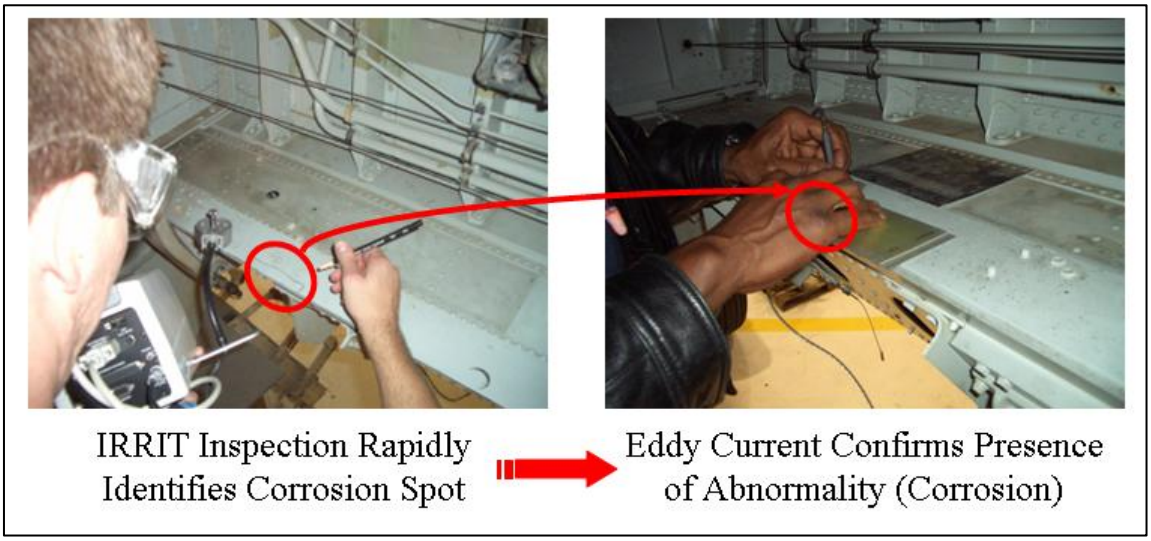


Figure 4-6: IRRIT versus Eddy Current

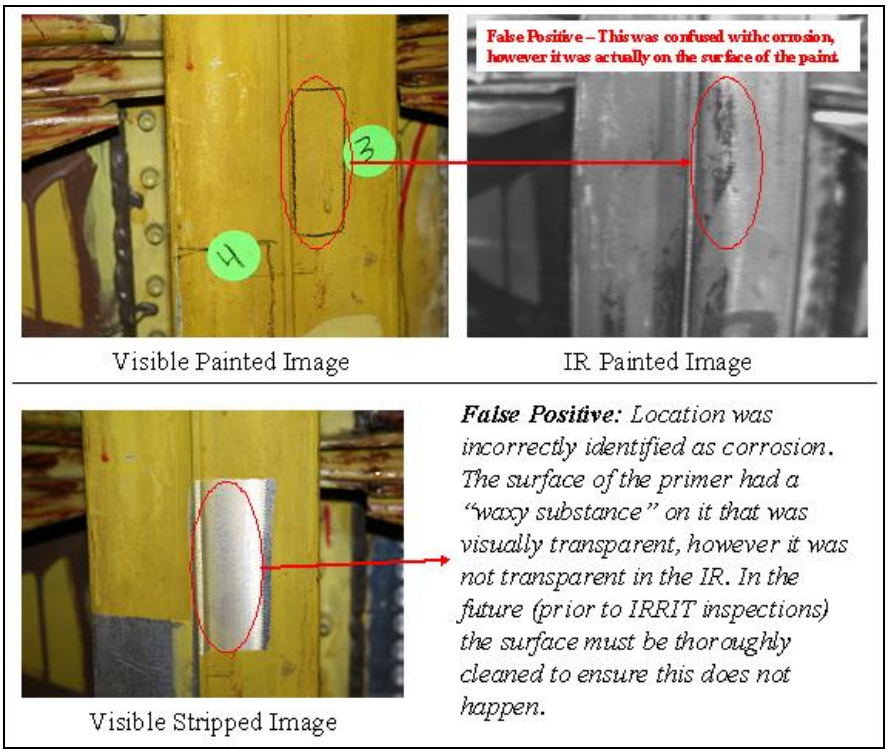


Figure 4-7: False Positive – Location Incorrectly Identified as Corrosion by IRRIT

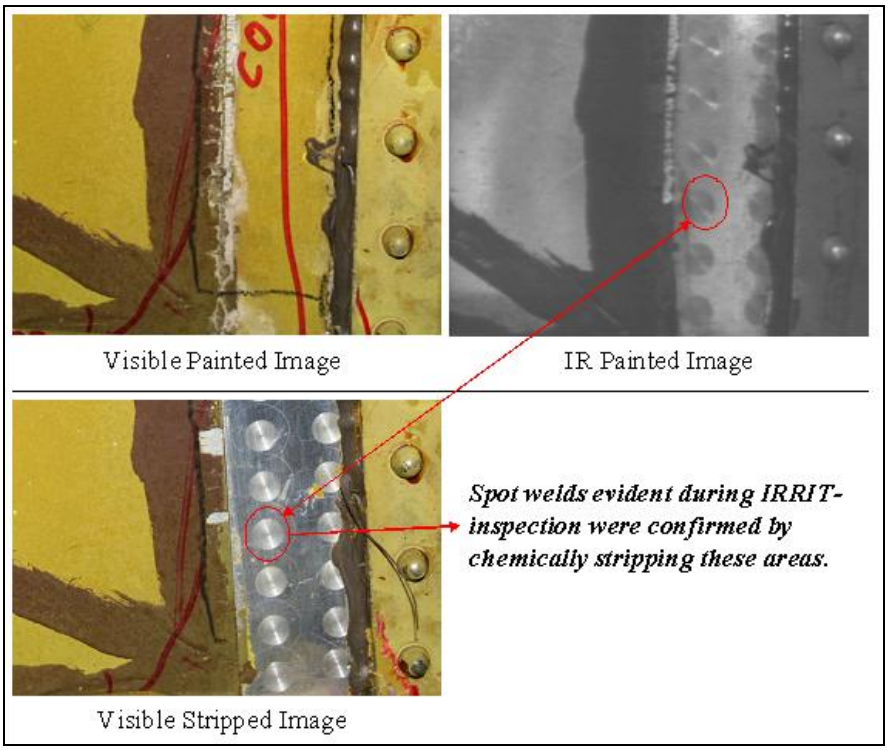


Figure 4-8: Spot welds evident via IRRIT inspection

Table 4-8: USAF KC-135 and B-52 IML Dem/Val Data Points Acquired (Raw Data)

KC-135 #1	Primer						
	KC-135 IML Location	Paint Thickness Measurements	Air Temperature Measurements	Aircraft Skin Temperature Measurements	Visible Photos	IR Photos	Date Data Acquired
	Bulkheads	6 Measurements (AVG = 0.95 mils)	0 Measurements (AVG = N/A)	2 Measurements (AVG = 71.5°F)	19 Images	31 Images	10/23/2006
	Post Selected Spot Chemical Stripping						
	KC-135 IML Location	Paint Thickness Measurements	Air Temperature Measurements	Aircraft Skin Temperature Measurements	Visible Photos	IR Photos	Date Data Acquired
	Bulkheads	*Not Required*	0 Measurements (AVG = N/A)	0 Measurements (AVG = N/A)	22 Images	9 Images	10/24/2006
KC-135 #2	Primer						
	KC-135 IML Location	Paint Thickness Measurements	Air Temperature Measurements	Aircraft Skin Temperature Measurements	Visible Photos	IR Photos	Date Data Acquired
	Cargo Door	11 Measurements (AVG = 1.31 mils)	4 Measurements (AVG = 75.2°F)	5 Measurements (AVG = 75.9°F)	10 Images	5 Images	10/25/2006
KC-135 #3	Primer						
	KC-135 IML Location	Paint Thickness Measurements	Air Temperature Measurements	Aircraft Skin Temperature Measurements	Visible Photos	IR Photos	Date Data Acquired
	Port Wing Spar	*NO MEASUREMENTS TAKEN – Purpose of IRRIT inspection was to show capability of the system in tight spaces.*					10/26/2006
B-52 #1	Primer + Topcoat						
	B-52 IML Location	Paint Thickness Measurements	Air Temperature Measurements	Aircraft Skin Temperature Measurements	Visible Photos	IR Photos	Date Data Acquired
	Longerons	6 Measurements (AVG = 1.57 mils)	1 Measurement (AVG = 67°F)	3 Measurements (AVG = 67.1°F)	21 Images	17 Images	10/24/2006
	Post Selected Spot Chemical Stripping						
	B-52 IML Location	Paint Thickness Measurements	Air Temperature Measurements	Aircraft Skin Temperature Measurements	Visible Photos	IR Photos	Date Data Acquired
	Longerons	*Not Required*	0 Measurements (AVG = N/A)	0 Measurements (AVG = N/A)	10 Images	21 Images	10/25/2006
B-52 #2	Primer + Topcoat						
	B-52 IML Location	Paint Thickness Measurements	Air Temperature Measurements	Aircraft Skin Temperature Measurements	Visible Photos	IR Photos	Date Data Acquired
	Longerons	7 Measurements (AVG = 3.39 mils)	1 Measurement (AVG = 70°F)	4 Measurements (AVG = 71°F)	11 Images	10 Images	10/25/2006
	Post Selected Spot Chemical Stripping						
	B-52 IML Location	Paint Thickness Measurements	Air Temperature Measurements	Aircraft Skin Temperature Measurements	Visible Photos	IR Photos	Date Data Acquired
	Longerons	*Not Required*	0 Measurements (AVG = N/A)	0 Measurements (AVG = N/A)	10 Images	12 Images	10/26/2006

Table 4-9: USAF KC-135 and B-52 IML Real-Time Results

KC-135 #1	Real-Time Results (KC-135 IML Bulkhead)					
	Inspection Technique	Suspected Areas of Corrosion	False Positives	Misses	Confirmed Corrosion Sites	% Accuracy
	Visual Inspection Results	*No visual corrosion sites confirmed.*				
	IRRIT Inspection Results	4	2	*	2	**
KC-135 #2	Real-Time Results (KC-135 IML Cargo Door)					
	Inspection Technique	Suspected Areas of Corrosion	False Positives	Misses	Confirmed Corrosion Sites	% Accuracy
	Visual Inspection Results	*No visual corrosion sites confirmed.*				
	IRRIT Inspection Results	1	*Unknown – No selective spot stripping occurred.*			
KC-135 #3	Real-Time Results (KC-135 IML Port Wing Spar)					
	Inspection Technique	Suspected Areas of Corrosion	False Positives	Misses	Confirmed Corrosion Sites	% Accuracy
	Visual Inspection Results	*NO MEASUREMENTS TAKEN –*				
	IRRIT Inspection Results	*Purpose of IRRIT inspection was to show capability of the system in tight spaces.*				
B-52 #1	Real-Time Results (B-52 IML Longerons)					
	Inspection Technique	Suspected Areas of Corrosion	False Positives	Misses	Confirmed Corrosion Sites	% Accuracy
	Visual Inspection Results	*No visual corrosion sites confirmed.*				
	IRRIT Inspection Results	8	1***	*	7	**
B-52 #2	Real-Time Results (B-52 IML Longerons)					
	Inspection Technique	Suspected Areas of Corrosion	False Positives	Misses	Confirmed Corrosion Sites	% Accuracy
	Visual Inspection Results	*No visual corrosion sites confirmed.*				
	IRRIT Inspection Results	2	1***	*	1	**

Notes:
* = Due to the fact that selective spot stripping occurred (only for locations that were identified by the IRRIT as having corrosion beneath the coating), it is impossible to know if any other corrosion locations were missed.
** = Cannot determine accuracy solely based on spot stripping, because it is unknown whether or not corrosion was missed in areas that were not stripped.
*** = Corrosion may have been removed by stripping process, mechanical abrasion may have occurred.

Table 4-10 below illustrates the IRRIT scan rates of the USAF KC-135 and B-52 IML Dem/Val. The total average scan rate was 132 ft²/hour. During the Dem/Val process the scan rate improves as the experience in IRRIT operation and procedures are refined. The Dem/Val process required extensive documentation which reduced the scan rate. Typical field operation of the IRRIT inspection would not require this level of documentation.

Table 4-10: USAF KC-135 and B-52 Dem/Val IRRIT Scan Rates

KC-135 #1	Primer	
	KC-135 IML Location	Scan Rate
	Bulkheads	133 ft²/hour
KC-135 #2	Primer	
	KC-135 IML Location	Scan Rate
	Cargo Door	150 ft²/hour
KC-135 #3	Primer	
	KC-135 IML Location	Scan Rate
	Port Wing Spar	*NO MEASUREMENTS TAKEN – Purpose of IRRIT inspection was to demonstrate capability of the system in areas of limited access.*
B-52 #1	Primer + Topcoat	
	B-52 IML Location	Scan Rate
	Longerons	108 ft²/hour
B-52 #2	Primer + Topcoat	
	B-52 IML Location	Scan Rate
	Longerons	135 ft²/hour

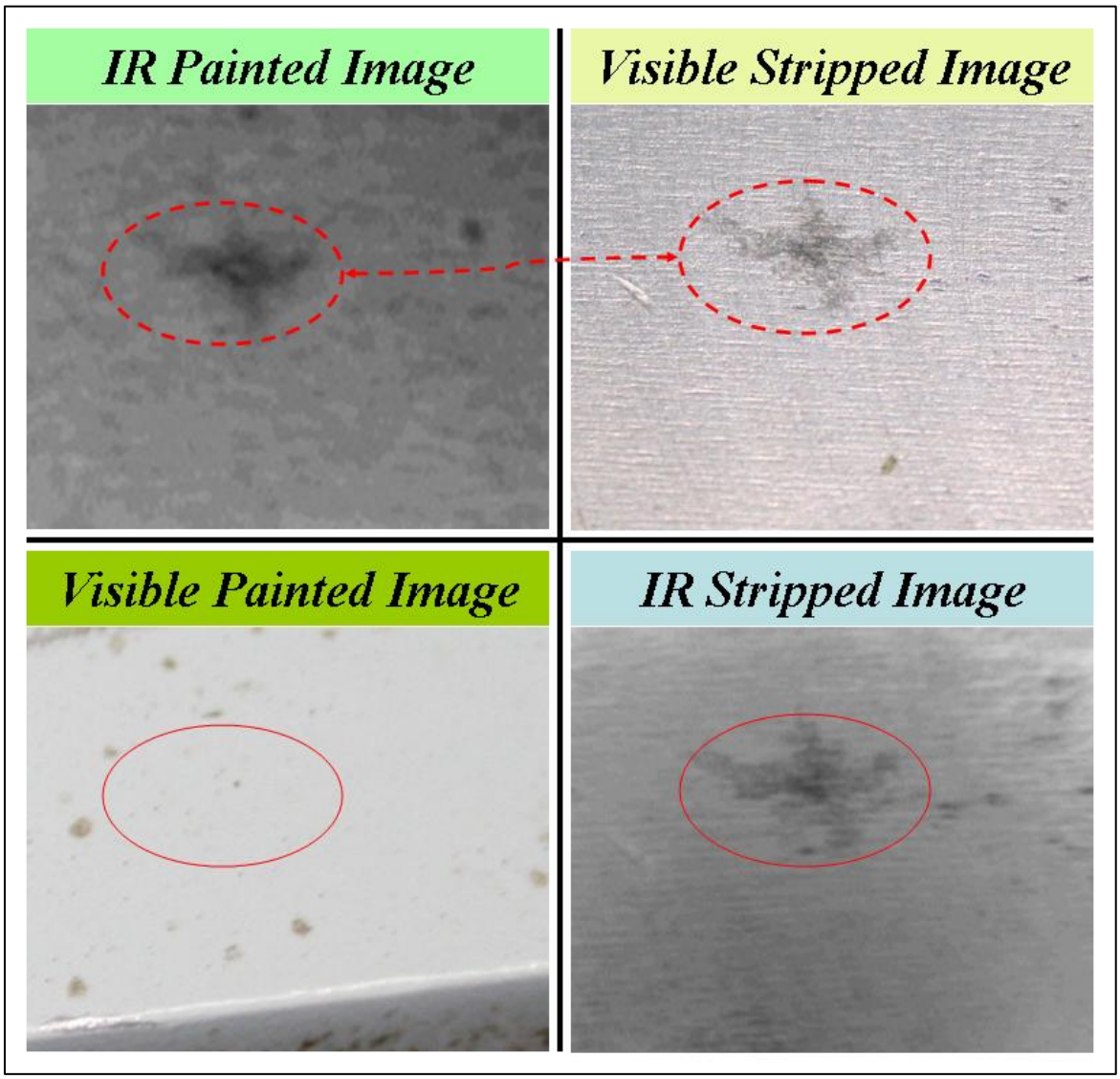


Figure 4-9: B-52 #1 (Longeron Section) - IR Image

4.3.3 Summation of Dem/Val Results

Figure 4-10 illustrates the high level of accuracy of the IRRIT inspection method (79%, 80%, and 86% Post-Processing IRRIT) as compared to the visual inspection method (5%, 7%, and 25% Real-Time Visible), during the Navy P-3 OML Dem/Val. The IRRIT inspection identified three times (3X) the amount of corrosion located by visual inspection. The IRRIT as compared to the visual inspection method allows for post-processing the images after the inspection, which can assist the identification of corrosion present but not observed during the real-time inspection. Probable IRRIT inspection errors can be found in Table 4-3.

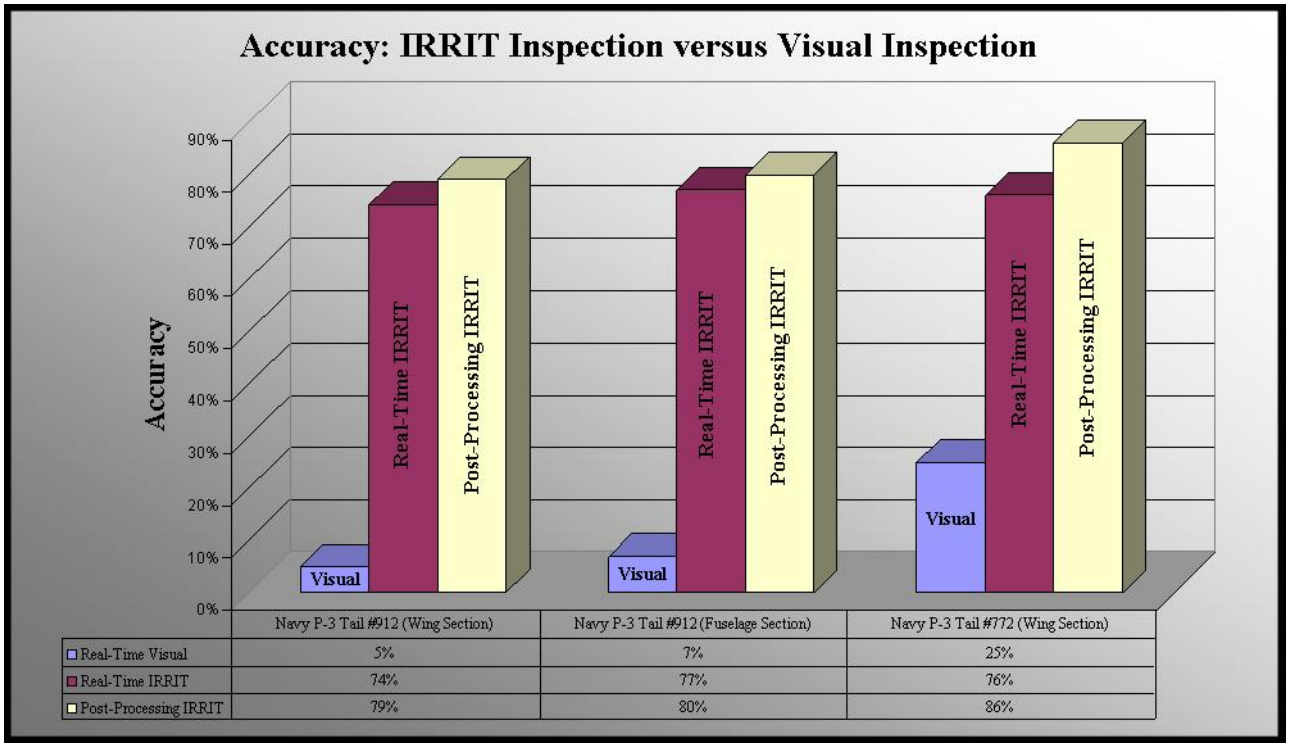


Figure 4-10: Navy P-3 OML - Accuracy of IRRIT Inspection versus Visual Inspection

Figure 4-11 illustrates the high level of accuracy of the IRRIT inspection (50%, 88%, and 50%) method as compared to the visual inspection method (0%, no corrosion visually noted), during the USAF KC-135 and B-52 IML Dem/Val. During this Dem/Val the inspected aircraft had low levels of corrosion, thus reducing the data set that was recorded. No corrosion was detected via visual inspection, whereas IRRIT successfully identified several corrosion locations. Probable IRRIT inspection errors can be found in Table 4-7.

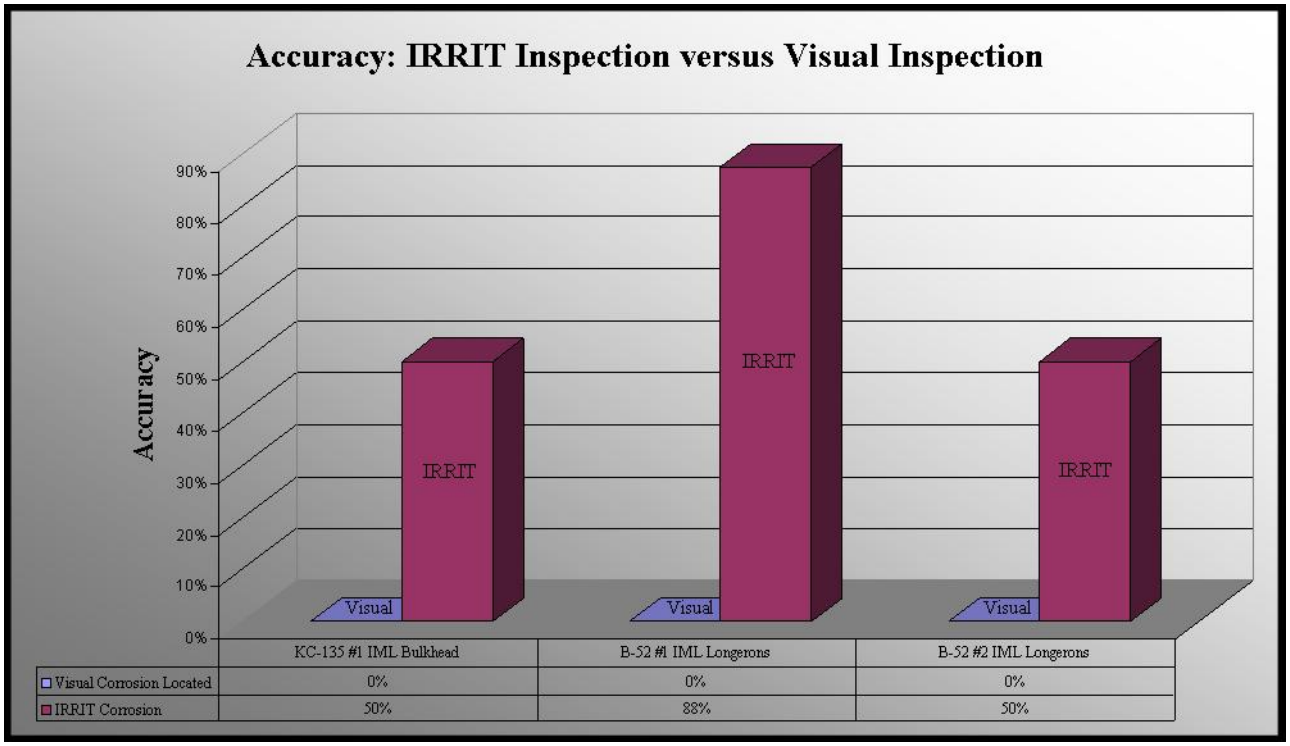


Figure 4-11: KC-135/B-52 IML - Accuracy of IRRIT Inspection versus Visual Inspection

Figure 4-12 illustrates the average level of detection, comparing visual inspection versus IRRIT inspection. This is a weighted average, where all corrosion sites where weighted equally for both OML and IML Dem/Vals. This chart illustrates the high level of accuracy of the IRRIT inspection method as compared to the visual inspection method. In total (including OML and IML Dem/Vals) there were 352 corrosion sites. The IRRIT found 287 corrosion sites out of the 352, equaling 82% accuracy. Visual inspection found 42 corrosion sites out of the 352, equaling 12% accuracy.

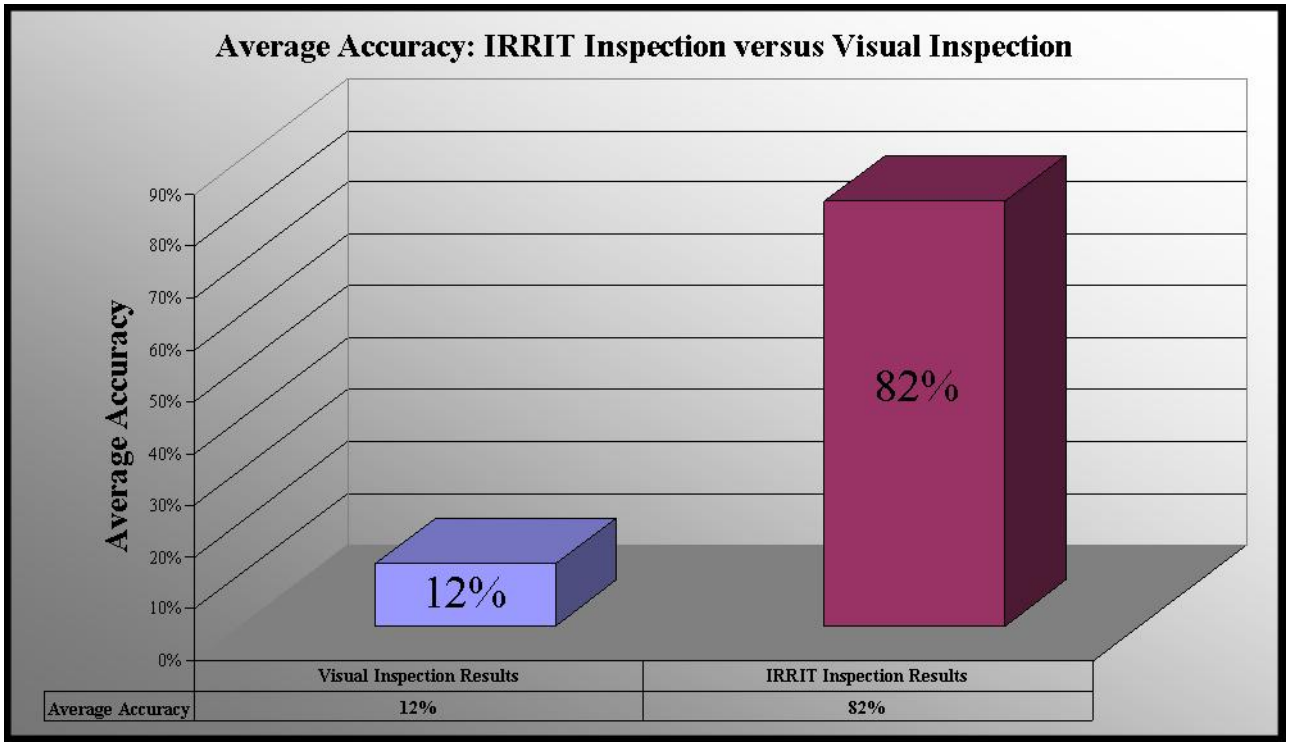


Figure 4-12: Average Accuracy of IRRIT Inspection versus Visual Inspection

It was found during demonstration and validation testing that the contributing factor for such a large deviation of inspection results between visual and IRRIT was due to the detection methods utilized for each technique. The IRRIT method directly images corrosion by-product through the paint system due to reflectance contrast differences of the substrate. The visual method relies upon the identification of paint surface irregularities/blistering (i.e., paint degradation) as a result of substrate volume changes associated with corrosion formation.

5. COST ASSESSMENT

As discussed in previous sections, the IRRIT system was demonstrated on both OML and IML applications. Potential economic and environmental savings from use of the IRRIT arise largely from the opportunity to reduce coating removal and repaint activities. However, it should be emphasized that the IRRIT is an inspection tool that may identify reduction opportunities but does not change the extent of corrosion on an aircraft or improve the performance of its coating system. The primary function of the IRRIT is to increase user knowledge of the real condition of the substrate, enabling engineering disposition to occur with greater confidence.

When the regular maintenance cycle and maintenance costs are known, potential savings from reduced maintenance can be projected. The other source of potential economic savings is that early detection and treatment of corrosion to reduce structural damage could aid in extending the over-all service life of affected aircraft and minimize the magnitude of corrosion repair. However, the degree to which the IRRIT could create potential savings from increased service life is difficult to quantify without program specific understanding of corrosion history for the particular weapon system.

In aviation-related maintenance, decision-making on when or whether corrosion treatment and/or coating repair should occur is based primarily on expert knowledge. There is no standardized formula across aircraft programs where 'x' corrosion locations indicate that the surface must be stripped and treated while 'y' corrosion locations indicates that the surface can be treated with lesser measures. Instead it is a qualitative evaluation guided by experience and multiple considerations of coating condition, past coating performance, current corrosion, the service conditions under which the aircraft is expected to operate, and many other factors. As seen in Section 4.3, during the Dem/Vals the IRRIT system showed on average a three times (3X) or greater improvement over visual inspection techniques.

The regular strip and repaint of the Navy P-3 OML, has been used as a baseline process against which to measure potential alternate processes made possible by use of data gathered by the IRRIT. For these purposes, the P-3, with an OML surface area of 6500 square feet, is considered a "medium sized aircraft" and can be used as a broad approximate for other medium sized aircraft. Approximately every four years each P-3 is completely stripped of paint using a chemical stripping agent and then repainted. One cost analysis scenario for the IRRIT is a transition to condition-based maintenance. In condition-based maintenance, aircraft are assessed and treated to varying maintenance procedures, according to the extent of actual corrosion present.

It is also possible that weapon system managers could use the increased confidence granted by the IRRIT to extend the maintenance interval between strip and repaint events. A scenario was considered where it was assumed the improved information and user confidence provided by the camera allows a lasting change to aircraft maintenance cycles. This demonstrates the potential impact of even a one year shift to the maintenance cycles. This is an example of potential savings if increased user confidence

provided by the IRRIT can be translated into a less conservative maintenance procedure interval.

In IML corrosion inspection processes, the baseline process is less clear. For both the KC-135 and the B-52 aircraft, the IML is not stripped and repainted as a matter of routine during each maintenance cycle. Instead there are two scenarios when the IML may be partially stripped. In the first, a visual (and for some critical areas, NDI) inspection is carried out when an aircraft enters depot maintenance. Detected corrosion is then treated on an as-needed basis. This occurs in the KC-135, when during the regular maintenance cycle support bulkheads within the cargo area are inspected for signs of weakening, fracture, and/or corrosion.

In the second, a "one time order" may require that all aircraft of a particular model have a specific IML location stripped during their maintenance cycle, in order to gather information on substrate condition in that area. This recently occurred on the B-52, when each B-52 in the fleet had its bomb bay longerons stripped for inspection and then repainted. The longerons are not scheduled to be stripped a second time on subsequent maintenance cycles.

The potential impact of the IRRIT on IML maintenance work is difficult to quantify due to the lack of regular strip and repaint activity on the surveyed aircraft IML areas. Accordingly, this cost assessment will focus on the potential impact of the IRRIT on the OML maintenance work, using the P-3 data as a baseline. Potential savings from use of the IRRIT on aircraft IMLs will be discussed in Section 5.2.7.

5.1 Cost Reporting

An economic analysis was conducted using the Environmental Cost Analysis Methodology (ECAM^{SM}) cost estimating tool, comparing the current chemical depainting process of aircraft that is performed at NAVAIR Jacksonville on the P-3 aircraft (Baseline Scenario) to potential savings from purchase and use of an IRRIT system. The objective of the cost assessment is to provide cost analysis information, such as yearly savings, net present value, and payback period, for use alongside other information (e.g., performance data) to make decisions about implementation of the IRRIT system. The ECAM^{SM} methodology was used to perform this analysis to the level necessary to ensure the following types of information were included:

- Direct process costs, (e.g., labor, materials);
- Indirect costs (e.g., hazardous waste management and disposal); and
- Other cost data (e.g., data related to the maintenance interval that impacts costs).

The baseline process involves maintenance activities performed at NAVAIR Jacksonville in which each P-3 aircraft is completely stripped and repainted approximately every four years. The alternatives below are general models that use available real world data but do not directly describe a particular weapon system.

Condition-based Maintenance scenario involves changing maintenance from the baseline approach of stripping 100% of every aircraft to one where several alternative maintenance options are available based on condition of the aircraft. These options may require a smaller surface area of the aircraft to be stripped and/or repainted. Use of the IRRIT is required, because currently a pre-strip visual-based inspection method would not provide accurate enough information on aircraft condition.

Maintenance Cycle Extension scenario involves changing the baseline stripping/repainting maintenance from its current interval to adding an additional +1, +2, +3, or +4 years to the maintenance cycle.

To understand the cost data for these usage scenarios, it is first important to outline them in detail. This is done in Sections 5.1.1, 5.1.2, and 5.2.3.

5.1.1 Baseline Maintenance Procedure

Currently, P-3 aircraft undergo paint strip, corrosion treatment, and repaint at NAVAIR Jacksonville. The baseline chemical stripping and repainting process of P-3 aircraft evaluated for this report was broken down into three basic steps that are generally repeated every four years for each aircraft. Approximately 25 P-3 aircraft are processed in this manner each year. As illustrated in Figure 5-1, each step generates air emissions and wastes.

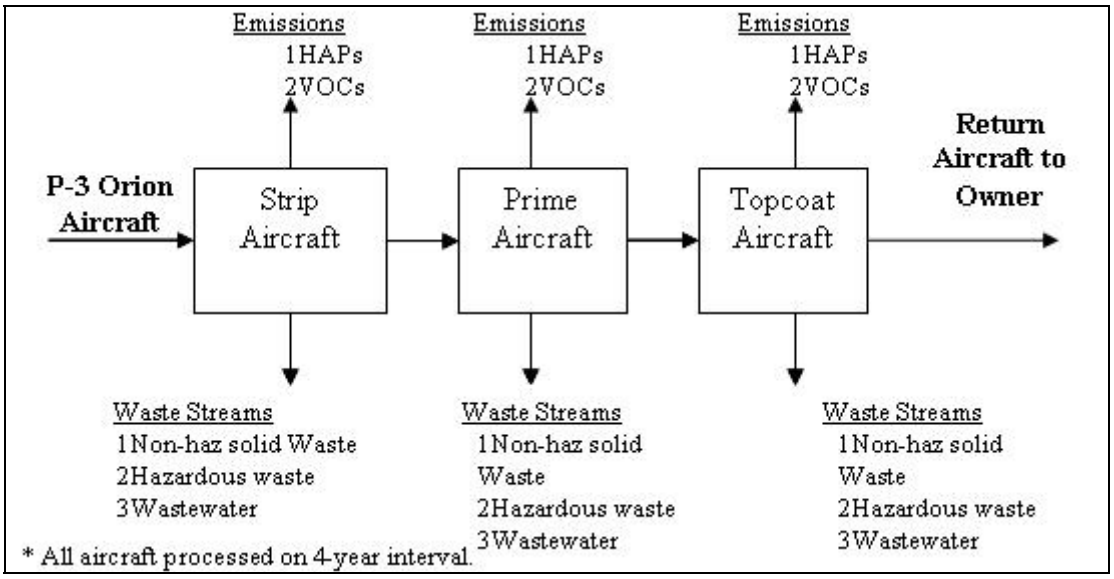


Figure 5-1: Baseline Maintenance Process

In the first step, the aircraft is brought into the strip hanger, where it is secured, stripped of paint using a chemical agent, and surface corrosion is treated. In the second and third steps, the aircraft is taken to the paint hanger where the entire surface area is primed and repainted. Significant costs for the baseline procedure include:

- Labor;
- Materials;
- Utilities; and
- Environmental, Health, and Safety (EHS).

The costs for the baseline maintenance process will be broken out in detail in Section 5.2.

5.1.2 Alternative Scenario Description: Condition-Based Maintenance

In the condition based maintenance alternative scenario, it is assumed that when an aircraft enters the depot on its regular maintenance cycle, the IRRIT system is used to perform inspections to assess the actual amount of corrosion present on the aircraft. This inspection is planned to occur during what is currently aircraft non-active wait time, rather than on a critical path. Overall process flow would therefore not be affected. Rather than the baseline scenario, where all P-3 aircraft are treated identically, condition-based maintenance calls for one of four possible maintenance options. One of the following options would be ordered by a qualified inspector based on the results of the IRRIT inspection findings:

- **Full Strip** – This is the same as the baseline process, with the exception of an expanded inspection procedure. In a condition-based scenario, full-strip will be used whenever over 30% of the aircraft shows signs of corrosion heavy enough to require stripping to treat.

- **Scuff/Sand/Overcoat** – In this procedure, intended for aircraft where corrosion is relatively minor over less than 30% of the aircraft, only selected corroded areas are scuffed and sanded to access the corroded portions of the aircraft substrate. These areas are then treated. For the purposes of the cost analysis, it is assumed that the area treated will constitute 25% of the surface area on average. The entire aircraft is then primed, and painted with topcoat in accordance with normal procedures.

- **Selected Strip** – This option is intended for aircraft that exhibit heavy corrosion that is limited less than 30% of the surface area. Only the heavily corroded areas of the aircraft are stripped. For the purposes of the cost analysis, it is assumed that the area treated will constitute 25% of the surface area on average. The selected area is stripped, treated for corrosion, and then the entire aircraft is primed and painted with topcoat in accordance with normal procedures.

- **Spot Repair** – In this procedure, intended for aircraft where the corrosion is minor, the aircraft is not stripped. Unlike the scuff/sand/overcoat procedure, no large areas of the aircraft are scuffed to expose substrate. Instead individual spots/locations where corrosion is detected are treated. These areas are expected to be present over less than 15% of surface area of the aircraft and, for the purposes of the cost analysis, are assumed to constitute 15% of the aircraft surface

area. Unlike the other maintenance procedures, only the treated areas of the aircraft are repainted.

The percentages of the baseline strip and repaint process required by each of the alternative maintenance procedures are illustrated in Figure 5-2 below.

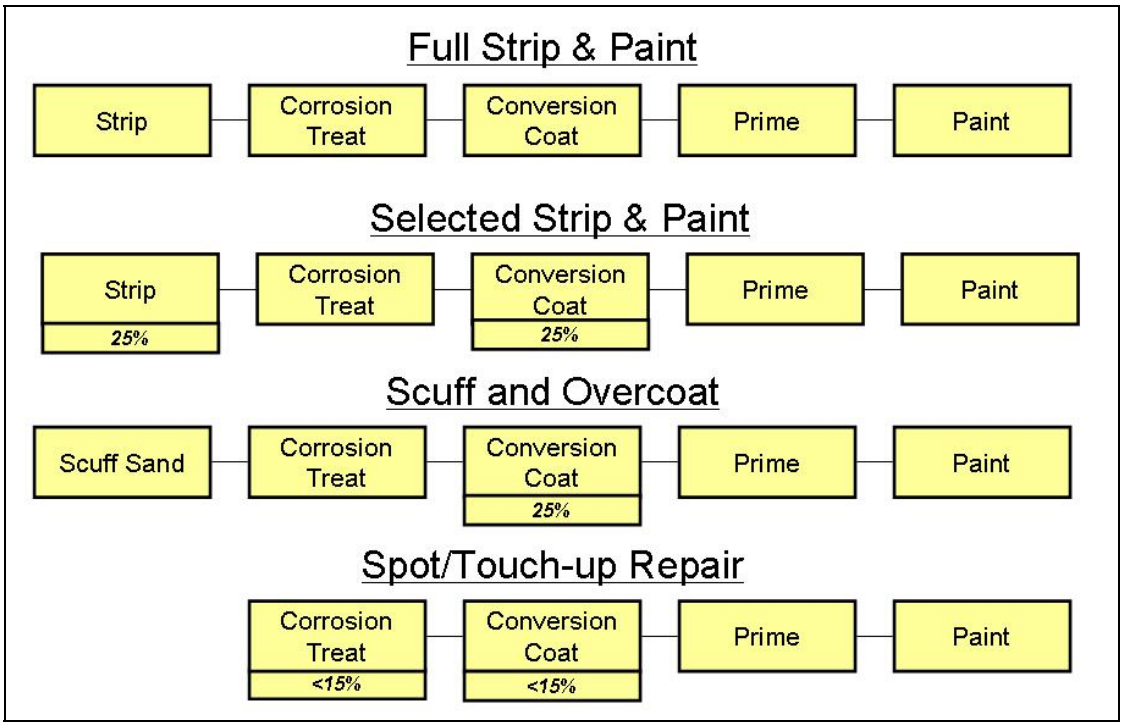


Figure 5-2: Percentage of Baseline Labor and Materials Used in Alternatives

Historical data for condition-based maintenance on the H-53 aircraft was obtained from Marine Corps Air Depot– Cherry Point (MCAD Cherry Point). The H-53 is deployed in environments as harsh as or harsher than the P-3. Therefore, the H-53 data was used to estimate the percentage and total numbers of medium sized aircraft that would pass through each of the maintenance options on a yearly basis. Table 5-1, below, illustrates these estimated percentages and numbers of aircraft using the P-3 fleet as a baseline.

Table 5-1: Estimated % of A/C Directed Through Four Condition-Based Maintenance Options

Maintenance Option	Population Distribution	Aircraft Processed Assuming 25 Aircraft per Year
Full Strip	50%	12.5*
Scuff/Sand/Overcoat	40%	10
Selected Strip	5%	1.25*
Spot Repair	5%	1.25*

*Numbers remain fractional for purpose of average value per year calculation.

All of the condition-based maintenance scenarios other than full strip are less costly than a full strip. Therefore condition-based maintenance could lead to a cost savings if the reduction from conducting procedures other than full-strip are greater than the capital and labor costs of inspecting each aircraft using the IRRIT system.

5.1.3 Maintenance Cycle Extension Scenario

It is assumed that the only change to the baseline maintenance activities under this scenario will be the interval shift between stripping and repainting events. All other maintenance activities will remain the same for the purpose of this scenario.

5.1.3.1 Current Method for Maintenance Period Determination

Because of the importance of preventing corrosion damage, aircraft strip and repaint schedules are determined through a survey of a significant portion of the fleet in the field by the weapons system engineer. NDI methods currently available for these inspections are not fast or portable enough to inspect a significant portion of each aircraft's surface area, leaving the inspecting engineer(s) only the option of a visual inspection. Pre-strip, this visual inspection can only identify corrosion that has progressed sufficiently to cause peeling or flaking of the aircraft topcoat. Consequently, strip-and-repaint maintenance schedules are determined on an extremely conservative basis, as it is difficult to track the speed, frequency, and nature with which corrosion is forming underneath topcoat.

In coatings with a long history of implementation, this disadvantage can be overcome by the cumulative experience over many years of inspecting aircraft as they are stripped. However, a number of new coatings designed for longer wear life and improved durability are being tested and/or implemented by the Navy and other service branches. Without a history of observation to fall back on, strip and repaint cycles must be estimated more conservatively.

5.1.3.2 Potential Influence of IRRIT System on Maintenance Cycle

The IRRIT system represents a unique opportunity to collect more accurate corrosion data for the purposes of determining strip and repaint maintenance intervals. While this technique could potentially be used on most aircraft models, this scenario examines the potential costs and benefits of using information and experience gained from use of the IRRIT technology as a decision-making tool in extending the maintenance interval of a medium sized aircraft fleet. The following process assumptions were made:

- The IRRIT system is used to collect data that justifies extending the maintenance cycle (i.e., 100% removal of the topcoat) from its current interval (baseline P-3 of 4 years) to either +1, +2, +3, or +4 year periods.
- Inspections utilizing an ergonomically packaged IRRIT system require time and labor on the part of the inspecting engineer comparable to performing a detailed visual inspection.
- Only a single IRRIT system will be required for its use as a decision-making tool.
- No economies of scale will be lost in the reduced number of aircraft stripped per year.

Table 5-2 illustrates the estimated current and future number of aircraft stripped per year for the baseline and calculated based off the baseline for the proposed interval shifts. The baseline throughput quantity was provided by NAVAIR Jacksonville (25 aircraft per year). Throughput quantities for the alternative scenarios were estimated by dividing the current maintenance interval (4 years) by the new maintenance interval (+1, +2, +3, and +4 years), multiplying the result by 25 (current aircraft per year), and rounding up. For example, the calculation for throughput for the +3 year maintenance alternative is as follows:

$$(4 \text{ yrs})/(7 \text{ yrs}) * (25 \text{ aircraft/yr}) = 15 \text{ aircraft/yr}$$

To quantify potential impact to throughput, the numbers of P-3 aircraft stripped per year was divided by the baseline quantity (25 aircraft/yr). This gives the percentage of aircraft stripped per year for the alternative relative to the baseline (the baseline is 100%). For example, assuming a +3 year depainting interval, the following calculation was performed:

$$(15 \text{ aircraft/yr}) / (25 \text{ aircraft/yr}) = 60\%$$

These percentages are also provided in Table 5-2.

Table 5-2: Estimated Annual Quantities of Aircraft Stripped

Depainting Interval	Number of Aircraft Stripped per Year	Percentage of Baseline Aircraft Stripped per year
Baseline Scenario		
4 Years (current)	25	100%
Alternative Scenarios		
+1 Years	20	80%
+2 Years	17	68%
+3 Years	15	60%
+4 Years	13	52%

Fewer aircraft processed per year could result in a reduced annual cost for stripping, corrosion treatment, and repainting.

5.2 Cost Analysis

Cost data that was used for this economic analysis was accumulated throughout the Dem/Val of the P-3 at NAVAIR Jacksonville. Additionally, information on the current P-3 stripping and coating operations was obtained with cooperation from NAVAIR Jacksonville. Costs for the IML scenario described in Section 5.2.8 were based off of P-3 strip and repaint costs.

5.2.1 Cost of Demonstration

There was no significant demonstration cost occurred at the Dem/Val sites because the IRRIT system did not alter the baseline process for the aircraft surveyed and work was conducted on a non-interference basis around the maintenance schedule.

5.2.2 Baseline Cost Analysis

The cost categories considered for the baseline process were labor, materials, utilities, and EHS costs. As no new equipment was required for the baseline process, no capital costs for the baseline were noted. Equipment costs were not included in the baseline because alternate scenarios would only cause some equipment to be used less often, not eliminate it entirely. The cost of stripping and repainting capital equipment therefore remains the same across baseline and alternate scenarios. Additional cost savings might occur due to extension of equipment life, but the analysis will first consider if the scenarios as given show cost savings without factoring in such third tier costs.

Table 5-3, Table 5-4, and Table 5-5 illustrate the data and assumptions used to estimate costs for the baseline process. Table 5-3 illustrates the hours of labor allowed by P-3 work instructions for each step of the strip and repaint process, and converts these labor hours into a dollar value using the baseline labor rate. Table 5-4 illustrates costs of materials and utilities for each aircraft stripped and repainted. Table 5-5 illustrates disposal costs for the hazardous wastes being produced. Table 5-6 illustrates the sum total of all reoccurring costs, Table 5-7 illustrates the VOC emissions produced by each P-3 aircraft processed, and Table 5-8 illustrates the chromate usage.

Table 5-3: Baseline Labor Requirements

Category	Qty.	Units	Source
Labor to chemical strip/ID/treat corrosion	547	hrs/ aircraft	NAVAIR Jacksonville
Labor to prime aircraft	92	hrs/ aircraft	NAVAIR Jacksonville
Labor to paint/seal aircraft	201	hrs/ aircraft	NAVAIR Jacksonville
Labor to paint aircraft	474	hrs/ aircraft	NAVAIR Jacksonville
Sub-Total of labor	**1,314**	**hrs/ aircraft**	**Calculated**
Labor Rate	65.00	$/hr	Generic burdened rate. Not specific to any depot. This rate was calculated using a partially burdened amount to include standard benefits (e.g., medical, vacation).
Cost per Aircraft	**85,397***	**$/ aircraft**	**Calculated**

*Note that quantities were calculated to four decimal places but in table have been rounded to the nearest whole number. This may result in slight discrepancies in sums.

As illustrated in Table 5-3, over 1300 man-hours of labor are required for each P-3 aircraft stripped and repainted. These ours include all secondary required labor such as moving the aircraft from location to location and preparing set up and take down equipment. Using a generic burdened labor rate of 65 dollars per hour the labor cost per aircraft to strip and repaint a P-3 is $85,410. The impact of varying the labor rate is discussed further in Section 5.2.6.

Table 5-4 illustrates the cost of materials and utilities required to strip and repaint a P-3 aircraft.

Table 5-4: Baseline Materials and Utilities Cost Data and Assumptions

Category	Qty	Units	Source
Materials			
Aluminum/Barrier Tape	1,000	$/aircraft	NAVAIR Jacksonville - June 2006
Stripper, De-sealant, Grinder, Solvent, Soap, Bead, and Sanding Disk Material	11,749	$/aircraft	NAVAIR Jacksonville - June 2006
Priming and Sealing Material	4,370	$/aircraft	NAVAIR Jacksonville
Paint	3,614	$/aircraft	Report on P-3 Chemical Strip Materials & Cost Data, authored by T. Cowherd, NAVAIR Jacksonville
Miscellaneous	500	$/ aircraft	Engineering estimate
Total Materials	**21,233***	**$/aircraft**	**Calculated**
Utilities			
Electric/Steam	$1.00	$/hr	Per T. Cowherd report
Production Hours	144	hrs/aircraft	Per T. Cowherd report
Total Utilities	**144**	**$/aircraft**	**Calculated**

*Note that quantities were calculated to four decimal places but in table have been rounded to the nearest whole number. This may result in slight discrepancies in sums.

Table 5-5 illustrates the disposal costs for wastes generated by stripping and repainting a P-3 aircraft. Note that because NAVAIR Jacksonville remains underneath its VOC emissions limits, there is no direct economic cost per unit of individual VOC emission. VOC emissions are therefore considered separately in Table 5-7 from a purely environmental perspective.

Table 5-5: Baseline EHS Cost Data and Assumptions

Category	Qty.	Units	Source of Assumptions
Impact, Alum Mask Tapes per aircraft	600	lbs/ aircraft	Environmental Engineering Office ($1.03/lb disposal)
Glass Bead Media	7,800	lbs/ aircraft	Environmental Engineering Office ($1.03/lb disposal)
Wastewater: Hazardous Waste	114	lbs/ aircraft	Environmental Engineering Office ($1.03/lb disposal)
Subtotal	**8,514**	**lbs/ aircraft**	**Calculated from Tapes, Glass Bead, and Haz. Wastewater**
Subtotal – Disposal Cost	**8,769***	**$/aircraft**	**Calculated from $1.03/lb**
Wastewater: Sludge	1,638	lbs/ aircraft	Environmental Engineering Office ($0.45/lb disposal)
Wastewater: Liquid Waste (Brine)	1,121	lbs/ aircraft	Environmental Engineering Office ($0.45/lb disposal)
Subtotal	**2,759**	**lbs/ aircraft**	**Calculated from Tapes, Glass Bead, and Haz. Wastewater**
Subtotal – Disposal Cost	**1,242***	**$/aircraft**	**Calculated from $0.45/lb**
Wastewater generated requiring treatment	15,000	gal/ aircraft	Environmental Engineering Office ($0.8520/gallon disposal)
Subtotal – Wastewater Disposal Cost	**12,780**	**$/aircraft**	**Calculated from $0.8520/gallon**
VOC Emissions unit cost	$0	$/ton	Due to NAVAIR Jacksonville remaining under its emissions limit, there is no dollar cost
Subtotal (EHS)	**22,791***	**$/aircraft**	**Calculated**
Total lbs hazardous waste generated	**11,273**	**lbs/ aircraft**	**Calculated**

*Note that quantities were calculated to four decimal places but in table have been rounded to the nearest whole number. This may result in slight discrepancies in sums.

Table 5-6 illustrates the total baseline costs of an aircraft strip and repaint per aircraft.

Table 5-6: Total Baseline Strip and Repaint Costs

Category	Qty.	Units	Source of Assumptions
Labor	85,397	$/aircraft	Table 5-3
Materials	21,233	$/aircraft	Table 5-4
Utilities	144	$/aircraft	Table 5-4
EHS	22,791	$/aircraft	Table 5-5
Total	**129,565**	**$/aircraft**	**Calculated**

As can be seen, aircraft strip and repaint is a labor-intensive process, with labor comprising over 60% of the cost per aircraft. EHS costs are also considerable, as many of the hazardous wastes created during the process must be disposed of properly. These costs are incurred each time a P-3 is stripped. If the rate of aircraft being stripped is reduced, or if some are allocated to less intensive corrosion-treatment processes, then there is significant potential for cost savings. This will be discussed further in the alternative scenario cost analyses.

Though not considered as a dollar value, Table 5-7 illustrates the VOC emissions from the painting and stripping materials used. These were calculated from the usage numbers give by NAVAIR Jacksonville and the Material Safety Data Sheet (MSDS) for each material. As illustrated in Table 5-7, the chemical stripper, Turco 6881, is

responsible for the majority of VOCs released during the baseline strip and repaint process.

Table 5-7: Baseline VOC Emissions

Material	VOC (lbs/gallon)	Used/aircraft (gallons)	VOCs/ aircraft (lbs)
Chemical Stripper: Turco 6881	6.38	450	2,873
Primer: MIL-PRF-85582, TY I, Class C1	3.22	40	129
Sealant: AMS 3276	0.29	4.24	1.23
Topcoat: MIL-PRF-85285, TY I	3.31	50	166
Solvent: TT-T-2935	6	42.5	255
Total	**N/A**	**N/A**	**3423***

*Note that quantities were calculated to two decimal places but in the indicated cell have been rounded to the nearest whole number. This may result in slight discrepancies in sums.

In addition to the VOC emissions, the MIL-PRF-85582D Deft primer used on P-3 aircraft contains 0.6 lbs/hexavalent chromium per gallon. Regulatory drivers (see Section 1.3) mandate that used of chromate containing materials be minimized in order to protect against worker exposure. Total pounds of chromate in primer applied to aircraft are illustrated in Table 5-8 below.

Table 5-8: Baseline Chromate Use

Material	Chromates (lbs/gallon)	Used/aircraft (gallons)	Chromate/ aircraft (lbs)
Primer: MIL-PRF-85582, TY I, Class C1	0.6	40	24

In previous tables, costs and emissions have been given per aircraft stripped and repainted. Under the baseline scenario, 25 P-3 aircraft will be stripped and repainted per year. Table 5-9 illustrates the annual baseline costs and environmental emissions for the baseline process.

Table 5-9: Baseline Costs Per Year

Category	Baseline (per aircraft)	Units	Baseline (25 P-3/ year)	Units
Capital Costs	**N/A**		**N/A**	**N/A**
Annual Operating and Maintenance (O&M) Costs				
Labor	85,397	$/aircraft	2,134,925*	$/year
Materials	21,233	$/aircraft	530,829*	$/year
Utilities	144.00	$/aircraft	3,600	$/year
EHS	22,791	$/aircraft	569,774*	$/year
TOTAL	**129,565***	**$/aircraft**	**3,239,128***	**$/year**
VOC Release	**3,423**	**lbs VOC /aircraft**	**85,577***	**lbs VOC /year**
Total lbs chromates applied	**24**	**lbs chromate /aircraft**	**600**	**lbs chromate /year**
Total lbs hazardous waste generated	**11,273**	**lbs haz waste/ aircraft**	**281,825**	**lbs haz waste/ year**

*Note that quantities were calculated to four decimal places but in table have been rounded to the nearest whole number. This may result in slight discrepancies in sums.

5.2.3 Condition-based Maintenance Scenario Cost Analysis

As discussed in Section 5.1.1, a potential condition-based maintenance scenario would cause each medium sized aircraft to undergo one of four alternate maintenance options. The maintenance option recommended for each aircraft under this alternative is based on the condition of the aircraft. As these options are only theoretical, the costs calculated for each are estimates based on discussions with NAVAIR Jacksonville. For the majority of the processes, the costs are estimated by beginning with the baseline and omitting or reducing in scope certain steps. Only in the Scuff/Sand/Overcoat process is a new step created in which selected areas of the aircraft are sanded and scuffed instead of stripped.

Per NAVAIR Jacksonville, the requirement for condition-based maintenance is that 70% of the OML be scanned in a single shift of 8 hours. Given the surface area of the P-3 and the estimated scan rate for an ergonomic IRRIT of 280 sq. ft./hour, it was calculated that this would require two IRRIT systems. Consequently, the capital cost of for condition-based maintenance is calculated as requiring purchase of two IRRIT systems.

Table 5-10 illustrates the capital costs and maintenance costs associated with implementing a single IRRIT camera system. These costs were then used to determine the cost of purchasing two IRRIT systems in Table 5-11.

Table 5-10: Single IRRIT System Cost

Category	Quantity	Units	Source of assumptions
Training Costs (Capital Cost)			
Number of personnel to train on system	4	persons	NAVAIR Jacksonville
Hours required for initial training	8	hrs/person	Estimated by Northrop Grumman
Total Training Labor	32	hrs/camera system	Calculated
Training Labor Cost	2,080	$/training session	Calculated at labor rate of $65/hr
Cost to purchase training	15,000	$/training	Estimated by Northrop Grumman
Subtotal (training)	**17,080**	**$/training**	**Calculated**
IRRIT Equipment Cost (Capital Cost)			
Camera, filter, lenses	64,000	$/system	Northrop Grumman
Software	5,000	$/system	Northrop Grumman
Laptop computer	5,000	$/system	Northrop Grumman
Illumination System	1,000	$/system	Northrop Grumman
Camera tripod head	100	$/tripod	Northrop Grumman
Camera Vest/backpack	2,100	$/vest	Northrop Grumman
Heads up display eyeglasses	2,000	$/glasses	Northrop Grumman
LCD small display	400	$/LCD	Northrop Grumman
Data transfer cables (set)	8,000	$/set	Northrop Grumman
Subtotal (Equipment)	**87,600**	**$/camera system**	**Calculated**
Equipment Maintenance Costs (Annually Reoccurring Cost)			
Maintenance Costs	**8,760**	**$/year**	**Engineering estimate based on 10% of capital cost ($87,000); agreed upon by Northrop Grumman**

Table 5-11 illustrates the capital and equipment maintenance costs for the two IRRIT systems estimated as required for conducting condition-based maintenance.

Table 5-11: Alternative Capital & Equipment Maintenance Costs

Category	Quantity	Units	Source of Assumptions
Equipment (Capital Cost)			
IRRIT System Cameras (2)	**175,200**	**$**	**Calculated cost for two cameras; from single camera cost in Table 5-10.**
Training Costs (Capital Cost)			
Training Subcon & Labor	**17,090**	**$**	**As per Table 5-10. (No increased cost for multiple cameras.)**
Equipment Maintenance Cost (Annually Reoccurring Cost)			
Maintenance Costs	**17,520**	**$/year**	**Calculated cost for two cameras; from single camera cost in Table 5-10.**

Table 5-12, Table 5-13, and Table 5-14 illustrate the potential costs for each of the procedures in the condition-based scenario. Table 5-12 illustrates equipment labor costs, Table 5-13 illustrates materials and utilities costs, and Table 5-14 illustrates EHS costs. The source of all assumptions is data provided from NAVAIR Jacksonville.

Table 5-12: Condition-Based Maintenance Labor Requirements

Category	Full Strip	Scuff/ Sand	Selected Strip	Spot Strip	Units	Source
Labor for 70% surface inspection with IRRIT system (P-3 has 6500 sq. ft. surface area)	33	33	33	33	Hours/ aircraft	4,550 sq. ft. inspected and 280 sq.ft./hr. inspection rate for 2 workers
Labor hours to chemical strip/ID/treat corrosion per aircraft	547	78	168	28	Hours/ aircraft	NAVAIR Jacksonville
Labor hours to prime aircraft	92	92	92	28	Hours/ aircraft	NAVAIR Jacksonville
Labor hours to paint/seal aircraft	202	202	202	49	Hours/ aircraft	NAVAIR Jacksonville
Labor hours to paint aircraft	474	474	474	84	Hours/ aircraft	NAVAIR Jacksonville
Sub-total Labor (hrs)	**1347***	**878***	**968***	**221***	**Hours/ aircraft**	**Calculated**
Sub-Total Labor (at $65/hr labor rate)	**87,555**	**57,070**	**62,920***	**14,365**	**$/ aircraft**	**Calculated based on $65/hr rate.**

*Note that quantities were calculated to four decimal places but in table have been rounded to the nearest whole number. This may result in slight discrepancies in sums.

As can be seen, the different maintenance procedures vary greatly in the amount of labor required on a per aircraft basis and hence on the cost required on a per aircraft basis. It is in this drastic reduction of labor required that provides most of the potential cost-savings.

Table 5-13 illustrates the estimated materials, equipment maintenance, and utilities costs for each of the maintenance procedures. Note that material costs are estimates based on anticipated P-3 aircraft surface area to be stripped, assuming correspondence to full strip and repaint needs. Even thought the procedures will differ, the material costs

for scuff/sand and selected strip are assumed to be about the same as a rough estimate. As the same cycle time (144 hours) is allotted to every scenario, the utility usage does not change.

Table 5-13: Condition-Based Materials and Utilities Cost Data and Assumptions

Category	Full Strip Cost	Scuff/Sand Cost	Selected Strip Cost	Spot Strip Cost	Units
Materials/ Equipment for stripping, priming, and painting		**(25% of full strip stripping, 100% repaint)**	**(25% of full strip stripping, 100% repaint)**	**(No strip, 15% repaint)**	
Total Aluminum/Barrier Tape Costs	1000	250	250	0.00	$/ aircraft
Total Stripper, De-sealant, Grinder, Solvent, Soap, Bead, and Sanding Disk Material Costs	11,749	2,937	2937	1762	$/ aircraft
Total Priming and Sealing Material Costs	4370	4370	4370	655	$/ aircraft.
Total Painting Material Costs	3615	3615	3615	542	$/ aircraft
Miscellaneous Materials	500	500	500	75	$/ aircraft
Subtotal (Materials)	**21,233**	**11,671**	**11,671**	**3,035***	**$/ aircraft**
Utilities					
Electric/Steam	144	144	144	144	hours/ aircraft
Subtotal (Utilities); at $1/hour	**144**	**144**	**144**	**144**	**$/ aircraft**

*Note that quantities were calculated to four decimal places but in table have been rounded to the nearest whole number. This may result in slight discrepancies in sums.

Table 5-14 illustrates EHS costs for the alternate condition-based maintenance procedures. Note that EHS costs are estimates based on anticipated P-3 materials requirements for alternative scenarios, assuming correspondence to full strip and repaint needs.

Table 5-14: Condition-Based EHS Costs

Category	Full Strip Cost	Scuff / Sand Cost	Selected Strip Cost	Spot Strip Cost	Units
EHS					
Impact, Alum Mask Tapes	600	150	150	90	lbs/ aircraft
Glass Bead Media	7,800	-	7,800	-	lbs/ aircraft
Wastewater: Hazardous Waste	114	114	114	17	lbs/ aircraft
Subtotal	**8514**	**264**	**8064**	**107**	**lbs/ aircraft**
Subtotal – Disposal cost $1.03/lb	**8769***	**272***	**8,306***	**110***	**$/aircraft**
Wastewater: Sludge	1,638	1,638	1,638	246	lbs/ aircraft
Wastewater: Liquid Waste (Brine)	1,121	1,121	1,121	168	lbs/ aircraft
Subtotal	**2759**	**2759**	**2759**	**414**	**lbs/ aircraft**
Subtotal – Disposal cost $0.45/lb	**1242***	**1242***	**1242***	**186***	**$/aircraft**
Wastewater requiring treatment	15,000	1,875	7,125	750	gallons/ aircraft
Subtotal – Wastewater Disp. cost $0.8520/gal	**12,780**	**1598***	**6071***	**639**	**$/aircraft**
VOC Emissions unit cost	0	0	0	0	$/ton
Subtotal (EHS)	**22,791***	**3,111***	**15,618***	**936***	**$/aircraft**
Total lbs hazardous waste generated	**11,273**	**3,023**	**10,823**	**521**	**lbs/ aircraft**

*Note that quantities were calculated to four decimal places but in table have been rounded to the nearest whole number. This may result in slight discrepancies in sums.

Table 5-15 combines the information from the above tables to provide the cost per aircraft of each of the condition-based maintenance alternatives.

Table 5-15: Cost Per Aircraft of Condition-Based Maintenance

Category	Full Strip Cost/ Aircraft	Scuff/Sand Cost/Aircraft	Selected Strip Cost/Aircraft	Spot Strip Cost/ Aircraft	Units
Labor	87,509	57,006	62,897	14,355	$/aircraft
Materials	21,233	11,671	11,671	3,035	$/aircraft
Utilities	144	144	144	144	$/aircraft
EHS	22,791	3,111	15,618	936	$/aircraft
Total	**131,678**	**71,933***	**90,330***	**18,470**	**$/aircraft**

*Note that quantities were calculated to four decimal places but in table have been rounded to the nearest whole number. This may result in slight discrepancies in sums.

Table 5-16 illustrates the total cost per aircraft for condition-based maintenance and multiplies it by the number to aircraft processed per year to determine the costs if all aircraft were processed by that maintenance procedure. This total is then multiplied by the actual expected percentage of aircraft that year to undergo each process to determine the expected total costs per year from that condition-based maintenance process.

Table 5-16: Total Procedure Costs

Category	Full Strip Cost/ Aircraft	Scuff/Sand Cost/ Aircraft	Selected Strip Cost/ Aircraft	Spot Strip Cost/ Aircraft
Total (Labor, Materials, Utilities, EHS)	$131,678	$71,933*	$90,330*	$18,470
Aircraft per year	25			
Cost if all 25 aircraft were treated with procedure	**$3,291,950***	**$1,798,325***	**$2,258,250***	**$461,750***
Percentage of aircraft per year (see Table 5-1)	50%	40%	5%	5%
Cost per Year	**$1,645,971***	**$719,331***	**$112,913***	**$23,087***

*Note that quantities were calculated to four decimal places but in table have been rounded to the nearest whole number. This may result in slight discrepancies in sums.

Table 5-17 illustrates the capital cost from condition-based maintenance and sums the annual costs of each condition-based maintenance scenario to determine the total operating cost of the condition-based maintenance alternative, compared to the baseline.

Table 5-17: Capital and Annual Cost of Condition-Based Maintenance

Category	Quantity
Capital Costs	
Equipment Cost	$175,200
Training Cost	$17,080
Total Capital Cost	**$192,290**
Annual Costs	
Full Strip	$1,645,971
Scuff/Sand	$719,331
Selected Strip	$112,913
Spot Strip	$23,087
Equipment Maintenance	$17,520
Total Condition-Based Maintenance Annual Costs	**$2,518,822**

Table 5-18 illustrates the simple pay-back period for condition-based maintenance, comparing the capital cost and total annual cost in Table 5-17 against the baseline annual cost of $3,239,128 illustrated in Table 5-6.

Table 5-18: Condition-Based Maintenance Simple Pay-back Period

Simple Payback Period	
Baseline (per year)	$3,239,128
Condition-based	$2,518,822
Annual Savings (Loss)	$720,306*
Simple payback on Capital cost ($192,290)	**0.27 years**

*Note that quantities were calculated to four decimal places but in table have been rounded to the nearest whole number. This may result in slight discrepancies in sums.

As can be seen in Table 5-18, assuming condition-based maintenance practices were implemented, then even with the cost of purchasing and maintaining two IRRIT systems and an extra inspection labor cost added to each aircraft, potential condition-based maintenance using IRRIT would be expected to pay for itself in a single year. A more extensive life cycle analysis is illustrated in Section 5.2.7.

Table 5-19 illustrates the estimated condition-based VOC emissions per aircraft in the baseline and condition-based maintenance alternative processes. Because several of the alternative methods require a reduced amount of chemical stripper and in some cases a reduced amount of paint, the quantity of VOCs released is greatly reduced. These numbers are estimates based on an anticipated percent reduction in required material.

Table 5-19: VOC Emissions per Aircraft for Condition-Based Processes

Material	Baseline VOCs/ aircraft (lbs)	Usage Full Strip (lbs)	Usage Scuff/ Sand (lbs)	Usage Selected Strip (lbs)	Usage Spot Strip (lbs)
Chemical Stripper: Turco 6881	2,873	2,873	0	718	0
Primer: MIL-PRF-85582, TY I, Class C1	129	129	129	129	19.3
Sealant: AMS 3276	1.23	1.23	1.23	1.23	0.18
Topcoat: MIL-PRF-85285, TY I	166	166	166	166	24.8
Solvent: TT-T-2935	255	255	0	63.8	0
Total	**3423***	**3423***	**296***	**1077***	**44***

*Note that quantities were calculated to four decimal places but in table have been rounded to the nearest whole number. This may result in slight discrepancies in sums.

Table 5-20 illustrates the estimated hexavalent chromium used in primer coating applied per aircraft in the baseline and condition-based maintenance alternative processes. Because the spot strip application would utilize less primer, the quantity of chromium utilized would be somewhat reduced. These numbers are estimates based on an anticipated percent reduction in required material.

Table 5-20: Hexavalent Chromium Applied

Baseline (lbs) / aircraft	Usage Full Strip (lbs) / aircraft	Usage Scuff/ Sand (lbs) / aircraft	Usage Selected Strip (lbs) / aircraft	Usage Spot Strip (lbs) / aircraft
24	24	24	24	3.6

Table 5-21 illustrates anticipated total VOC emissions, hexavalent chromium use, hazardous waste, and wastewater produced per year under the condition-based maintenance alternative.

Table 5-21: Condition-Based EHS Emissions

Emissions Generated	Usage Full Strip/ Aircraft	Usage Scuff/ Sand / aircraft	Usage Selected Strip / aircraft	Usage Spot Strip / aircraft
VOC per aircraft (lbs)	3423	295.5	1077.4	44.3
Chromates per aircraft (lbs)	24	24	24	3.6
Hazardous Waste per aircraft (lbs)	11,273	3,023	10,823	521
Aircraft per year	25			
Percentage of aircraft per year (see Table 5-1)	50%	40%	5%	5%
VOC Emissions/year (lbs)	**42,788**	**2,955**	**1,347**	**55**
Total VOC Emissions/year (lbs)	**47,146**			
Hexavalent chromium used/year (lbs)	**300**	**30**	**240**	**5**
Total Chromium used (lbs)	**575**			
Hazardous waste/year (lbs)	**140,913**	**30,230**	**13,529**	**651**
Total Hazardous waste/year (lbs)	**185,323**			

Table 5-22 illustrates the annual VOC emission, hexavalent chromium use, hazardous waste, and wastewater savings between condition-based maintenance and the baseline process.

Table 5-22: Baseline vs. Condition-Based VOC Emissions

Category	Baseline	Condition-based	Annual Savings
VOC/year	90,407 lbs	47,146 lbs	38,431 lbs
Hexavalent chromiums/year	600 lbs	575 lbs	25 lbs
Hazardous waste/year	281,825 lbs	185,323 lbs	96,502 lbs

5.2.4 Maintenance Cycle Extension Scenario Cost Analysis

As discussed in Section 5.1.3, scenarios where IRRIT inspection data was used to shift the maintenance interval would not involve altering the baseline maintenance process. As proposed, only the frequency with which the maintenance process is carried out would be altered. The only additional costs anticipated are those associated with the purchase and use of one IRRIT camera system as an evaluation tool. Because the information being gathered for interval shift is derived from a weapons system engineer taking the camera into the field and using it to inspect in-service aircraft, multiple cameras are not required under this scenario. Labor for inspections in not considered, since it is assumed time would be spent gathering data in the field due to use of the IRRIT system would be equivalent to the visual inspection that would be performed if the IRRIT was unavailable.

A cost comparison and life-cycle cost analysis was conducted on this scenario. As was illustrated in Table 5-10, the capital cost for a single IRRIT camera system (total of training costs and equipment costs) is estimated to be approximately $105K. In addition, the camera will add a continuing yearly camera maintenance cost of $8,760.

Table 5-23 illustrates the capital costs and yearly operating costs of the baseline compared to potential maintenance cycle extensions created through use of the IRRIT system.

Table 5-23: Maintenance Cycle Extension Cost Comparison

	Baseline (25 aircraft /year)	+1 Year (20 aircraft /year	+2 Year (17 aircraft /year)	+3 Year (15 aircraft /year	+4 Year (13 aircraft /year)
Capital Costs					
Equipment	$0	$87,600	$87,600	$87,600	$87,600
Training	$0	$17,080	$17,080	$17,080	$17,080
Annual O&M Costs					
Labor/ Equip.	$2,134,925	$1,716,700	$1,460,509	$1,289,715	$1,118,921
Materials	$530,829	$424,663	$360,964	$318,498	$276,031
Utilities	$3,600	$2,880	$2,448	$2,160	$1,872
EHS	$569,774	$455,819	$387,446	$341,865	$296,283
TOTAL	**$3,239,128***	**$2,600,063**	**$2,211,367**	**$1,952,237**	**$1,693,107**
VOC Release	**85,577 lbs***	**68,461 lbs**	**58,192 lbs**	**51,346 lbs**	**44,500 lbs**
Hexavalent Chromium applied	**600 lbs**	**480 lbs**	**408 lbs**	**360 lbs**	**312 lbs**
Total lbs hazardous waste generated	**281,825 lbs**	**225,460 lbs**	**191,641 lbs**	**169,095 lbs**	**146,549 lbs**

*Note that quantities were calculated to four decimal places but in table have been rounded to the nearest whole number. This may result in slight discrepancies in sums.

Table 5-24 illustrates the simple pay-back period for condition-based maintenance, comparing the capital cost and total annual cost in Table 5-17 against the baseline annual cost of $3,239,128 illustrated in Table 5-23. It also illustrates the annual environmental savings in VOC, chromates, solid waste, and wastewater emissions if an interval shift were to occur.

Table 5-24: Maintenance Cycle Extension Payback Period and EHS Savings

	+1 Years	+2 Years	+3 Years	+4 Years
Annual Savings/(Loss)	**$639,066**	**$1,027,761**	**$1,286,891**	**$1,546,022**
Simple Payback (yrs)	**0.16**	**0.10**	**0.08**	**0.07**
Annual VOC savings (lbs)	**17,115**	**27,384**	**34,231**	**41,077**
Annual Hexavalent Chromium use reduction (lbs)	**120**	**192**	**240**	**288**
Annual (lbs) waste savings	**56,365**	**90,184**	**112,730**	**135,276**
Annual (gal) wastewater savings	**75,000**	**120,000**	**150,000**	**180,000**

5.2.5 Scenario-Based EHS Savings

As discussed in previous sections, the alternative scenarios could result in considerable EHS savings. These savings have been rendered graphically below, based on information previous presented.

The annual VOC emissions and the alternative scenarios for a medium-sized aircraft (using P-3 as a baseline) are compared graphically in Figure 5-3 below (rationale for Figure 5-3 can be found in Table 5-24).

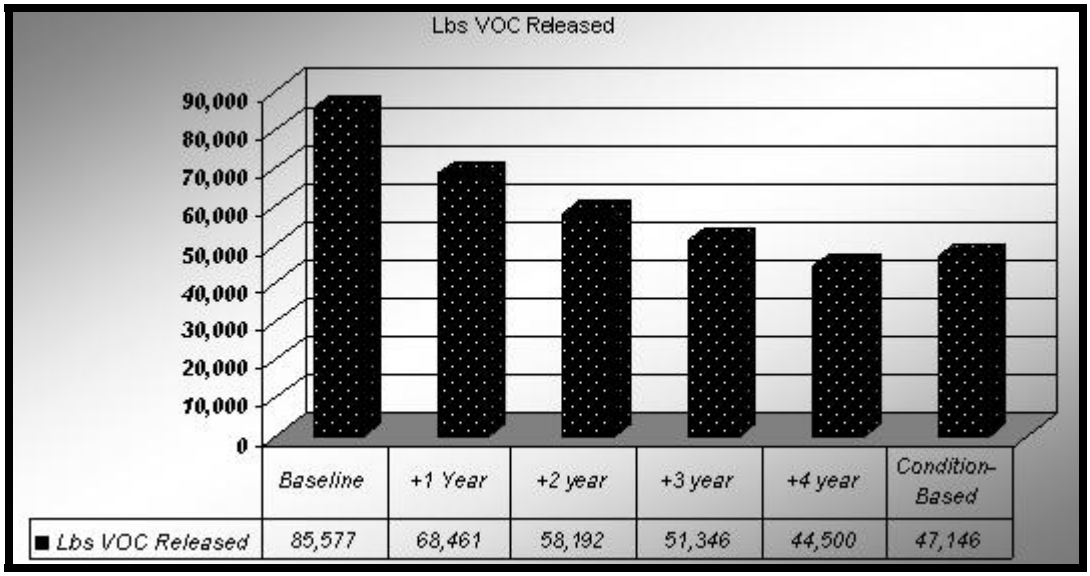


Figure 5-3: Annual VOC Emissions for Alternative Scenarios

The annual hexavalent chromate use in the alternatives scenarios is illustrated graphically in Figure 5-4 (rationale for Figure 5-4 can be found in Table 5-24).

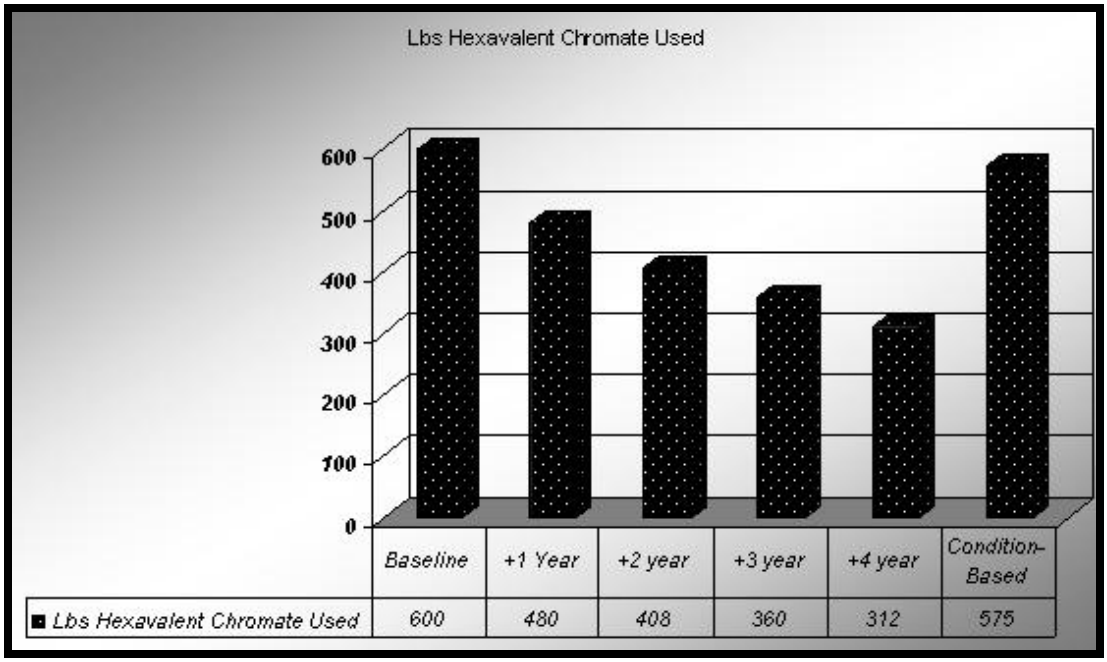


Figure 5-4: Annual Hexavalent Chromate Use for Alternative Scenarios

Annual hazardous waste generated in the alternatives scenarios are illustrated graphically in Figure 5-5 below (rationale for Figure 5-5 can be found in Table 5-24).

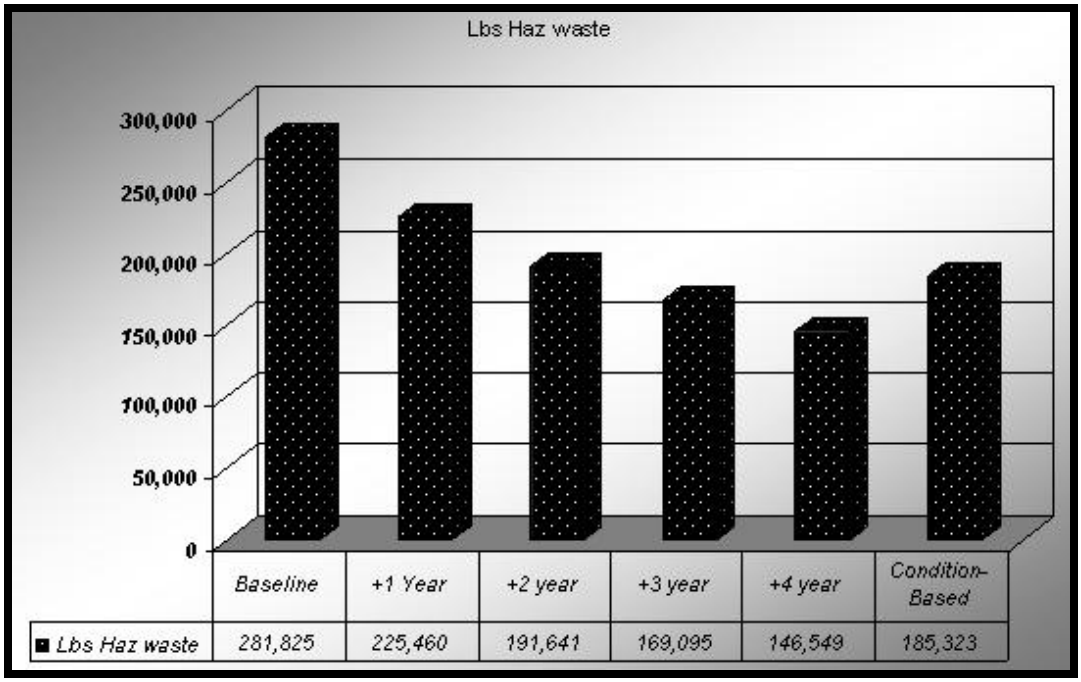


Figure 5-5: Annual Hazardous Waste Produced in Alternative Scenarios

5.2.6 Impact of Varying Labor Rate

A burdened labor rate is often used to account for various other costs incurred by the employer to maintain a competent team of personnel. For example, in addition to paying for salaries or hourly wages, the employer must also cover costs for medical benefits, training, administrative tasks (e.g., annual reviews), and more. In addition to these costs, some employers can also factor in material and utility costs to determine a "shop rate" to recuperate sufficient funds to stay in business.

Due to the nature of this IRRIT task, many of the material and utility costs have been accounted for elsewhere in an effort to estimate cost savings by reducing certain costs. For example, materials such as paint and blast media have been captured, as well as utilities and EHS costs such as wastewater treatment. Often times, due to the competitive nature of various businesses and the fact that personal salaries may be involved, these rates can be sensitive. To accommodate for the sensitive of labor and shop rates, and to avoid the possibility of double-counting costs for items such as materials and utilities, an estimated value of $65 per hour was used that would include salary and benefits, but exclude material and utility costs already accounted for in other data collection efforts.

However, due to the significance of the labor rate on the overall cost assessment, a more in-depth analysis was conducted to evaluate impact that the labor rate has on three of the financial indicators calculated in this cost assessment: Annual Savings, Payback Period, and Savings per Aircraft. The labor rate was varied from a low of $45 per hour to a high of $100 per hour. Table 5-25 and Table 5-26 illustrate the values for the three financial indicators for each labor rate, which was adjusted in $5 increments. An example of annual savings based on a $65 labor rate from Table 5-25 can be found in Table 5-24. Values are illustrated for each of the four possible increases in maintenance cycles, from the standard cycle to increase of 1 to 4 years.

Table 5-25: Impact of Labor Rate on Savings for +1 and +2 Year Interval Shift

	+ 1 Year			+2 Years		
Labor Rate	Annual Savings	Payback Period (years)	Savings per Aircraft	Annual Savings	Payback Period (years)	Savings per Aircraft
$45	$507,686	0.20	$2,744.25	$817,553	0.13	$4,419.21
$50	$540,531	0.19	$2,921.79	$870,105	0.12	$4,703.27
$55	$573,376	0.18	$3,099.33	$922,657	0.11	$4,987.34
$60	$606,221	0.17	$3,276.87	$975,209	0.11	$5,271.40
$65	$639,066	0.16	$3,454.41	$1,027,761	0.10	$5,555.47
$70	$671,911	0.16	$3,631.95	$1,080,313	0.10	$5,839.53
$75	$704,756	0.15	$3,809.49	$1,132,865	0.09	$6,123.60
$80	$737,601	0.14	$3,987.03	$1,185,417	0.09	$6,407.66
$85	$770,446	0.14	$4,164.57	$1,237,969	0.09	$6,691.72
$90	$803,291	0.13	$4,342.11	$1,290,521	0.08	$6,975.79
$95	$836,136	0.13	$4,519.65	$1,343,073	0.08	$7,259.85
$100	$868,981	0.12	$4,697.19	$1,395,625	0.08	$7,543.92

Table 5-26: Impact of Labor Rate on Savings for +3 and +4 Year Interval Shift

	+3 Years			+4 Years		
Labor Rate	Annual Savings	Payback Period (years)	Savings per Aircraft	Annual Savings	Payback Period (years)	Savings per Aircraft
$45	$1,024,131	0.10	$5,535.85	$1,230,710	0.08	$6,652.48
$50	$1,089,821	0.10	$5,890.93	$1,309,538	0.08	$7,078.58
$55	$1,155,511	0.09	$6,246.01	$1,388,366	0.08	$7,504.68
$60	$1,221,201	0.09	$6,601.09	$1,467,194	0.07	$7,930.78
$65	$1,286,891	0.08	$6,956.17	$1,546,022	0.07	$8,356.87
$70	$1,352,581	0.08	$7,311.25	$1,624,850	0.06	$8,782.97
$75	$1,418,271	0.07	$7,666.33	$1,703,678	0.06	$9,209.07
$80	$1,483,961	0.07	$8,021.41	$1,782,506	0.06	$9,635.17
$85	$1,549,651	0.07	$8,376.49	$1,861,334	0.06	$10,061.26
$90	$1,615,341	0.07	$8,731.58	$1,940,162	0.05	$10,487.36
$95	$1,681,031	0.06	$9,086.66	$2,018,990	0.05	$10,913.46
$100	$1,746,721	0.06	$9,441.74	$2,097,818	0.05	$11,339.55

The results of Table 5-25 and Table 5-26 are illustrated graphically in the following figures. Figure 5-6, Figure 5-7, and Figure 5-8 illustrate Labor Rate vs. Annual Savings, Payback Period, and Savings per Aircraft, respectively.

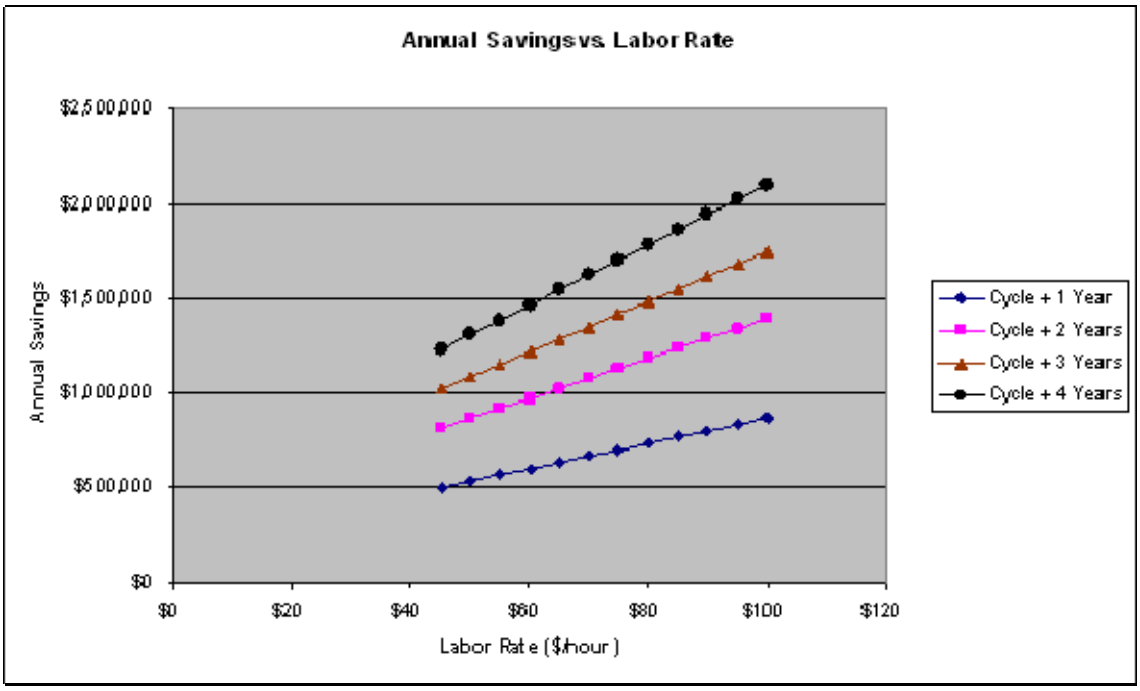


Figure 5-6: Annual Savings vs. Labor Rate

Figure 5-6 illustrates that, as the labor rate increases, so does the estimated annual savings. This is due to the fact that savings related to labor are anticipated when the IRRIT camera is implemented and/or when the maintenance cycle is increased. Therefore, as labor rates increase, the potential for savings related to labor costs also increases. The amount of savings for the 1-year increase in maintenance cycle is significant moving from about $500,000 to nearly $900,000 – an increase of about $400,000. This increase becomes more substantial for each incremental increase in the maintenance cycle. At the 4-year cycle, the values range from just over $1 million to over $2 million, which is an increase of $1 million.

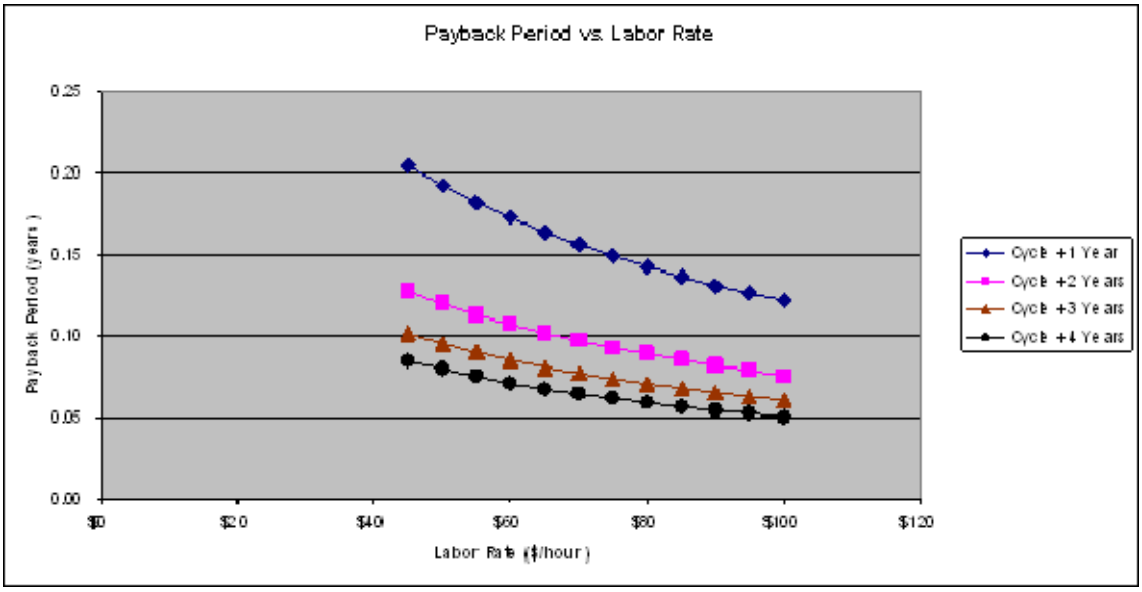


Figure 5-7: Payback Period vs. Labor Rate

Figure 5-7 illustrates that the payback period decreases as labor rate increases. This is logical because annual savings increase with the rising labor rate, so the time required recovering the capital investment is expected to be reduced.

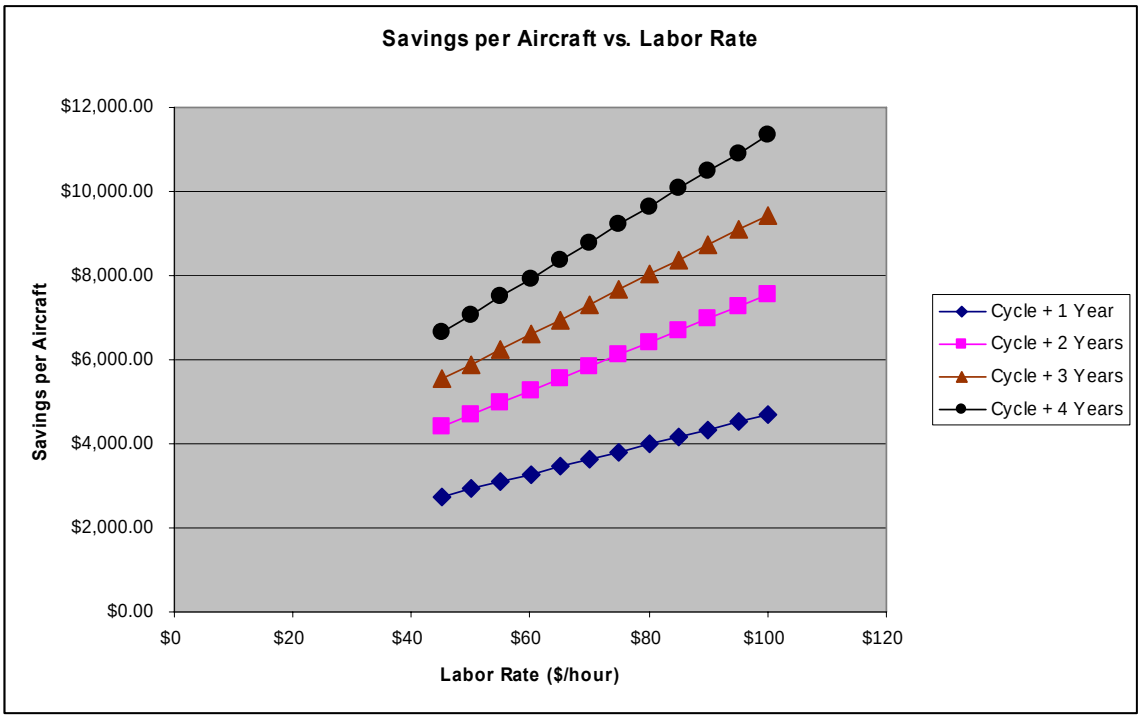


Figure 5-8: Savings per Aircraft vs. Labor Rate

As was the case with Annual Savings, the Figure 5-8 illustrates the Savings per Aircraft also increases with the labor rate. As noted previously, this is expected because labor is expected to be saved by using the IRRIT camera and/or increasing the maintenance cycle. The expected savings by increasing the cycle one year is significant (ranging from about $3,000 to $4,500), and if the maintenance cycle increase to four years, the estimated savings is expected to more than double (ranging from about $6,500 to over $11,000).

5.2.7 Life Cycle Analysis

In addition, a life cycle cost analysis was carried out on the IRRIT system for the condition-based maintenance alterative and interval shift alternative. Note that the maintenance interval extension analysis will hold true only for weapon systems where the actual condition of the fleet, as revealed by IRRIT inspection, allows an interval shift.

Per data from the manufacturer, an IRRIT camera is estimated to have a service life of 8000 hours (the internal IR camera detector compressor has a lifetime of 8000 hours). In the condition-based scenario, no more than 8 hours is spent on inspecting with a single camera on any single P-3 aircraft, and no more than 25 aircraft would pass through the facility per year. This would lead to a camera working life of 40 years. As per ESTCP guidance for weapon systems and platforms technology, this has been shortened to a 15-year life-cycle.

Table 5-27 illustrates the 15 year Life Cycle.

Table 5-27: 15 Year Life Cycle

Alternative	Capital Cost	Annual Cost	Life Cycle Cost	Life Cycle Cost Savings
Baseline	$0	$3,239,128	$48,586,920	-
Condition-Based Maintenance	$192,290	$2,518,822	$37,782,330	$10,804,590
+1 Year Interval	$104,680	$2,600,063	$39,000,942	$9,585,985
+2 Year Interval	$104,680	$2,211,367	$33,170,511	$15,416,417
+3 Year Interval	$104,680	$1,952,237	$29,283,556	$19,303,371
+4 Year Interval	$104,680	$1,693,107	$25,396,602	$23,190,325

Three performance measures were considered in the ECAM evaluation: payback period, Net Present Value (NPV), and Internal Rate of Return (IRR). The payback period is the time required to recover all of the capital investment with future cost avoidance. NPV calculates the difference between capital investments and the present value of future annual cost benefits associated with the alterative. This value represents the life cycle costs associated with the alternative. The IRR is the discount rate at which NPV is equal to zero.

NPV and IRR account for the time value of money and discount the future capital investments or annual cost benefits to the current year. For NPV and IRR, a 15 year life cycle and 2.9% discount rate have been used. The 2.9% discount rate is based off the Office of Management and Budget's estimates as of January 2007[1]. Table 5-28 illustrates the calculated 15 year net present value, internal rate of return, and discounted payback period for the condition-based maintenance scenario. Once again it must be cautioned that while these results appear extremely favorable, they are built on the assumption that the IRRIT will be the sole contributor to allowing radically different maintenance procedures. The accuracy of this assumption rests with the expert evaluation of each weapon system owner considering potential use of the IRRIT and with the actual condition of the aircraft under evaluation.

Table 5-28: NPV, IRR, and Discounted Payback

Alternative	NPV at 15 Years	IRR at 15 years	Discounted Payback Period
Condition-Based Maintenance	$8,469,204	374 %	0.27 Years
+1 Year Interval	$7,579,912	611 %	0.17 Years
+2 Year Interval	$12,253,774	982 %	0.10 Years
+3 Year Interval	$15,369,853	1230 %	0.08 Years
+4 Year Interval	$18,485,825	1477 %	0.07 Years

[1] http://www.whitehouse.gov/omb/circulars/a094/a94_appx-c.html

5.2.8 Inner Mold Line Costs and Savings

IML surface areas on surveyed aircraft were spot stripped on an irregular basis. There was no standardized baseline process that could be used for purposes of comparison and the potential impact of the IRRIT system is difficult to quantify. This cost analysis has concentrated on potential costs and benefits from use of the IRRIT in OML maintenance processes. This was due to current maintenance practices, where OML surface areas on surveyed aircraft were stripped regularly and completely, with the 6500 sq. ft. of surface area on the P-3 used as an example baseline.

However, there are potential corrosion-prevention benefits by employing IRRIT on IML. IML contains exposed critical support structure of aircraft. Early detection of corrosion could prevent damage to costly and difficult to replace structurally significant components. In addition, the fact that IML surfaces are not stripped on a regular maintenance cycle means that if the weapons system engineer desires to inspect surfaces below the coating for potential corrosion, a costly one-time stripping order must be issued to strip, inspect, and repaint selected areas of the IML on one or more aircraft. Potentially, use of the IRRIT could eliminate these 'inspection strips' entirely rather than merely deferring them, as in the case of OML applications.

For purposes of estimating the impact of eliminating a one-time inspection, consider the recently completed B-52 longerons one-time inspection. The B-52 longerons run down each side of the bomb bay. During the one-time inspection, these areas were stripped by plastic media blast (PMB) as each not previous inspected B-52 arrived at OC-ALC for maintenance. These longerons and the surrounding areas (also stripped) composed about 400 sq. ft. of area. Approximately 20 B-52 aircraft pass through OC-ALC each year.

Table 5-29 and Table 5-30 illustrate the estimated environmental impacts of the one time inspection. It should be noted that these coating quantities and EHS emissions are estimates based on the surface area stripped, inspected, and repainted and VOC and chromium content for the primer and topcoat used on the P-3. B-52 specific information was unavailable.

Table 5-29: One Time Strip, Inspect, and Repaint Coating usage

Category	Quantity for full strip and repaint (per B-52 aircraft)	Quantity to spot treat corrosion (estimated as no more than 10% surface area)	Savings per aircraft from spot corrosion treatment
Primer – MIL-PRF-85582	0.4 gallons	0.04 gallons	0.36 gallons
Topcoat – MIL-PRF-85285	0.25 gallons	0.025 gallons	0.22 gallons

Table 5-30: Annual VOC and HAP Savings from IRRIT Inspection

Category	Estimated Quantity Saved (per aircraft)	Estimated Annual Quantity Saved (20 aircraft)	Annual Estimated VOC Emissions Saved	Estimated Hexavalent Chromium Content (20 aircraft)
Primer – MIL-PRF-85582	0.36 gallons	7.2 gallons	23 lbs	4.3 lbs
Topcoat - MIL-PRF-85285	0.22 gallons	4.4 gallons	15 lbs	N/A

Figure 5-9 below illustrates the potential impact the elimination of a single one-time inspection through use of IRRIT could have on EHS emissions.

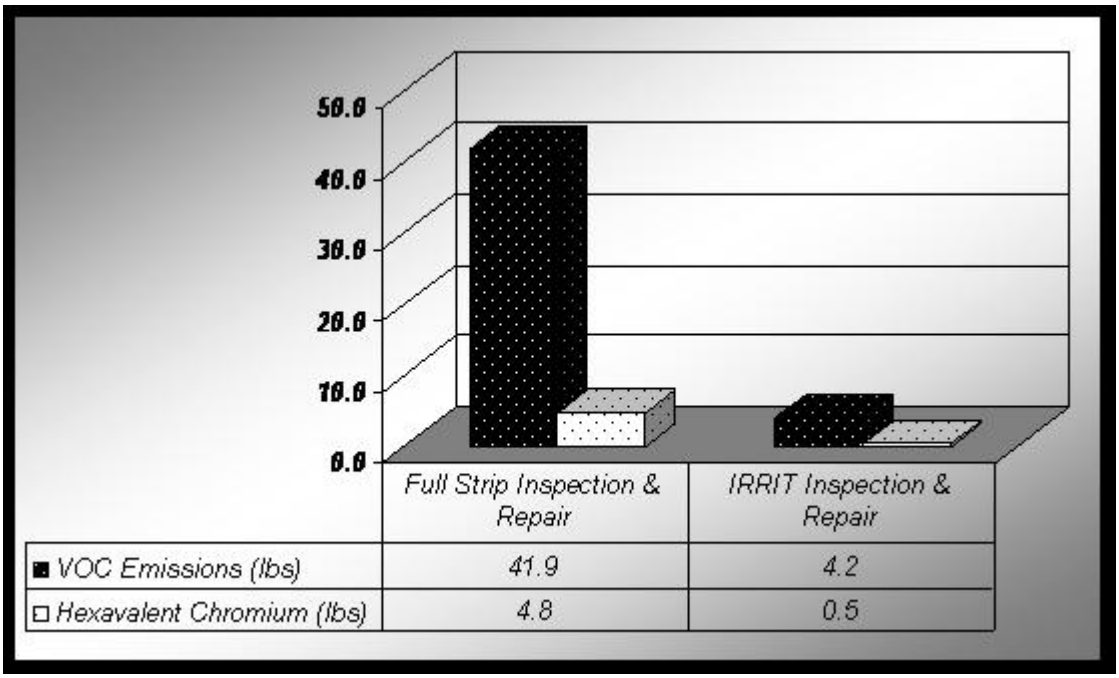


Figure 5-9: IML Full Strip vs. IRRIT Inspection EHS

5.2.9 Cost Analysis Summary

As can be seen, use of the IRRIT system illustrates an extremely favorable payback period in the alternative scenarios, as well as substantial pollution-prevention savings. Under all OML scenarios considered, the payback period never exceeds 0.3 years. Complete strip and repaint of an aircraft is an expensive process in terms of labor, material, and EHS emissions. The value of deferring the strip and repaint of a single aircraft OML equal or greater in size than the P-3 is greater than the cost of an IRRIT system.

As stated, however, these potential benefits are solely dependent on providing weapon system managers with sufficient increased confidence to alter the maintenance procedure/cycle. Before purchase of an IRRIT system for a particular maintenance facility, it should be demonstrated to appropriate weapon system managers and/or

inspection team leads. If and only if agreement is obtained that the IRRIT can be used to substantially alter the current maintenance procedure/cycle should purchase of the IRRIT be recommended.

These maintenance scenarios are not meant to be P-3 OML specific, and should be considered as generic examples of a potential IRRIT impact on a wide range of DoD aircraft OML applications. When applied to aircraft of equal or greater size to the P-3, cost savings are likely to be in the same range due as illustrated in P-3 due to the labor reduction from having to process less of the aircraft surface area. Most of the pollution prevention savings come from a reduction in chemical stripping. For aircraft where stripping is accomplished by plastic media blast (PMB) as opposed to chemical stripping, pollution prevention savings may not be as extensive.

For smaller aircraft there will be less labor and pollution prevention savings. However in the case of condition-based maintenance, fewer IRRIT systems will be required for a smaller surface area, resulting in less of a capital cost to payback and a lower inspection labor per aircraft processed.

In an effort to evaluate the potential savings from use of the IRRIT on other OML applications, a "Spreadsheet Tool for Assessing Costs and Benefits of Increasing the Maintenance Interval Between Recoating and Stripping Activities" was developed using the P-3 data. This spreadsheet tool and the instructions for its use have been added as Appendix H.

6. IMPLEMENTATION ISSUES

6.1 Environmental Permits

The IRRIT System is a hardware specific technology implementation that does not generate or produce hazardous waste or other environmental pollutants. As a result, technology permitting is not required by the user community. Additionally, the improved inspection capability of the IRRIT system is projected to reduce hazardous waste and emissions by lessening inspection driven depaint process requirements of applicable aircraft and components. The pertinent environmental regulations and the necessary permits required for waste streams/emissions produced by the depaint and repaint process will not change at local implementation sites.

6.2 Other Regulatory Issues

No regulatory issues are identified due to the passive nature of the IRRIT technology.

6.3 End-User/Original Equipment Manufacturer (OEM) Issues

End users for the IRRIT system consist of in-service depot level maintainers of fielded weapon systems and their associated support equipment within the sustainment community. End users include inspectors, quality assurance specialists, and engineers within applicable maintenance and engineering departments of the DoD. IRRIT system usage depends upon several process functions related to the specific requirements of the end user. For inspectors, usage is targeted towards a conditional based assessment of weapon system repair requirements, while quality assurance specialists may utilize the IRRIT system as a tool for process verification and monitoring of corrosion control program effectiveness. Engineering departments can utilize the IRRIT system for program related logistical support functions associated with corrosion, paint and wash cycle interval evaluations or reliability centered maintenance (RCM) events.

Due to continual technology development and improvement, it must be understood that the equipment presently used to demonstrate and validate IR inspection capability will not necessarily be the same equipment procured by end users for implementation. The IRRIT system equipment utilized for field demonstration was a commercially available MWIR camera procured from FLIR Systems and modified by Northrop Grumman as a demonstration prototype. Modifications included installation of an external IR illuminator, data transfer interfaces for image recording and data capture, installation of internal IR filtering for improved image resolution, and the use of ergonomic support equipment. Future MWIR cameras are expected to be smaller, lighter, with improved integrated capabilities (i.e., memory size for recording images, built in software, and filtering). The IRRIT system requires the use of a MWIR camera (3-5 micrometer) with an array size of at least 320x256 pixels. Array size effects image resolution of the camera, and correspondingly the level of detection (in regards to the size of corrosion). A 320x256 pixel array size is the minimum desired for use as an inspection tool through organic coatings.

Technology costs of currently available MWIR cameras range from $50K to $70K which will require pre-procurement planning and budgeting by the user community. As a result, initial implementation strategies include the procurement of MWIR cameras within an organizational structure that encourages dual use in support of both maintenance and field applications. Examples of applicable non-program related organizations are depot Corrosion Control and NDI engineering departments. A program budget should be established to fund and develop this technology across the Joint Services. A possible avenue is through collaboration with the Corrosion Steering Group (CSG) of the Joint Council of Aging Aircraft (JCAA), the DoD Corrosion Exchange or through service specific environmental and engineering program sponsors. Technology budgeting within the depot user community would require coordination with the applicable capital equipment procurement program at each field location.

6.3.1 Interested Customers

End users for the IRRIT system consist of in-service depot level maintainers of fielded weapon systems and their associated support equipment that utilize coating systems which allow for sufficient MWIR transmission (refer to Table 2-3). Refer to Appendix G for Letters of Endorsement obtained from programs following project demonstration and data analysis.

Scale-up of this technology across Navy and USAF aircraft inventories compatible with IRRIT system OML and IML inspection requirements would result in significant environmental reductions of VOC, HAZMAT, and chromate waste with corresponding process cost savings (refer to Figure 6-1, Figure 6-2, and Figure 6-3) as a result of reduced inspection driven depaint functions and/or paint process deferments. The methodology or rationale that was used in generating Figure 6-1, Figure 6-2, and Figure 6-3 is as follows: all aircraft within the Navy and USAF total active inventory (based on 2006 estimates) were taken into account. P-3 data was used as the baseline values for subsequent calculations. The baseline P-3 values are as follows:

Baseline Area (sqft) = 6,500
Baseline VOC "Chemically Stripped" (lbs) = 3,423
Baseline VOC "No Stripper" (lbs) = 551
Baseline HAZMAT (lbs) = 11,273
Baseline Chromate (lbs) = 24
Baseline Cost ($) = 133,505

Applicability of IRRIT on aircraft OML and IML was based on coating spectral studies. Each aircraft's OML and IML surface areas were estimated as a ratio of the P-3. The values were calculated based on the following scenarios:

1. Aircraft OML ("Chemically Stripped") and IML ("No Stripper") applicable to IRRIT
2. Aircraft OML ("No Stripper") and IML ("No Stripper") applicable to IRRIT
3. Only Aircraft IML ("No Stripper") applicable to IRRIT

All aircraft IMLs within the Navy and USAF inventories were found to be applicable to IRRIT and a value of 100 square feet was used in the calculations. It should

also be noted that a value of 5,636 lbs was used for the USAF HAZMAT calculations, due to the use of plastic bead media for OML paint removal.

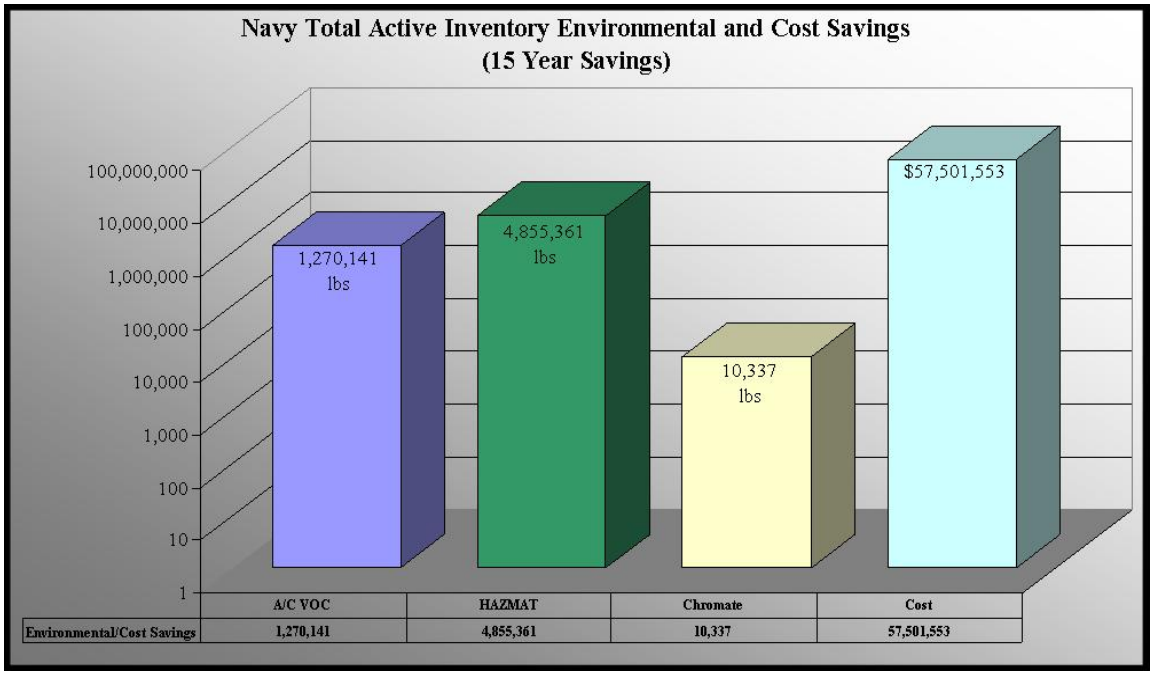


Figure 6-1: Potential Navy Environmental and Cost Savings

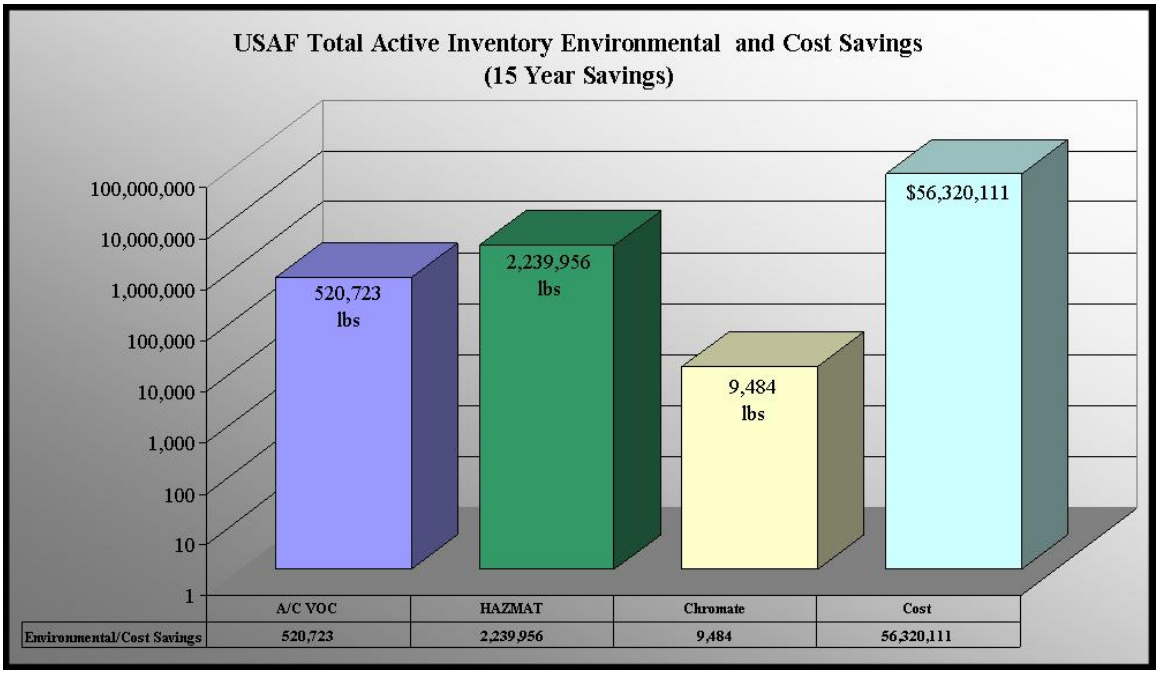


Figure 6-2: Potential USAF Environmental and Cost Savings (without APC's/ELT's)

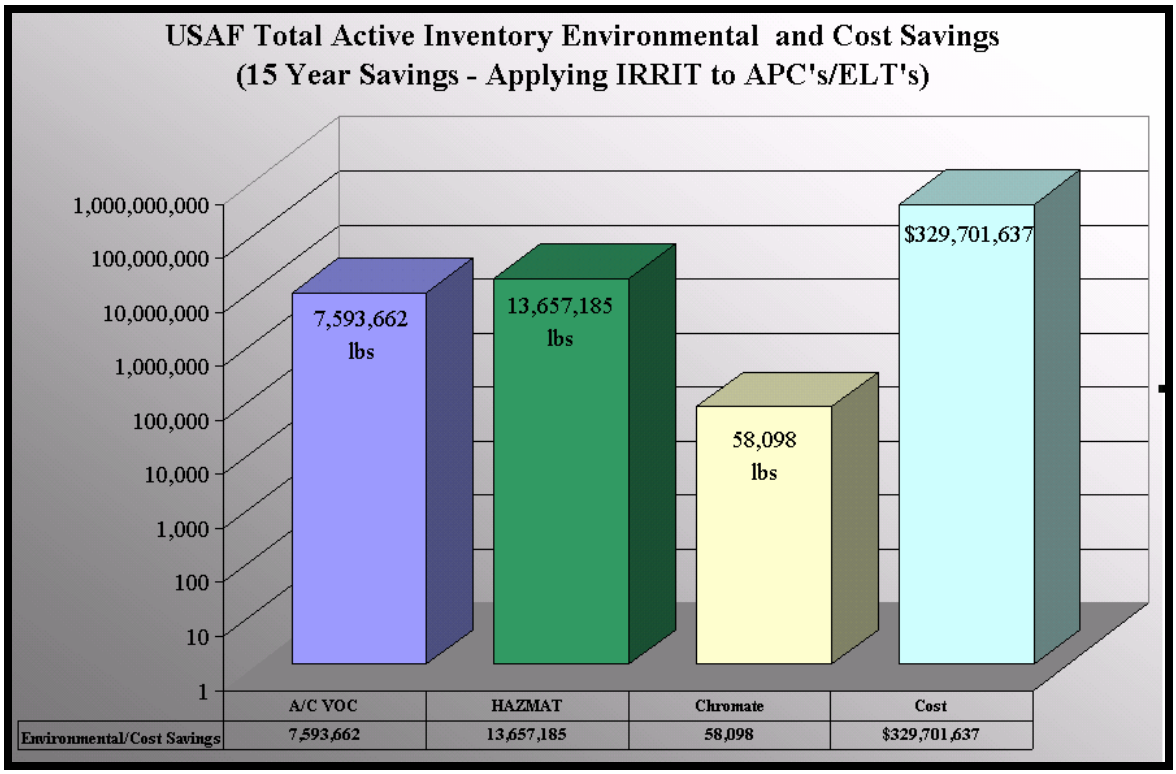


Figure 6-3: Potential USAF Environmental and Cost Savings (with APC's/ELT's)

6.3.2 IRRIT System Modifications

- MWIR Camera (3-5 micrometer) with a minimum array size of 320x256 pixels. Specific camera operating instructions can be found within the manufacturer's operation manual for the specific mid-IR camera procured (refer to Appendix A).
- IR Band-Pass Filter (3.75–5 micrometer) for enhance imaging through improved signal to noise ratio and reduction of paint surface reflections.
- IR Illuminators: Illuminators must supply sufficient illumination in the 3-5 micrometer range. Sufficient illumination is defined as enough illumination to penetrate the coating system and reflect off the substrate to the camera system detector array. Mag-Lite® halogen flashlights, commonly available within the user community, have demonstrated suitable capability for use as IR illuminators for the IRRIT system. A 3M Paint Preparation System (PPS) Sun Gun is also commercially available for use as a hand held IR illuminator.
- IRRIT Operation Standard: A standard is required to check operational ability of IRRIT, and to ensure all internal camera settings are appropriate. Recommended operational standard is the use of a commercially available camera resolution standard (Air Force Target Standard) coated with the applicable coating system representative of the material for inspection. Target standards can be procured from Edmund Industrial Optics.

- General IR Inspection Training and Procedures are presented within Appendix K as a "Draft" Technical Work Package provided in standard manual format. Engineering offices may customize this instruction to their specific process functions for inclusion into the appropriate program manual.

6.3.3 Service and Support Package

IRRIT system procurement may be performed as individual component purchases later integrated by the user community or through IRRIT System Kits produced and provided by Northrop Grumman Technical Services (Bethpage, NY), to include, operating instructions and support for the IRRIT MWIR camera plus all required accessories.

7. REFERENCES

1. Strategic Environmental Research & Development Program (SERDP). *Final Report, "Non-Destructive Testing of Corrosion Under Coatings",* Project Number 1137, Dated 1 September 2004.

2. Environmental Security Technology Certification Program (ESTCP). *Guidance for Pollution Prevention Projects*. April 2004.

3. Environmental Security Technology Certification Program (ESTCP). "*Navy P-3 OML Demonstration/Validation Plan",* Project Number WP-0407. December 14, 2005.

4. Environmental Security Technology Certification Program (ESTCP). "*USAF KC-135 and B-52 IML Demonstration/Validation Plan",* Project Number WP-0407. August 10, 2006.

5. National Defense Center for Environmental Excellence (NDCEE). 1999. *Environmental Cost Analysis Methodology (ECAM) Handbook*, March 29, 1999. http://www.estcp.org

6. Indigo MWIR Merlin® Camera Manual

7. OPNAVINST 5100.23F (July 15, 2002) Navy Occupational Safety and Health (NAVOSH) Program Manual

8. NAVAIR Jacksonville, Florida – Local Process Specification (LPS) 650

9. NAVAIR Jacksonville, Florida – Local Process Specification (LPS) 250

10. United States Patent 7,164,146 - System for Detecting Structural Defects and Features utilizing Blackbody Self-Illumination

11. United States Patent 7,193,215 - System and Method for Imaging of Coated Substrates

12. United States Patent Application 20060289766 - Spectral Filter System for Infrared Imaging of Substrates Through Coatings

8. POINTS OF CONTACT

Point of Contact	Organization	Phone/Email	Role in Project
Allen, David	ASM Management	478-335-3316 dallen3@netscape.com	Technical Consultant/QA Officer
Benavides, Sam	USCG	252-335-6123 sbenavides@arsc.uscg.mil	USCG Materials Engineer/Corrosion
Benfer, Jack	NAVAIR Jacksonville	904-542-4516 x153 john.benfer@navy.mil	Senior Corrosion Engineer, ESTCP Principal Investigator
Campbell, Matthew	*CTC*	412-992-5382 campbell@ctc.com	ESTCP Program Manager
Cargill, Steve	*CTC*	772-546-7718 cargill2@comcast.net	NDI Expert
Chu, Steve	NGC	516-346-9285 steven.chu@ngc.com	Technical Support
Cowherd, Tom	NAVAIR Jacksonville	904-317-2037 thomas.cowherd@navy.mil	Environmental Cost Support
Davis, Carvel	Tinker AFB	405-736-5020 carvel.davis@tinker.af.mil	NDI Expert
DiMarzio, Don	NGC	516-575-6452 donald.dimarzio@ngc.com	Spectral NDI Principal Investigator
Fonneland, Nils	NGC	516-346-2893 nils.fonneland@ngc.com	Technical Support
Gintert, Larry	*CTC*	727-549-7092 gintert1@ctc.com	Special Army Consultant
Habib, Bernie	Tinker AFB	405-736-5686 bernie.habib@tinker.af.mil	B-52 Engineer
Hanson, Mike	USCG	252-335-6451 mhanson@arsc.uscg.mil	USCG Manager
Kalhor, Justin	Tinker AFB	405-736-5401 justin.kalhor@tinker.af.mil	B-52 Engineer
Kenny, Paul	NAVAIR Jacksonville	904-542-4521 x138 paul.kenny@navy.mil	Senior NDI Engineer
Kelley, Jack	ARL	410-306-0837 jkelley@arl.army.mil	Army Materials Engineer
Leyble, Dennis	NGC	516-346-7403 dennis.leyble@ngc.com	Technical Support
Marlowe, Dan	NAVAIR Jacksonville	904-545-5407 x154 daniel.marlowe@navy.mil	P-3 Field Support Team (FST) Engineering
McPherson, Scott	*CTC*	904-722-2503 mcpherso@ctc.com	Cost Benefit Analysis
Miller, Mike	*CTC*	727-549-7285 millermi@ctc.com	Technical Support
Pollock, Brian	AFRL/MLSC	937-255-0498 brian.pollock@wpafb.af.mil	ESTCP IRRIT Program Liaison
Rowten, Ryan	Tinker AFB	405-736-5020 ryan.rowten@tinker.af.mil	NDI Expert
Smith, Kriston B.	ITT Fort Bragg	910-396-9478 smithkris@bragg.army.mil	Army Paint Shop Supervisor
Speers, John	AFRL/MLSC	937-656-5699 john.speers@wpafb.af.mil	ESTCP IRRIT Program Liaison
Tanner, David	Tinker AFB	405-736-5005 david.tanner@tinker.af.mil	B-52 Engineer
Thoms, John	*CTC*	814-269-6805 thoms@ctc.com	Cost Benefit Analysis
Waldrop, Rusty	USCG	252-335-6935 RWaldrop@arsc.uscg.mil	USCG NDI Expert
Washburn, Larry	NAVAIR Jacksonville	904-542-2641 larry.washburn@navy.mil	Occupational Safety Specialist
Weir, John	NGC	516-575-5422 john.weir@ngc.com	NGC Program Manager
West, Steve	Tinker AFB	405-736-5020 steven.west@tinker.af.mil	USAF NDI Expert
Westover, Ryan	NAVAIR Jacksonville	904-542-4516 x126 robert.r.westover@navy.mil	NAVAIR Jacksonville Liason

Mr. John Benfer is the Principal Investigator (PI) for the ESTCP program. He provided strategic direction, technical leadership, and directs overall programmatic and major decisions to the program. He was also the POC for performing the Dem/Val at NAVAIR, Jacksonville. He works closely with key functional specialists and artisans there, most notably the four lead personnel noted in Figure 8-1. Their functions are identified in the figure. These four individuals work with Mr. Benfer on an active basis, and were involved in the Dem/Vals since late 2004.

The Air Force is providing overall administrative, budget, and contract management, with Mr. Brian Pollack (formerly Mr. John Speers) performing these functions.

CTC is the prime contractor for the program. Mr. Matthew Campbell is the Program Manger for *CTC*, and also the lead for CBA. *CTC* provided weekly program status updates, and assessed/reported overall cost/schedule data. Additionally, Mr. Mike Miller (*CTC*), Mr. John Thoms (*CTC*) and Mr. Scott McPherson (*CTC*) performed the cost benefit analyses. Mr. Mike Miller was also responsible for documenting and writing the USAF KC-135 and B-52 IML Dem/Val Plan.

NGC executed the actual hands-on portion of the Dem/Vals, which included, in part, the proper use of the IR Camera, collection of data, and data analysis. At the Dem/Val sites, NGC was managed by Mr. John Weir, under the overall direction of Mr. Benfer. NGC worked on a non-interference basis, to ensure unreasonable or unexpected work stoppages did not occur for A/C production. Prior to conducting any activity, the applicable shop production management was informed of NGC's intent to perform that activity. A time estimate to finish this activity was given by Mr. Benfer and NGC, and discussed with shop personnel prior to testing.

Mr. David Allen (Aircraft Structural Maintenance Management) was the Quality Assurance Officer for the purpose of this Dem/Val. He also documented areas of non-compliance with the procedures of the Dem/Vals (Navy P-3 OML Dem/Val and USAF KC-135 and B-52 IML Dem/Val), and document necessary corrective action procedures.

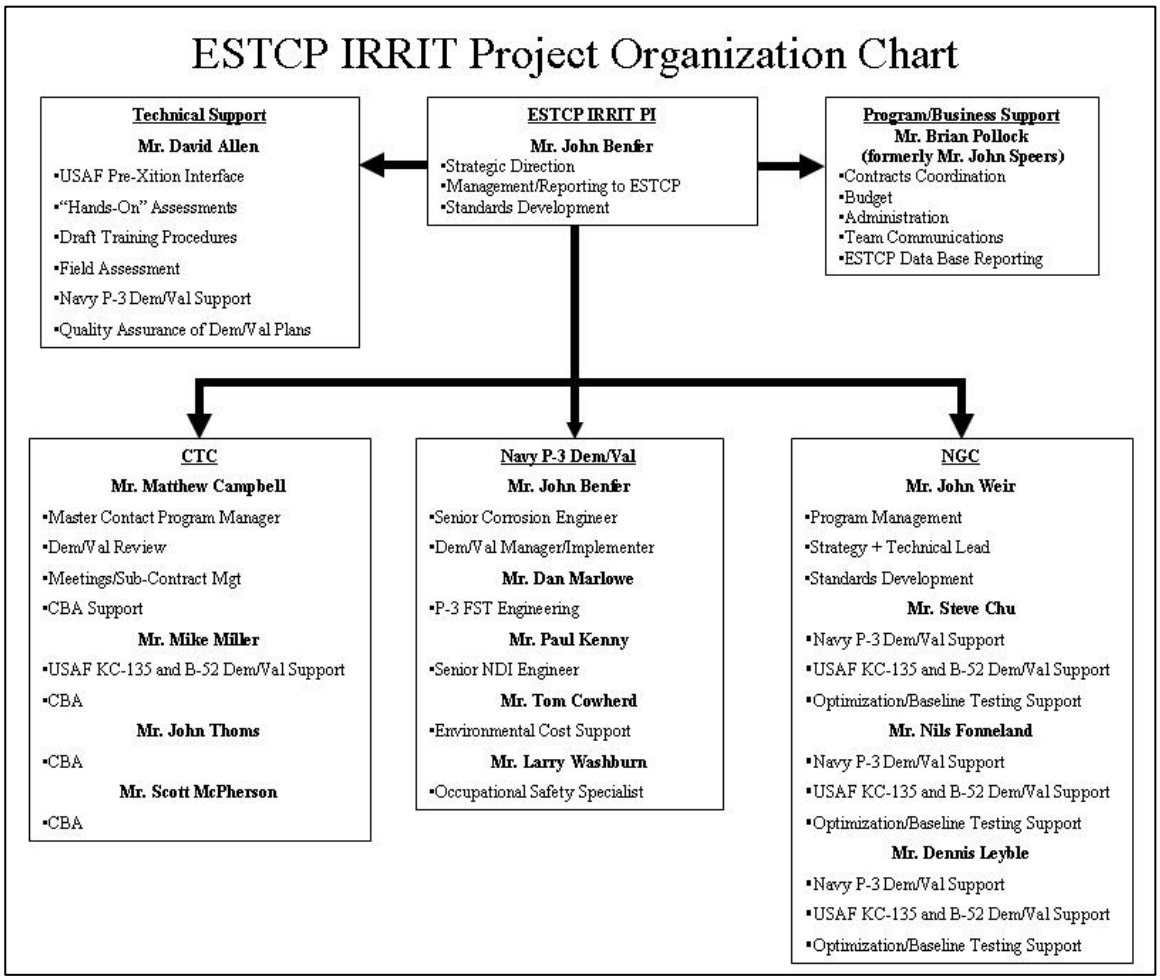


Figure 8-1: Organization Chart

APPENDIX A ANALYTICAL METHODS SUPPORTING THE EXPERIMENTAL DESIGN

IRRIT Technology Theory

Spectral reflectance signatures may be used to detect the presence of various chemical species, including corrosion products. An IR beam must be able to pass through the coating, reflect off the metal surface, and pass back out through the coating (Figure 2-2). Coatings are normally designed with pigment sizes tailored so that they are opaque in the visible region of the spectrum (0.40 to 0.75 micrometer (μm)), so they preclude using optical techniques in the visible to "see" through the coating to the metal. However, the scattering power of pigments is diminished as the probe wavelength becomes longer. For many coatings, a spectral window opens in the near and mid-wave infrared (MWIR) spectral regions.

Figure A-1 below illustrates a schematic of the IRRIT. In this schematic the IR camera lens is between the spectral filter and the coated aircraft part. The camera body includes the spectral (or bandpass filter) and the focal plane detector.

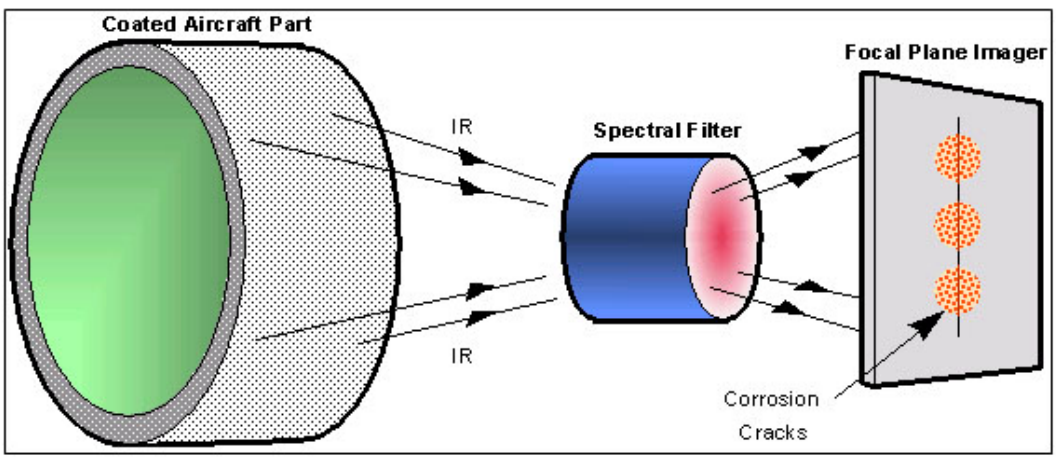


Figure A-1: Principal of IRRIT on Corroded Painted Metal Components

The spectral imaging concept depends on the generation of a database of spectral signatures of corroded surfaces and various coating reflectance and transmission data. Directional Hemispherical Reflectance (DHR) was utilized to determine the spectral properties of surfaces. As illustrated in Figure A-2, a collimated IR beam in the range of 1.8 to 15.4 μm was directed near normal to the surface, and the reflected light, both specular and diffuse, was measured in an integrating sphere. Reflectance was then plotted as a function of wavelength or wavenumber or equivalent wavelength in micrometers (μm). It was important to collect the diffuse component of the reflected light since the reflectance signal from any corrosion at the metal surface will be significantly scattered by the overlying paint layer.

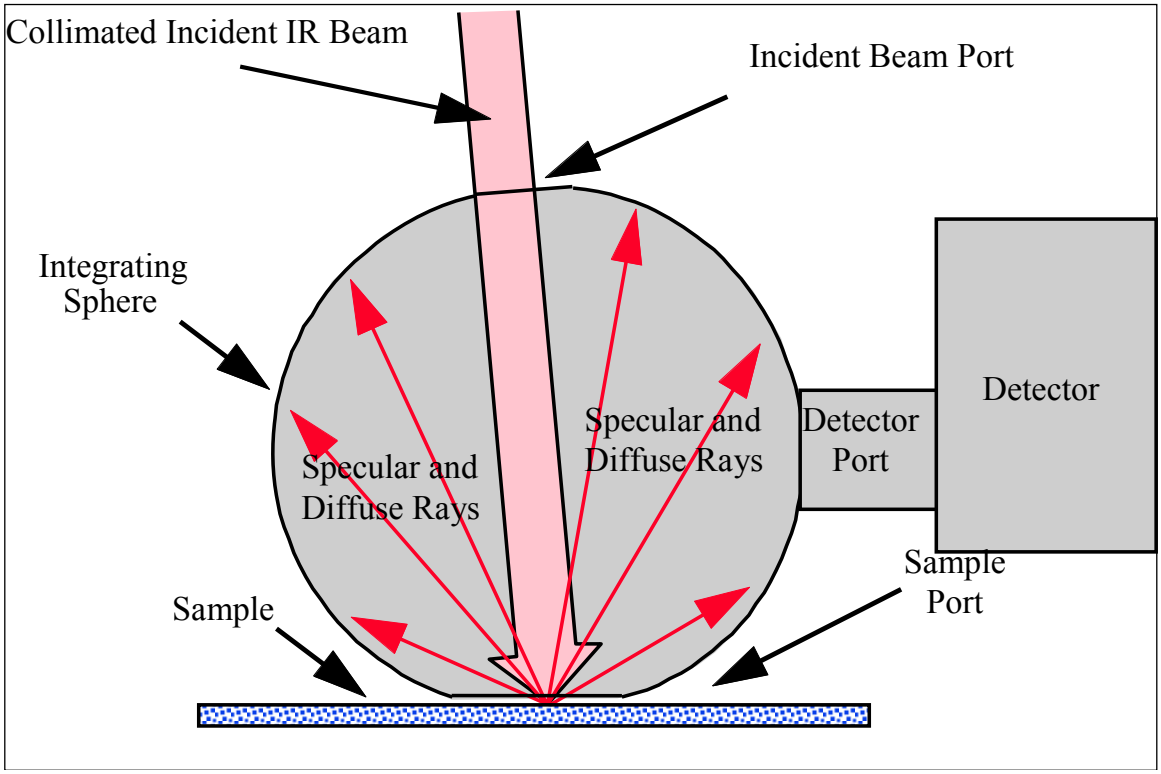


Figure A-2: Integrating Sphere System used to Measure DHR

To test the spectral imaging concept using DHR measurements, NGC layered paint films of various thicknesses over non-corroded and corroded aluminum panels. The corroded aluminum panels were made by exposing them to salt fog. This resulted in a thin surface layer of oxide on the panel. Figure A-3 illustrates the DHR spectra of the same paint coating on two substrates, one non-corroded, the other corroded. The prominent reflectance of the non-corroded substrate between 3.5 to 5.0 μm is the result of the substrate reflecting the IR light through the transmissive window of the paint. Clearly the corrosion signature in the substrate is affecting the overall reflectance of paint on substrate combination.

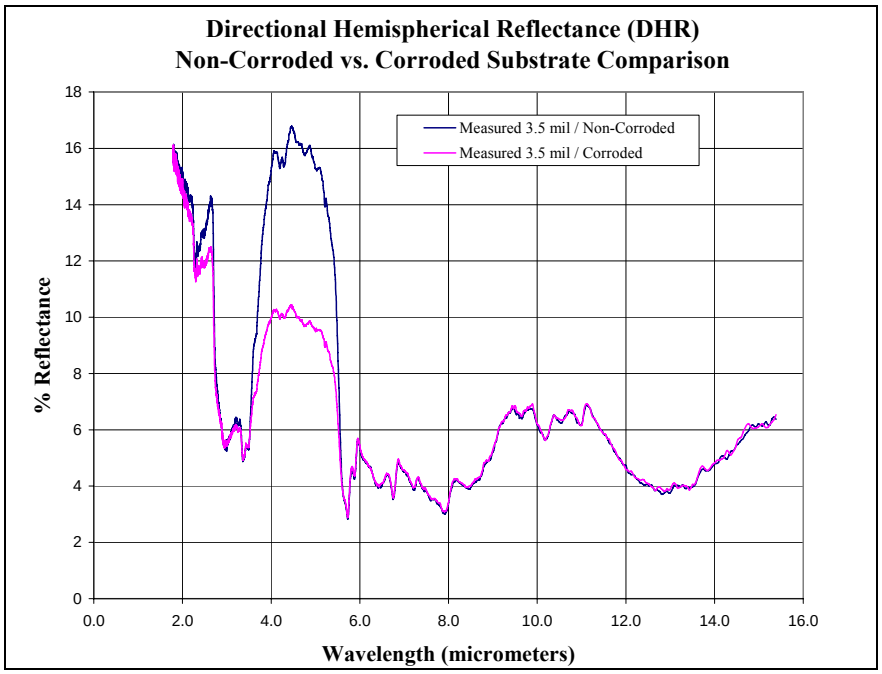


Figure A-3: DHR Comparison Between Non-Corroded and Corroded Substrates

Figure A-4 illustrates the DHR of a series of topcoat films of various thicknesses on top of a corroded aluminum substrate. The transmissive window in the 3.5 – 5.0 µm range becomes less prominent as the coating thickness increases.

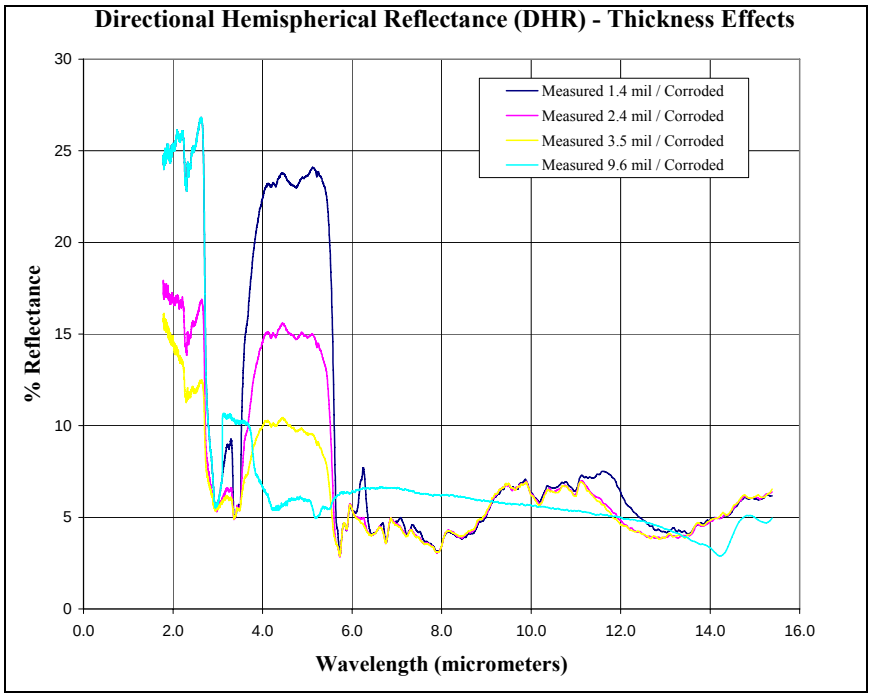


Figure A-4: DHR of Aluminum Panels with Variations in Coating Thickness

IRRIT Equipment Description

The Merlin® MWIR camera (refer to Table A-1) is manufactured by FLIR Systems Incorporated. FLIR Systems Incorporated contact information is as follows:

FLIR Systems Incorporated
Indigo Operations
70 Castilian Drive
Goleta, CA 93117
Corporate Office: 805-964-9797
www.indigosystems.com
www.flir.com

Merlin® Mid-Wave IR Camera System Setup

(Note: Refer to the Merlin® MWIR Camera Manual for specific operation details.)

Connections (refer to Figure A-5):

- 9-pin serial cable goes from the button panel to the remote control pad on Merlin® mid-wave IR camera.
- S-video cable goes from the S-video "out" on the Merlin® mid-wave IR camera to distribution amplifier that allows multiple S-video connections.
- S-video cable from the distribution amplifier out to the Sony HandyCam (or other video camcorder) and to a S-video "in" monitor.
- Optionally: BNC can go from composite video "out" on the Merlin® mid-wave IR camera to a BNC video "in" of an external monitor.
- DC power entry on the Merlin® mid-wave IR camera connects to the AC/DC transformer (Line supplied 24V DC) which is then plugged into a power strip outlet.
- AC power connects the IR illuminators power supply to the power strip outlet.

To "power-up" IRRIT:

- Connect power supply to the Merlin® mid-wave IR camera and turn on Power Strip. Green light on transformer will be illuminated.
- Turn on Merlin® mid-wave IR camera with the power switch on back of camera. Thermal cycling will be loud for 10-15 minutes as the Stirling cooler engages.
- Turn on HY1802D power supply to power IR source and set dial to selected voltage and current.
- Once the Merlin® mid-wave IR camera has cooled down, an image will be observed on the monitor. The Merlin® mid-wave IR camera should be allowed to stabilize for 30 minutes for best performance.
- Perform a one-point calibration (offset correction if using the Merlin® mid-wave IR camera keypad control, to clean up the noise. This can be accomplished via the remote control pad. Press the 1PT button. A message on the monitor will prompt the user to place the cool black painted panel in front of the lens. Press enter (the center

button) and wait for the screen to equilibrate to a uniform pattern. Then remove the black plate from the lens. At this point the Merlin® mid-wave IR camera should be pointed at the scene (surface) that is to be imaged to check for general image quality. If the scene area of interest appears too dark or too light, adjust the display brightness and contrast. If this does not improve the image quality an alternate non-uniformity correction (NUC) setting may be used to improve the image for the conditions encountered. The count level should be about 3000 counts of 4096 for the area of interest. Hold the black plate in front of the Merlin® mid-wave IR camera lens. The counts should be between 500 to 800 counts. If either the upper or lower count is much different use another NUC setting. Use one with a longer integration time if the counts are low or one with a shorter integration time if the counts are high. If the NUC setting is changed the offset correction will need to be repeated. The check of the A/D count levels should then be checked as well.

- A similar procedure using the analog display monitor could be used to view the Merlin® mid-wave IR camera output, as well as the control menu. Hold up the black plate in front of the Merlin® mid-wave IR camera lens and press the 1PT button to do a 1 point correction. Check the video levels by activating the Waveform function in the Calibration menu. There will be an oscilloscope like line displayed at the bottom of the display monitor. The line should show near the top of the oscilloscope display but not a clipped flat line at the top which would mean saturation. Similarly with the black plate in front of the lens the trace should be near the bottom of the display but not a flat line which indicates the offset is incorrect for the conditions. If needed a different NUC setting should be selected and the above repeated until a good image is achieved.

To "power-down" IRRIT:

- Power down devices: camcorder, blackbody sources, etc.
- Turn off Merlin® mid-wave IR camera.
- Power down the Merlin® mid-wave IR camera power supply.
- Power down the power strip.
- Put lens cap on Merlin® mid-wave IR camera.

Table A-1: Merlin® MWIR Camera Specifications

Merlin® MWIR Camera Specifications	
Detector Type	InSb
Spectral Range	1 - 5.4 µm (3 - 5 µm set by cold filter)
Detector Size	30 x 30 µm
Array Format	320 x 256
Integration Time	5 µs - 16.5 ms
Camera f/#	2.5 or 4.1
Cooling Type	Integral Stirling
Noise Equivalent Delta Temperature (NEΔT)	< 25 mK (< 18 mK typical)
Analog Video	NTSC @ 30 Hz (PAL @ 25 Hz optional); S-Video
Digital Video	60, 30*, 15* Hz (50 Hz PAL), 12-bit corrected/uncorrected (*Reduced frame rate option disables analog video.)
Remote Control	Button Panel & RS-232
Size	5.5 "H x 5.0 "W x 9.8 "L
Weight	9 lbs
Standard Temperature Measurement	0˚C to +350˚C
Extended Temperature Measurement	+300˚C to +2,000˚C
Temperature Accuracy	±2˚C , or ±2% of reading
Optics	Microscope: 1X 13 mm (41 x 31 degrees FOV) 25 mm (22 x 16 degrees FOV)

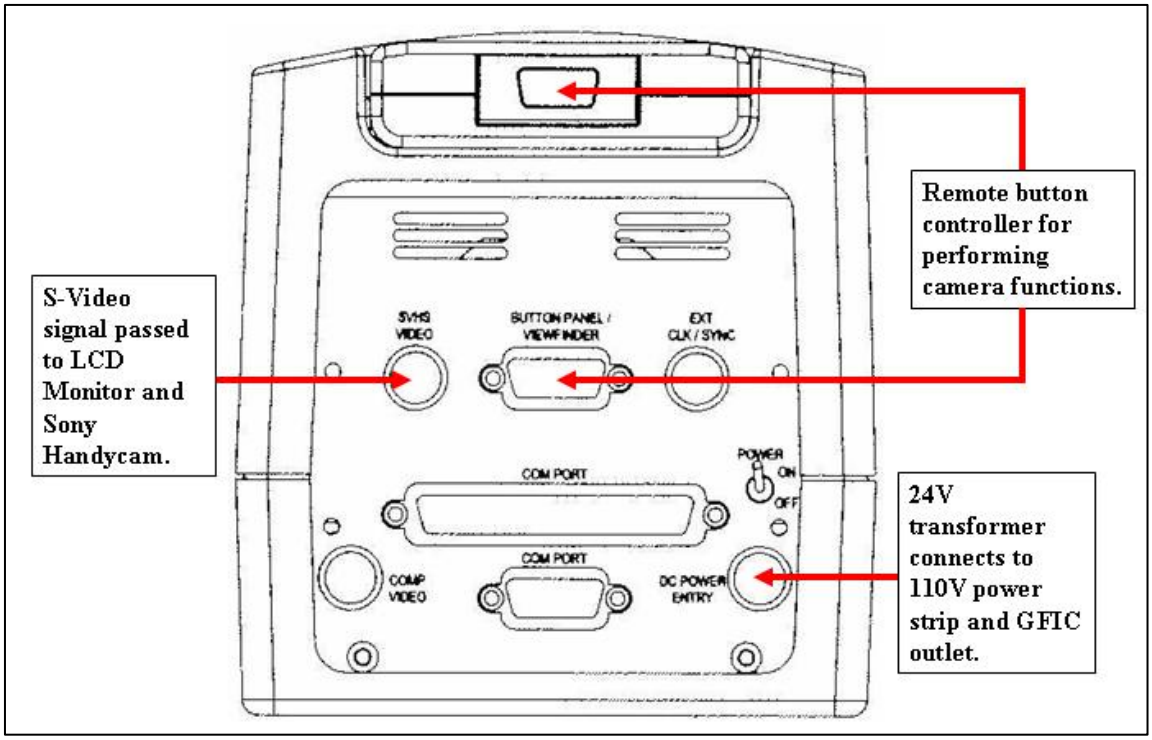


Figure A-5: Merlin® MWIR Camera Rear Panel

APPENDIX B ADDITIONAL PRODUCT TESTING

B.1 Dry Run (Risk-Reduction) @ NAS Jacksonville, FL

Objective:

The objective of this trip was to demonstrate a final risk reduction of the IRRIT system, prior to beginning the Dem/Val on the Navy P-3 in February 2006. This objective was achieved and the IRRIT system successfully imaged through the coating system that is currently used on the Navy P-3 aircraft (refer to Figure B-1).

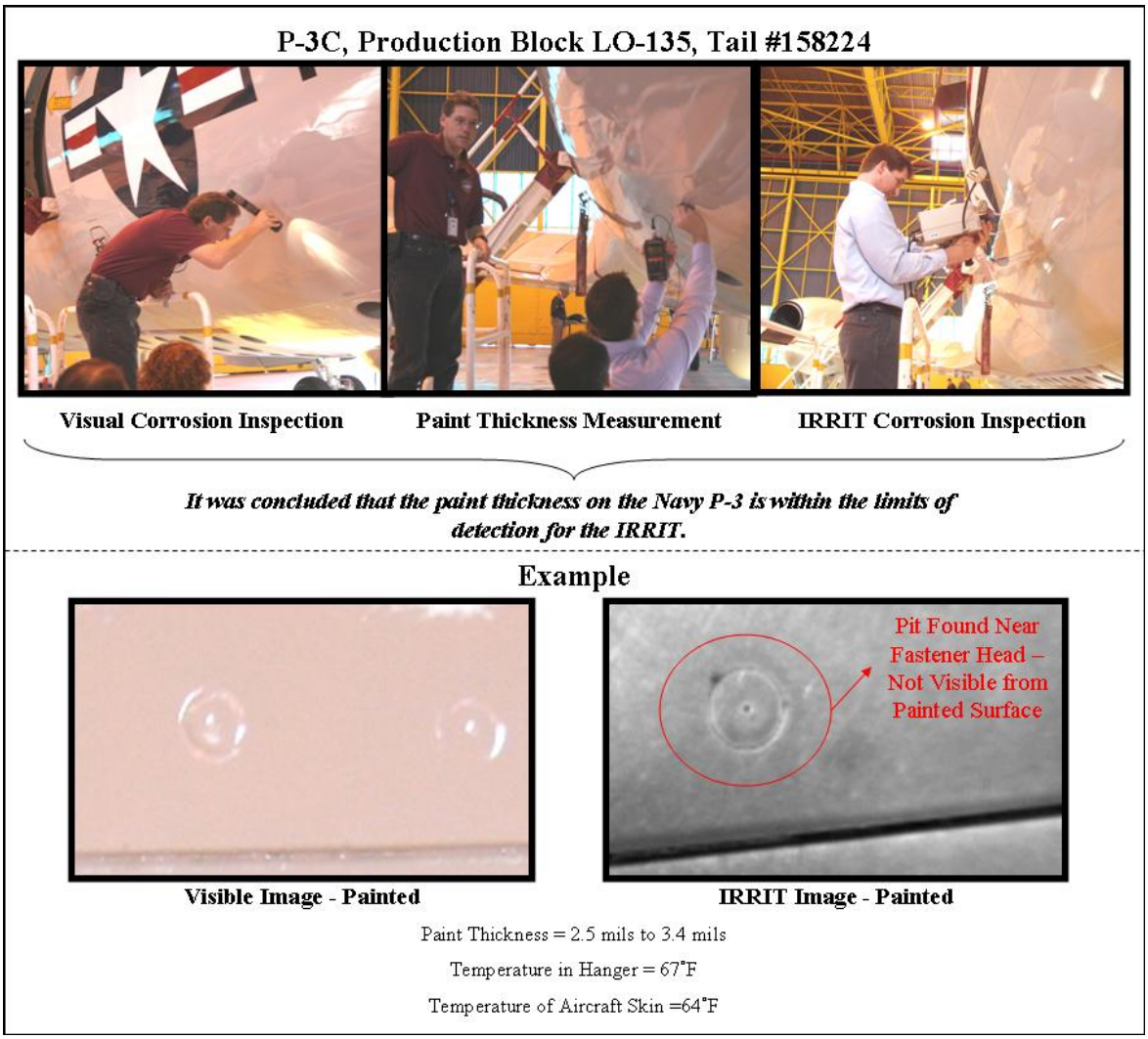


Figure B-1: Risk Reduction at NAS Jacksonville

In addition to the risk reduction, as previously reported the IRRIT team also demonstrated the IRRIT system for some NAVAIR personnel at NAS/NAVAIR Jacksonville (refer to Figure B-2).

Mr. Jack Benfer (NAVAIR) and Mr. John Weir (NGC) brief attendees on IRRIT and potential applications.

Figure B-2: Briefing on IRRIT System at NAS Jacksonville

B.2 USAF - Warner Robins, Georgia

Objective:
The objective of this trip was to demonstrate the IRRIT system to Warner Robins AFB Personnel.

Trip Summary:
25 October 2005

- Demonstrated IRRIT system on two C-130 aircraft (C-130 USAF Tail # 0987, C-130 USAF Tail # 51366). This was the first time the IR camera was used utilizing 110 power supplied from a portable power unit. No problems were observed with the utilization of this type of power. The first survey was of a C-130 (C-130 USAF Tail # 0987) with a coating thickness of approximately 9 to 16 mils. It was reported that the aircraft came from Hill AFB and that the top coat was the Deft Advanced Polyurethane Topcoat (APC) or also known as the Extended Life Top Coat. This aircraft was difficult to image the substrate under the coatings and it is surmised that this was due to the thickness of the coating present as well as the APC formulation in the darker color which may contain carbon black that tends to block IR transmission if the concentration is too high in the coating. The coating was also heavily "orange peeled", which may have been a contributing factor with contrast issues of the local coating thickness variations. The second survey was of another C-130 (ANG 51366 from the Texas Air National Guard) exhibiting coating thicknesses approximately 4.5 mils on exterior sections. Both IR photographs and conventional photographs were taken on this exterior location (refer to Figure B-3). The IML was also investigated on this aircraft (refer to Figure B-4). The IRRIT system successfully imaged through the thinner coated sections of the aircraft.

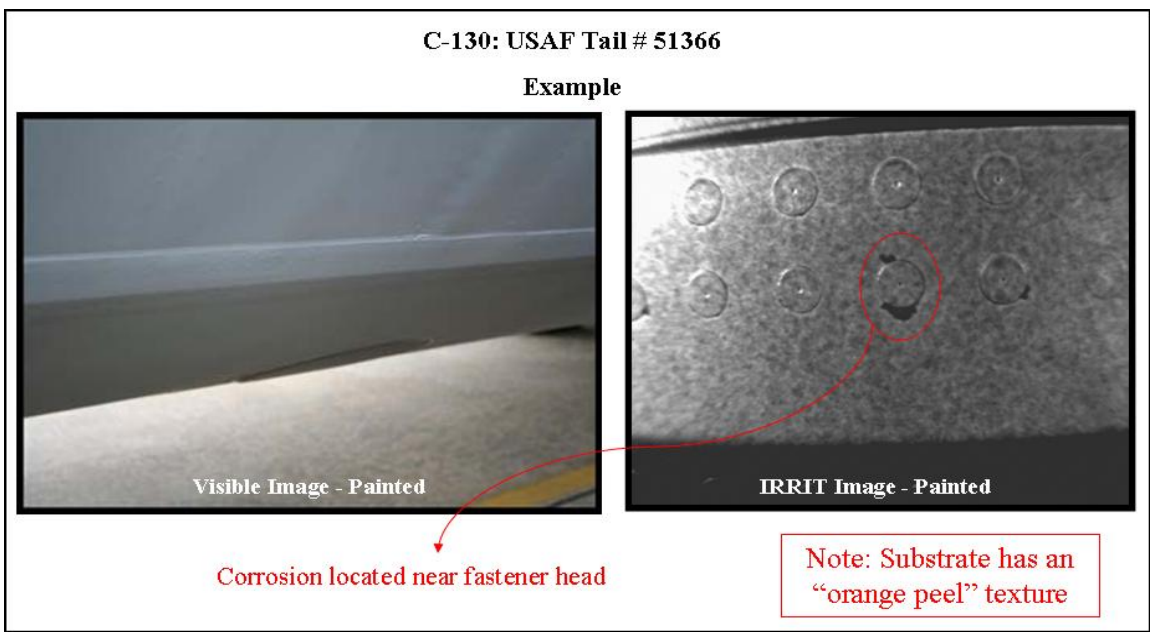


Figure B-3: Corrosion Under OML Coating of C-130

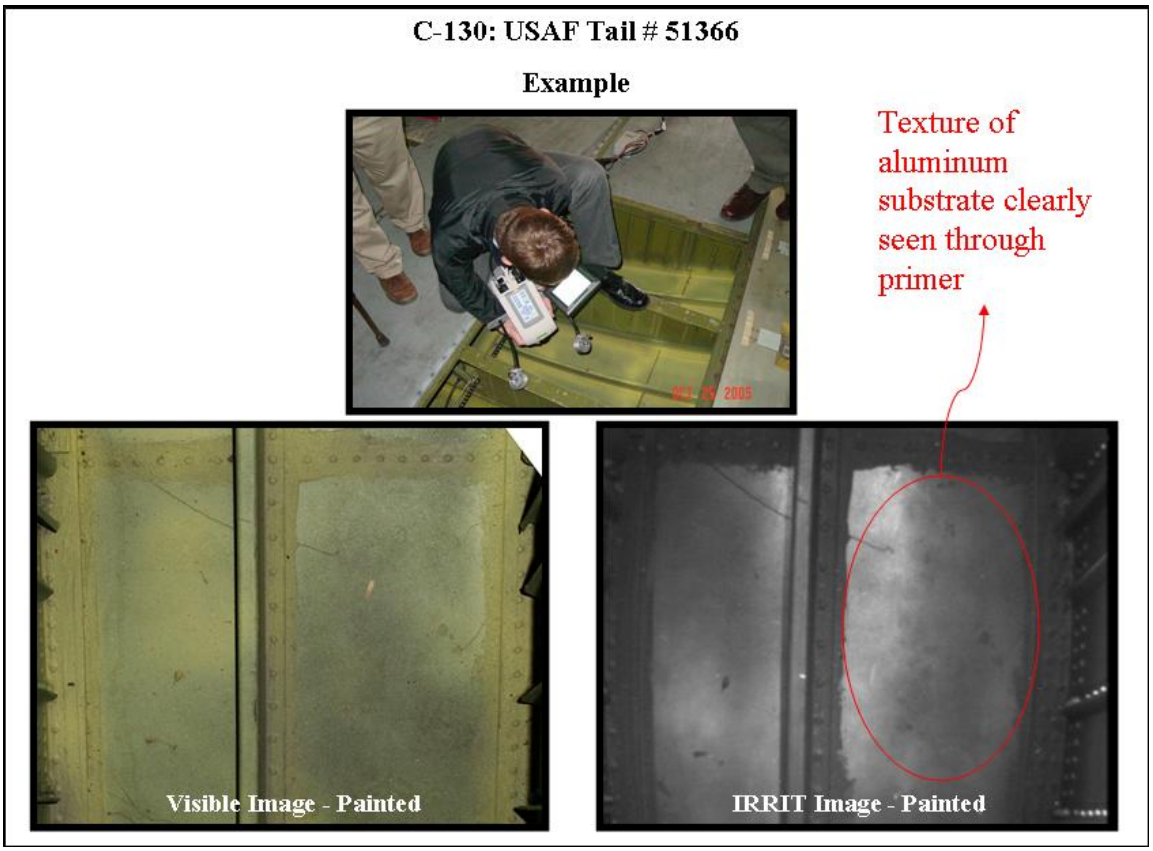


Figure B-4: Substrate Texture Under IML Coating of C-130

26 October 2005

- Demonstrated IRRIT system on C-17 aircraft (C-17 USAF Tail # 60006). The third airplane surveyed was a C-17 (AMC Charleston 60006). The paint thickness was on the order of 7 mils. This aircraft was difficult to image the substrate through the coatings and it is surmised that this was due to the thickness of the coating present as well as the APC formulation in the darker color which may contain carbon black that tends to block IR transmission if the concentration is too high in the coating. The coating was also heavily "orange peeled", which may have been a contributing factor with contrast issues of the local coating thickness variations. Due to the fact that the coating was difficult to image through, it was agreed that an FTIR measurement be conducted to establish the transmissibility of this finish system.

27 October 2005

- Demonstrated IRRIT system on C-130 aircraft (C-130 USAF Tail # 60215). The fourth survey was of another C-130 (USAF Tail # 60215) exhibiting coating thicknesses approximately 3.5-9 mils on exterior sections. Both IR photographs and conventional photographs were taken on this exterior location (refer to Figure B-5). The IRRIT system successfully imaged through the thinner coated sections of the aircraft. However, the IRRIT system was unable to image through the thicker coated sections.

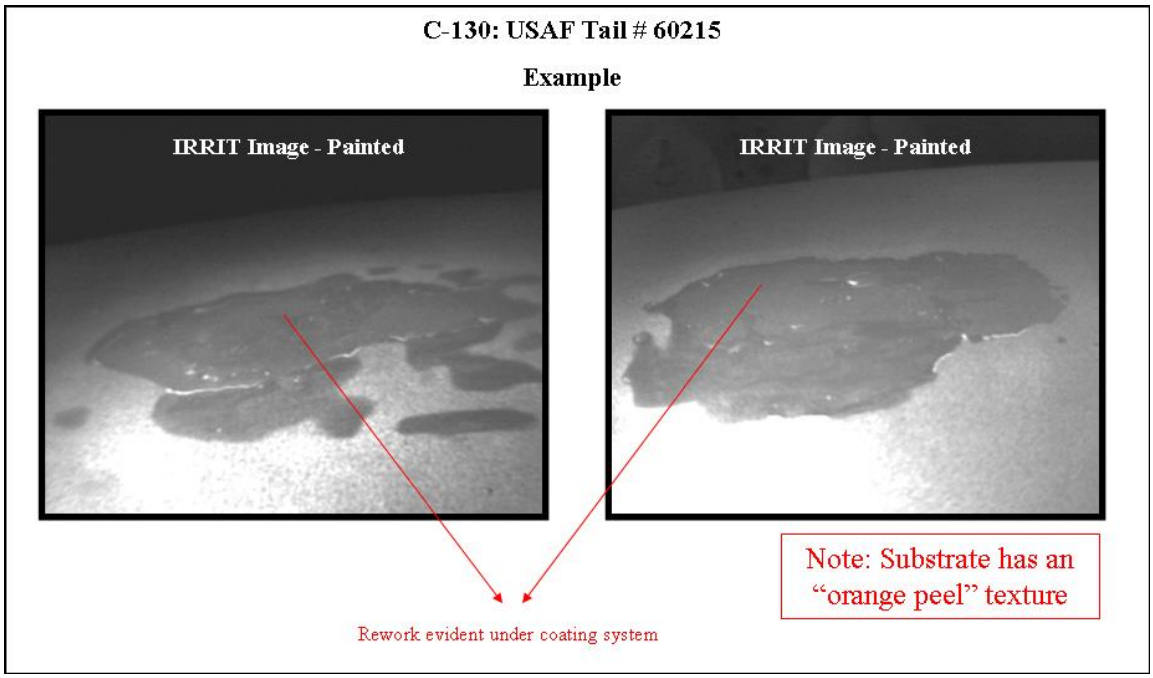


Figure B-5: Rework Under OML Coating of C-130

Conclusion:

- C-130 USAF Tail # 0987: Due to coating thickness (refer to Figure B-6) and type the IRRIT system appeared to have little success in imaging through the coating.
- C-130 USAF Tail # 51366: The IRRIT system successfully imaged through the thinner coated sections of the aircraft. However, the IRRIT system was unable to image through the thicker coated sections.
- C-17 USAF Tail # 60006: Due to coating thickness and type the IRRIT system appeared to have little success in imaging through the coating.
- C-130 USAF Tail # 60215: The IRRIT system successfully imaged through the thinner coated sections of the aircraft. However, the IRRIT system was unable to image through the thicker coated sections.
- It was concluded that the C-130 would not be a good platform to Dem/Val the IRRIT system due to the following:
    - Thick/Dark Coating System
    - Little Corrosion Under Coatings
- Future studies (coating transmission data required via free-standing films) must completed on the following coatings (varying thicknesses):
    - MIL-PRF-85285: Deft APC Color # 36173
    - MIL-PRF-85285: Deft APC Color # 36118
    - MIL-PRF-85285: Deft High Solids Color # 36293
    - TT-P-2756: Deft Self-Priming Color # 16440
    - TT-P-2760 Type 1: Deft Primer
    - MIL-PRF-85285: Deft APC Color # 17925
    - MIL-PRF-85285: Deft APC Color # 36375

- Investigate a replacement USAF platform to Dem/Val the IRRIT system on, potentially the KC-135 at Tinker AFB.

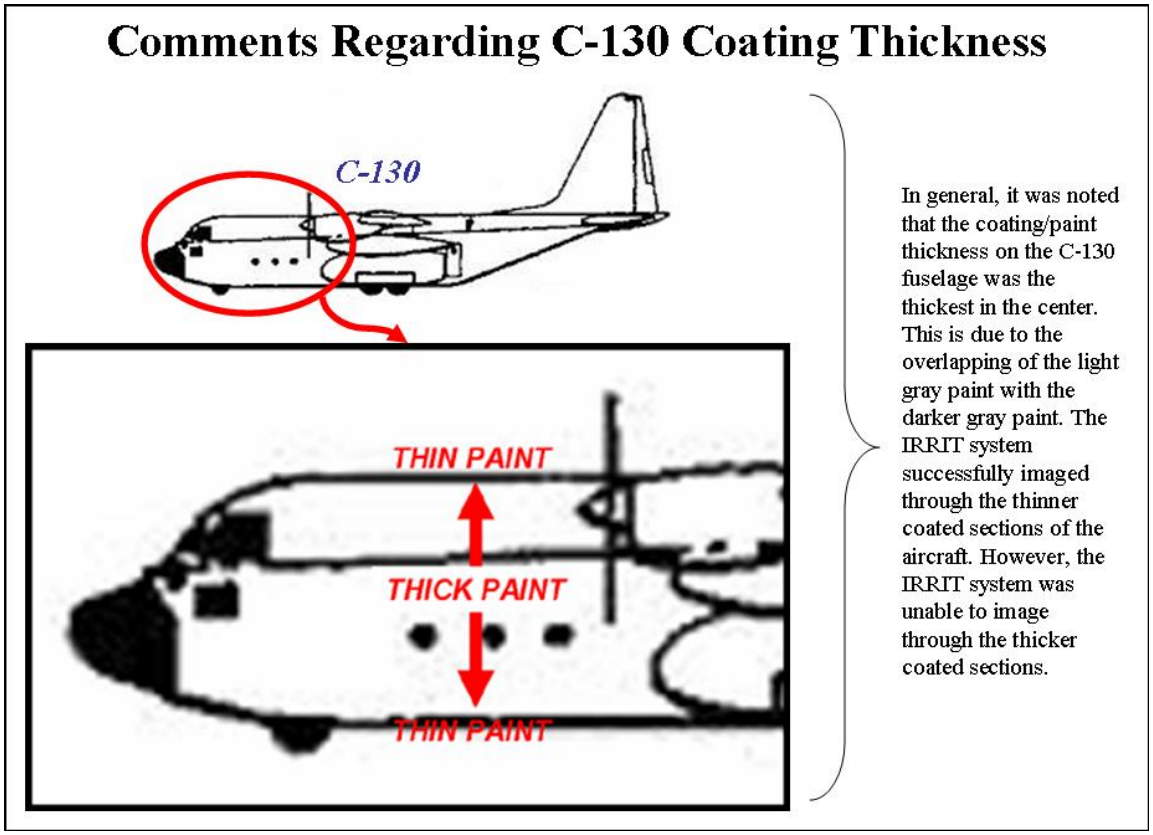


Figure B-6: Coating Thickness on C-130 OML

B.3 Dry Run (Risk Reduction) @ OC-ALC

Objective:
The objective of this trip was to check the feasibility of doing a Dem/Val on current IML KC-135 and B-52 aircraft at OC-ALC. The trip occurred from 17-20 April 2006. The IRRIT was demonstrated on the KC-135 and B-52 to OC-ALC personnel (refer to Figure B-7 and Figure B-8).

The trip conclusions are as follows:

- OC-ALC personnel are willing to support IRRIT Dem/Val on the KC-135, B-52.
- OC-ALC personnel are willing to arrange "time on aircraft", and schedules.
- OC-ALC personnel are willing to supply or direct us to who would be able to answer questions regarding environmental/cost data.

Dem/Val activities as shown below were discussed and agreed upon by OC-ALC Personnel:

Dem//Val Activities (Prior to Chemical Strip)	Dem/Val Activities (Post Chemical Strip)
• Record ambient/inspection area temperatures	• Record ambient/inspection area temperatures
• Record coatings thickness measurements	• Visually inspect indexed sites
• Visually inspect target areas	• Digitally photograph visible anomalies
• Mark/index and digitally photograph visible corrosion sties	• Inspect indexed sites using IRRIT
• Inspect target areas using IRRIT	• Record IR images of indexed sites
• Mark/index and record IR imaged corrosion sites	• Back-up and review data for analysis
• Chemically strip marked/indexed sites	

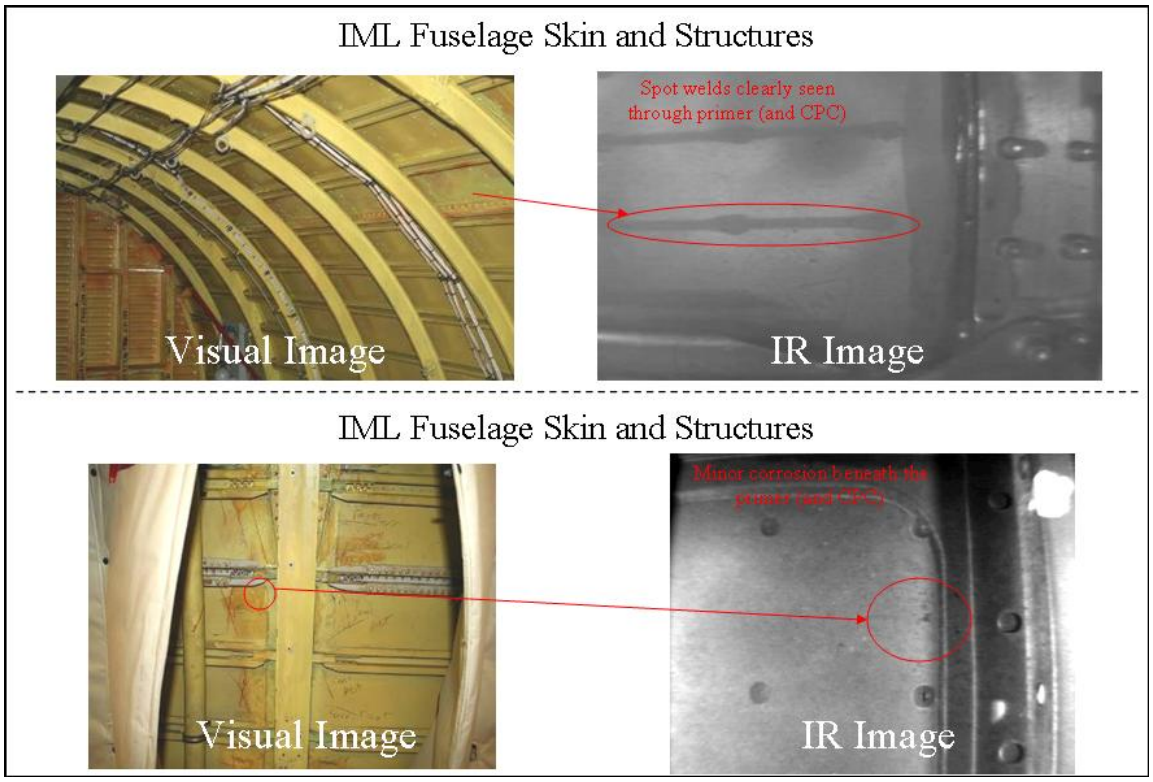


Figure B-7: KC-135 IML Visual and IR Images

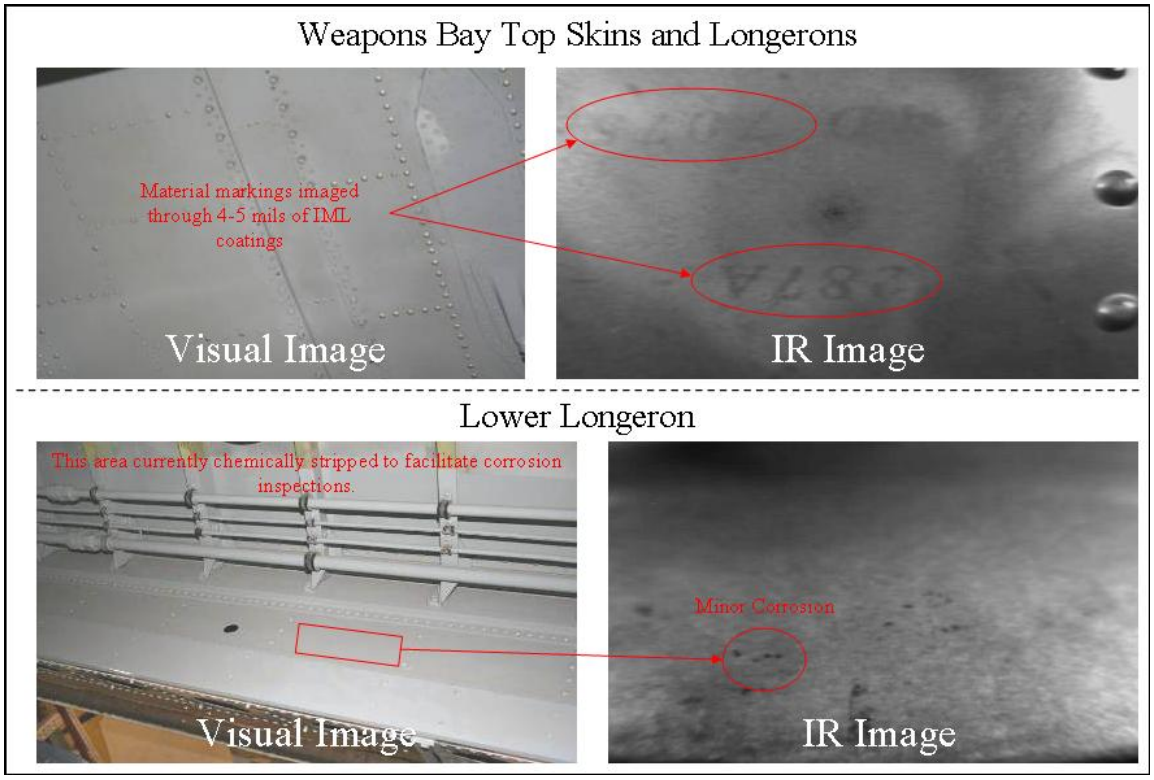


Figure B-8: B-52 IML Visual and IR Images

APPENDIX C IRRIT DEM/VAL QUALITY ASSURANCE/QUALITY CONTROL PLAN

1) Purpose and Scope:

This IRRIT Quality Plan is applicable to all persons participating in IRRIT Dem/Val Program. The purpose of this plan is to assure that data obtained during the IRRIT Dem/Val at NAVAIR Depot Jacksonville and OC-ALC, is recorded and stored for future analysis in accordance to ESTCP directions. It is the responsibility of IRRIT Principal Investigator (PI), government employees, and contractors to carryout programmatic and technical activities so as to meet any Government and/or NGC quality requirements. .

2) Quality Assurance (QA) Officer Responsibility:

The IRRIT Organization and Responsibility Organization Chart, (Figure C-1) depicts personnel and their responsibility in the IRRIT Quality Program.

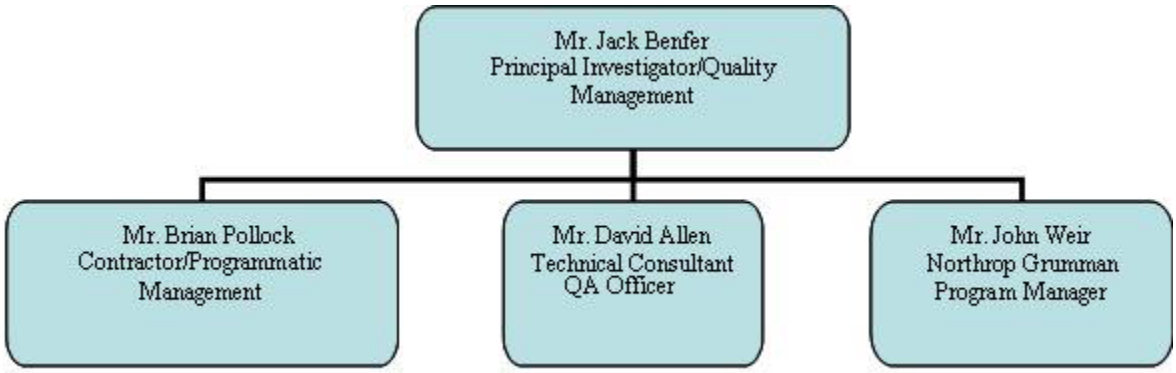


Figure C-1: IRRIT Organization and Responsibility Chart

a) Mr. Jack Benfer, IRRIT PI is ultimately responsible for planning, implementing, and assessing all quality control procedures applicable to the IRRIT Program.
b) Mr. David Allen, an independent contractor separate from the personnel engaged in the execution of IRRIT Dem/Val, was appointed by the PI to oversea the IRRIT Quality Program as the QA Officer. The QA Officer has a broad responsibility for managing/monitoring the IRRIT Quality Program to ensure proper implementation of quality guidelines. Specific QA Officer responsibilities are as follows:
    i) The QA Officer shall periodically inspect activities during the Dem/Val at adequate intervals to evaluate its integrity. The QA Officer shall record the date of the inspection, the Dem/Val activity inspected, the phase or segment of the Dem/Val inspected, the person performing the inspection, any findings and problems, actions recommended and taken to resolve existing problems, and any scheduled date for re-inspection.
    ii) The PI and QA Officer shall review the Dem/Val report to ensure that it accurately describes the Dem/Val Plan methods and standard operating procedures, and that the reported results accurately reflect the raw data required of the Dem/Val.
    iii) The QA Officer shall ensure that all relevant documents, procedures, and corrective actions pertaining to activities covered under the IRRIT Quality

Plan are reviewed and approved for use by the PI. For example, IRRIT Data Sheets and the Corrective Action Report developed for this Dem/Val Plan.

iv) The QA Officer shall maintain control of unassigned serialized laboratory notebooks and the list of numerically indexed serialized laboratory notebooks for the Program.

c) NGC's project manager, Mr. John Weir and his staff, are responsible for all quality control needed to collect meaningful data, as it relates to the detection of corrosion under coating and the use of all equipment such as the IR camera, photographic images, and data storage. NGC personnel shall report quality or procedural concerns to the IRRIT PI or QA Officer.

d) All contractors or government employees involved in the IRRIT Program shall familiarize themselves with the IRRIT Quality Plan and implement applicable procedures to ensure that essential data are collected and that collected data will be useful. All personnel participating in the IRRIT Program shall avoid involvement in any activities that would diminish confidence in the program's competence, impartiality, judgment or operational integrity.

3) Data Quality Parameters and Format:

The data to be collected will include IR images of the test areas, visual images of the preprocessed test areas, and visual images of the chemically stripped test areas. Images from before and after various stages in the strip/paint process will be compared in order to validate the performance of IRRIT. All parameters associated with the process [equipment (camera and IR source), vehicles (paint thickness and color), and environment (temperature and sunlight)] shall be recorded on IRRIT Data Sheets.

4) Calibration Procedures, Quality Control Checks, and Corrective Actions:

a) <u>Calibration Procedures</u>: equipment and its software used for the IRRIT Dem/Val shall be capable of achieving the accuracy required of the camera equipment/DAS specified in the Dem/Val Plan, and shall comply with relevant specifications or procedures.

- The IR camera will be checked at the beginning of the day, as a minimum, for image quality and at the end of operations or the end of an eight hour shift, which ever comes first. The same image standard will be used to perform this function. This image will be documented and stored for future reference. This procedure will also be repeated, if any change to the camera is made such as modification of the temperature correction factor. In the event the image quality has degraded, the corrective action will be to understand what camera parameters have changed or if the camera is defective. Parameters will be adjusted to establish acceptable image quality, prior to use. In the unlikely event the camera is defective or is broken, NGC has a backup camera that will be used to continue the Demonstration and Validation

b) <u>Quality Control Checks, and Corrective Actions</u>: if technical activities deviate from the Optimization/Baseline Test Plan, or if Dem/Val activities fail to function as expected, the person performing the activity shall originate an IRRIT Dem/Val Corrective Action Report and complete the following actions;

i) The originator shall immediately halt activities if its continuation results in an unsafe condition or adversely affects data integrity.
ii) The originator shall then notify the PI or QA Officer via email, phone or on-site who will began to track and monitor the corrective action report.
iii) The QA Officer shall ensure that all pertinent information is entered correctly and the corrective action report is distributed to the appropriate people.
iv) The originator shall document corrective actions/preventive measures and notify the PI or QA Officer.
v) The originator, PI, and QA Officer shall maintain a copy of the IRRIT Corrective Action Report. Once closed, corrective action reports shall be maintained together in a single binder and filed with other data in conformance with the ESTCP approved data quality requirements.
vi) Note: the originator shall also document and immediately notify the PI or QA Officer of problems involving material shortages or hardware failure in support of the Dem/Val.

5) Demonstration Procedures:

The inspection operating parameters will be determined prior to Dem/Val during camera optimization/baseline testing. Once the data acquisition setup is connected, powered, and the camera is cooled, an image should appear on the monitor. A rapid survey scan of the target area will be completed, with a monitor displaying the region for any signs of corrosion. Sites of interest will be marked with a grease pencil. Results from the visual inspection and images prior to and after various stages in the strip/paint process will be compared in order to validate the performance of the IRRIT technique.

6) Quality Program Review:

The PI and the QA Officer shall review the IRRIT Quality Program to ensure personnel, equipment, activities, records, and controls are in conformance with the ESTCP quality requirements.

a) All personnel shall review all applicable quality requirements prior to, during, and following any activity under the scope of the IRRIT Quality Plan.
b) The PI and QA Officer shall review discrepancies and corrective actions/preventive measures to ensure all discrepancies were properly documented and resolved.
c) The PI and QA Officer shall review the final Dem/Val report to ensure that it accurately describes the Dem/Val methods and standard operating procedures, and that the reported results accurately reflect the raw data required of the Dem/Val.

7) Data Storage and Archiving:

a) Personnel performing activities shall ensure all relevant data is entered at the time of activity into a serialized, bound laboratory notebook or onto the IRRIT Data Sheet. Activity, performance method, the specific equipment, and individual performing the activity shall be recorded. When the laboratory notebook is full the QA Officer shall issue a new bound serialized notebook. The PI will have

access to all notebooks at all times. The notebooks will be indexed numerically. Upon program completion, all bound serialized notebooks shall be disposed of according to ESTCP direction. All laboratory notebooks shall be signed and dated at the beginning and end of each workday by all persons making notes and recording data. Analog video will be captured, as well as digital images and saved to disk.

b) Upon program completion, all bound serialized notebooks, Data Sheets, diskettes, and corrective action reports shall be archived in accordance with ESTCP direction.

c) Any deviations or recommendations for the modification to this plan shall be reported to the PI for his review and approval.

APPENDIX D OPTIMIZATION/BASELINE TEST PLAN

1. INTRODUCTION

The purpose of this laboratory test plan is to evaluate the capabilities and limits of the Infrared Reflectance Imaging Technique (IRRIT), in addition to the blackbody technique (these techniques are defined in Section 1.2). Through various test evaluations in the laboratory, a database will be created, along with procedures that may be applied onsite in the field as applicable. The focus of the testing shall be primarily to create a system that is optimized for field use; in particular the Navy's P-3 Orion aircraft (refer to Figure D-1 for potential use on other platforms).

1.1. Scope

This document shall optimize and baseline the IRRIT for use in the "field". The test matrices shall encompass representative military coatings and coating thicknesses, along with the potential and anticipated variables that may be encountered in field and depot operations. A number of test specimens will be created to simulate these potential variables. The test specimens will utilize alloys, surface preparations, and coatings that are identical to the preparations and materials used on the military platforms. Whenever possible, screening tests will be utilized to minimize unnecessary work and to focus resources on the relevant issues. Optimization of the camera type associated variables will also be addressed along with the field variables. Optimization of the technique shall be achieved by testing and coming to conclusions regarding the following variables:

- **Typical Military Coatings (Primers and Topcoats)**
  - *How transparent (allowing IR reflection) is the coating in the 3-5µm IR range?*
- **Thickness Range of Coatings (Simulate "Real-Life" Coating Stack-Ups, and Limits of IRRIT)**
  - *At what thickness will the coating no longer be transparent in the 3-5µm IR range?*
- **Surface Temperature**
  - **IR Reflection**
    - *Is external IR illumination required to penetrate coating, thus allowing IR reflection?*
  - **Blackbody**
    - *Is the substrate naturally emitting IR (no external IR illumination required)?*
- **Distance from Surface (IR Camera Lens to Surface of Substrate)**
  - *How large of a corrosion defect can be seen at a certain distance away from the substrate (corrosion/defect sensitivity)?*

Upon completion of testing the above variables, a "database/library" shall be created. The goal of this laboratory test plan is to supply the "field" user with the answers to the following questions:

- *Can the method of IRRIT be used on this particular platform?*

- *What would the optimized internal camera settings be for this particular paint scheme, coating thickness, and surface temperature (Non-Uniformity Correction, NUC)?*
- *Is external IR illumination required, or is the part naturally emitting IR?*

Navy

Army

Coast Guard

Air Force

Figure D-1: Military Vehicle Platforms

1.2. Technology Description

IRRIT: The IR passes directly through the coating and then reflects off the metallic substrate back through the coating and into an IR camera. Since the corroded areas do not reflect the IR energy as well as the non-corroded areas, a picture or image is generated by the IR camera much the same as observing the corrosion under standard visual techniques. The corrosion does not reflect the energy, as will the smooth aluminum surfaces that that is why the corrosion appears dark.

Blackbody Technique: This method has the advantage in that the illumination is provided by the part itself and not by an external source. The aluminum parts emit or transmit IR radiation at room temperature (RT) or slightly above RT. In the case of aircraft paints the paint has a transmission window in the 3-5μm region, so the IR can be viewed, as it is emitted from the surface. The corrosion emits more energy due to its emissive characteristics than the smooth aluminum surface and that is why the corrosion looks white.

1.3. Referenced Documents

Specifications:

Department of Defense, Federal, and Military

MIL-C-5541	Chemical Conversion Coatings on Aluminum and Aluminum Alloys
MIL-PRF-85582	Primer Coatings: Epoxy, Waterborne
MIL-PRF-85285	Coating: Polyurethane, Aircraft and Support Equipment
QPL-85285	Qualified Product List of Products Qualified Under Performance Specifications MIL-PRF-85285 Coating: Polyurethane, High-Solids
FED-STD-595	Colors Used in Government Procurement

American Society for Testing and Materials

ASTM B117	Standard Practice for Operating Salt Spray (Fog) Apparatus
ASTM D1654	Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments
ASTM D2803	Filiform Corrosion Resistance of Organic Coatings on Metal
ASTM E1213	Standard Test Method for Minimum Resolvable Temperature Difference for Thermal Imaging Systems
ASTM E1311	Standard Test Method for Minimum Detectable Temperature Difference for Thermal Imaging Systems
ASTM E1543	Standard Test Method for Noise Equivalent Temperature Difference of Thermal Imaging Systems
ASTM F1110	Sandwich Corrosion Test
ASTM G1	Preparing, Cleaning, and Evaluating Corrosion Test Specimens
ASTM G46	Examination and Evaluation of Pitting Corrosion

Indigo Merlin® Mid-Wave IR (MWIR) Camera Manual

2. HEALTH AND ENVIRONMENTAL CONSIDERATIONS

While the methods, applications, and processes described or referenced in this document may involve the use of HAZMATs, this document does not address the handling of HAZMATs. It is the sole responsibility of the user to ensure familiarity with the safe and proper use of any HAZMATs and to take necessary precautionary measures to ensure the health and safety of all personnel involved.

3. TESTING PARAMETERS

Test specimens shall be manufactured and tested to the following test parameters. Once the testing parameters (the limits of the system) are well understood, the final system configuration(s) and performance baselines shall be established (and documented) for the demonstration/validation on the P-3 aircraft.

3.1. Test Panel Design

All test panels created shall be documented with the IR camera in addition to a digital visible camera prior to the any coating (primer/topcoat) is applied. The test specimens that will be created will be manufactured and tested via IRRIT and Blackbody, and will be representative of the various military platforms, in terms of coating types, coating thickness, and corrosion defects.

3.1.1. Coating Substrates Types and Thicknesses

The coatings used in this laboratory test plan are based on those used on the P-3 Orion aircraft. If the intent is to use this technique on a different paint scheme other than that used on the P-3, the "different" paint scheme must be tested with a Fourier-Transform Infrared (FTIR) instrument. An FTIR will basically provide a spectral "fingerprint" of the coating, or coating stack up. Whether or not the IRRIT works for a particular coating is based on how much 3-5μm IR wavelength can be transmitted thru the coating, the more IR that is transmitted thru the coating the better your imaging with the IRRIT.

3.1.1.1. Navy Paint Schemes (P-3 Aircraft)

3.1.1.1.1. Primer and Topcoat

The P-3 (OML) uses Deft Primer Part No. 44-GN-7 Epoxy Primer meeting MIL-PRF-85582 Type 1. The Top Coat is Hentzen, MIL-PRF-85285 Type 1 Urethane, Federal Standard Color No. 16440, part # 04644AUX-3. The normal thickness of these coatings will be investigated, as well as thickness values that may be encountered in service. For example it is anticipated that thickness of coatings up to 4.8 mils total (paint spec) and 7.2 mils total (fleet touchup) will be tested, as worst-case scenarios. Thickness values above 7.2 mils total will not be tested, for this particular paint scheme. It is assumed that the aircraft would be stripped and hence no pollution savings would justify the requirement to see under coatings thicker than 7.2 mils.

3.2 Optimization/Baseline

A 13 mm lens (primary lens to be used) will be used with the Indigo Merlin® mid-wave IR (MWIR) camera since it will give reasonable standoff distances for the demonstration/validation work. This lens gives FOV angles of 41 degrees in the horizontal axis and 31 degrees in the vertical axis of the camera focal plane. Table D-1 illustrates the FOV in inches corresponding to a distance in inches from the object surface. The instantaneous field of view (IFOV) resolution is essentially the FOV of an individual pixel of the focal plane. This is the minimum size feature the camera can resolve at a particular distance with this lens. The camera may detect smaller features depending on the contrast of the feature to the surrounding area, but it will be displayed at the IFOV resolution. Refer to Table A-1 in Appendix B for the Merlin® mid-wave IR camera specifications. Information relating to the field of FOV and working distance and resolution for the 13mm and 25mm lenses can be found in Table D-1 and Table D-2.

Table D-1: FOV in Inches for 13mm Lens

Distance to Surface Inches	Horizontal FOV	IFOV Resolution in Inches	IFOV Resolution in Millimeters	Vertical FOV	IFOV Resolution in Inches	IFOV Resolution in Millimeters
4	2.99	0.01	0.24	2.22	0.01	0.23
5	3.74	0.01	0.30	2.77	0.01	0.29
6	4.49	0.01	0.36	3.33	0.01	0.35
7	5.23	0.02	0.42	3.88	0.02	0.41
8	5.98	0.02	0.47	4.44	0.02	0.47
9	6.73	0.02	0.53	4.99	0.02	0.53
10	7.48	0.02	0.59	5.55	0.02	0.59
11	8.23	0.03	0.65	6.10	0.03	0.65
12	8.97	0.03	0.71	6.66	0.03	0.70
14	10.47	0.03	0.83	7.77	0.03	0.82
15	11.22	0.04	0.89	8.32	0.03	0.88
16	11.96	0.04	0.95	8.87	0.04	0.94
17	12.71	0.04	1.01	9.43	0.04	1.00
18	13.46	0.04	1.07	9.98	0.04	1.06
19	14.21	0.04	1.13	10.54	0.04	1.12
20	14.96	0.05	1.19	11.09	0.05	1.17
21	15.70	0.05	1.25	11.65	0.05	1.23
22	16.45	0.05	1.31	12.20	0.05	1.29
23	17.20	0.05	1.37	12.76	0.05	1.35
24	17.95	0.06	1.42	13.31	0.06	1.41
25	18.69	0.06	1.48	13.87	0.06	1.47
26	19.44	0.06	1.54	14.42	0.06	1.53
27	20.19	0.06	1.60	14.98	0.06	1.58
28	20.94	0.07	1.66	15.53	0.06	1.64
29	21.69	0.07	1.72	16.08	0.07	1.70
30	22.43	0.07	1.78	16.64	0.07	1.76
31	23.18	0.07	1.84	17.19	0.07	1.82
32	23.93	0.07	1.90	17.75	0.07	1.88
33	24.68	0.08	1.96	18.30	0.08	1.94
34	25.42	0.08	2.02	18.86	0.08	2.00
35	26.17	0.08	2.08	19.41	0.08	2.05
36	26.92	0.08	2.14	19.97	0.08	2.11
37	27.67	0.09	2.20	20.52	0.09	2.17
38	28.42	0.09	2.26	21.08	0.09	2.23
39	29.16	0.09	2.31	21.63	0.09	2.29
40	29.91	0.09	2.37	22.19	0.09	2.35
41	30.66	0.10	2.43	22.74	0.09	2.41
42	31.41	0.10	2.49	23.30	0.10	2.47
43	32.15	0.10	2.55	23.85	0.10	2.52
44	32.90	0.10	2.61	24.40	0.10	2.58
45	33.65	0.11	2.67	24.96	0.10	2.64
46	34.40	0.11	2.73	25.51	0.11	2.70
47	35.15	0.11	2.79	26.07	0.11	2.76
48	35.89	0.11	2.85	26.62	0.11	2.82

Note = Items in yellow are the prime distances of interest for the optimization/baseline testing.

Table D-2: FOV in Inches for 25mm Lens

Distance to Surface Inches	Horizontal FOV	IFOV Resolution in Inches	IFOV Resolution in Millimeters	Vertical FOV	IFOV Resolution in Inches	IFOV Resolution in Millimeters
12	4.67	0.01	0.37	3.37	0.01	0.36
13	5.05	0.02	0.40	3.65	0.02	0.39
14	5.44	0.02	0.43	3.94	0.02	0.42
15	5.83	0.02	0.46	4.22	0.02	0.45
16	6.22	0.02	0.49	4.50	0.02	0.48
17	6.61	0.02	0.52	4.78	0.02	0.51
18	7.00	0.02	0.56	5.06	0.02	0.54
19	7.39	0.02	0.59	5.34	0.02	0.57
20	7.78	0.02	0.62	5.62	0.02	0.59
21	8.16	0.03	0.65	5.90	0.02	0.62
22	8.55	0.03	0.68	6.18	0.03	0.65
23	8.94	0.03	0.71	6.46	0.03	0.68
24	9.33	0.03	0.74	6.75	0.03	0.71
25	9.72	0.03	0.77	7.03	0.03	0.74
26	10.11	0.03	0.80	7.31	0.03	0.77
27	10.50	0.03	0.83	7.59	0.03	0.80
28	10.89	0.03	0.86	7.87	0.03	0.83
29	11.27	0.04	0.89	8.15	0.03	0.86
30	11.66	0.04	0.93	8.43	0.04	0.89
31	12.05	0.04	0.96	8.71	0.04	0.92
32	12.44	0.04	0.99	8.99	0.04	0.95
33	12.83	0.04	1.02	9.28	0.04	0.98
34	13.22	0.04	1.05	9.56	0.04	1.01
35	13.61	0.04	1.08	9.84	0.04	1.04
36	14.00	0.04	1.11	10.12	0.04	1.07
37	14.38	0.04	1.14	10.40	0.04	1.10
38	14.77	0.05	1.17	10.68	0.04	1.13
39	15.16	0.05	1.20	10.96	0.05	1.16
40	15.55	0.05	1.23	11.24	0.05	1.19
41	15.94	0.05	1.27	11.52	0.05	1.22
42	16.33	0.05	1.30	11.81	0.05	1.25
43	16.72	0.05	1.33	12.09	0.05	1.28
44	17.11	0.05	1.36	12.37	0.05	1.31
45	17.49	0.05	1.39	12.65	0.05	1.34
46	17.88	0.06	1.42	12.93	0.05	1.37
47	18.27	0.06	1.45	13.21	0.06	1.40
48	18.66	0.06	1.48	13.49	0.06	1.43
49	19.05	0.06	1.51	13.77	0.06	1.46
50	19.44	0.06	1.54	14.05	0.06	1.49
51	19.83	0.06	1.57	14.34	0.06	1.52
52	20.22	0.06	1.60	14.62	0.06	1.55
53	20.60	0.06	1.64	14.90	0.06	1.58
54	20.99	0.07	1.67	15.18	0.06	1.61
56	21.77	0.07	1.73	15.74	0.07	1.67
57	22.16	0.07	1.76	16.02	0.07	1.70
58	22.55	0.07	1.79	16.30	0.07	1.73
59	22.94	0.07	1.82	16.58	0.07	1.76
60	23.33	0.07	1.85	16.86	0.07	1.78
61	23.71	0.07	1.88	17.15	0.07	1.81
62	24.10	0.08	1.91	17.43	0.07	1.84
63	24.49	0.08	1.94	17.71	0.07	1.87
64	24.88	0.08	1.97	17.99	0.07	1.90
65	25.27	0.08	2.01	18.27	0.08	1.93
66	25.66	0.08	2.04	18.55	0.08	1.96
67	26.05	0.08	2.07	18.83	0.08	1.99
68	26.44	0.08	2.10	19.11	0.08	2.02
69	26.82	0.08	2.13	19.39	0.08	2.05
70	27.21	0.09	2.16	19.68	0.08	2.08

When the camera is looking at a gloss painted surface care must be taken with the IR illumination. If the camera is looking at a gloss reflective surface, hot sources within the virtual FOV will be imaged (see Figure D-2), as with a mirror. Hot IR sources should be placed outside the virtual FOV with the sources directed toward the area to be viewed. An approach that may be used is to illuminate the area with a low temperature broad area diffuse source within the FOV, which would not saturate the camera, but would provide sufficient illumination to see under the paint. If the surface is a matt or "camouflage" type surface the light would be diffused and would not be re-imaged.

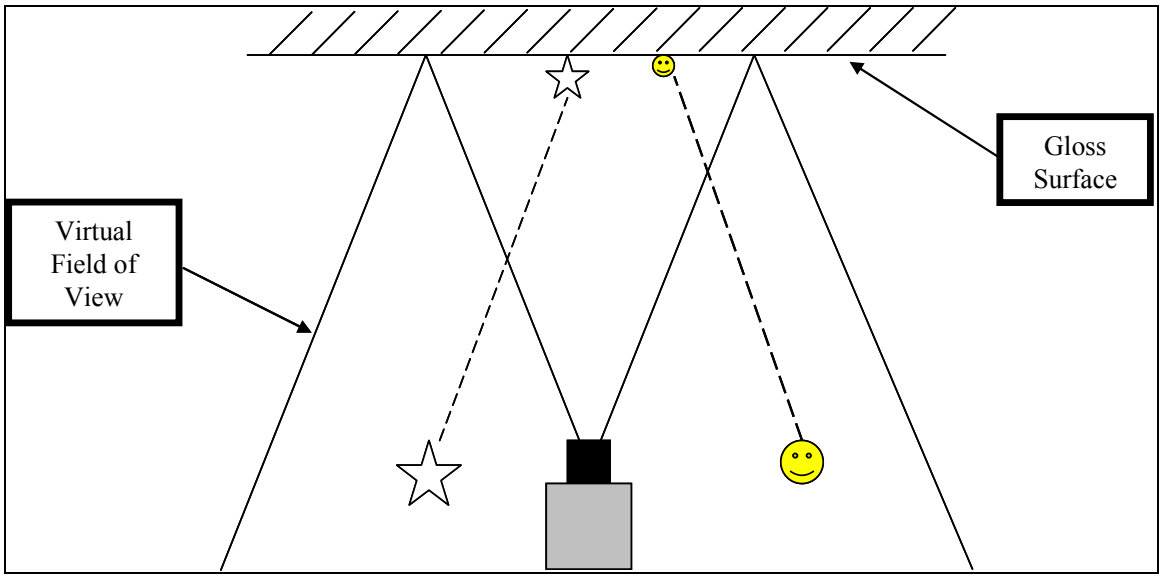


Figure D-2: Virtual FOV

3.3. Specialty Coating Types and Thicknesses

The regions on the P-3 Orion that we are completing the Dem/Val are composed of typical aircraft coatings that we have tested (via FTIR and with the IRRIT) and know to be transparent in the wavelength that we are interested in. Optimized camera settings that will be established upon completion of this test plan will be used as the same settings that will be accomplished while imaging specialty coatings. An example of a specialty coating is:
AMS-C-27725 Fuel Tank Coating, QPL PRC DeSoto Part # 825X309

3.4. Part Contours and Geometry

Due to the fact that the surfaces on aircraft are not all flat, studies must be accomplished to find the optimized camera distance to the surface and proper IR illumination. IR illumination becomes sensitive in regions that are extremely curved. The goal of the laboratory studies shall be to find the optimized distance that the illuminators shall be from the camera so that they do not reflect (and become bright spots/locations) on the focal plane. The illuminators should be out of the FOV, yet still provide sufficient illumination to penetrate the coating. A few samples with varying geometry (refer to

Figure D-6, Figure D-7, Figure D-8, and Figure D-9) and bulk corrosion defects will be manufactured and coated with the P-3 paint scheme, to establish the optimized distance. The following optimized parameters shall be recorded, as a result of a given contour/geometry:

- FOV at a given distance
- Optimized illuminator distance and angles

3.5. Dust, Dirt, Oils, and Grease

Surface contaminations will be investigated, including oil, grease, dust, fuel, water, and hydraulic fluid. In the Dem/Val for the P-3, the aircraft will be inspected in the "as washed condition". Effectiveness of the cleaning procedures is questionable. This requires testing lab samples with various surface contaminants.

3.6. Illumination Method

Various angles and intensities of the IR illuminators will be studied for the optimized settings for the various scenarios that could occur during the Dem/Val. The goal of the laboratory testing of the IR illuminators is to determine the optimized position and intensity of the IR illuminators at various distances and contours/geometries. The following variables must be studied in order to achieve an optimized system for the P-3 Dem/Val in regards to IR illumination:

- Wattage, Source design
- Angles/Part Geometry
- Substrate Temperature

3.7. Image Processing Software and Data Acquisition System

- Data Integration Time
- Non-Uniformity Correction (NUC)

3.8. Ergonomics

Ergonomics is an ongoing effort that shall be worked on in the laboratory to achieve a system that is friendly and easy to use. The following items shall be optimized to meet our needs:

- Size
- Weight
- Attachments
- Comfort/Ease of Use
- Visual Displays

It should be noted that we are currently working on issues relating to cable management, mounting an LCD display, handles, and mounting the illuminators in such a way that we can measure the angles that they are directed.

4. TEST LABORATORIES/FACILITIES

- Northrop Grumman Integrated Systems – Bethpage, NY
- Concurrent Technologies Corporation (*CTC*) – Largo, FL
- NAVAIR (Navy) – Jacksonville, FL
- Fort Bragg (Army) - Fayetteville, NC
- USCG Air Station (Coast Guard) – Elizabeth City, NC
- FLIR Systems Incorporated, Indigo Operations – Goleta, CA

5. SUMMARY OF OPTIMIZATION/BASELINE TEST PLAN

The goal of this optimization/baseline test plan is to test variables that could be encountered in the field and test them in the lab. This will allow the IRRIT to be better "prepared" for use at the Dem/Val.

In order for the technique to be successful the capabilities and the limits of the system must be defined and tested.

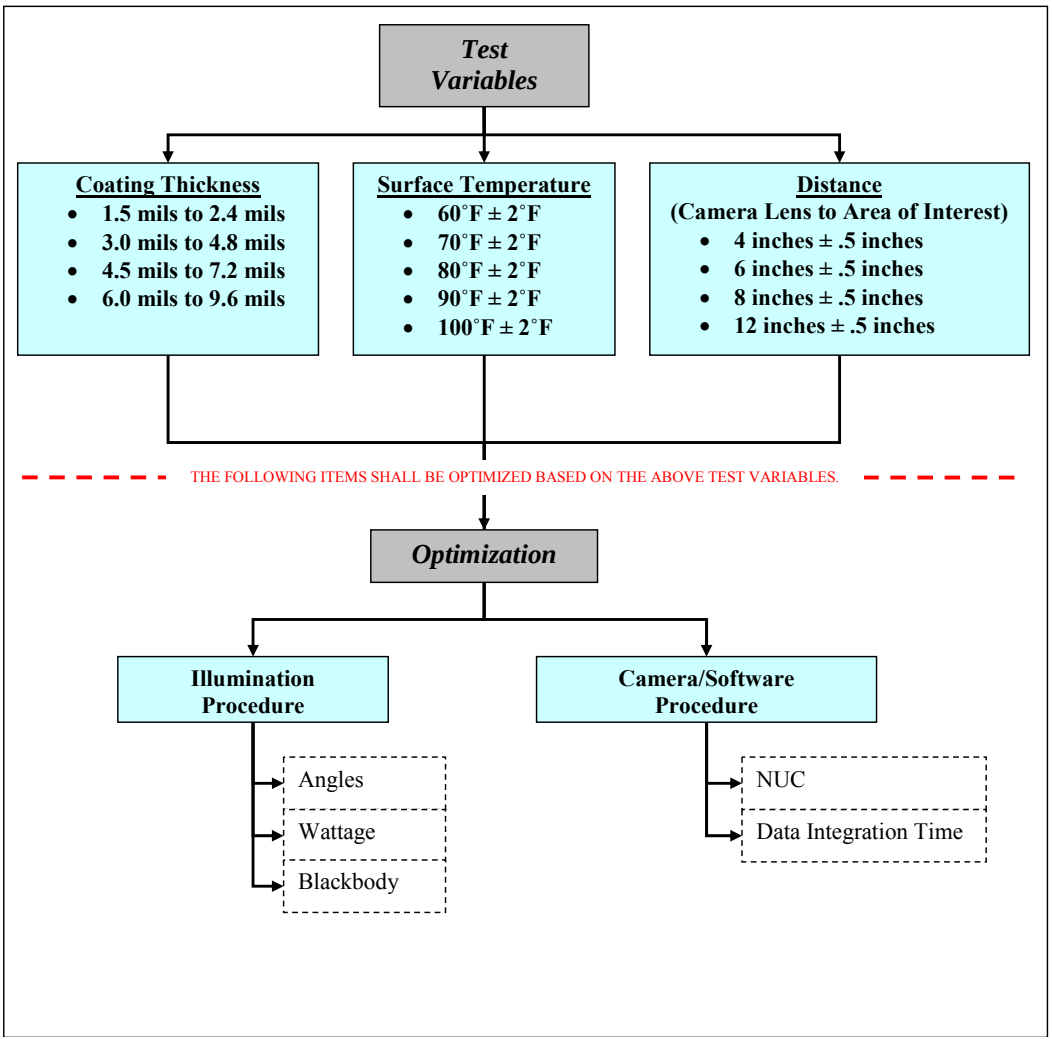


Figure D-3: Approach for Optimizing/Baselining the IRRIT + Blackbody Technique

Table D-3: Optimization/Baseline Variables

Optimized Resolution Results and Settings (w/1951 USAF Glass Slide Resolution Target - Negative, Filiform Samples, and P-3 Fuselage Contour Samples)										
Variables			IR Illumination Method Settings					Camera Settings		Sample Result
Coating Thickness (Navy P-3 Paint Scheme)	Sample Temperature	Distance from Sample (Camera Lens to Sample)	IR Illuminators (Left-Right) α	IR Illuminators (Up-Down) β	IR Illuminator Arm Support γ	Distance from Camera Lens (Center) to Illuminators	Wattage (Range = 0-22 watts)	NUC (2-Point Correction)	Data Integration Time	
1.5 mils to 2.4 mils	60°F ± 2°F	4 inches ± .5 inches								
1.5 mils to 2.4 mils	60°F ± 2°F	6 inches ± .5 inches								
1.5 mils to 2.4 mils	60°F ± 2°F	8 inches ± .5 inches								
1.5 mils to 2.4 mils	60°F ± 2°F	12 inches ± .5 inches								
1.5 mils to 2.4 mils	70°F ± 2°F	4 inches ± .5 inches								
1.5 mils to 2.4 mils	70°F ± 2°F	6 inches ± .5 inches								
1.5 mils to 2.4 mils	70°F ± 2°F	8 inches ± .5 inches								
1.5 mils to 2.4 mils	70°F ± 2°F	12 inches ± .5 inches								
1.5 mils to 2.4 mils	80°F ± 2°F	4 inches ± .5 inches								
1.5 mils to 2.4 mils	80°F ± 2°F	6 inches ± .5 inches								
1.5 mils to 2.4 mils	80°F ± 2°F	8 inches ± .5 inches								
1.5 mils to 2.4 mils	80°F ± 2°F	12 inches ± .5 inches								
1.5 mils to 2.4 mils	90°F ± 2°F	4 inches ± .5 inches								
1.5 mils to 2.4 mils	90°F ± 2°F	6 inches ± .5 inches								
1.5 mils to 2.4 mils	90°F ± 2°F	8 inches ± .5 inches								
1.5 mils to 2.4 mils	90°F ± 2°F	12 inches ± .5 inches								
1.5 mils to 2.4 mils	100°F ± 2°F	4 inches ± .5 inches								
1.5 mils to 2.4 mils	100°F ± 2°F	6 inches ± .5 inches								
1.5 mils to 2.4 mils	100°F ± 2°F	8 inches ± .5 inches								
1.5 mils to 2.4 mils	100°F ± 2°F	12 inches ± .5 inches								
3.0 mils to 4.8 mils	60°F ± 2°F	4 inches ± .5 inches								
3.0 mils to 4.8 mils	60°F ± 2°F	6 inches ± .5 inches								
3.0 mils to 4.8 mils	60°F ± 2°F	8 inches ± .5 inches								
3.0 mils to 4.8 mils	60°F ± 2°F	12 inches ± .5 inches								
3.0 mils to 4.8 mils	70°F ± 2°F	4 inches ± .5 inches								
3.0 mils to 4.8 mils	70°F ± 2°F	6 inches ± .5 inches								
3.0 mils to 4.8 mils	70°F ± 2°F	8 inches ± .5 inches								
3.0 mils to 4.8 mils	70°F ± 2°F	12 inches ± .5 inches								
3.0 mils to 4.8 mils	80°F ± 2°F	4 inches ± .5 inches								
3.0 mils to 4.8 mils	80°F ± 2°F	6 inches ± .5 inches								
3.0 mils to 4.8 mils	80°F ± 2°F	8 inches ± .5 inches								
3.0 mils to 4.8 mils	80°F ± 2°F	12 inches ± .5 inches								
3.0 mils to 4.8 mils	90°F ± 2°F	4 inches ± .5 inches								
3.0 mils to 4.8 mils	90°F ± 2°F	6 inches ± .5 inches								
3.0 mils to 4.8 mils	90°F ± 2°F	8 inches ± .5 inches								
3.0 mils to 4.8 mils	90°F ± 2°F	12 inches ± .5 inches								
3.0 mils to 4.8 mils	100°F ± 2°F	4 inches ± .5 inches								
3.0 mils to 4.8 mils	100°F ± 2°F	6 inches ± .5 inches								
3.0 mils to 4.8 mils	100°F ± 2°F	8 inches ± .5 inches								
3.0 mils to 4.8 mils	100°F ± 2°F	12 inches ± .5 inches								
4.5 mils to 7.2 mils	60°F ± 2°F	4 inches ± .5 inches								
4.5 mils to 7.2 mils	60°F ± 2°F	6 inches ± .5 inches								
4.5 mils to 7.2 mils	60°F ± 2°F	8 inches ± .5 inches								
4.5 mils to 7.2 mils	60°F ± 2°F	12 inches ± .5 inches								
4.5 mils to 7.2 mils	70°F ± 2°F	4 inches ± .5 inches								
4.5 mils to 7.2 mils	70°F ± 2°F	6 inches ± .5 inches								
4.5 mils to 7.2 mils	70°F ± 2°F	8 inches ± .5 inches								
4.5 mils to 7.2 mils	70°F ± 2°F	12 inches ± .5 inches								
4.5 mils to 7.2 mils	80°F ± 2°F	4 inches ± .5 inches								
4.5 mils to 7.2 mils	80°F ± 2°F	6 inches ± .5 inches								
4.5 mils to 7.2 mils	80°F ± 2°F	8 inches ± .5 inches								
4.5 mils to 7.2 mils	80°F ± 2°F	12 inches ± .5 inches								
4.5 mils to 7.2 mils	90°F ± 2°F	4 inches ± .5 inches								
4.5 mils to 7.2 mils	90°F ± 2°F	6 inches ± .5 inches								
4.5 mils to 7.2 mils	90°F ± 2°F	8 inches ± .5 inches								
4.5 mils to 7.2 mils	90°F ± 2°F	12 inches ± .5 inches								
4.5 mils to 7.2 mils	100°F ± 2°F	4 inches ± .5 inches								
4.5 mils to 7.2 mils	100°F ± 2°F	6 inches ± .5 inches								
4.5 mils to 7.2 mils	100°F ± 2°F	8 inches ± .5 inches								
4.5 mils to 7.2 mils	100°F ± 2°F	12 inches ± .5 inches								
6.0 mils to 9.6 mils	60°F ± 2°F	4 inches ± .5 inches								
6.0 mils to 9.6 mils	60°F ± 2°F	6 inches ± .5 inches								
6.0 mils to 9.6 mils	60°F ± 2°F	8 inches ± .5 inches								
6.0 mils to 9.6 mils	60°F ± 2°F	12 inches ± .5 inches								
6.0 mils to 9.6 mils	70°F ± 2°F	4 inches ± .5 inches								
6.0 mils to 9.6 mils	70°F ± 2°F	6 inches ± .5 inches								
6.0 mils to 9.6 mils	70°F ± 2°F	8 inches ± .5 inches								
6.0 mils to 9.6 mils	70°F ± 2°F	12 inches ± .5 inches								
6.0 mils to 9.6 mils	80°F ± 2°F	4 inches ± .5 inches								
6.0 mils to 9.6 mils	80°F ± 2°F	6 inches ± .5 inches								
6.0 mils to 9.6 mils	80°F ± 2°F	8 inches ± .5 inches								
6.0 mils to 9.6 mils	80°F ± 2°F	12 inches ± .5 inches								
6.0 mils to 9.6 mils	90°F ± 2°F	4 inches ± .5 inches								
6.0 mils to 9.6 mils	90°F ± 2°F	6 inches ± .5 inches								
6.0 mils to 9.6 mils	90°F ± 2°F	8 inches ± .5 inches								
6.0 mils to 9.6 mils	90°F ± 2°F	12 inches ± .5 inches								
6.0 mils to 9.6 mils	100°F ± 2°F	4 inches ± .5 inches								
6.0 mils to 9.6 mils	100°F ± 2°F	6 inches ± .5 inches								
6.0 mils to 9.6 mils	100°F ± 2°F	8 inches ± .5 inches								
6.0 mils to 9.6 mils	100°F ± 2°F	12 inches ± .5 inches								

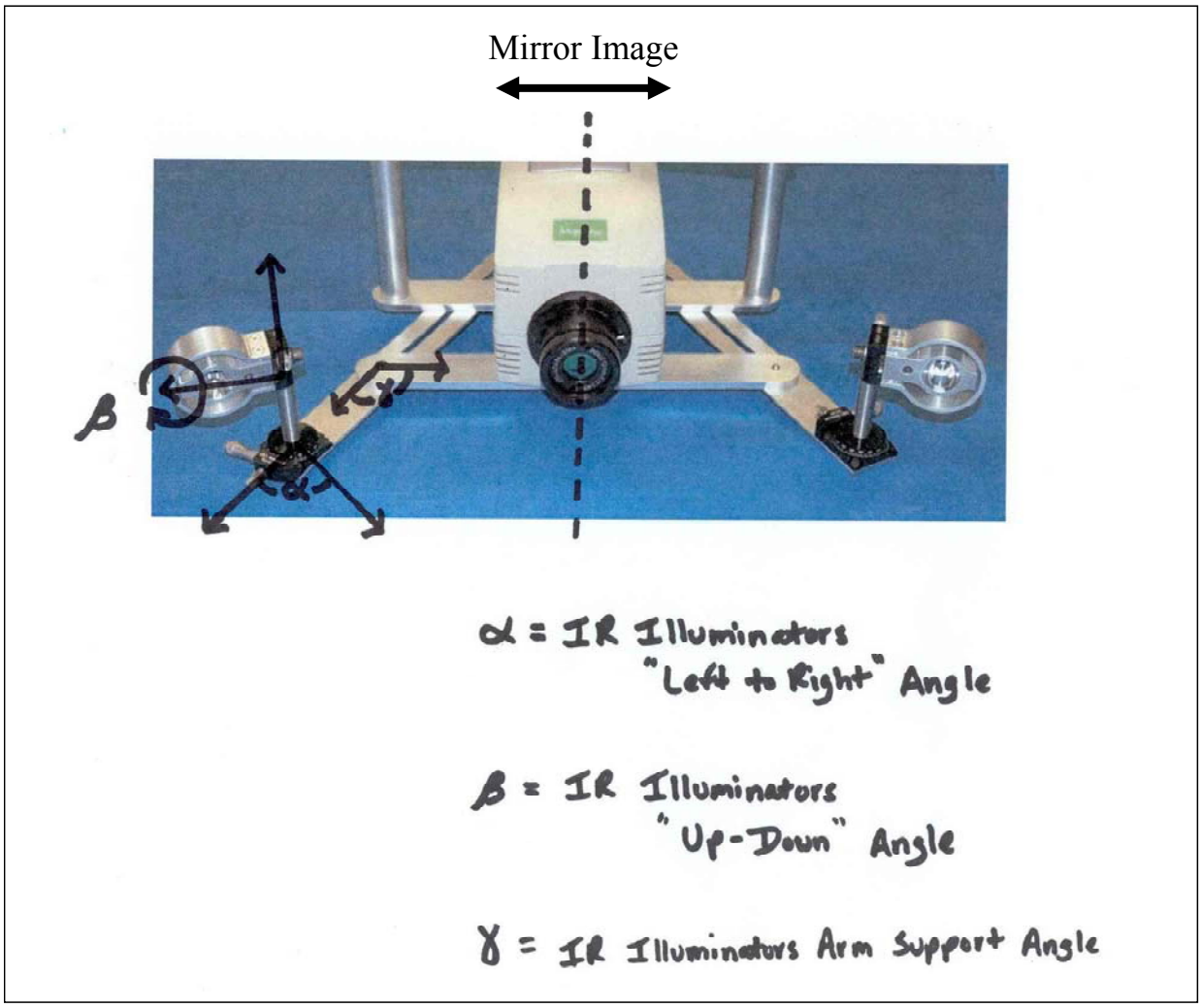
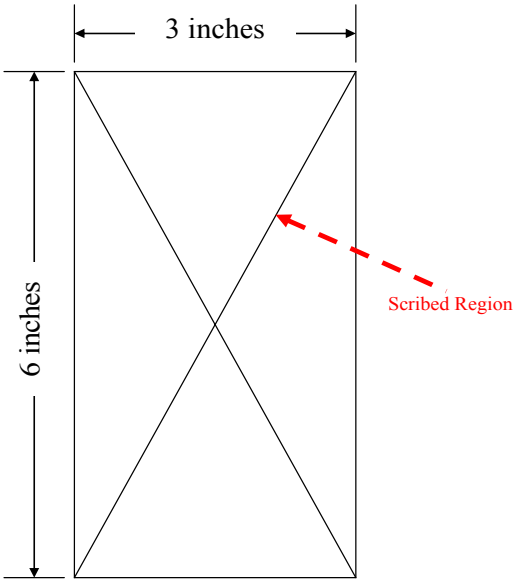


Figure D-4: Angle Designations for IR Illuminators

Test Panel Design #1A→ Lab Induced Corrosion – Filiform Exposure

2024-T3 Clad Aluminum



Filiform Exposure:

This design shows corrosion due to filiform exposure. The duration of filiform exposure per ASTM D2803 is 1000 hours. This scenario will show filiform corrosion along the scribed region and under the primer + topcoat.

Figure D-5: Panel Design #1A

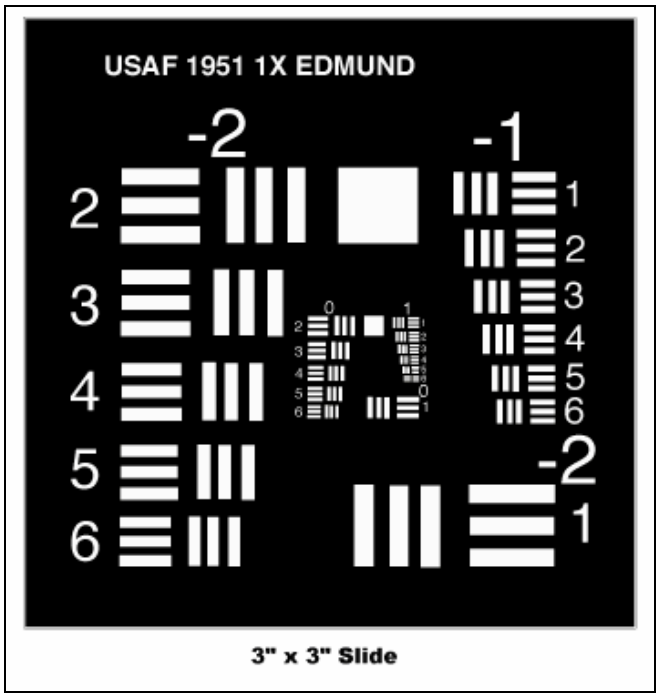


Figure D-6: 1951 USAF Glass Slide Resolution Target (Negative)

Figure D-7 and Figure D-8 illustrates the curvature of the P-3 fuselage at fuselage station (FS) 901 and fuselage station (FS) 1117 respectively.

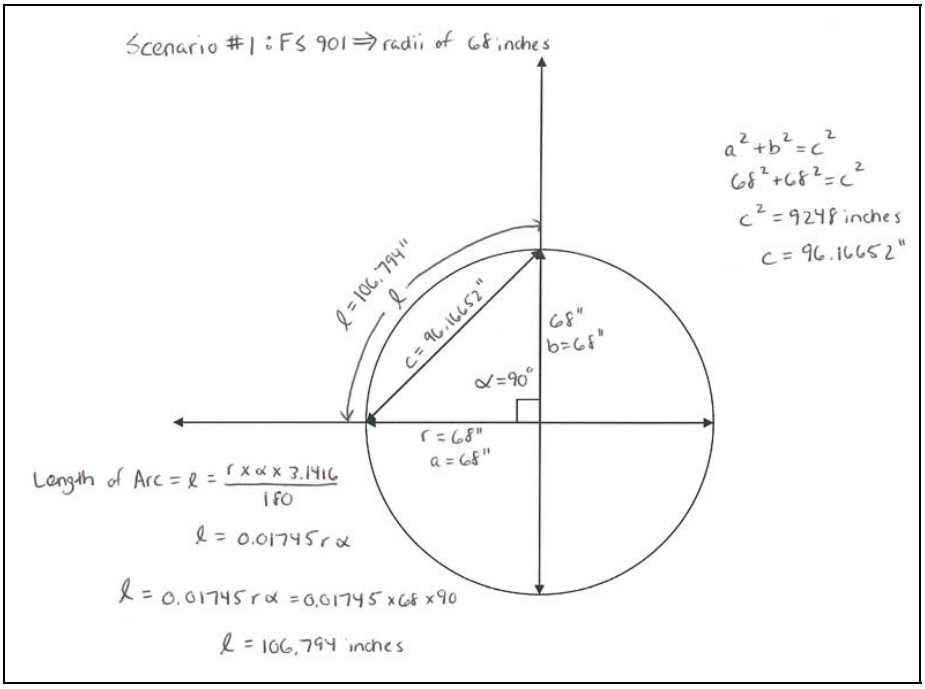


Figure D-7: P-3 Fuselage Contour Scenario #1 - FS901 (Radii = 68 inches)

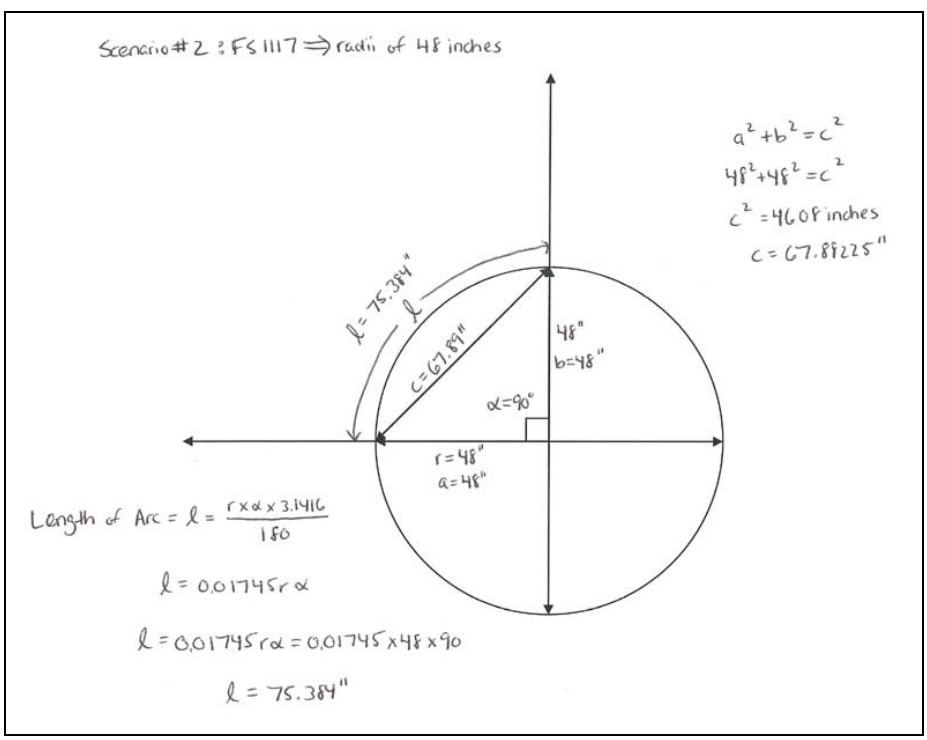


Figure D-8: P-3 Fuselage Contour Scenario #2 - FS1117 (Radii = 48 inches)

Figure D-9 shows the calculations that were required to generate a scaled down test article, which were based on the calculations shown in Figure D-7. This test article will simulate the curvature of the fuselage that will be encountered on the P-3 aircraft during the Dem/Val.

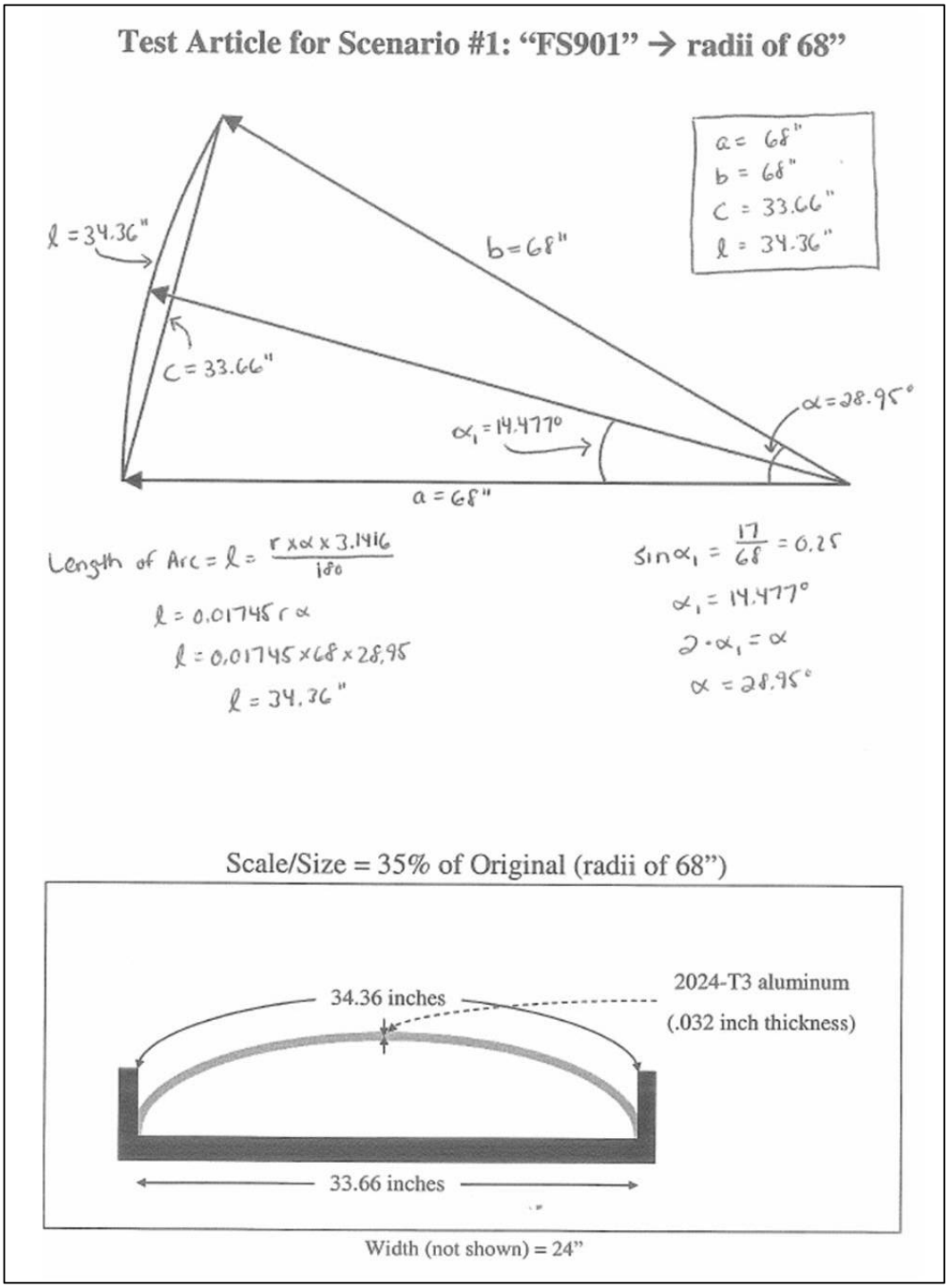


Figure D-9: P-3 Fuselage Contour - Test Article for Scenario #1

Figure D-10 shows the calculations that were required to generate a scaled down test article, which were based on the calculations shown in Figure D-8. This test article will simulate the curvature of the fuselage that will be encountered on the P-3 aircraft during the Dem/Val.

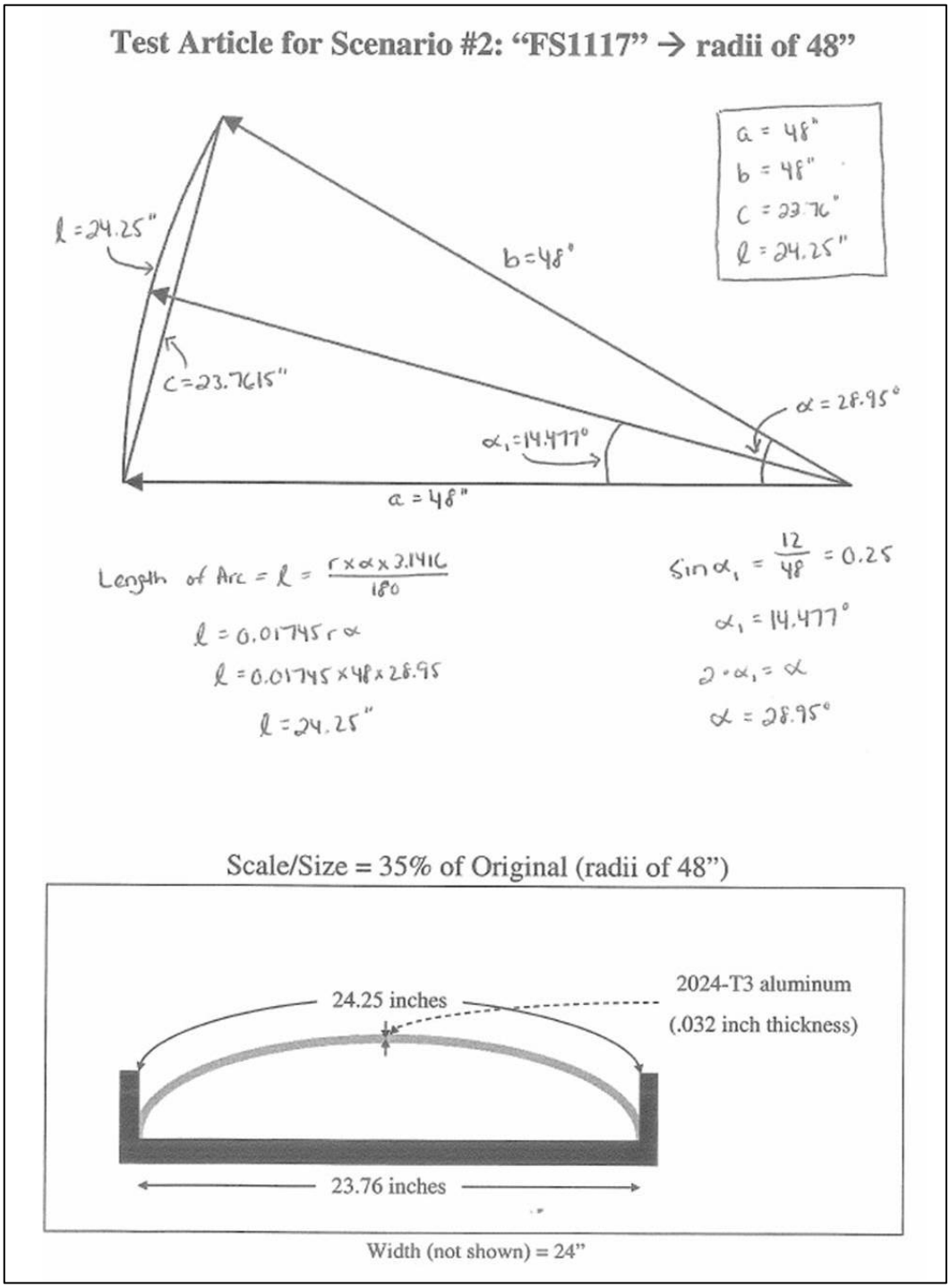


Figure D-10: P-3 Fuselage Contour - Test Article for Scenario #2

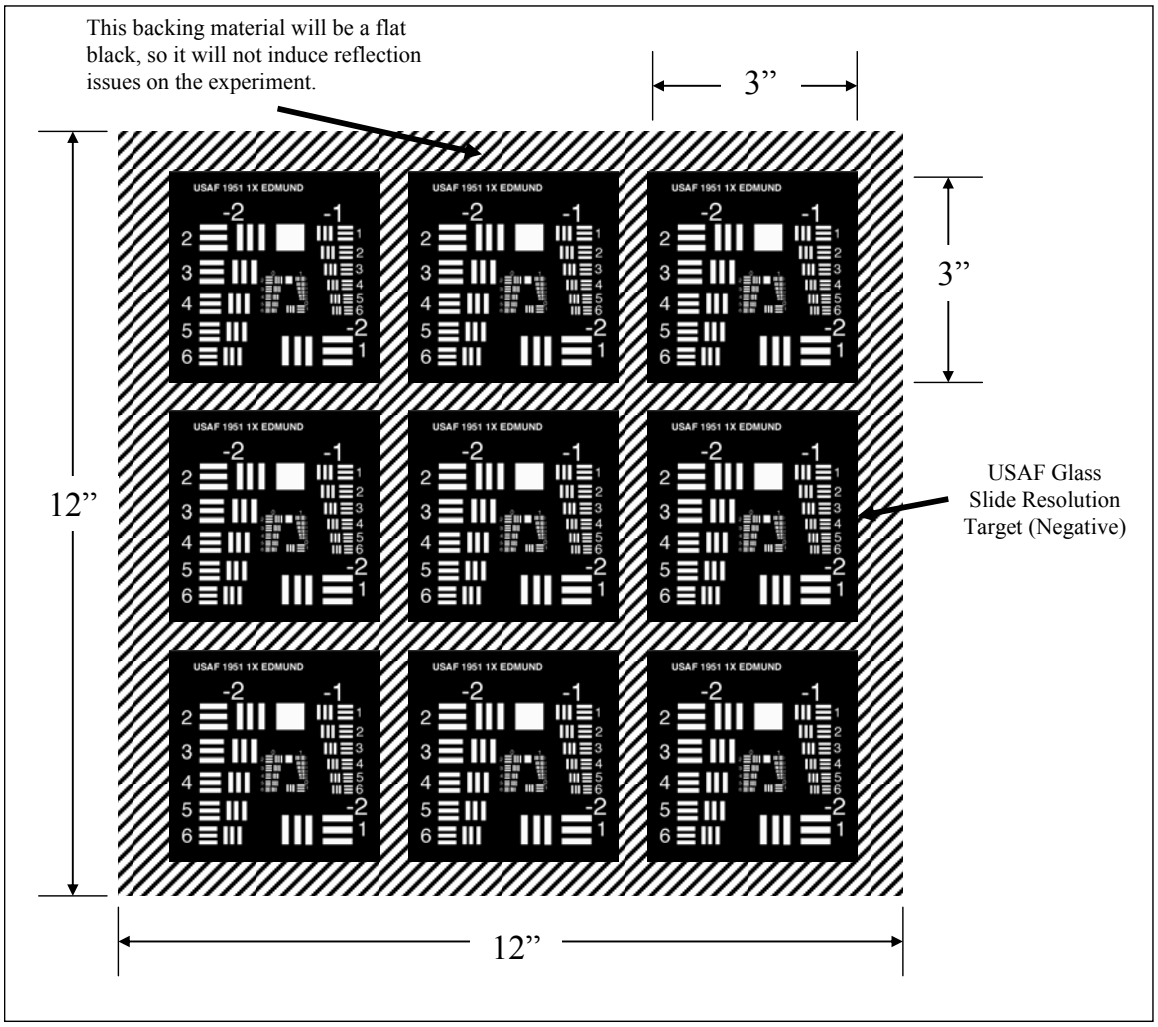


Figure D-11: Sample Required to Resolve Curvature of Camera Lens Issues (FOV)

Table D-4: Specification Table - USAF Glass Slide Resolution Target

Number of Lines per mm in USAF Resolving Power Test Target 1951 (Edmund Optics Incorporated Stock Number NT36-275)									
	Group Number								
Element	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**5**	**6**
1	0.25	0.5	1	2	4	8	16	32	64
2	0.28	0.561	1.12	2.24	4.49	8.98	17.95	36	71.8
3	0.315	0.63	1.26	2.52	5.04	10.1	20.16	40.3	80.6
4	0.353	0.707	1.41	2.83	5.66	11.3	22.62	45.3	90.5
5	0.397	0.793	1.59	3.17	6.35	12.7	25.39	50.8	102
6	0.445	0.891	1.78	3.56	7.13	14.3	28.5	57	114
Substrate	1.5mm (0.06") soda lime glass with beveled edges								
Flatness	0.0001" or better								
Surface Quality	40-10								
Coating	Vacuum-deposited durable chromium, density 3.0 or greater								
Minimum Resolution	Group -2, Element 1								
Maximum Resolution	Group 7, Element 6								

Table D-5: P-3 OML Paint Scheme - Laboratory Panels

P-3 OML Paint Scheme					
Test Panel Design	**Substrate**	**Surface Preparation**	**Total Thickness of Primer**	**Total Thickness of Topcoat**	**Total Coating Thickness**
			MIL-PRF-85582 Type 1 (Deft 44-GN-7)	**MIL-PRF-85285 Type 1 (Hentzen Color # 16440)**	
#1A "Filiform"	2024-T3	*Clad and Bare	0.5 mils to 0.9 mils	1.0 mils to 1.5 mils	1.5 mils to 2.4 mils
	2024-T3	*Clad and Bare	1.0 mils to 1.8 mils	2.0 mils to 3.0 mils	3.0 mils to 4.8 mils
	2024-T3	*Clad and Bare	1.5 mils to 2.7 mils	3.0 mils to 4.5 mils	4.5 mils to 7.2 mils
	2024-T3	*Clad and Bare	2.0 mils to 3.2 mils	4.0 mils to 6.0 mils	6.0 mils to 9.6 mils
1951 USAF Resolution Target (Negative)	Soda Lime Glass	Vacuum-Deposited Durable Chromium	0.5 mils to 0.9 mils	1.0 mils to 1.5 mils	1.5 mils to 2.4 mils
	Soda Lime Glass	Vacuum-Deposited Durable Chromium	1.0 mils to 1.8 mils	2.0 mils to 3.0 mils	3.0 mils to 4.8 mils
	Soda Lime Glass	Vacuum-Deposited Durable Chromium	1.5 mils to 2.7 mils	3.0 mils to 4.5 mils	4.5 mils to 7.2 mils
	Soda Lime Glass	Vacuum-Deposited Durable Chromium	2.0 mils to 3.2 mils	4.0 mils to 6.0 mils	6.0 mils to 9.6 mils

Note *Clad and Bare = Traditionally clad aluminum is used in filiform testing. Clad aluminum and bare aluminum will be manufactured and the panels that create the filiform filaments the quickest shall be used in our optimization/baseline testing.

APPENDIX E LABORATORY DATA

E.1 Navy P-3 Coating System Samples

1P = .9 mils
2P = 3.2 mils
1P1T = 2.1 mils
2P1T = 4.16 mils
2P2T = 4.61 mils

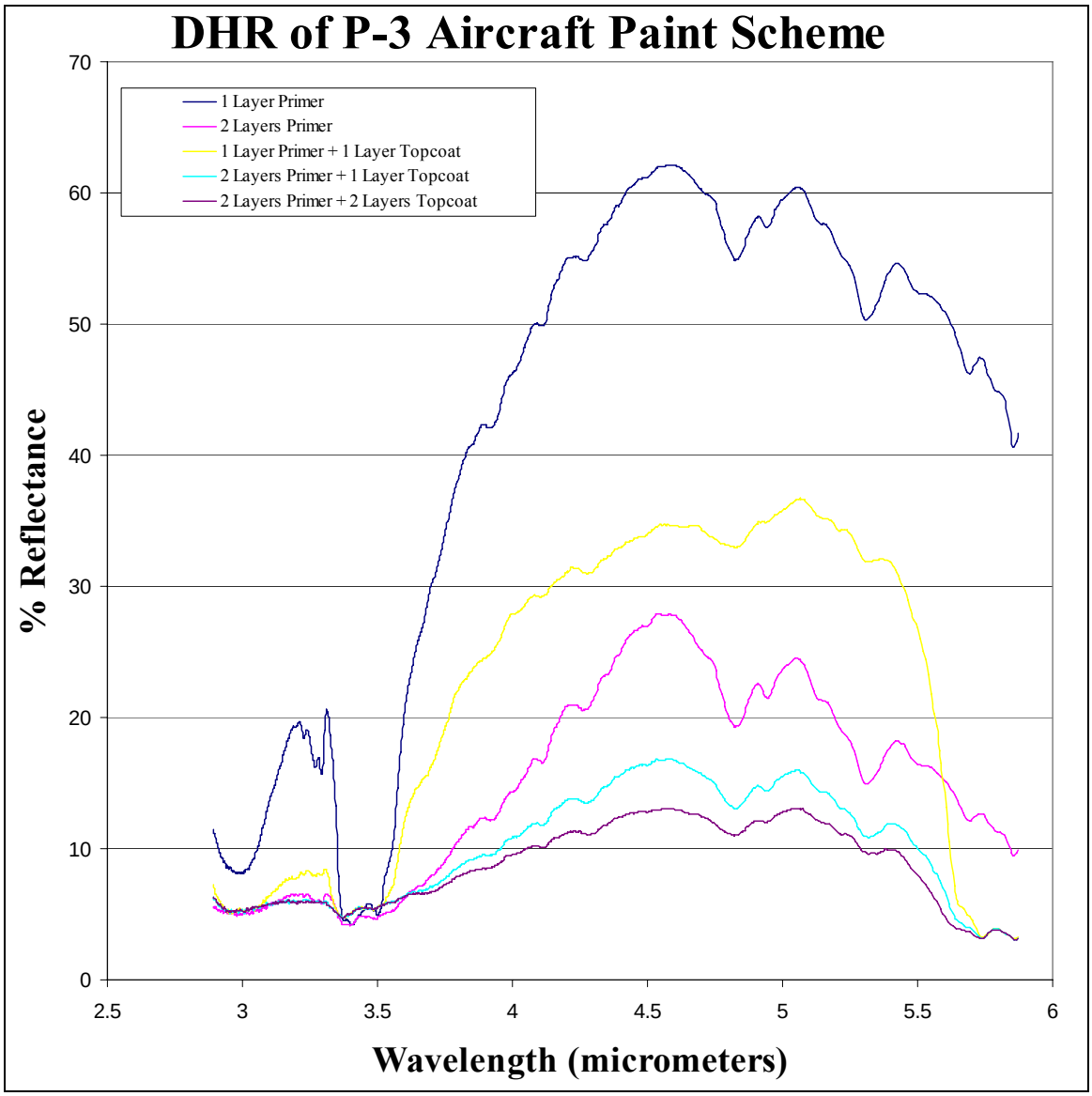


Figure E-1: Spectral Signature of Navy P-3 Coating

E.2 Filter Evaluation

Issue:

IR filter optimization activity was performed based on the transmission spectra of the P-3 paint scheme (see Figure E-2). Selection of the optimized filter was conducted at FLIR/Indigo Operations in Goleta, California. Several possible spectral filters were considered. Figure E-3 illustrates DHR spectra for individual candidate spectral filters. The filters were installed on a filter wheel that was connected to a laboratory Merlin® Mid IR camera (liquid-nitrogen cooled). Figure E-4 illustrates the filter evaluation setup whereby a sample was imaged using both a standard Merlin® IR camera and a Merlin® IR camera equipped with a filter wheel.

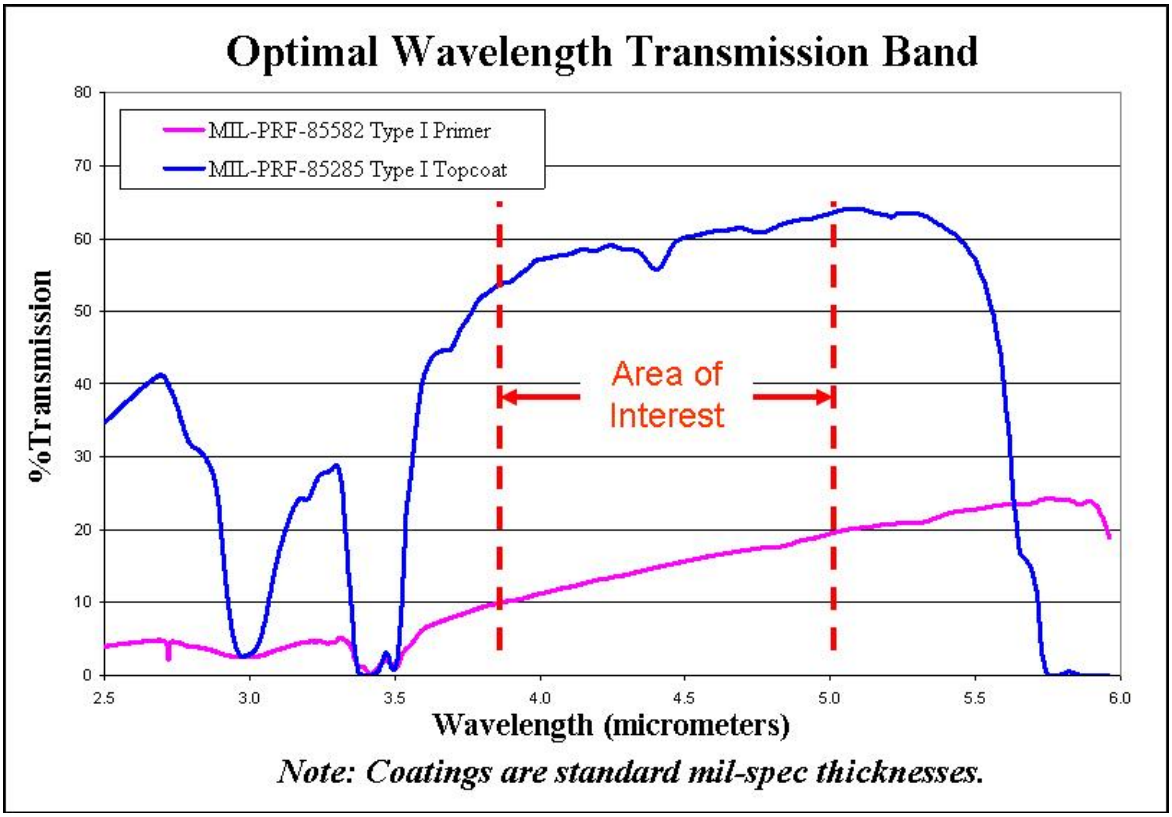


Figure E-2: Improved Spectral Window for IRRIT

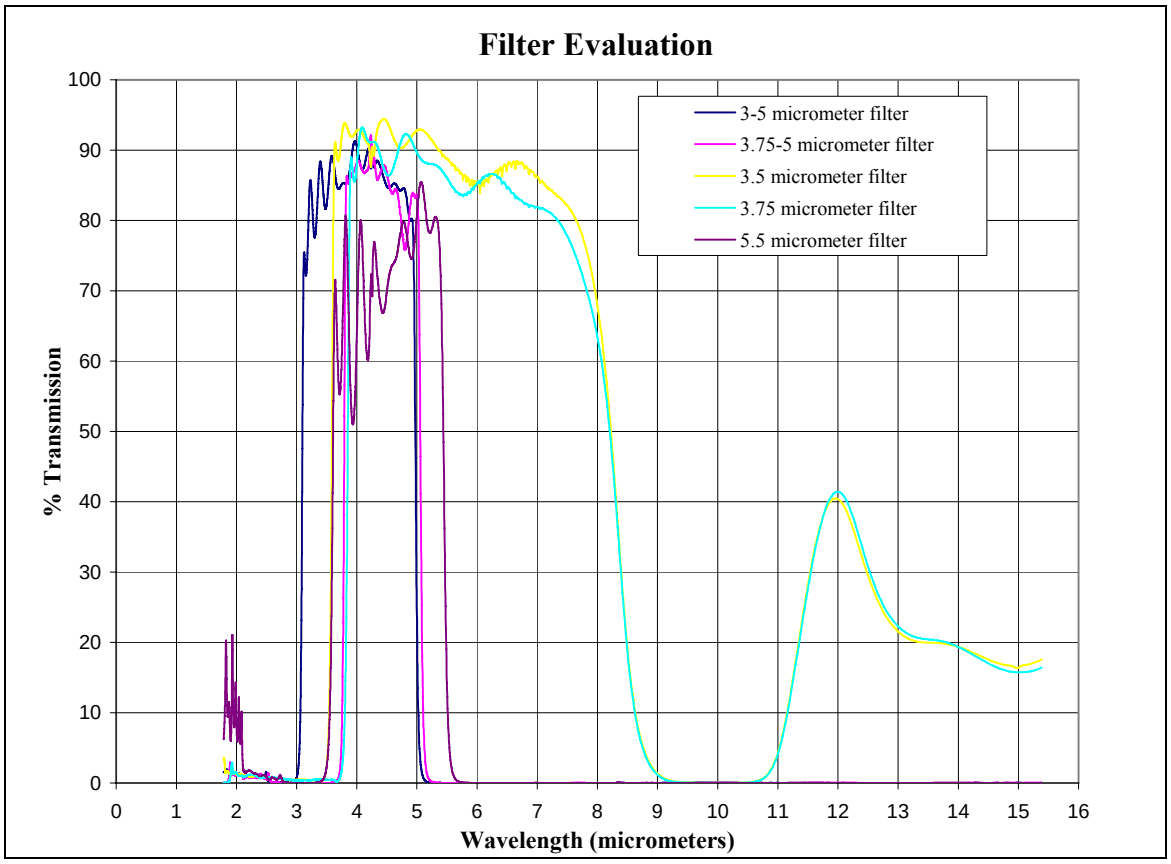


Figure E-3: Spectra of Filters Evaluated

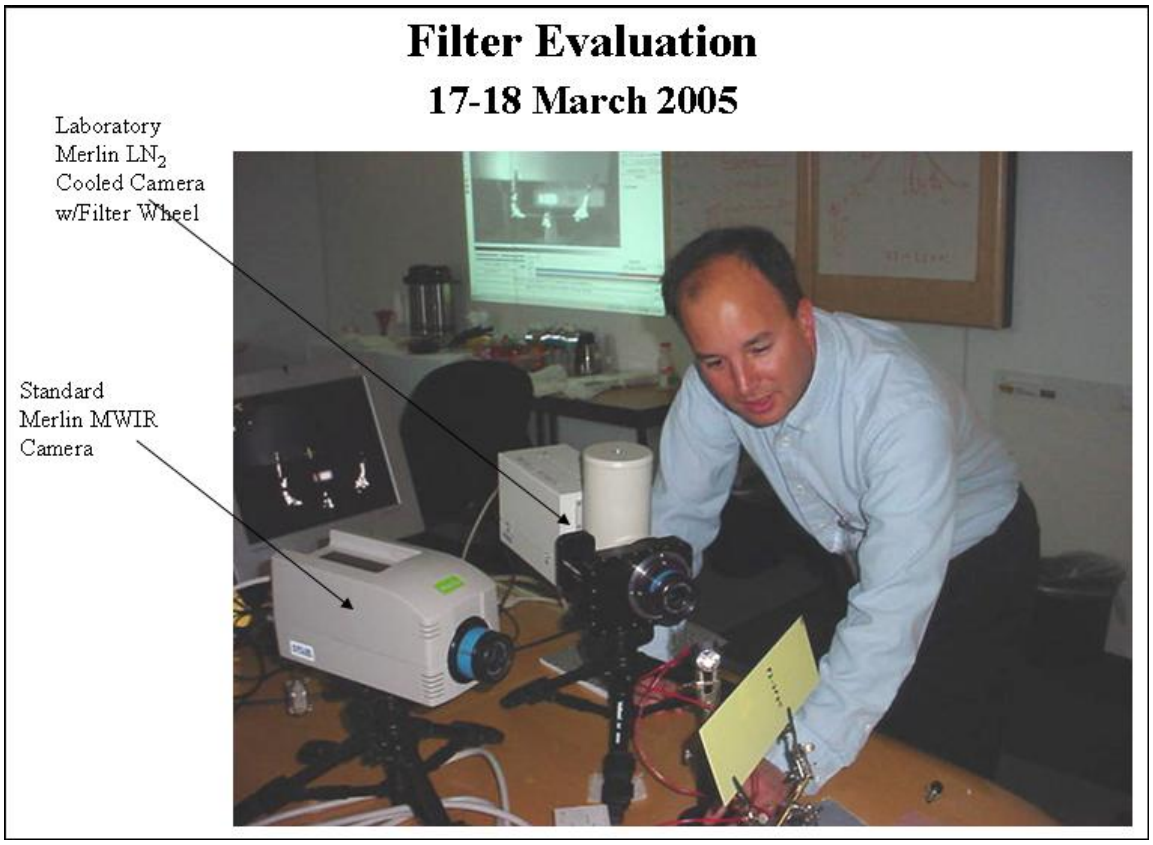


Figure E-4: Filter and Camera Comparison

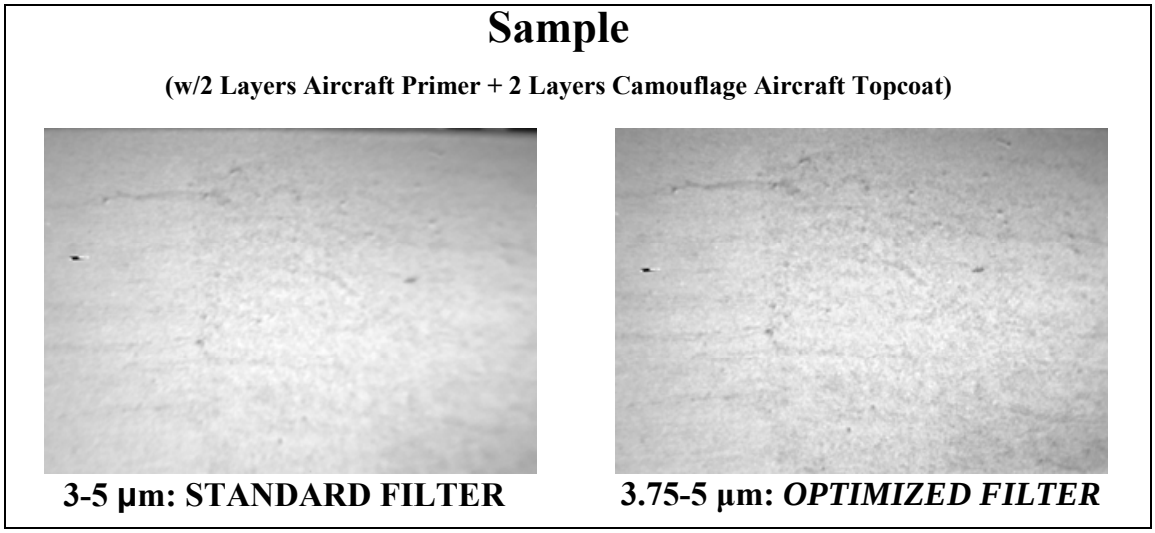


Figure E-5: Optimized Filter versus COTS Filter

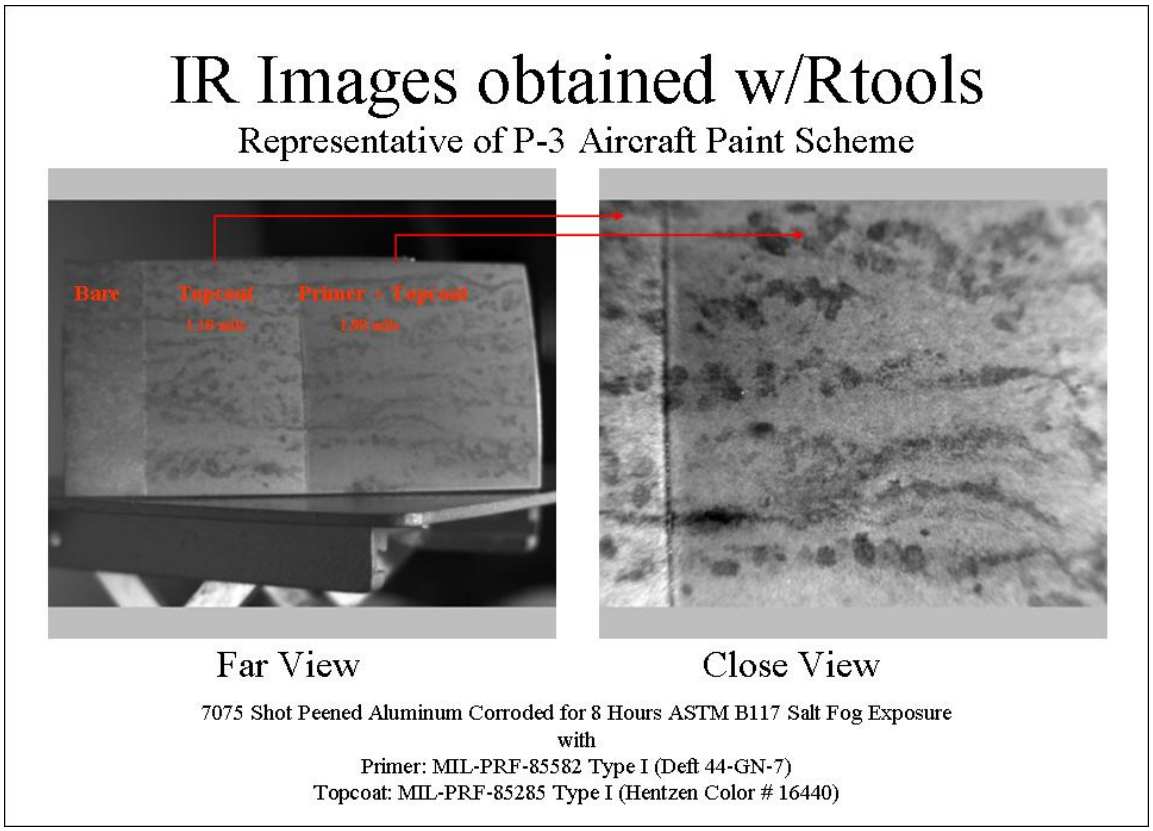


Figure E-6: Rtools Results

Figure E-6 represents images that were obtained using the RTools software. In addition to optimizing the IR camera filter, it was also thought that the RTools software would be able to generate superior images compared to the previous method which was to capture them directly from the IR camera and store them as digital files. However, the results concluded that the RTools software, for this particular application was of no added benefit to the Dem/Val, and actually complicates an otherwise simple process.

Figure E-6 also shows the results of the optimized filter system, which cuts off the lower wavelength glare allowing the camera to be more sensitive in the 3.75 to 5 µm window. It was found that the 3.75 -5 micrometer filter produced the best contrast between corroded and non-corroded surfaces as seen in Figure E-5. The final selected filter was incorporated into the Merlin® Mid IR camera. Indigo measured the spectral response of the specialized filter system. Figure E-7 illustrates the normalized performance of the Merlin® camera lens system with the specialized filter.

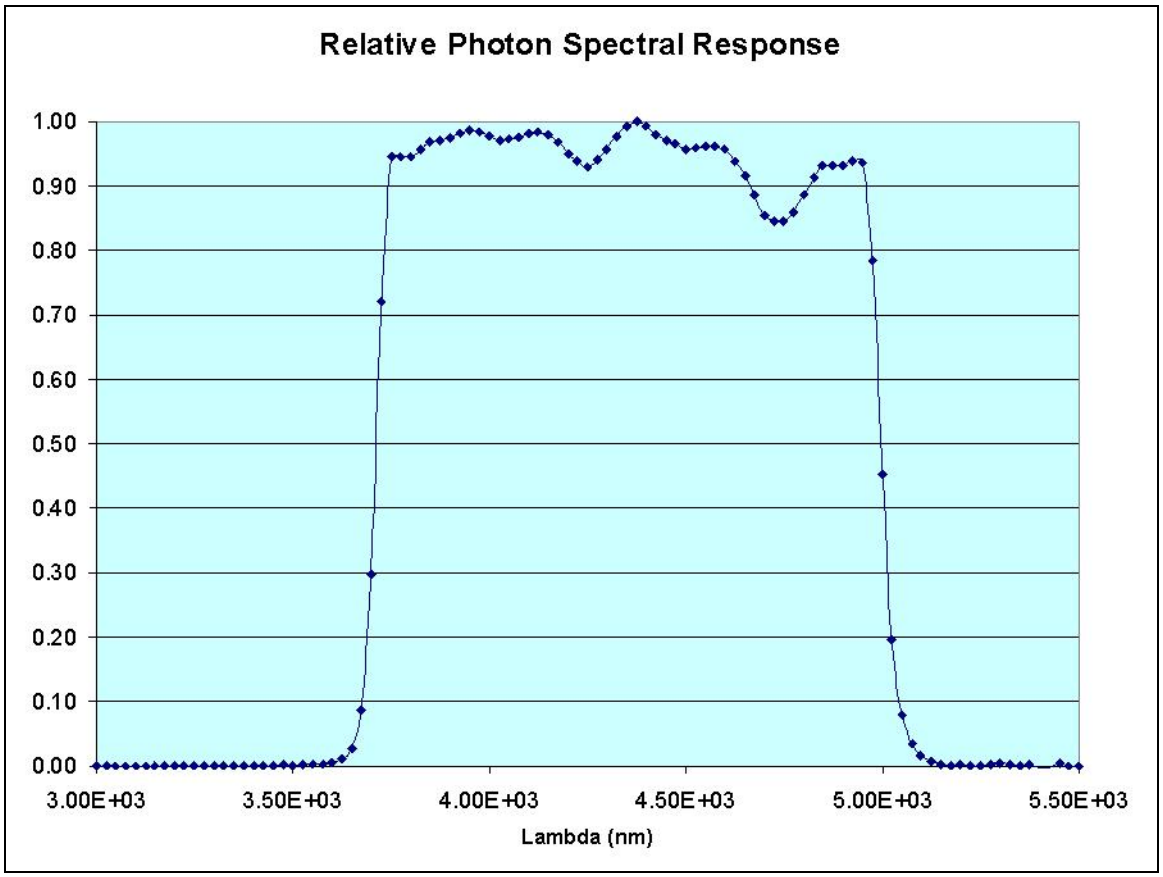


Figure E-7: Spectral Response Curve for Optimized Filter

Indigo-measured spectral response curve for filter-lens system to be incorporated into the IRRIT camera.

E.3 Free Standing Films

Types of Free Standing Films (FSF) used are illustrated Table E-1:

MIL-PRF-85285, Deft APC Color # 36118
MIL-PRF-85285, Deft APC Color # 36173
MIL-PRF-85285, Deft High Solids Color # 36293
MIL-PRF-23377, Deft Primer Type 1
TT-P-2760, Deft Primer Type 1

Table E-1: Type and Thickness of Free Standing Films

Free Standing Film Thickness Measurements					
Coating	# of Layers	Thickness (mils)	Thickness (mils)	Thickness (mils)	Average thickness (mils)
MIL-PRF-85285, Deft APC Color # 36118	1	1.3	1.5	1.4	1.40
	2	1.8	1.6	1.5	1.63
	3	2.0	2.5	2.2	2.23
	4	2.6	2.8	2.7	2.70
MIL-PRF-85285, Deft APC Color # 36173	1	1.9	1.8	2.0	1.90
	2	2.6	2.5	2.4	2.50
	3	3.7	3.8	3.4	3.63
	4	3.6	3.7	3.7	3.67
MIL-PRF-85285, Deft High Solids Color # 36293	1	2.8	2.9	2.9	2.87
	2	4.5	4.2	4.5	4.40
	3	5.3	5.2	5.4	5.30
	4	5.5	5.6	5.6	5.57
MIL-PRF-23377, Deft Primer Type 1	1	1.3	1.4	1.2	1.30
	2	4.5	4.5	4.4	4.47
	3	3.9	4.2	4.0	4.03
	4	4.5	4.8	4.4	4.57
TT-P-2760, Deft Primer Type 1	1	1.3	1.4	1.5	1.40
	2	2.9	2.6	2.7	2.73
	3	2.9	3.1	3.0	3.00
	4	3.7	3.6	3.8	3.70

Standard FTIR transmission scans were performed on a Thermo Magna 550 FTIR Spectrometer. The wavelength range of the scans was 1.78–15.3µm. The area of interest for these films is in the range of 3-5µm. The samples were prepared by painting 12 inch square polyethylene bags. The paint coatings were cut and peeled off the bag once they were fully cured.

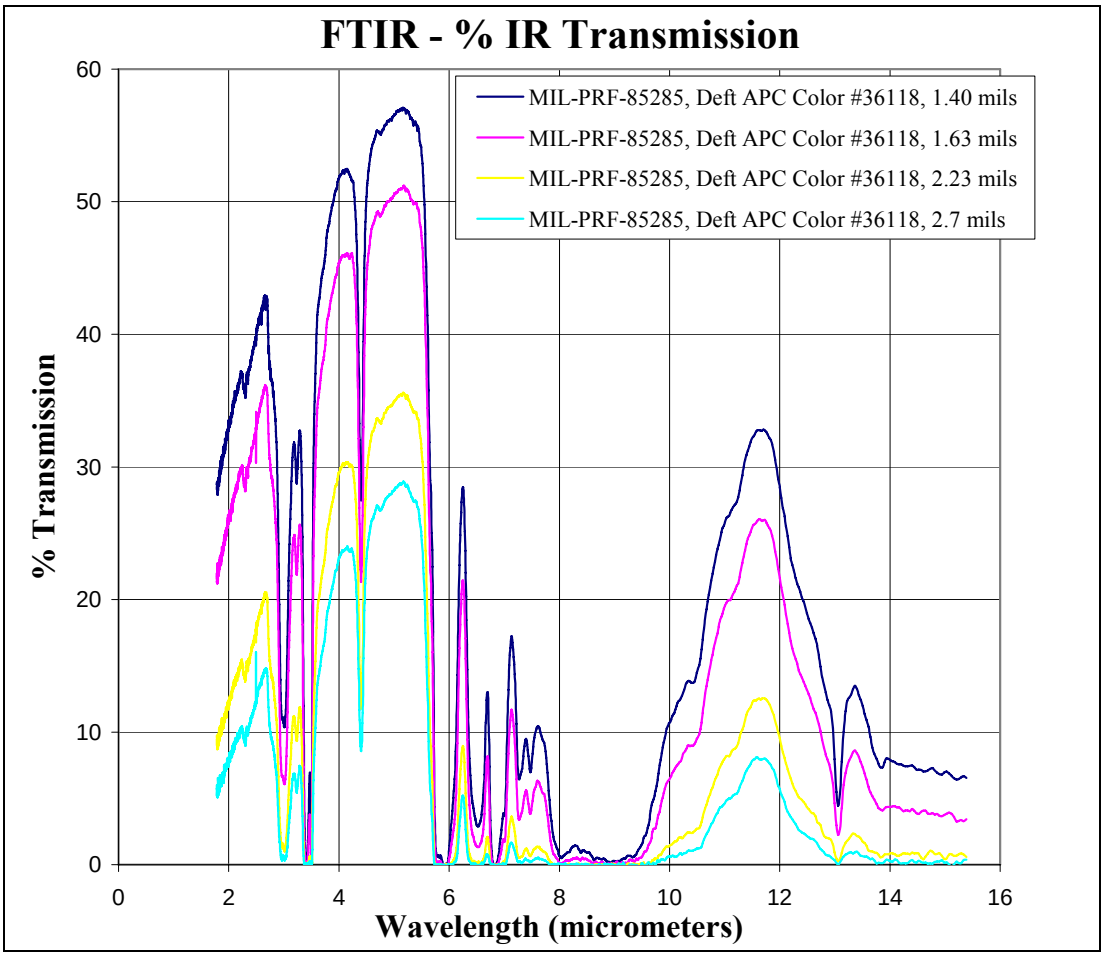


Figure E-8: FTIR Results of MIL-PRF-85285 (Color #36118)

Figure E-8 illustrates the dark camo gray topcoat has a big transmission drop off with increasing film thickness.

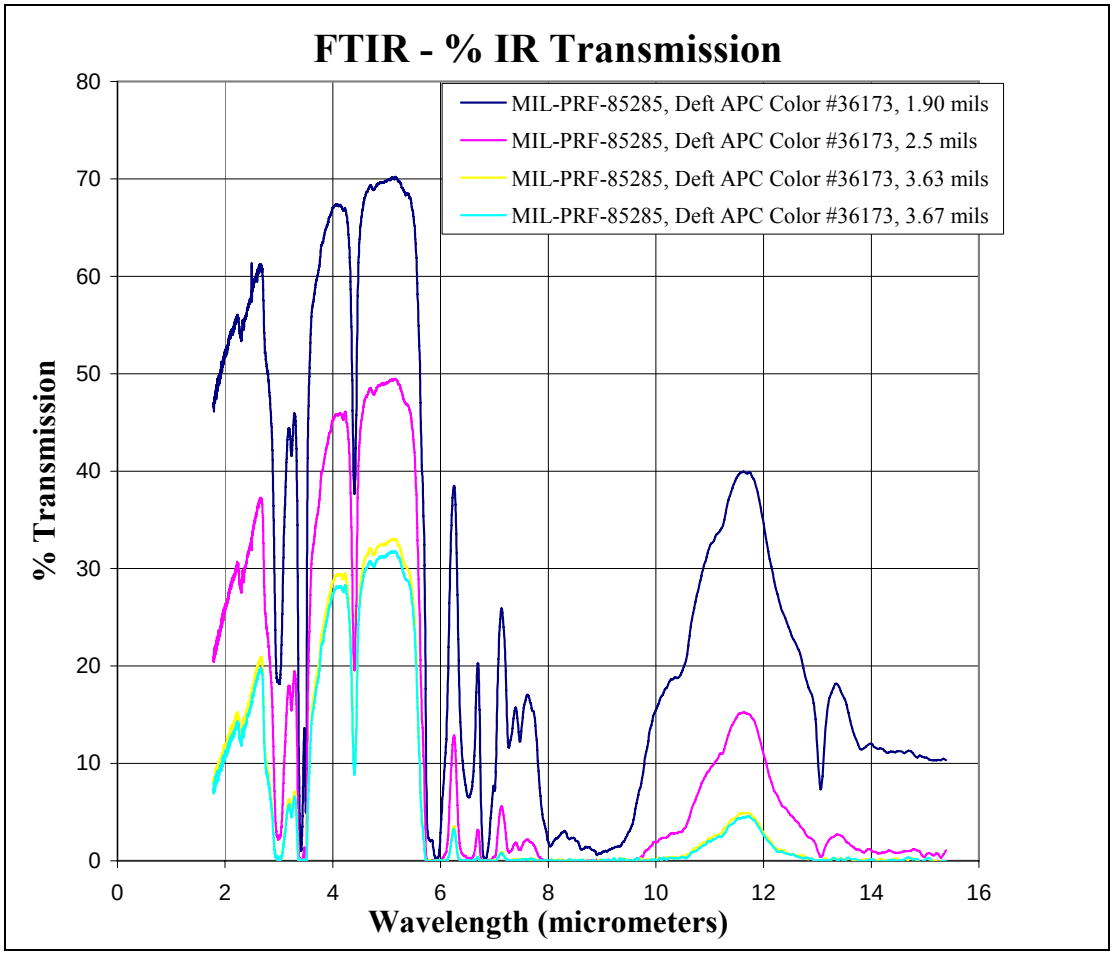


Figure E-9: FTIR Results of MIL-PRF-85285 (Color #36173)

Figure E-9 illustrates the light camo gray topcoat is a little more transmissive than the dark camo gray when comparing thicknesses.

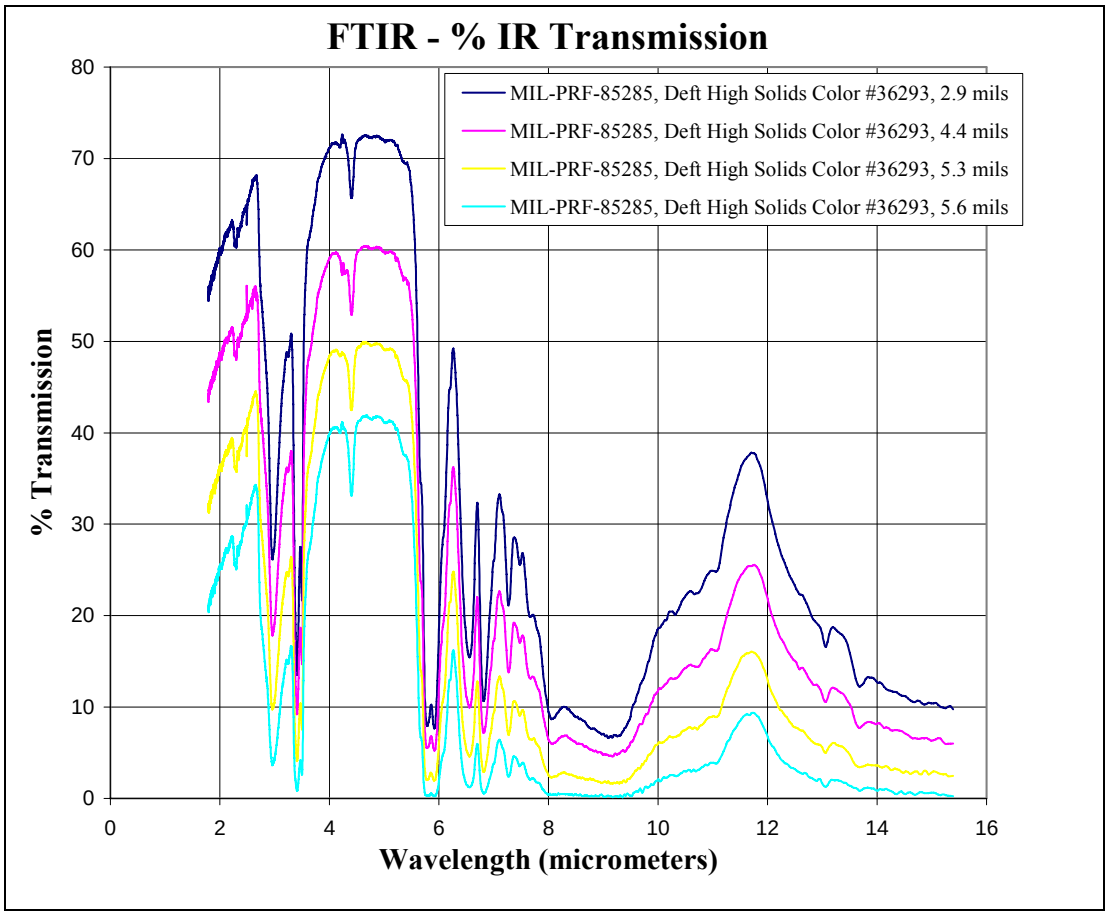


Figure E-10: FTIR Results of MIL-PRF-85285 (Color #36293)

Figure E-10 illustrates the high solids topcoat and as coating thickness increases, transmission capability in the 3-5µm wavelength region decreases. This spectra is on the same scale as the primer FTIR spectra. A typical coating of 3 mils yields about 70% transmission.

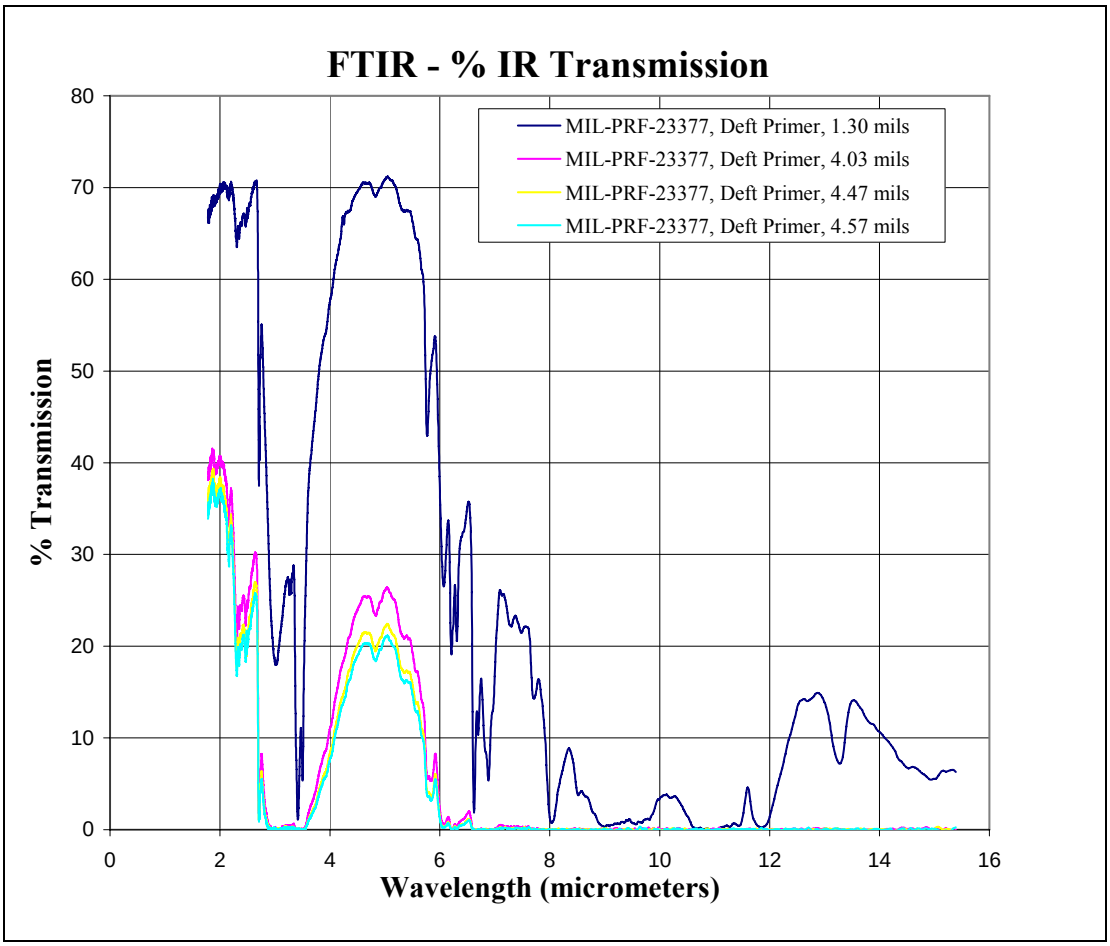


Figure E-11: FTIR Results of MIL-PRF-23377

Figure E-11 illustrates the thick primer has very little transmission in the region of interest (3-5µm). If the 23377 primer is properly applied on the aircraft, the Merlin® MWIR camera should be able to image through to the substrate.

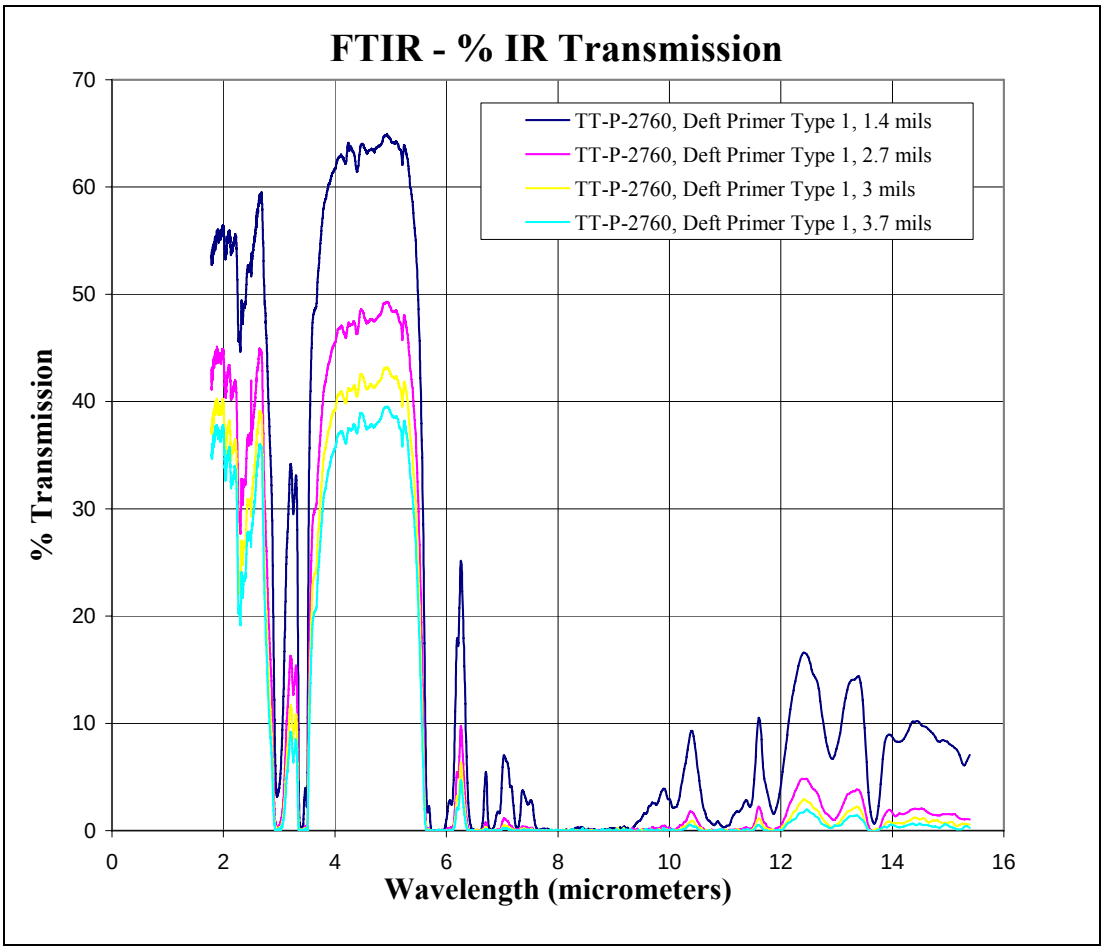


Figure E-12: FTIR Results of TT-P-2760 Type I

Figure E-12 illustrates the 2760 primer is just as transmissive as the 23377 primer when it is thin. Note the large absorbance at 3.4µm.

E.4 Ergonomics

Issue:
The purpose of this test report was to investigate methods of improvement regarding ergonomics and the IRRIT system. During initial technology demonstrations it was noted that the IRRIT system operator could only hold the camera for short durations (minutes) before becoming physically fatigued. Packaging the MWIR camera into a smaller/lighter system will improve ergonomics (Figure E-13, Figure E-14, and Figure E-15).

In general, it is good practice (ergonomically) to use the largest appropriate muscle groups available when muscular force is exerted. However, the initial set-up of the IRRIT system required the operator to hold the camera. Holding the camera caused fatigue in the users arm and shoulder muscles. This led to mounting the IRRIT system on a vest/harness and also on a tripod. Implementation of the vest/harness and the tripod occurred during the Navy P-3 Dem/Val. Previously, the operator could only hold the IRRIT system for a matter of minutes before becoming fatigued; with the use of the vest/harness the operator was able to use the IRRIT system for hours. Mounting the IRRIT system on a tripod (Figure E-17) or harness/vest (Figure E-16) requires little to no effort (physically) on the operator.

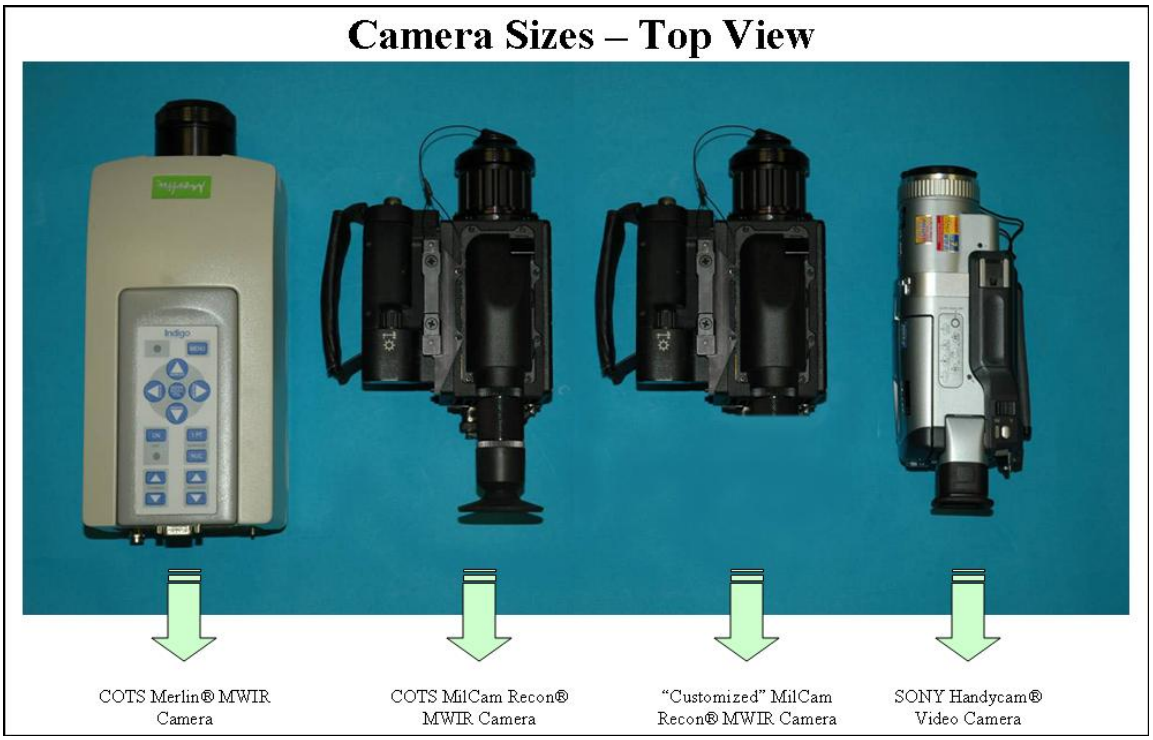


Figure E-13: Camera Dimension Comparison (View 1)

Figure E-14: Camera Dimension Comparison (View 2)

Figure E-15: FLIR MilCam w/IR Illuminators and LCD

Figure E-16: User with IRRIT Equipment Mounted on Vest/Harness

Figure E-17: User with IRRIT Equipment Mounted on Tripod

E.5 CARC Coatings

Issue:

The purpose of this test report was to investigate the IR transmission of various CARC coatings. These CARC coating are on almost all of the Army land and air platforms/vehicles. Free standing films of these CARC coatings were required for Fourier Transform Infrared (FTIR) transmission testing. These free standing films were also placed in front of the Merlin® Mid-Wave IR Camera (3-5 micrometers) with an IR source in back of the film. This will test whether or not the IR source can be detected through the free standing film via the Merlin® Mid-Wave IR Camera. Results were documented and are summarized in this report.

The list of the CARC free standing films used in this report is as follows:

Table E-2: CARC Free Standing Films

Coating Specification	Color #	Manufacturer	Coating/Film Thickness
MIL-C-46168 Type IV	Green # 34094	Sherwin Williams	3.3 mils
MIL-C-46168 Type IV	Black # 37030	Sherwin Williams	4 mils
MIL-C-46168 Type IV	Black # 37030	Sherwin Williams	9.3 mils
MIL-C-53039A	Green # 34094	Sherwin Williams	6 mils
MIL-C-64159 Type II	Black # 37030	Sherwin Williams	5.6 mils

Two different free standing film thicknesses of the Navy P-3 topcoat were also included in testing for comparison purposes. They are as follows:

Table E-3: Navy P-3 Free Standing Films (for comparison purposes only)

Coating Specification	Color #	Manufacturer	Coating/Film Thickness
MIL-PRF-85285 Type I	Gloss Gray # 16440	Hentzen	2 mils
MIL-PRF-85285 Type I	Gloss Gray # 16440	Hentzen	4 mils

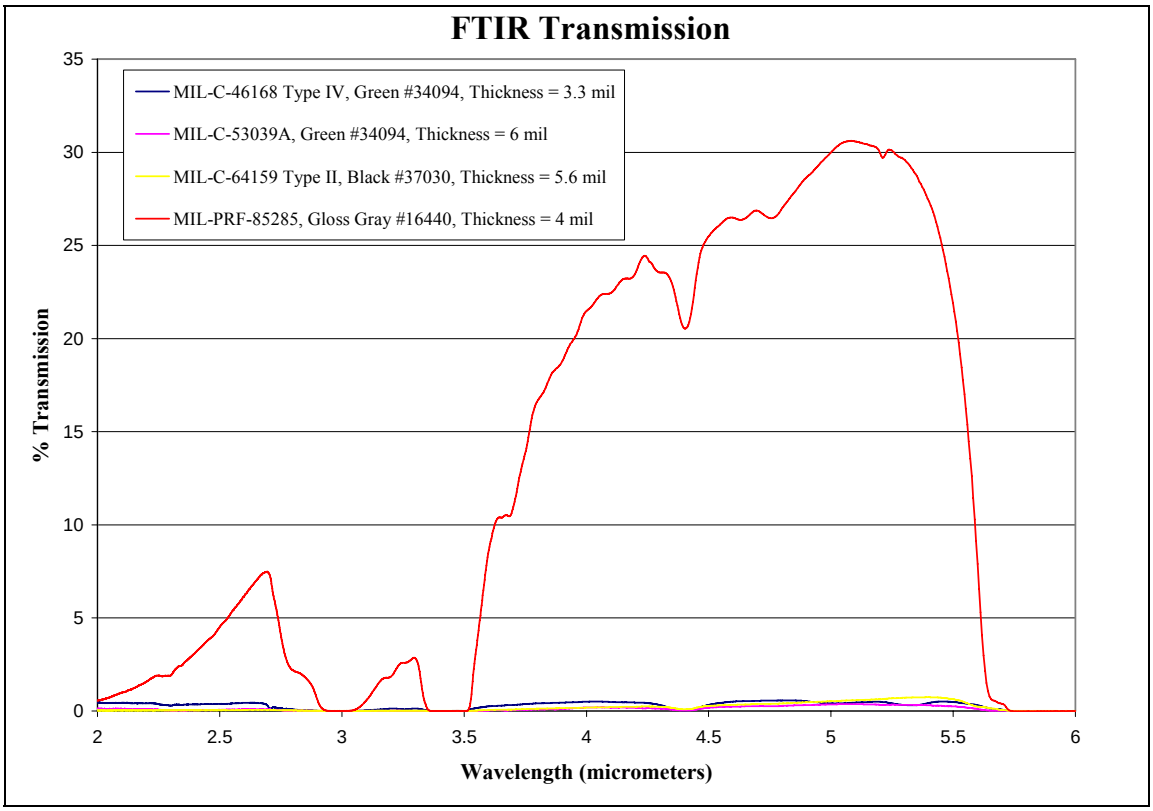


Figure E-18: FTIR Transmission Results of CARC Free Standing Films

Figure E-18 depicts the transmission spectra for the CARC free standing films compared to the Hentzen P-3 topcoat. The 46168 Black (both thicknesses) is not plotted as its spectra is zero in the 2-6μm range.

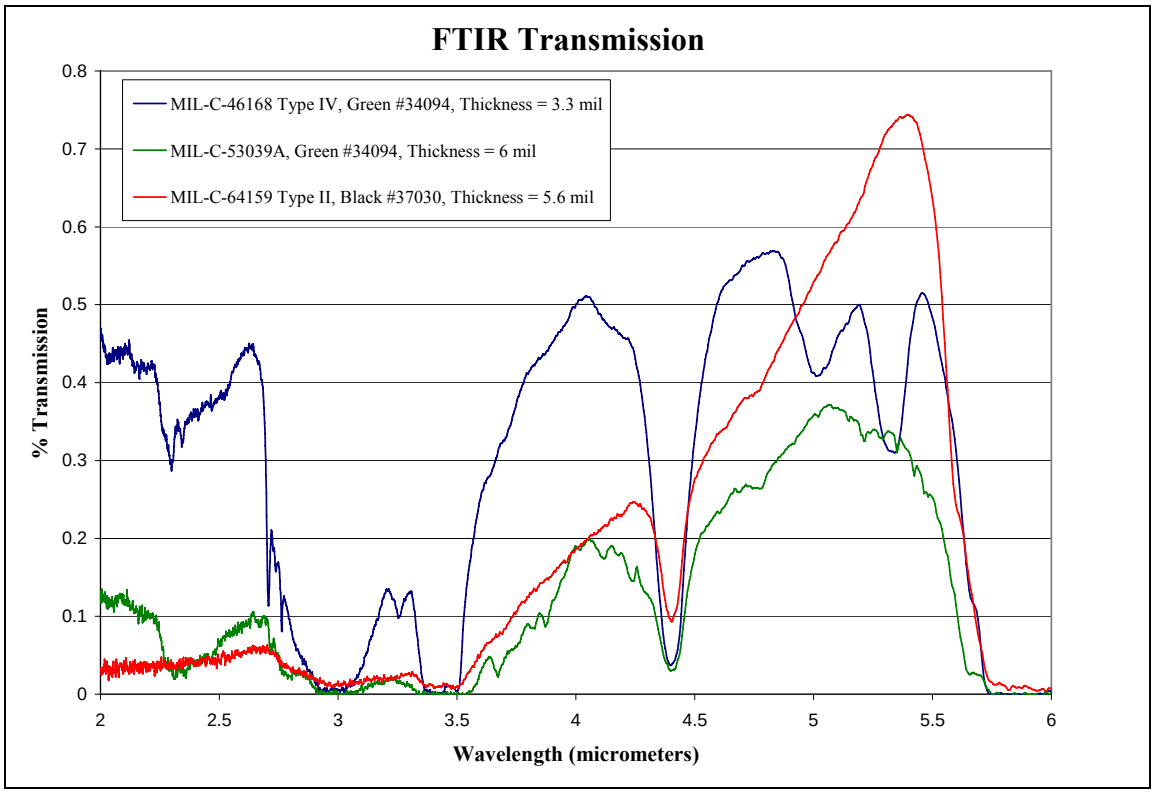


Figure E-19: FTIR Transmission Results of CARC Free Standing Films

Figure E-19 illustrates the expanded transmission scale of the CARC coatings FTIR. Note the scale of the % transmission.

The FTIR spectra illustrates the opaqueness of the CARC coatings in the 3-5 wavelength. This confirms the poor imaging performance of the Mid-IR camera utilizing the IRRIT methodology. We can not "see" through these coatings.

An additional test was utilized to determine the effectiveness of imaging though the CARC coatings with the IR camera.

A standard halogen light was used as a source to view the paint films with the Merlin® IR camera. The IR camera was set up to view the light source. The paint films on the plastic substrate were then introduced between the source and the IR camera. Photos were taken for no film in the FOV, Hentzen 2 mil P-3 paint film (single and double layer), and for a single layer of the CARC 3 mil 46168 Green top coat.

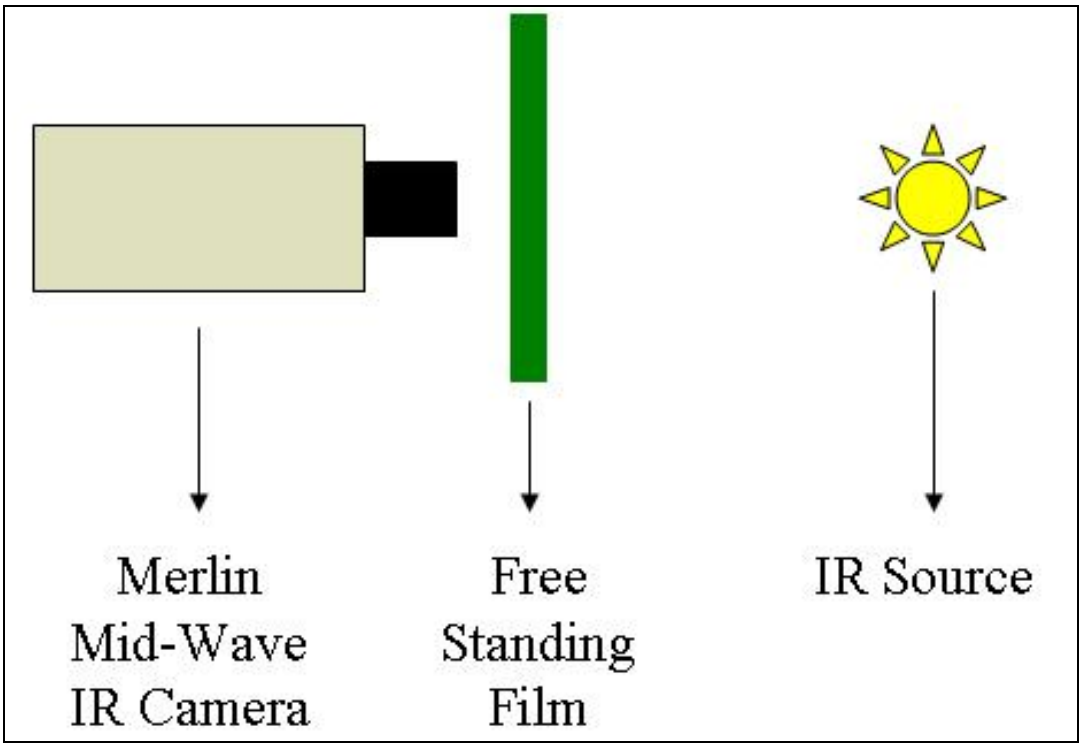


Figure E-20: Schematic of Free Standing Film Test

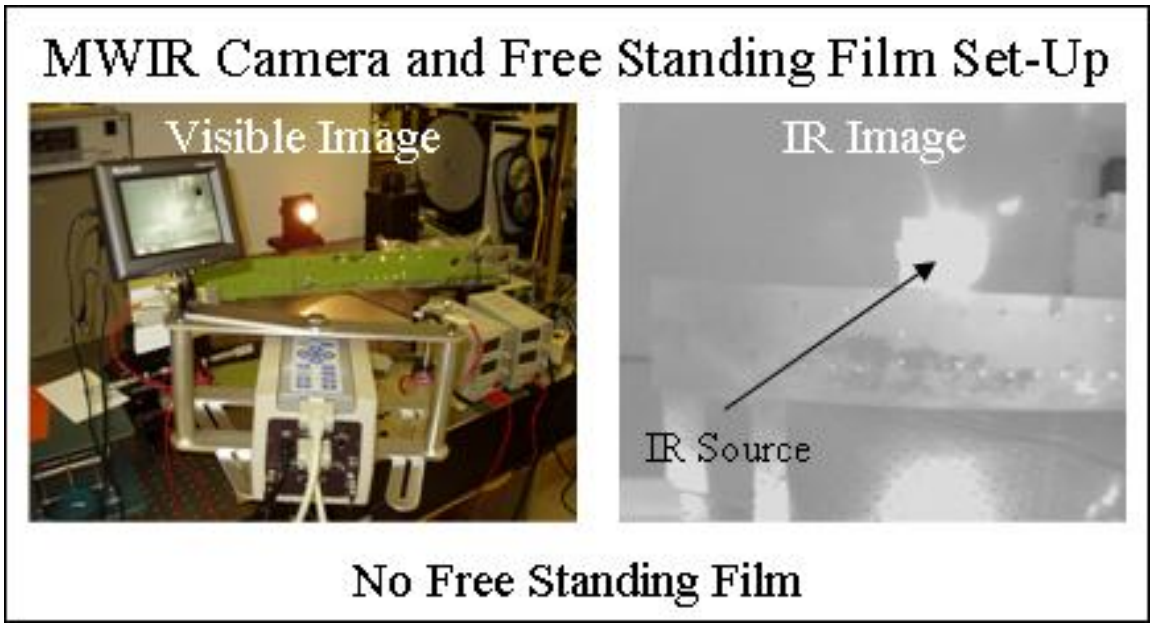


Figure E-21: No Sample Between IR Source and IR Camera

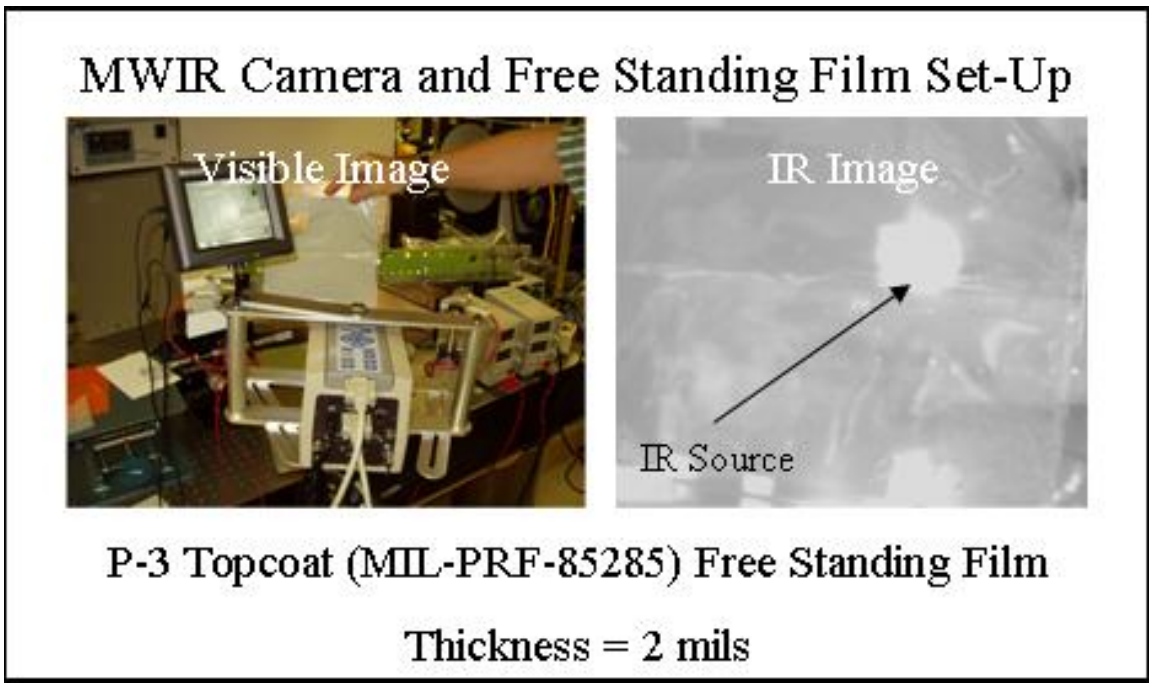


Figure E-22: IR Camera Detects IR Source through 1 Layer of P-3 Topcoat

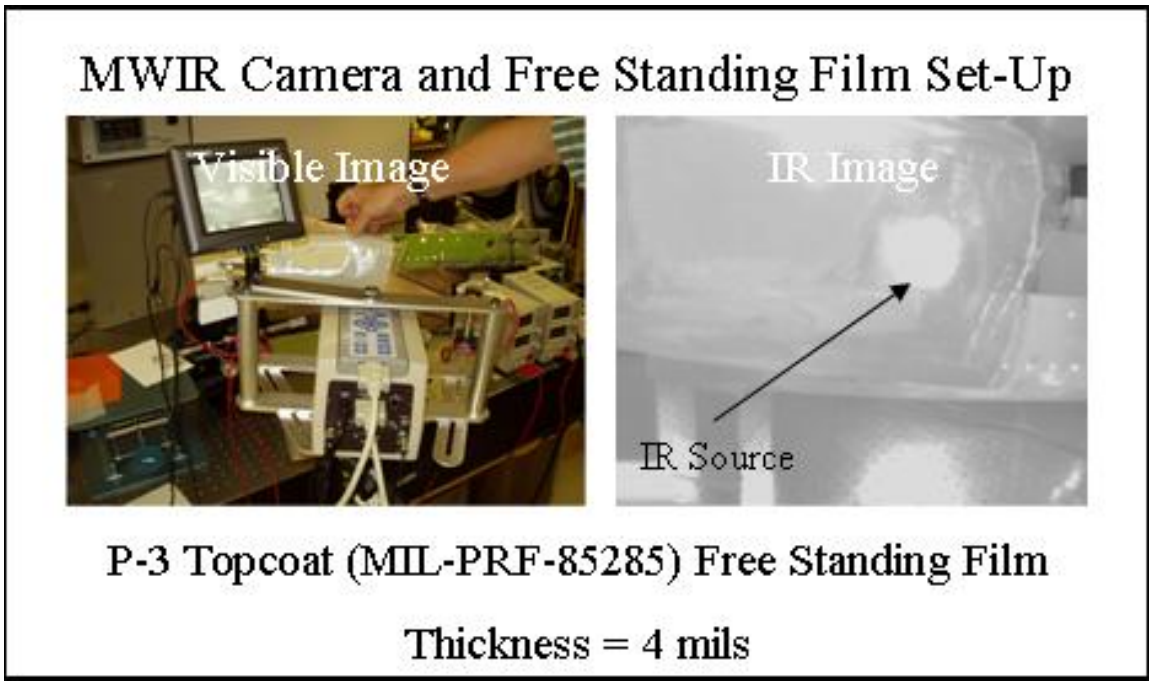


Figure E-23: IR Camera Detects IR Source through 2 Layers of P-3 Topcoat

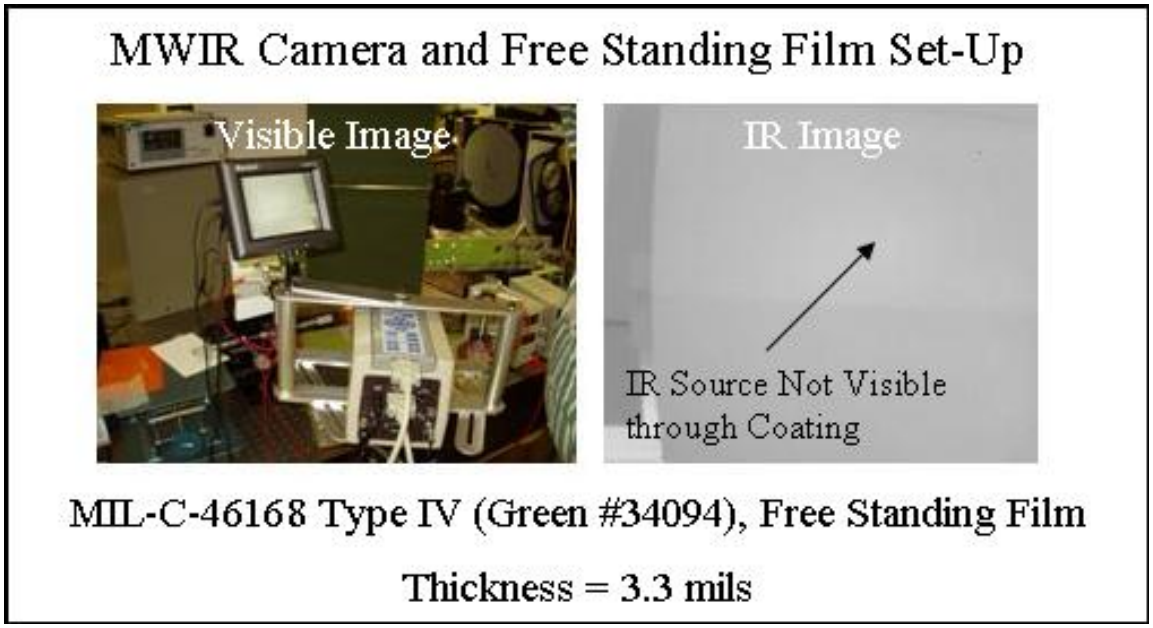


Figure E-24: IR Camera Cannot Detect IR Source through CARC Coating

Figure E-25: IR Camera Cannot Detect IR Source through CARC Coating

E.6 IR Camera Resolution Study

Fixture to Hold AF Target Specimens

A test set up was designed for the test program that fixtures the AF target sample produced to establish if the lens and FOV are uniform over the whole FOV. This is needed to confirm the uniformity of the field so that detection thresholds of various corrosion defect sizes can be established with accuracy. The test fixture was utilized in the Lab and produced images indicating the degree of distortion. The section, FOV Testing for Image Resolution and Quality, below illustrates some of the images produced in this on going study.

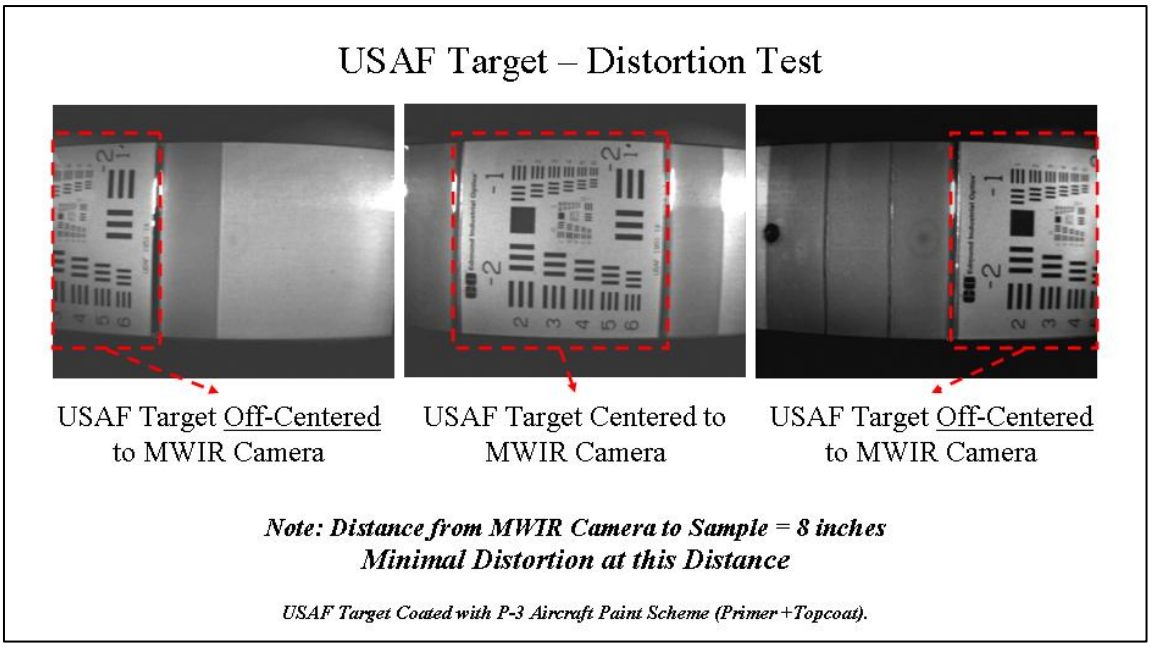


Figure E-26: AF Target Distortion Test

Figure E-26 illustrates IR Image of a 3 inch square Air Force resolution target. A 2 layer coating of the P-3 paint scheme covers this sample. The center of the sample was translated to the edges of the FOV of the camera. The smallest resolution pattern was maintained in the camera's FOV.

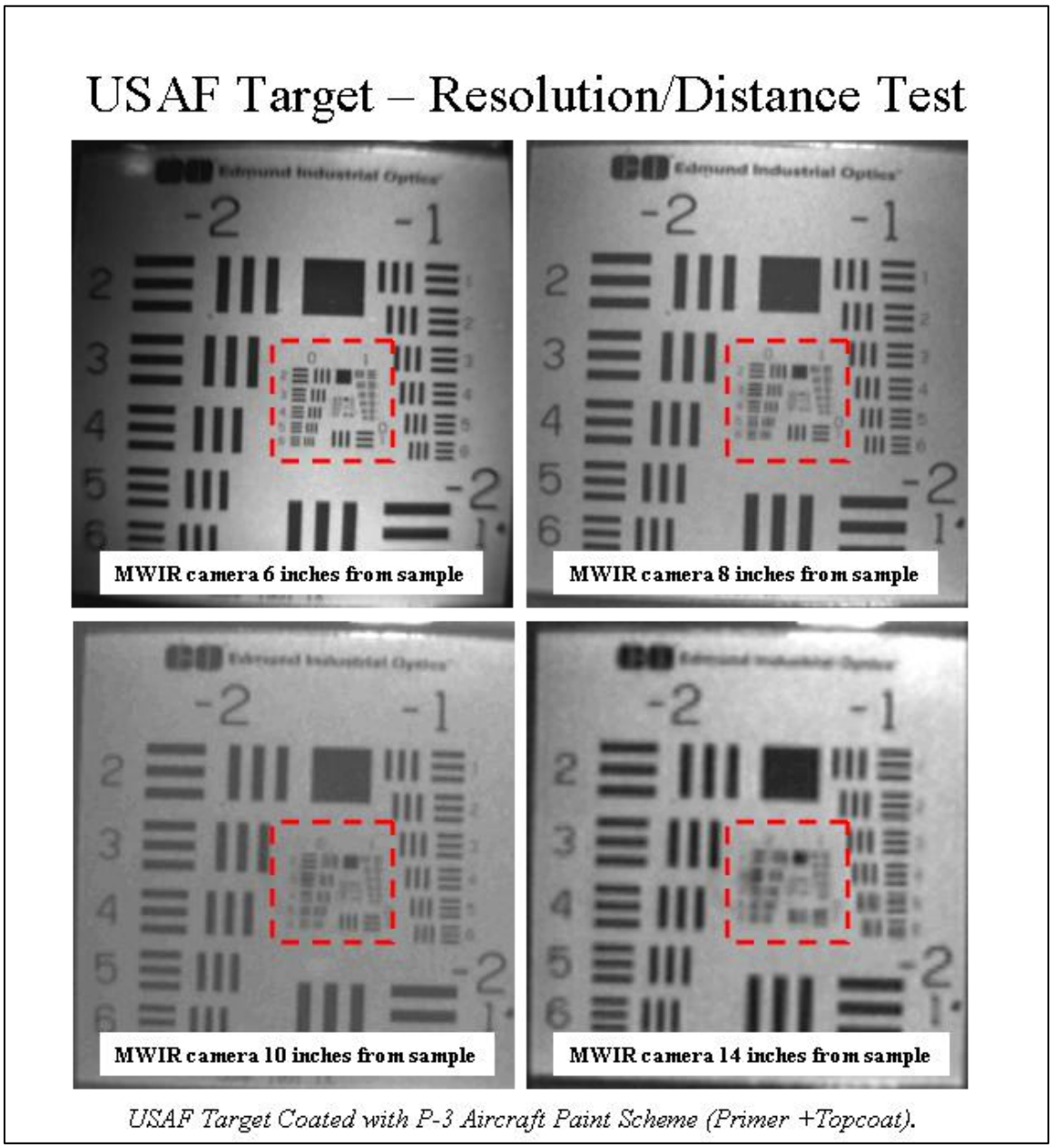


Figure E-27: AF Target Resolution-Distance Test

Figure E-27 illustrates IR Images of painted AF Target Standard taken from differing camera to sample distances.

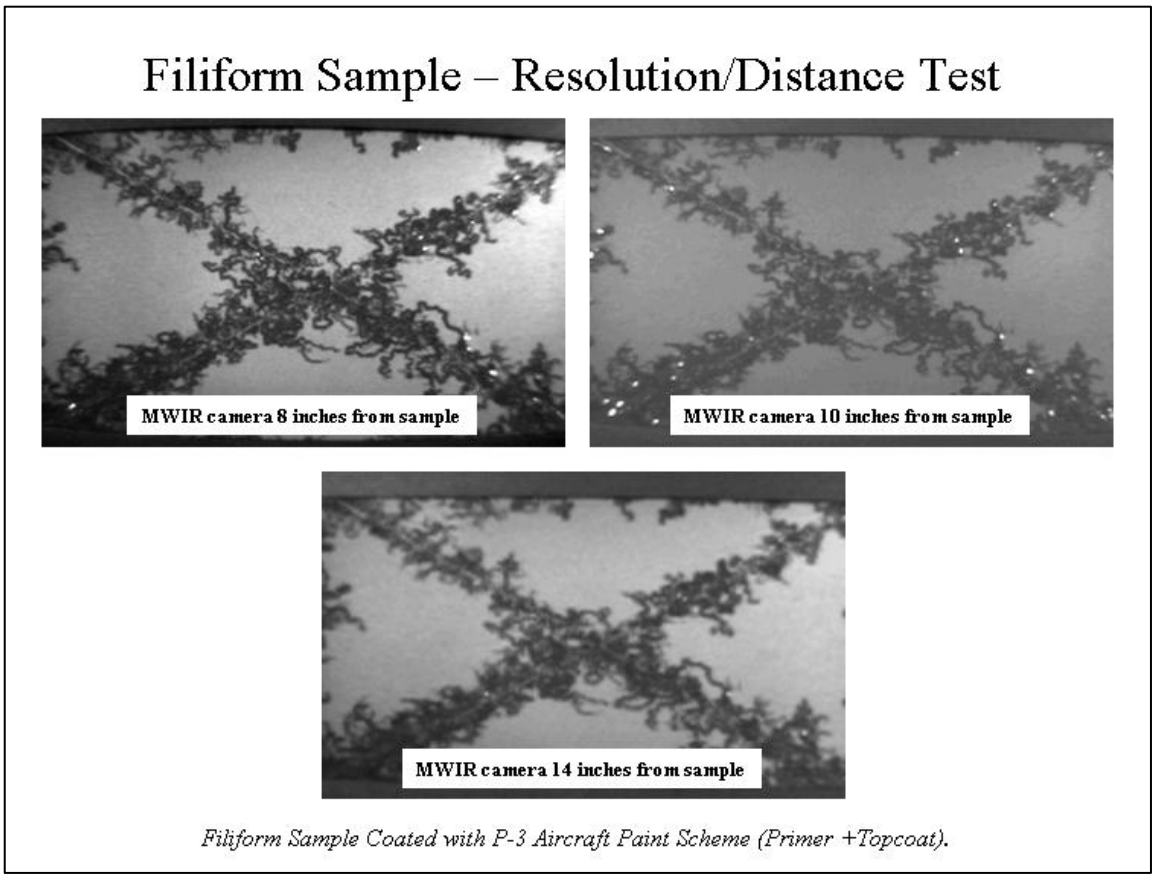


Figure E-28: Filiform Coupon Resolution-Distance Test

Figure E-28 IR Images of P-3 painted filiform coupon taken at differing camera to sample distances.

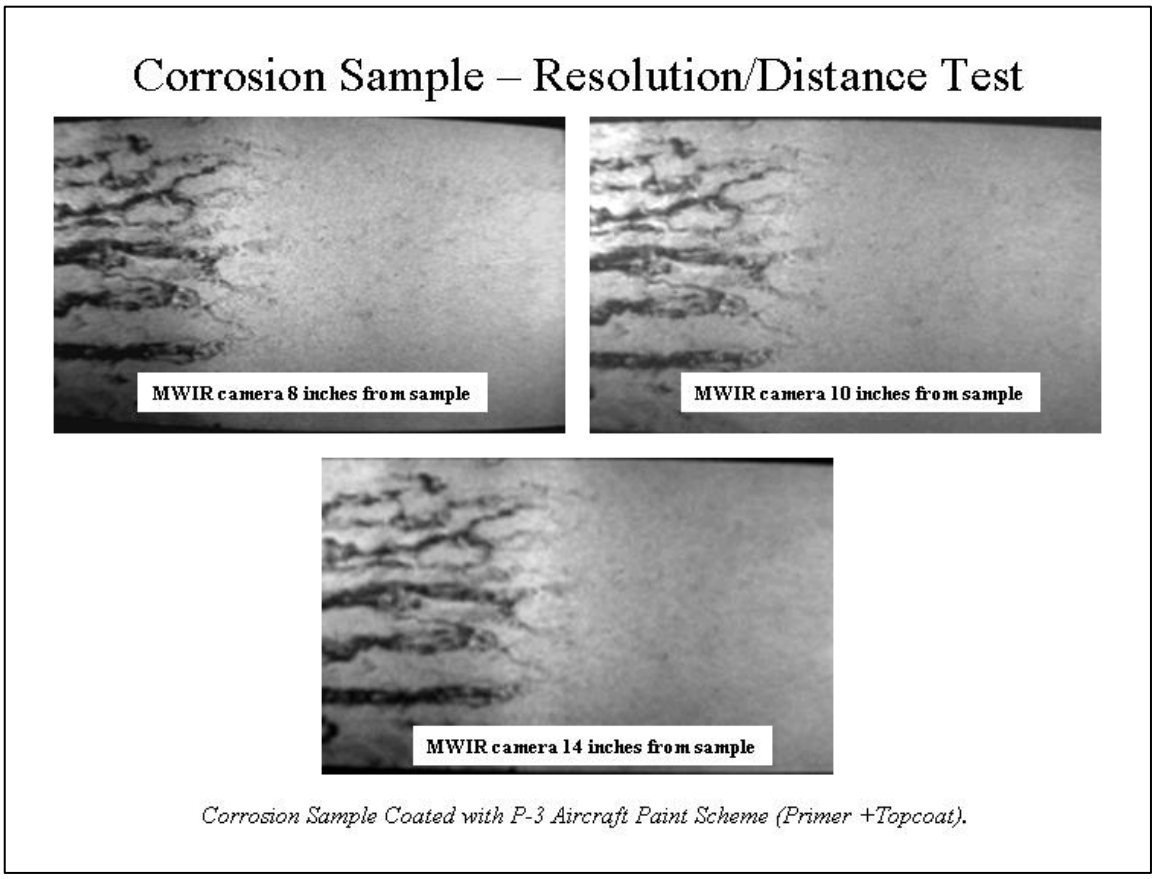


Figure E-29: Corrosion Coupon Resolution-Distance Test

Figure E-29 IR Images of P-3 painted corrosion coupon taken at differing camera to sample distances.

E.7 IR Reflectance vs. Blackbody

Thermal Analysis Conducted Utilizing a Controlled Water Bath

The contrast issue was studied with a very accurate and uniform surface temperature controlled by a water bath as illustrated in Figure E-30, as well as directionally controlled IR heaters in which the wattage could be precisely controlled along with angles and measurement techniques to control the direction of the IR flux off the illuminators.

An analysis of substrate temperatures was conducted to ensure the temperature conditions which may be encountered at the depot inspection areas would not degrade the performance of the IR camera corrosion detection system. This was accomplished by using a bath of water with enough thermal mass so that the temperature does not either cool down fast of heat up fast. Hot water was first added to the tank and the temperature of the painted corroded face that formed one of the faces of the thermal bath was monitored with a Raytech® Laser Pyrometer. Since water was directly against the face that was being observed a very close and uniform temperature was observed. This allowed for controlled analysis of the thermal illumination necessary to observe the corrosion. The first runs consisted of Blackbody observations of corrosion at elevated temperatures. The corrosion being more emissive than the surrounding metal (aluminum) appeared white under the IR camera and in fact was self illuminating. As the water temperature dropped the intensity of the blackbody self-illumination also dropped.

It was found that even at elevated temperature conditions found in the blackbody mode, it was possible for the IR illuminations lamps to override the effects of the blackbody condition and turn the corrosion observed in the IR camera from white to a dark condition, as normally seen in the IRRIT mode. It is important to note that the thermal conditions of the substrate will dictate the amount of illumination wattage of the heaters required to over-come the blackbody effects. In any case, the amount of wattage required to put the IR camera over from the blackbody mode to the IRRIT or reflectance mode was low and hence, the contrast issue should not be considered a problem in the inspection process, provided the illumination procedures include the use of controlled angled IR sources adjusted to optimize the image contrast.

Figure E-30 above illustrates the laboratory set up used to analyze the temperatures that are likely to be anticipated during inspection demonstrations at warm climate areas (e.g., Jacksonville, FL). A water bath was used to control the surface temperature of the epoxy primed (MIL-PRF-85582 Type I) and polyurethane topcoated (MIL-PRF-85285 Type I) corroded panels illustrated in Figure E-30. The monitor to the left of the IR camera was used to continuously monitor the corrosion image real time during the temperature analysis. A number of IR photographs were taken to understand the potential effects of temperature on contrast.

Additional testing was accomplished on a heavily corroded standard panel produced with the aid of ASTM 117 salt fog and Clorox® bleach. The following images illustrate the effect of a 95°F substrate temperature that has been primed and painted with a P-3 Orion equivalent finish system. As was illustrated in Figure E-31 (B), the corrosion can not be detected under certain illumination conditions with certain substrate conditions produced by the Blackbody emission for the corrosion when illuminated with IR heaters at 4.35 watts. Figure E-31 (A) illustrates the corrosion, as light in the blackbody mode, as the corrosion in this mode emits more energy than the surrounding non-corroded areas. Note: No illuminators were used for the imaging of Figure E-31 (A).

Heavy corrosion is illustrated by the light squares and the tapering rectangle to the right in Figure E-31 (A). In the blackbody mode corrosion gives off or emits more heat than the surrounding un-corroded aluminum structure. This physical transfer of heat is clearly seen as the corrosion appears white indicating a higher heat flux. Disregard the narcissus effect, which is an optical phenomenon of IR scanning systems which describes how a detector can look back at itself or view a mixture of active scene and itself for certain angles of scan. In Figure E-31 (A-C) the lens reflects off the substrate, as illustrated as a small black dot with a larger black circle surrounding the black dot.

Figure E-31 (B) illustrates the effect of almost zero contrast which is produced when both the corroded surface and the non-corroded surface give off approximately the same heat flux. This occurs when the blackbody heat flux from the corroded area is equal to the IR reflected flux of the non-corroded area. The competing modes of detection cancel out the contrast so the corrosion is not longer apparent, but in fact it is still present under the coating.

Figure E-31 (C) illustrates the effect of the heat flux when the IR reflected heat flux is greater in the non-corroded area of aluminum than from the corroded area, which appears cooler or darker. Note: Corrosion does not reflect IR, as well as the surrounding non-corroded areas. This demonstrates that the 95°F blackbody emission from the corroded area is over whelmed by the 7.7 watt illuminator source. In the example illustrated in Figure E-31, the surface of the aircraft is 95°F. The heat source is required to be at least 7.7 watts as oriented in the test to assure corrosion is detected by the IR illuminator system. Conversely the wattage needs to be less than 4.35 watts and preferably zero watts to observe the corrosion under the coating in the blackbody mode.

Conclusion: This study concluded that if the IR heat flux of the corroded areas equals the IR heat flux of the non-corroded areas, the corrosion would not be observable and hence the corrosion would not be detected through the coating. However, this study showed that a solution to this would be to increase the IR heat flux that is emitted from the IR illuminators, thus overpowering the blackbody effect. This solution would then allow the user once again to detect the corrosion via the IRRIT method. In most practical situations, the hanger temperature would not exceed 95° F degrees, and hence IR illuminator wattage of 7.7 watts would totally eliminate this problem.

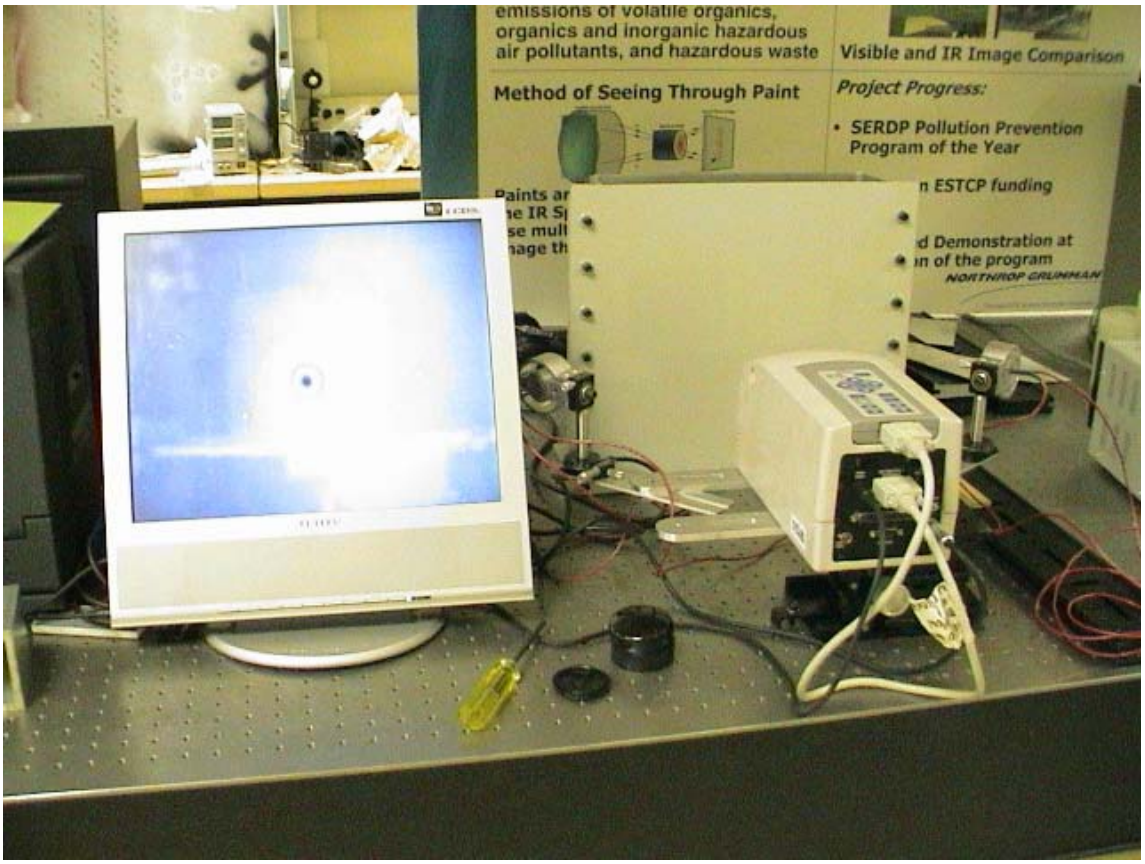


Figure E-30: NGC Laboratory Bench Top Set-Up

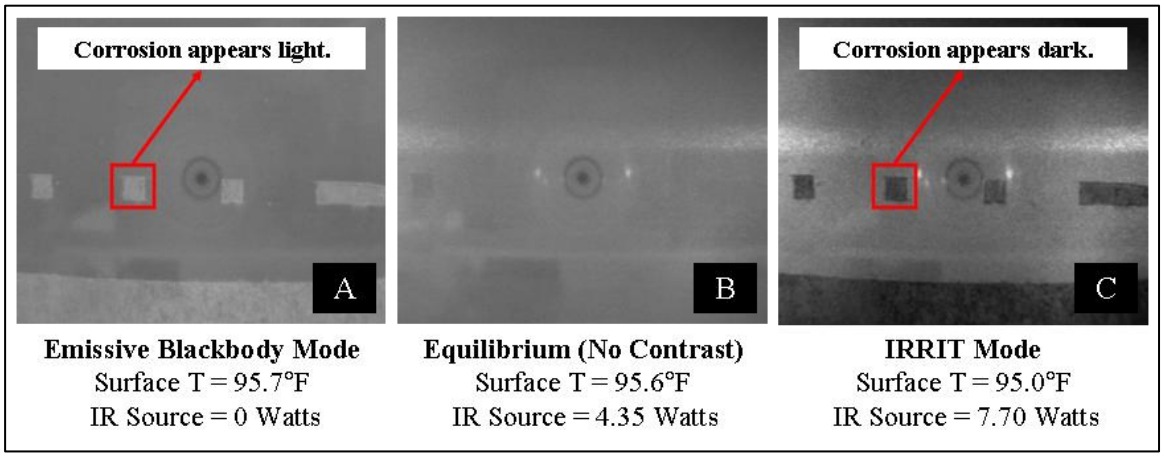


Figure E-31: Heat Flux Effect on IRRIT

E.8 Investigation to Correct Auto-Gain Image Issue

Issue:
Auto-gain tends to favor bright surfaces (bright surfaces are defined as reworked material, cadmium plated fasteners, and any other highly IR reflective surface), this results in the surrounding area appearing darker. However, if corrosion or other defects are present in this dark area they can be easily missed or go undetected via the IRRIT.

Solution:
After reviewing video data that was recorded during the 2nd P-3 Dem/Val (Tail #772) it was determined that by adjusting the contrast and brightness on the monitor the dark area becomes bright (the original bright surface also becomes brighter). This results in successfully detecting any corrosion or other defects that might have been missed if no changes were made on the monitor.

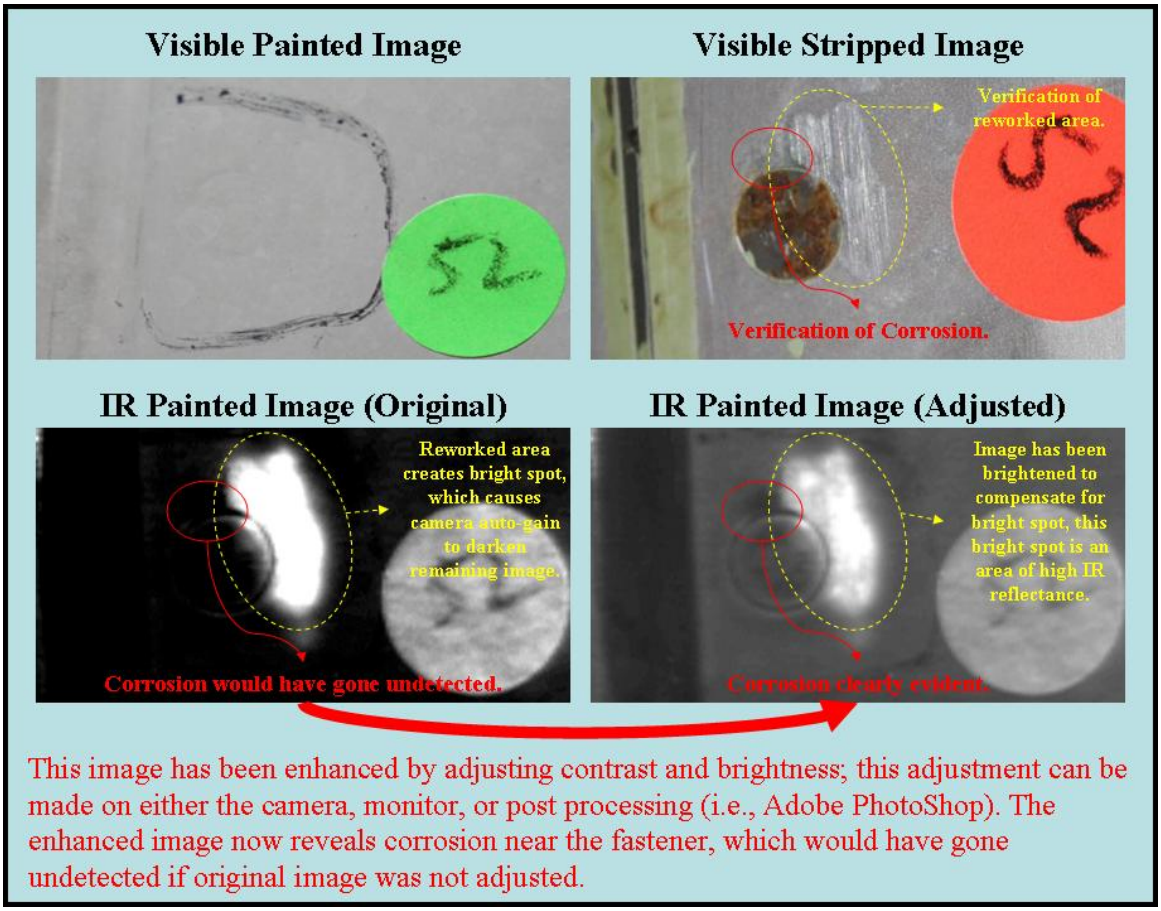


Figure E-32: Auto-Gain Issue

E.9 AF Coating Scheme's and CPC's

Corban 35 CPC was sprayed on a 2" x 2" piece of 23377 free standing film. The coating dried under a hood for 2 hours. The primer film thickness is 1.3 mils. The estimated thickness of the Corban 35 is 1-1.5 mils. A reddish discoloration can be visually observed on the surface of the free standing film.

Standard FTIR transmission scans were performed on a Thermo Magna 550 FTIR Spectrometer. The wavelength range of the scans was 1.78–15.3µm. The area of interest for these films is in the range of 3-5µm.

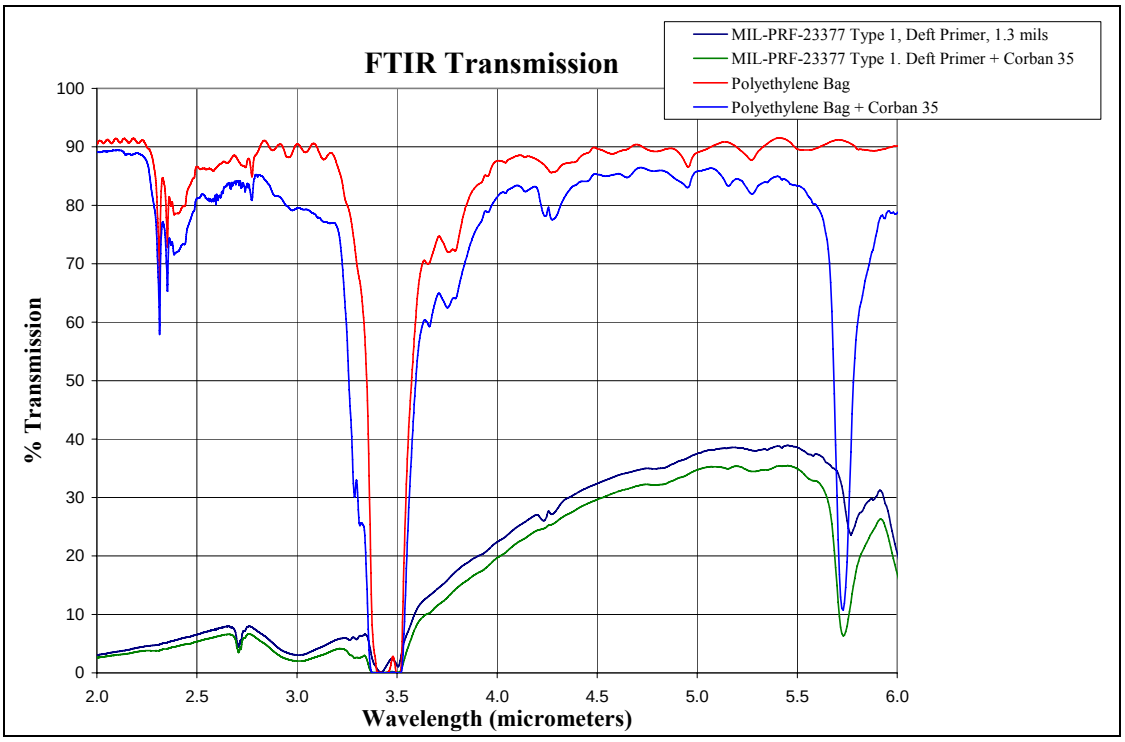


Figure E-33: IR Transmission Results for Free Standing Films and CPC

Two samples (an unsprayed free standing film and a film that was sprayed with Corban 35) were measured via FTIR. There were no additional spectral features introduced in the particular wavelength range (3-5µm). Overall transmission of the Corban 35-sprayed sample was reduced, most likely due to the additional thickness of the sample.

E.10 3-D Imaging

Background:

The current IRRIT system can easily detect corrosion surface area; however it is limited in its ability to detect corrosion depth due to the MWIR camera depth of field. The depth of field for MWIR camera systems is limited by the camera's ability to focus uniformly along a Z or vertical axis, similar to standard optical systems. This limits the ability of the observer from focusing on the bottom of non-flat planes such as a pit or bottom of a scratch and at the same time focus on the detail of the top of a scratch or pit. This is a classical optics problem, which can be solved by taking multiple images while scanning vertically up from the bottom (or down from the top) of the pit to the top and capturing a series of images and then reconstructing those images by means of an algorithm that results in one image with an improved depth of field. A multi-focus HIROX 3-D microscope (refer to Figure E-34) is used with software technology to reconstruct multiple focused visible images into one clear image with an improved depth of field. The 3-D IRRIT (refer to Figure E-35) exploits the same software technology (and technique stated above) used in conjunction with an MWIR camera (rather than a visible camera) to capture a series of IR images.

Description of 3-D IRRIT:

This innovative focusing idea, 3-D IRRIT, can be described as a method to observe, through organic coatings, detailed images utilizing multi-focused images in the MWIR and reconstructing them with an algorithm to obtain a clear image that is focused from the lower plane to the upper plane. This invention has particular applications in the aerospace industry. The stripping of organic coatings for aerospace structures is not only very expensive, but causes a great deal of pollution. If the technology of image enhancement utilizing this algorithm is combined with an MWIR system to detect corrosion, cracks, scratches and pits under coatings, an improved system will allow for enhanced inspection capabilities. This new method for inspection will give the user or inspector a capability to make structural decisions about the integrity of structure such as aircraft or other structures with out having to remove organic coatings. Previous MWIR reflective systems utilizing detectors have not been able to image with this improved detail which is needed to make better structural assessments as to depth, morphology or topography of a structural surface. Current MWIR systems assess details without the aid of this new technology, which makes them inferior to the newly proposed system with the improved imaging capability. The user will have more useful information to make informed decisions regarding structure, and this will save more pollution and cost less to inspect aircraft and other aerospace structure than in the past. This method is significantly improves and enhances existing conventional MWIR inspection systems such as an MWIR system that uses reflectance as the mode of inspection. By taking multiple images at different focal distances and reconstructing the images by using the focused portion of each image by means of an algorithm it is possible to not only reconstruct an image with superior depth of field, but to be able to rotate this image to measure the shape and depth of the topography.

Procedures:

- Mount Merlin® MWIR camera on adjustable stage controlled by a micrometer.
- Remove the standard 13 mm lens from Merlin® MWIR camera and replace with 4X IR microscope lens.
- Power-On Merlin® MWIR camera and with the power switch on back of camera. Thermal cycling will be loud for 10-15 minutes as the Stirling cooler engages.
- Turn on HY1802D power supply to power IR illuminators and set dial to selected voltage and current.
- Once the Merlin® MWIR camera has cooled down, an image will be observed on the monitor. The Merlin® MWIR camera should be allowed to stabilize for 30 minutes for best performance.
- 3-D IRRIT follows the same calibration methods used in standard IRRIT (refer in Appendix A).
- Place sample in front of the Merlin® MWIR camera and adjust IR illumination.
- Utilizing the Merlin® MWIR camera by taking multiple images along different evenly spaced locations along the Z-axis. Determine top and bottom planes and the interval of Z axis steps. Images are saved and captured at different evenly spaced locations. The 4X IR microscope lens is required for enhanced magnification and to demonstrate improved depth of field.
- Captured IR Images (jpeg format) will be blended into a single focused image based on the highest contrast area. At the same time, each image has height data embedded. Using the HIROX software algorithm to construct a de-blurred image with improved depth of field.
- The above procedure was repeated with a laboratory manufactured pitted sample and an actual Navy E-2 aircraft fastener head sample.

Results:

Laboratory testing was performed to show the feasibility of using the IRRIT camera system to acquire data resulting in an improved method to image pits, cracks and other structural defects through organic coatings. This 3-D IRRIT technique was tested on two (2) samples. The first sample was manufactured in NGC's laboratory with a corrosion pit; the second sample was a painted aircraft fastener head from an actual Navy E-2C. These samples were both investigated by the 3-D IRRIT with a 4X IR microscope lens was substituted for the standard 13 mm lens on the IRRIT camera (refer to Figure E-35). The camera system was then mounted to an adjustable stage controlled by a micrometer (refer to Figure E-35).

Figure E-36 illustrates a painted aluminum corrosion coupon (pit) that was mounted to a fixed stage and the IRRIT located and focused to view the top surface (Figure E-36 (A), starting image). The camera stage was then moved in small increments (25 μm), with an image acquired at each increment step, through the depth of the corrosion pit (Figure E-36 (B), ending image). Image processing software (as available

from HIROX) was used to build a composite focused image of the corrosion pit (Figure E-36 (C)).

Figure E-37 illustrates a painted aircraft fastener head from an actual Navy E-2C that was mounted to a fixed stage and the IRRIT located and focused to view the top surface (Figure E-37 (A), starting image). The camera stage was then moved in small increments (100 μm), with an image acquired at each increment step, through the depth of the fastener stamping mark (Figure E-37 (B), ending image). Image processing software (as available from HIROX) was used to build a composite focused image of the corrosion pit (Figure E-37 (C)).

Conclusions:

Using the 3-D IRRIT does allow for improved or enhanced images, as shown in Figures E-36 and E-37. However, the 3-D IRRIT requires additional work to be considered field ready. Specifically, a narrower depth of field IR lens system and a mounting reference system (mounted to aircraft) with a fine micrometer movement in order to accurately acquire the depth data (and for the software to accurately process IR images). The current IR optics (used in this test) have too great a depth of field. The smaller the increment of distance between images (or vertical displacement), assuming the IR optics have the shallower/narrower depth of field, the higher the resolution of the focused image will be. 3-D IRRIT as compared to standard IRRT provides an enhanced image for engineering investigation but does not lend itself as a rapid inspection technique (due to the time required to obtain the quantity of images at one location), thus the 3-D IRRIT is not considered a viable inspection method for depot/production use at this time.

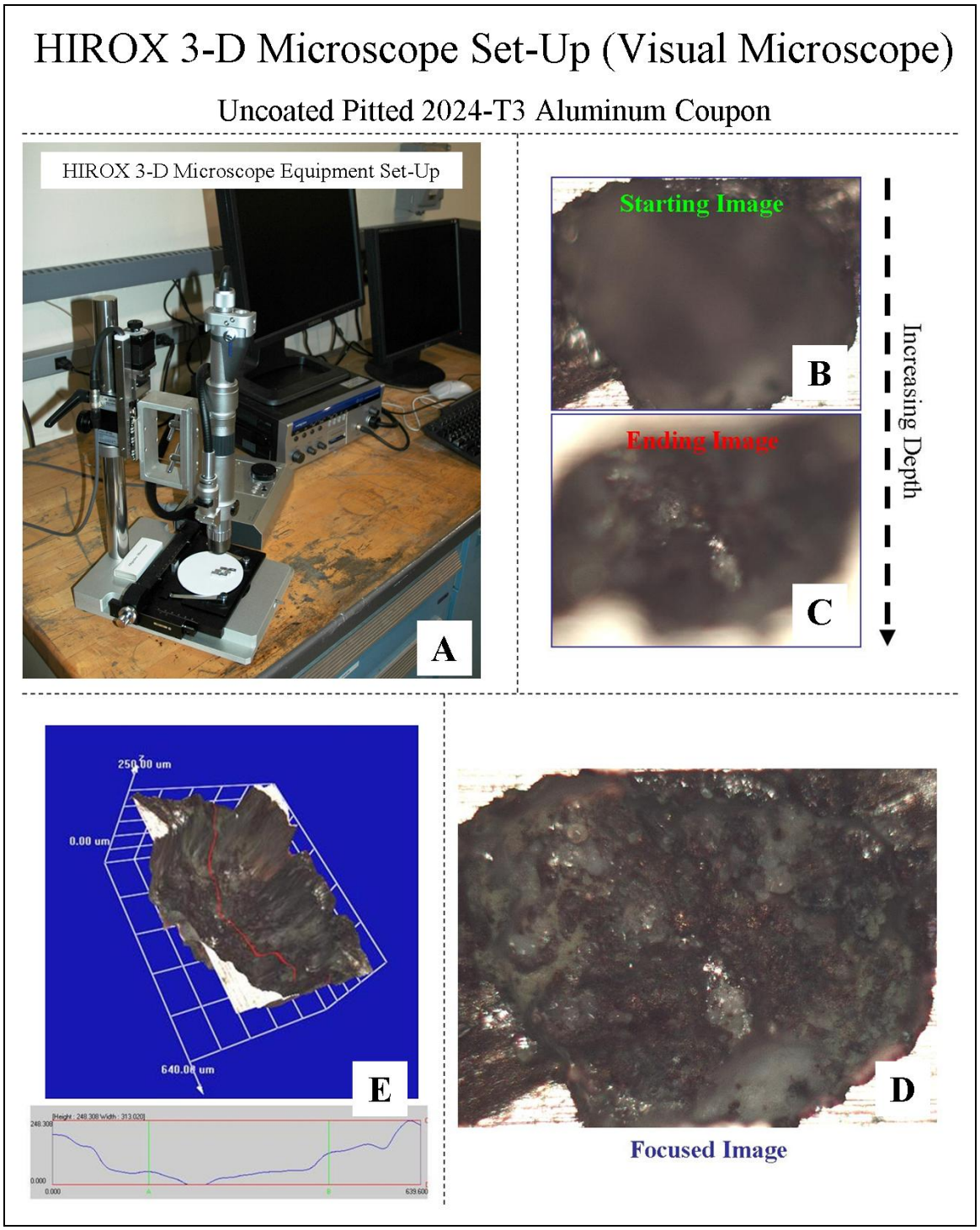


Figure E-34: HIROX 3-D Microscope Set-Up (Visual Microscope)

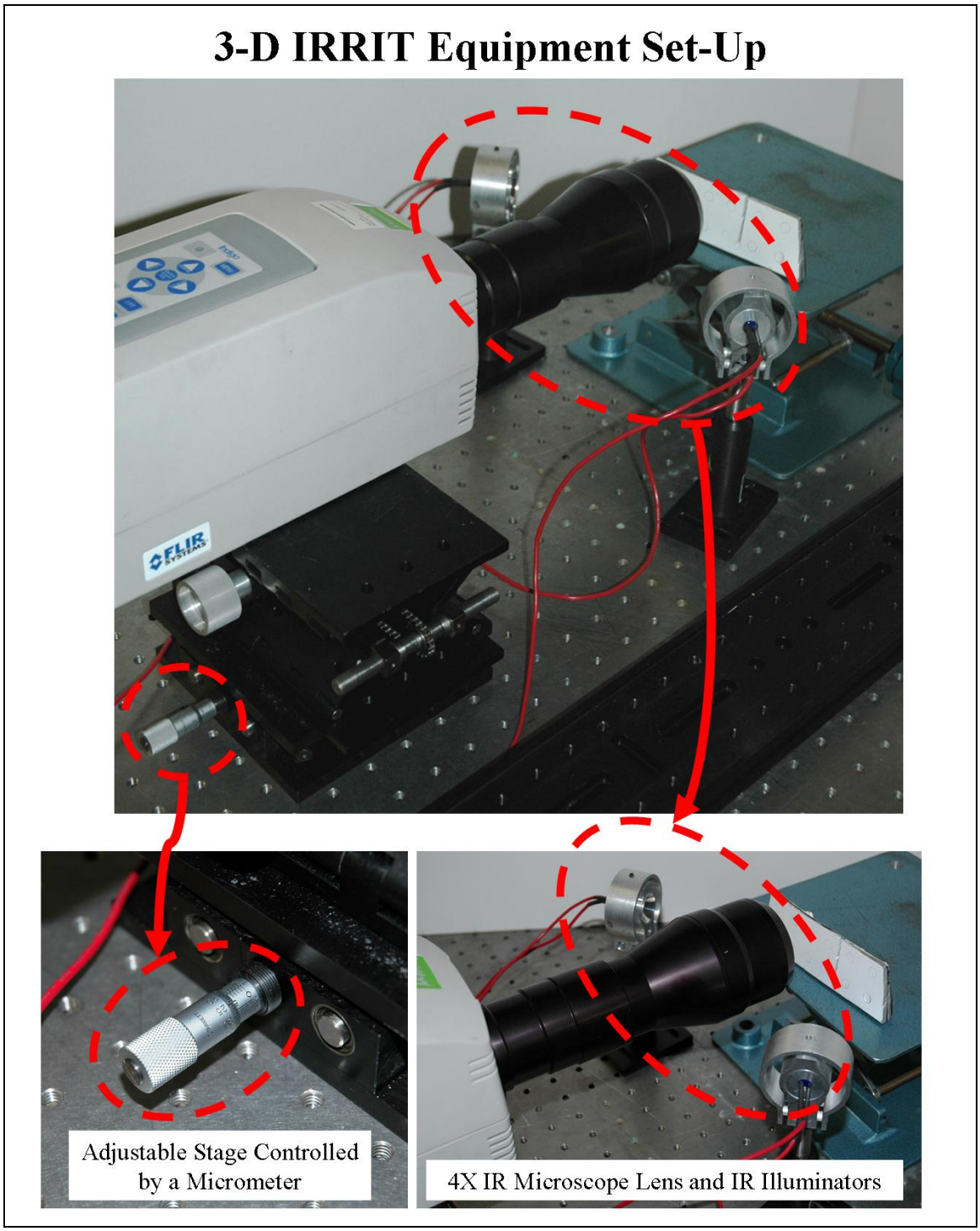
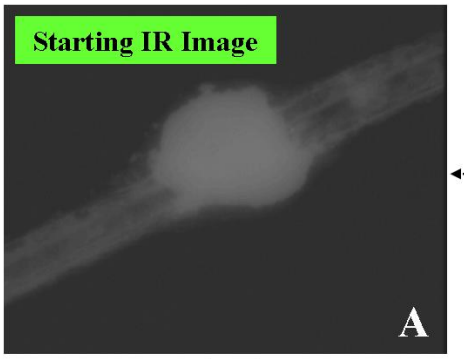
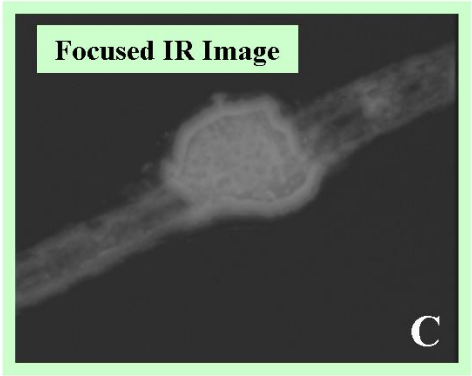


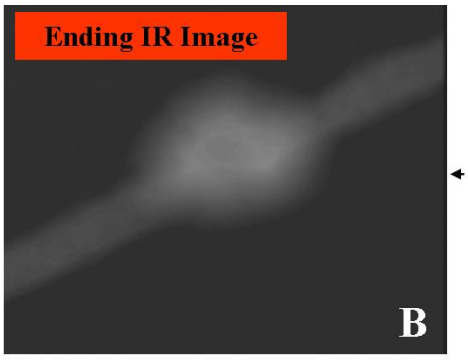
Figure E-35: 3-D IRRIT Equipment Set-Up

3-D IRRIT – Pitted 2024-T3 Aluminum Coupon

(Coated with MIL-PRF-85582 Epoxy Primer and MIL-PRF-85285 Polyurethane Topcoat)





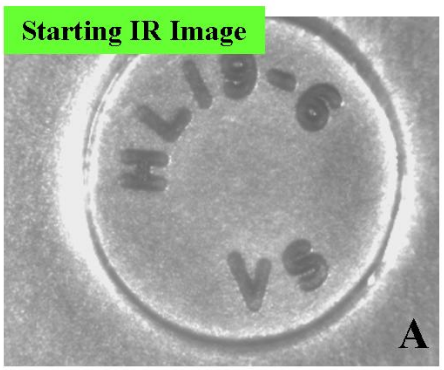


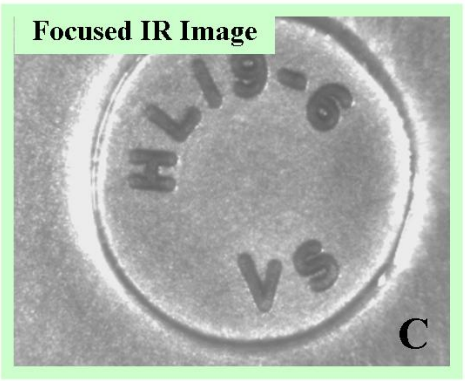
IR Image Number	Depth in Micrometers (µm)
1 (Starting Image)	0
2	25
3	50
4	75
5	100
6	125
7	150
8	175
9	200
10	225
11	250
12	275
13	300
14	325
15	350
16	375
17	400
18	425
19	450
20	475
21 (Ending Image)	500

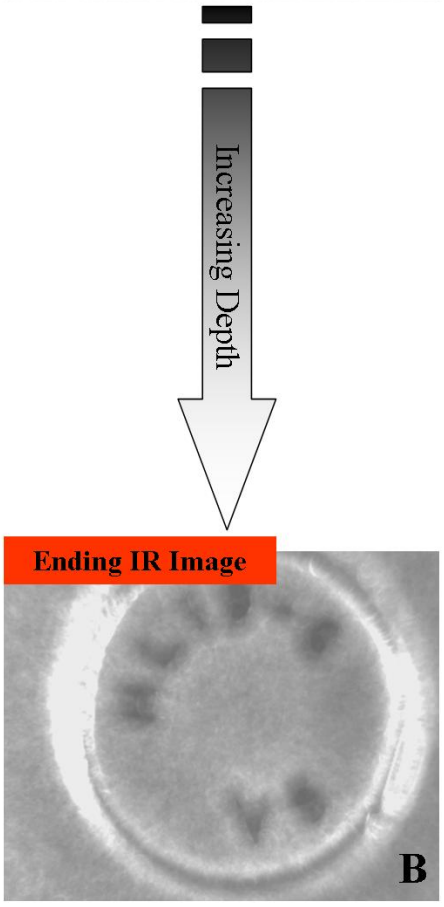
Figure E-36: 3-D IRRIT Images: Pitted Coupon

3-D IRRIT – Aircraft Fastener Head

(Coated with MIL-PRF-23377 Epoxy Primer and MIL-PRF-85285 Polyurethane Topcoat)







IR Image Number	Depth in Micrometers (µm)
1 (Starting Image)	0
2	100
3	200
4	300
5	400
6	500
7	600
8	700
9	800
10	900
11	1000
12	1100
13	1200
14	1300
15	1400
16	1500
17	1600
18	1700
19	1800
20	1900
21	2000
22	2100
23 (Ending Image)	2200

Figure E-37: 3-D IRRIT Images: Fastener Head

APPENDIX F DEM/VAL PLAN DEVIATIONS

F.1 Navy P-3 Dem/Val Plan Deviations

Deviation #1: Quantity of Aircraft (Navy P-3s) to be IRRIT Inspected.

Initial Navy P-3 Dem/Val Plan, Section 3.6.3 (Amount/Treatment Rate of Material to be Treated), stated "A random sampling of at least three P-3 aircraft with similar paint schemes will be used to demonstrate and validate the IRRIT. The object/goal of the Dem/Val is to inspect a combined total surface area of at least 600 square feet of P-3 surface." However, due to the large quantity and quality of data and positive results that the IRRIT system yielded from the first 2 aircraft (P-3s) it was considered to be of no benefit to do a 3rd aircraft (P-3). The reduction in the quantity of aircraft to Dem/Val the system also resulted in a reduction in surface area that was inspected. The Dem/Val plan states that a minimum of 600 square feet of P-3 surface shall be inspected; however, in reality 300 square feet were inspected.

Deviation #2: Locations to be IRRIT Inspected.

Initial Navy P-3 Dem/Val Plan, Section 3.6.5 (Experimental Design), stated "The lower section of the inner port wing made from corrosion prone aluminum alloy 7075-T6 will be inspected between the forward and aft spar and Stations 65 and 147. The fuselage section to be inspected is manufactured out of aluminum alloy 2024-T3 and located approximately between Stringers 10 to 25 and Stations 850-1050." However, due to NAVAIR Jacksonville production schedule and time available on the aircraft (P-3) it was determined that the available time would be better spent to focus on the lower section of the inner port wing. This determination was based on access time to the aircraft.

F.2 USAF KC-135 and B-52 Dem/Val Plan Deviations

Deviation #1: Locations to be IRRIT Inspected.

Initial OC-ALC KC-135 and B-52 Dem/Val Plan, Section 3.6.5 (Experimental Design), stated "the primary targets are the longerons (heavy lengthwise structural members) at the bottom sides of the bay and the light aluminum panel ceiling of the bay." However, due to OC-ALC B-52 production schedule and time available on the aircraft (B-52) it was determined that the longerons had the same coating/finish scheme as the ceiling panel, and the IRRIT was successful in identifying corrosion beneath the paint in that area. The final determination was based on access time to the aircraft.

APPENDIX G ENDORSEMENT LETTERS

G.1 Navy P-3

Letter of Endorsement

FROM: P-3 FST

TO: NAVAIR JAX 4.9.7.6; John E. Benfer (WP-0407 Principle Investigator)

SUBJ: INFRARED REFLECTANCE IMAGING THROUGH AIRCRAFT PAINT SYSTEMS

1. The P-3 Fleet Support Team Engineering Office has reviewed technical information and witnessed field demonstrations associated with infrared imaging of corrosion through aircraft paint systems. This technology has demonstrated the capability to detect and image any surface corrosion without disturbing the paint system in an industrial environment while utilizing a commercially available of-the-shelf (COTS) mid-IR camera.
2. This technology has shown applicability and promise for use by P-3 maintenance activity locations to ascertain the current condition and integrity of the OML/IML coating system.
3. Please contact me if further information is required. Tel: (904) 594-5901, or via email to daniel.marlowe@navy.mil

Sincerely,

Daniel L Marlowe

Daniel Marlowe

P-3 Fleet Support Team Engineer

G.2 Navy E-6

19 Jan 2007

Letter of Endorsement

FROM: E-6 FST RCM Lead

TO: NAVAIR JAX 4.9.7.6; John E. Benfer (WP-0407 Principle Investigator)

SUBJ: INFRARED REFLECTANCE IMAGING THROUGH AIRCRAFT PAINT SYSTEMS

1. The E-6 Fleet Support Team Engineering Office has reviewed technical information and witnessed field demonstrations associated with infrared imaging of corrosion through aircraft paint systems. This technology has demonstrated the capability to detect and image surface corrosion in an industrial environment while utilizing a commercially available off-the-shelf (COTS) mid-IR camera.
2. This technology has shown applicability and promise for use at E-6 field locations to ascertain the current condition and integrity of the OML coating system, for an engineering disposition of required maintenance and/or paint interval.
3. Please contact me if further information is required. Tel: (904) 317-1538.

Sincerely,

TRIEST.
DONALD.
E.12300383
13

Digitally signed by TRIEST.DONALD.E.1230038313
DN: cn=TRIEST.DONALD.E.1230038313, c=US, o=U.S. Government, ou=DoD
Date: 2007.01.19 13:43:30 -05'00'

Donald Triest

E-6 FST Supportability Deputy/
RCM Lead Engineer

G.3 Navy T-45

Letter of Endorsement

FROM: T-45 FST

TO: NAVAIR JAX 4.9.7.6; John E. Benfer (WP-0407 Principle Investigator)

SUBJ: INFRARED REFLECTANCE IMAGING THROUGH AIRCRAFT PAINT SYSTEMS

1. The T-45 Fleet Support Team Engineering Office has reviewed technical information and witnessed field demonstrations associated with infrared imaging of corrosion through aircraft paint systems. This technology has demonstrated the capability to detect and image surface corrosion in an industrial environment while utilizing a commercially available of-the-shelf (COTS) mid-IR camera.
2. This technology has shown applicability and promise for use at T-45 field locations to ascertain the current condition and integrity of the OML coating system, for an engineering disposition of required maintenance and/or paint interval.
3. Please contact me if further information is required. Tel: (904) 317-1911.

Sincerely,

Shannon Elliott

Shannon Elliott

T-45 Senior RCM Engineer

G.4 Navy Materials Engineering Division

11 April 2007

FROM: Materials Engineering Division (AIR-4.3.4)

TO: NAVAIR JAX 4.9.7.6; John E. Benfer (WP-0407 Principle Investigator)

SUBJ: INFRARED (IR) REFLECTANCE IMAGING THROUGH AIRCRAFT PAINT SYSTEMS

1. AIR-4.3.4 has reviewed technical information and witnessed field demonstrations associated with infrared reflectance imaging of corrosion through aircraft paint systems. This technology has demonstrated capability to detect and image surface corrosion in an industrial environment while utilizing a commercially available of-the-shelf (COTS) mid-IR camera.
2. Scheduled maintenance processes that involve stripping paint from aircraft surfaces or disassembling components for corrosion inspection can be reduced or eliminated using this technology by providing enhanced inspection capability in support of ground support equipment (GSE), weapons, avionics and component product lines. The availability of a quick, reliable, and simple nondestructive technique that can detect and characterize corrosion hidden under aircraft coating systems, would reduce inspection times and costs, and reduce hazardous waste generation from paint and depaint operations.
3. This technology is also capable of providing enhanced inspection data and documentation associated with corrosion-related failure analyses, engineering investigations, and research, development, testing, and evaluation (RDT&E) programs. Continued research in this area could lead to the development of a system that significantly improves the corrosion inspection process and thereby reduces the risk of failure in aircraft structural component and ultimately improve flight safety. All new and legacy platforms can benefit from this technology; therefore, AIR-4.3.4 recommends both the continued investment into this technology, as well as, the immediate application where applicable.
4. Please contact me if further information is required. I can be reached at (904) 542-4521 x101 or by e-mail at john.yadon@navy.mil.

John L. Yadon
Materials Engineering (AIR-4.3.4)

G.5 Coast Guard

To: John Benfer
Cc: John Speers, John Weir
From Rusty Waldrop USCG NDI Program Manager
Subject: ESTCP (IRRIT) USCG Dem/Val

Summary:

USCG ARSC EISD AAB NDI has been an active participant in a cross service program that includes corrosion detection under aircraft coatings. The program is known as "Environmental Friendly NDI for Corrosion Inspection through Coatings". This program has been in extensive planning with the AAB since April of 2003. The technology utilizes the reflectance properties of corrosion to be detected by means of thermal heat transfer. The reflectance of the surface corrosion would give definite contrast to the reflectance properties of the aircraft coatings and other organic or inorganic aircraft substrates thereby making the corrosion detectable by means of a thermal IR camera utilizing long wavelength of the IR light spectrum. Team participants of the program are Mr. John Speers of Wright Patterson Air Force Base (WP-AFB), Mr. John Weir of Northrop Grumman Bethpage Long Island NY, Mr. John Benfer of NAVAIR Jacksonville FL, Mr. Steven Chu and Mr. David Allen of ASM Management. Beside myself another participant of the USCG AAB Materials Engineer is Mr. Sam Benavides.

The initial concerns over the ability to detect corrosion under coatings were paint thickness and the ability to detect the reflectance properties of the corrosion with a gloss topcoat applied. Glossy paint enhances the reflectance properties of the topcoat and with this will also reduce the absorbance properties of the coating substrates there by reducing and possibly masking the reflectance properties of the underlying corrosion. Utilizing a gloss meter the glossy measurement of a USCG HU25 aircraft was in the range of 72-90 specular gloss at a 60n degree angle of incidence while the acceptable limit of other DoD military aircraft is in the range of 0-5 specular gloss at a 60-degree angle of incidence. The cross section thickness of the HU25 aircraft can be in the range of 3.0 mils to 13 mils. The USCG ARSC does not de-paint the aircraft upon every depot induction. The aircraft appear to be de-painted every third depot induction. During the 2 depot inductions the aircraft is scuffed up, primed and painted adding layer upon layer of primer and paint whereas the other military entities de-paint upon every depot induction giving these aircraft coating thickness around 5 mils. This scenario gives the USCG HU25 a heavy thick topcoat substrate scheme compared to the other military entities.

To prepare for these rather extreme parameters it was requested by Mr. John Weir that we develop some test panels with USCG aircraft paint scheme including the thickness that are normal to USCG aircraft. The USCG AAB was tasked to supply test panels with known corrosion painted to the USCG aircraft specifications. These panels were supplied to Mr. John Weir for IR camera optimization prior to attempting detection of corrosion on a USCG air vehicle. These test panels although not to USCG aircraft paint thickness parameters were still supplied to Mr. John Weir for camera optimization.

USCG AAB arranged for HU25 aircraft 2103 to be used for the USCG mini Dem/Val.

Sandia NDI Validation Center located in Albuquerque, New Mexico is host to the aircraft and hanger. The contact at the NDI validation center is Mr. David Moore. Sandia was task to evaluate the paint thickness of aircraft 2103 to verify the measurements are representative of USCG aircraft. The paint thickness of the 2103 was in the medium average range of 8-11 mils with some areas of 6 mils and other areas of 13 mils but for the most part between 8-11 mils. This aircraft is a good representation of the USCG HU25 air vehicle fleet. Sandia was also task to have the aircraft cleaned and hangered for our validation process. Sandia met their obligation with bonuses for the team we were offered a conference room for the entire week including projector and video hooks ups.

The teams' visual evaluation of aircraft 2103 was first performed identifying visible indicators of corrosion and numerous areas were identified. Visual indicators of corrosion are blistering / peeling paint/ rough surface. Most of the zones appeared to be a mild surface corrosion with a few zones showing signs of mild-to-severe surface corrosion. Once the areas were identified they were labeled into zones and digital real images were acquired prior to IR and de-paint of the zone. This was an important step prior to evaluating without knowledge. This step allowed the team to understand the camera and its capabilities and gain knowledge of the Reflectance properties of the corrosion under a highly reflective thick cross section coating structure. The mild corrosion was most important for it allows the team to prepare the inspection parameters to a more sensitive Reflectance indication.

Several issues arose during this process: Should the team prescribe to a scanning speed? Should the team prescribe to a specific distance of camera to aircraft skin defining a certain "Field of View" (FOV)? The concern over a calibration and / or reference standard also was discussed. What type of calibration should be designed or should there be a reference standard? In the NDI arena there is a contrast between the two where a calibration standard is designed to ensure the instrumentation is working has designed and set to a specific sensitivity a reference standard is specific to what the inspector is evaluating for such as in this case mild-to-severe surface corrosion. It is possible to design both into one standard thereby having a calibration / reference standard. The preliminary step of visual, digital images, IR and the de-painting opened engineering discussions that in all probability will direct to a more ground standing document.

The IR of the visually detected corrosion indicators was impressive for the team was able to adjust the thought process to what Snell Infrared preaches "To Think Thermally". The team was able to build the characteristics of the thermal Reflectance corrosion indicators in the human database. The team also detected more corrosion in these zones that went undetected visually. Zone 3 was the most impressive because forward of the visual indicators the IR camera demonstrated the ability to show more surface corrosion some slightly more severe and other less severe with resolution to distinguish the two different surface characteristics. All of the visually detectable corrosion indicators produce Reflectance indications that had a good contrast to the reflection and Reflectance properties of the glossy coating scheme.

A bonus to the program Sandia NDI validation center thermal expert Joe Dimambro offered to image the corrosion indicators with the thermal acquisition system known as the "Thermal-Scope" system designed by Thermal Wave Imaging. This system utilizes the same IR camera as the teams. The camera is a Merlin® MWIR camera developed by "Indigo". The thermal-scope system applies a pulsed heat source by way of a Zeon light source. The principle behind this system is to propagate heat into the component and through the thermal heat transfer detect the "delta T" (ΔT) (temperature difference) of the good material verses the corroded material. This technique was able to distinguish some of the corrosion but not with the reliability of the passive camera. My conclusion on this is that the acquisition and gating system needs to be adjusted to detect the "ΔT" right after the pre-flash envelope of the system reducing the Time-vs. -Temperature ratio. I believe the thermal scope system is set up to detect indicators that require more penetration into the component developing more of a time–vs.-temperature ratio.

The completion of the image acquisition was followed by a de-painting of all the visual indicators for the purpose of verification of detection. All zones produced corrosion that can be identified with the passive camera. The corrosion detected by the camera and not detected by visual means was also validated as surface corrosion.

The next process was to evaluate a portion of aircraft 2103 without any visual indications. The area of concern needed to meet a certain criteria. The area had to be representative of the aircraft paint scheme and cross section substrate thickness. The area could not have any visual signs of surface corrosion as described above. The area had to have a high gloss finish. The area the team deemed to meet our specifications was the right hand outboard upper wing surface. The scanned area is about 9' sq. The team detected several areas that appeared with a Reflectance thermal signature indicative of surface corrosion. These areas were marked and organized. The areas marked demonstrated no signs of visual corrosion indicators. We followed the steps of the first trail period and had Sandia representative Joe Dimambro perform a thermal imaging acquisition with the thermal-scope. This time there was a slight "ΔT" signature that was capable to be deciphered. The de-painting of these areas validated most of the calls. One area was a missed call this area demonstrated a previous reworked area of blending. This was probably done to remove corrosion at the last depot rework of aircraft 2103. The only answer I have for this detection is that the blended material concentrated a Reflectance signature similar to corrosion. With this said for the most part the system did detect surface corrosion under the coating as theorized it would.

Conclusion:

The process works as described. The camera can detect corrosion under fairly thick cross sections of aircraft coatings using a thermal Reflectance signature.

Recommendations;

1. Develop a calibration / reference standard that can be used to ensure proper instrumentation and provide a signature indicative of surface corrosion.
    a. Mr. John Benfer's suggestion of symbols etch into similar metals appears to have the potential to decimate resolution between shapes.

b. Mr. John Benfer's idea based on the Jaeger eye chart deserves a review. This I believe is a good suggestion, for it is, even though aided by instrumentation the inspection is still a visual with IR optics. This would have the credentials of obstetrician standards.
c. I recommend researching the following ASTM:
    i. ASTM E 1213 Standard Test Method for Minimum Resolvable Temperature Difference for Thermal Imaging Systems.
    ii. ASTM E 1311: Standard Test Method for Minimum Detectable Temperature Difference for Thermal Imaging Systems.
    iii. Standard Test Method for Noise Equivalent Temperature Difference of Thermal Imaging Systems.

These ASTM's describe the minimum resolution of IR cameras and systems and may have the potential to be used as a source to reference and adhere to. The use of an ASTM credits the project with some meat on the bones and can rest any speculation from colleagues in the same arena once a final draft process is developed.

d. I recommend that the terms mild, medium and severe surface corrosion be compared to a surface roughness measurement. This may be a means to quantify the corrosion better to determine if a removal process is warranted. This would not quantify area squared but it would be a way to measure severity of the surface corrosion. The camera can be used to measure area squared. Surface roughness can be measured in "Root mean squared" (rms) giving an arithmetic average of the surface roughness characteristics units are in the μ inch or μ meters. The instrument used to measure the surface roughness is a "Profilometer"

It is extremely important that a calibration / reference standard be developed prior to the next Dem/Val, which I believe is a P-3 aircraft at the NAVAIR in Jacksonville FL.

2. During consultation with the team it was mentioned that the team might get one day to evaluate the P-3.
    a. I recommend an organized scanning plan be developed prior to the Dem/Val of the P-3. This plan should also be accompanied with a schematic drawing of the aircraft with station and butt line measurements for data collection.
    b. I recommend the team gather a day prior to the Dem/Val and take paint thickness measurements through out the aircraft such as USCG AAB did prior to the evaluation of the HU25 aircraft 2103.
3. I recommend the same organization for any future aircraft such as the Air Force C-130.
4. I also recommend that once a process is finalized and the team agrees to the procedure and application. That an unknowing non-participating NDI inspector be chosen to evaluate an aircraft after a prescribed amount of training.
    a. I recommend this because the NDI arena is built and depends on the capabilities of inspectors that have acquired specialized training in the

application. This specialized training should have a curriculum developed prior to training an individual. The finalized procedure will not be utilized by a team of engineers that have the education and time to scrutinize the reflectance signatures, but will be performed by a level II inspector whom has no OJT hours in thermal IR, but given specialized training and designated has an operator till he/she acquired the hours to qualify for a level I and II status. The inspector that actually interprets the system will determine the cost savings.

b. This individual can solidify the ease of interpretation and use of the camera. All indications the inspector detects and calls should be categorized and verified.

c. The inspector also needs to call the severity of the detected surface referenced to the developed calibration / reference standard.

Endorsement: The system is quite impressive and does detect corrosion under the USCG coating scheme. I endorse the program up to this point and with what has been developed so far. The process needs to be refined with the recommendations set forward on the table for consultation. The instrument demonstrated the ability to detect corrosion under USCG paint scheme of cross section thickness greater than 8 mils. I believe this instrument and the application can be used in many capacities for the detection of surface corrosion not just to be used to prevent the de-painting of an aircraft but also on small components that would require de-painting for a visual inspection of corrosion. The camera is easy to use, light weight and can be utilized in a timely manner.

Rusty Waldrop
USCG NDI Program Manager

G.6 Air Force

PENDING

APPENDIX H COST ANALYSIS TOOL

1.0 Introduction

This appendix describes a spreadsheet tool developed to assess costs and benefits associated with use of the Infrared Reflectance Inspection Technique (IRRIT) as an inspection tool to reduce costs associated with stripping and recoating Department of Defense (DoD) weapon systems and/or equipment items. The purpose of this spreadsheet tool is to help maintenance personnel evaluate the feasibility of using the IRRIT camera. As discussed in Section 5, the primary area of potential savings is related to in increase in the time interval between stripping activities by using IRRIT. The assumption is that the IRRIT technology can provide the information needed to justify an increase in the period of time between "coating removal and repaint" events for a given type of equipment.

Cost data was collected, along with engineering estimates and assumptions, for stripping and recoating actions performed on the OML of P-3 Orion aircraft maintained at Naval NAVAIR Jacksonville. To develop this tool, these data, estimates, and assumptions were normalized to allow application to other equipment items, including other weapon systems and various types of support equipment. However, the cost data will have greater accuracy when used to calculate costs for maintenance processes similar to stripping and repainting the surface of an aircraft. The more variances between the process under consideration and the P-3 OML maintenance, the less reliable the results produced will be.

As was the case for the P-3 analysis, this spreadsheet tool assumes that the baseline process includes a visual inspection of coated surfaces for indications of corrosion. This analysis balances the costs of purchasing the IRRIT system and using it as a replacement inspection tool against the potential savings resulting from an increase in maintenance cycle times. The assumption is that the IRRIT will allow deferment of maintenance by providing information on corrosion that could only previously be obtained after stripping the unit.

2.0 User Data Requirements

2.1 Information Provided

The spreadsheet tool uses a combination of data obtained from past evaluation of the IRRIT camera and data to be provided by potential end users interested in specific applications. The data already incorporated into the tool are based on information collected during demonstration/validation (Dem/Val) activities performed on the OML of the Navy P-3 Orion at NAVAIR Jacksonville. These data include actual data either measured during the Dem/Val or provided by knowledgeable personnel from one of these maintenance facilities. In addition, other data points were based on engineering estimates and assumptions.

This cost analysis spreadsheet is based on surface area stripped. All strip and repaint costs and values for the P-3 aircraft were divided by the surface area of the P-3 to

calculate a "cost per square foot" for the strip and repaint process. Cost categories are described below:

- "Equipment" – For 'Equipment' only the cost of the IRRIT camera is calculated, as painting and stripping equipment is purchased under all scenarios and therefore is neither added cost nor contributed savings.
- "Labor" - 'Labor' is arrived at by taking the total number of man-hours required to inspect, strip, and repaint a P-3 aircraft, dividing this by the total surface area of the P-3, and arriving at a man-hours per square foot value. The spreadsheet then multiplies the labor hours by the user supplied 'Labor Costs' (see Section 2.3) to determine labor costs.
- "Materials" – Material costs are calculated by taking the cost of materials to strip and repaint a P-3, dividing this by the total surface area of the P-3, and arriving at a cost per square foot.
- "Utilities" – Utilities costs are determined by taking the value of the total process time for the P-3 and multiplying this by a supplied utility cost per hour of process time. The spreadsheet then converts this into a process time per square foot.
- "EHS" – Environmental, health, and safety costs are based on the costs of disposal of waste produced during the strip and repaint of a P-3 aircraft. In the same fashion as the other categories, these costs are calculated in terms of square footage. In addition, the Volatile Organic Compounds (VOC) emissions created by strip and repaint activities are calculated using the same surface area pro-rating processed as that described for the material costs.

The values underlying these costs for the P-3 can be seen on the "Gen Assump" (General Assumptions) worksheet and the "Labor Hours" worksheet in the spreadsheet embedded in Section 5.0. Values on these two worksheets should not be altered. Potentially, these values could be used as a template for conducting a more accurate weapon system specific cost analysis than the rough estimate provided through this spreadsheet.

2.2 Assumptions for Spreadsheet Use

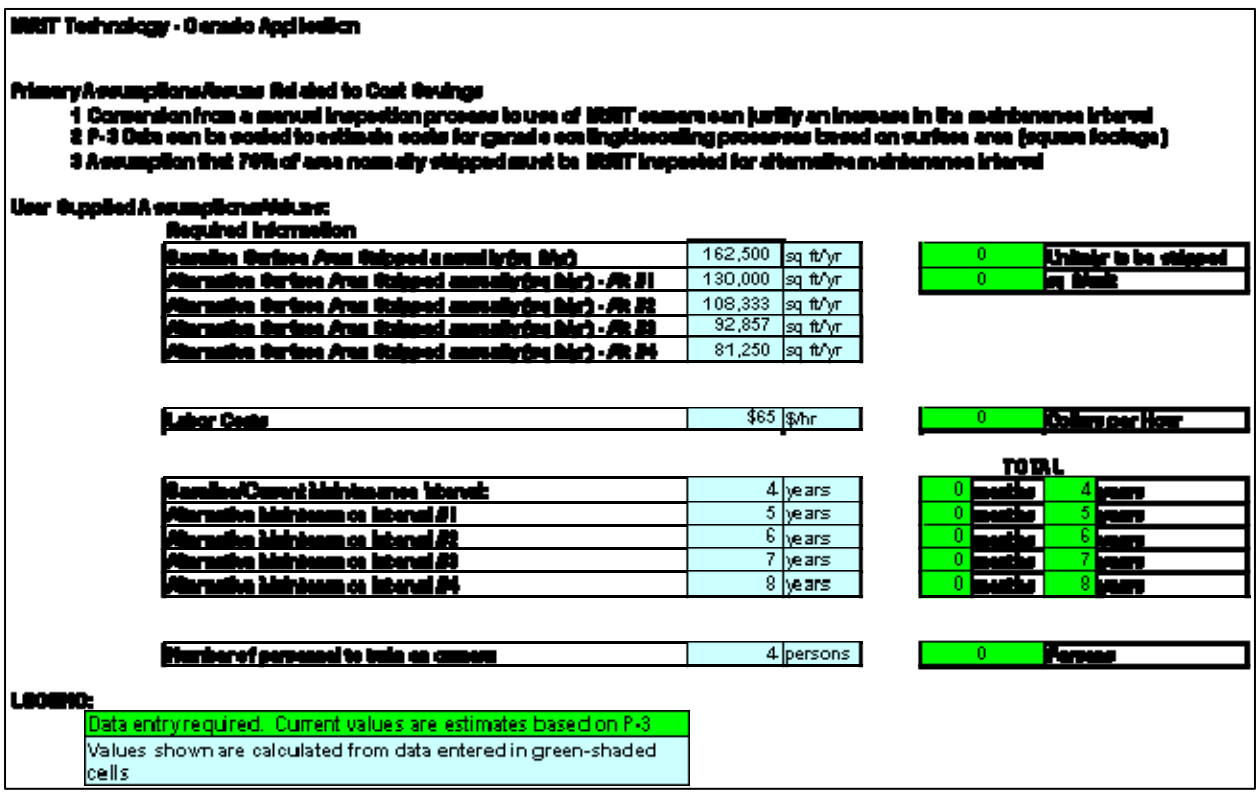
Before a potential end user considers using the spreadsheet tool, certain assumptions must hold true (e.g., data collected can be used to modify maintenance interval). Also, the end user must be able to provide actual data or reasonable estimates for use in the spreadsheet. These fundamental assumptions and data requirements are listed below:

- Information collected from the IRRIT camera can be used to justify increasing the interval between strip and repaints for units of the weapon system under consideration;
- The costs and benefits of the purchase and implementation of a single IRRIT camera will be analyzed (multiple applications not considered);

- The baseline process includes pre-strip visual inspections to of the weapon system before strip and repaint;
- The potential end user can adequately estimate the total surface area (square feet) currently stripped and recoated on an annual basis;
- The potential end user can adequately estimate the current time interval between stripping activities for individual units of the weapon system or equipment;
- The potential end user can estimate the potential increase in time interval between stripping activities allowed by the more accurate corrosion assessment through use of IRRIT and
- The end user can adequately estimate the number of personnel who will be trained to use the IRRIT camera.

2.3 User-Supplied Information

In order to utilize the evaluation spreadsheet, the potential end user must provide certain information. The first worksheet tab in the spreadsheet, labeled "Intro", provides opportunity to enter weapon-system specific data. A screenshot of this worksheet is provided below as Figure H-1.



IRRIT Technology - Grande Application

Primary Assumptions/Issues Related to Cost Savings
1 Conversion from a manual inspection process to use of IRRIT camera can justify an increase in the maintenance interval
2 P-3 Data can be scaled to estimate costs for grande coating/decoating processes based on surface area (square footage)
3 Assumption that 70% of area normally stripped must be IRRIT inspected for alternative maintenance interval

User Supplied Assumptions/Values:

Required Information

Baseline Surface Area Stripped annually (sq ft)	162,500	sq ft/yr	0	Unfeasible to be stripped
Alternative Surface Area Stripped annually (sq ft) - Alt #1	130,000	sq ft/yr	0	sq ft/yr
Alternative Surface Area Stripped annually (sq ft) - Alt #2	108,333	sq ft/yr		
Alternative Surface Area Stripped annually (sq ft) - Alt #3	92,857	sq ft/yr		
Alternative Surface Area Stripped annually (sq ft) - Alt #4	81,250	sq ft/yr		
Labor Costs	$65	$/hr	0	Dollars per Hour

			TOTAL			
Baseline/Current Maintenance Interval:	4	years	0	months	4	years
Alternative Maintenance Interval #1	5	years	0	months	5	years
Alternative Maintenance Interval #2	6	years	0	months	6	years
Alternative Maintenance Interval #3	7	years	0	months	7	years
Alternative Maintenance Interval #4	8	years	0	months	8	years
Number of personnel to train on camera	4	persons	0	Persons		

LEGEND:
Data entry required. Current values are estimates based on P-3
Values shown are calculated from data entered in green-shaded cells

Figure H-1: "Intro" Worksheet for Weapon-System Specific Data Input

There are four pieces of information necessary to evaluate the IRRIT for a specific weapon system. They are: "Baseline Surface Area Stripped Annually", "Baseline Maintenance Interval", "Labor Costs", and "Number of personnel to train on camera". The user can supply this information by entering numbers in the areas highlighted in green. The areas highlighted in blue are calculated automatically by the spreadsheet.

1. Baseline Surface Area

Because this cost analysis spreadsheet is based on surface area stripped, the user must supply the surface area stripped per year for the weapon system under consideration. To determine the baseline surface area stripped per year, the user should supply data for the green cells "units per year to be stripped" (the number of units of the weapon system expected to be stripped each year) and "sq ft/unit" (the surface area in square feet which must be stripped on each unit). Using these two values, the spreadsheet will calculate the baseline area stripped per year. This value will be referenced frequently in calculations. If no value is supplied, the spreadsheet will default to the P-3 value of 162,500 square feet stripped per year.

The Alternate Surface areas stripped are calculated by dividing the baseline maintenance interval by the alternative maintenance interval and multiplying the fractional results by the baseline surface area stripped to arrive at a new surface area stripped per year. The spreadsheet calculates this automatically.

2. Labor Costs

Labor costs will differ from facility to facility. In order to consider labor costs for a specific facility, enter the dollar value used for budgeting labor at the facility where the weapon system under consideration is serviced. Note that this number should be "loaded" to include overhead costs. If no value is supplied, this number defaults to a standard value of $65/hour.

3. Baseline and Alternative Intervals

Potential savings gained through use of IRRIT are assumed to be through an increase in the intervals between maintenance activities. A longer maintenance interval for the same fleet size means that fewer weapon system units must be stripped and repainted on a yearly basis, with a corresponding reduction in costs incurred.

The user must enter both the baseline maintenance interval as well as the estimated new maintenance interval allowed by use of the camera. Because the potential new maintenance interval is unlikely to be set at this stage of the IRRIT evaluation, the spreadsheet provides the option of entering up to four new maintenance interval alternatives for comparison. If use of all four alternatives is not desired, simply input no value for the alternatives not in use.

Options are provided to list the maintenance intervals in years or months or in a combination of years and months. Default values indicate a current interval of 4 years between stripping events with alternative periods of 5, 6, 7, and 8 years.

4. Number of Personnel to Train on the Camera

In addition to the capital costs of the IRRIT camera system, personnel must be trained in its use. By entering the number of personnel to be trained, training costs are taken into account. If no value is given, this number will default to four.

3.0 Analysis Results

On the tab marked 'Summary', the costs of using IRRIT technology, potential dollar savings from an interval shift created by use of IRRIT technology (if any), and potential VOC reduction and chromate use from an interval shift created by use of IRRIT technology. This tab is illustrated in Figure H-2 below. Note that the numbers illustrated are the results for the P-3 interval shift and will differ for differing inputs.

BASELINE COSTS

Visual Inspection	Capital Costs	
	Labor/Equipment	$0
	Installation	$0
	EHS	$0
	Other	$0
	TOTAL	$0
	Annual O&M Costs	
	Labor/Equipment	$2,134,925
	Materials	$530,829
	Utilities	$3,600
	Wastes	$0
	EHS	$569,774
	Shipping/Receiving	$0
	Other	$0
	TOTAL	$3,239,128
	Annual lbs VOC emitted	65,577
	Chromate in paint used (lbs)	600

ALTERNATIVE COSTS (Maintenance Interval Shift)

IRRIT Camera	Capital Costs	Alt 1	Alt 2	Alt 3	Alt 4
	Labor/Equipment	$87,600	$87,600	$87,600	$87,600
	Installation	$0	$0	$0	$0
	EHS	$0	$0	$0	$0
	Other	$17,080	$17,080	$17,080	$17,080
	TOTAL	$104,680	$104,680	$104,680	$104,680
	Annual O&M Costs				
	Labor/Equipment	$1,746,879	$1,457,192	$1,250,273	$1,095,084
	Materials	$424,663	$353,886	$303,331	$265,415
	Utilities	$2,880	$2,400	$2,057	$1,800
	Wastes	$0	$0	$0	$0
	EHS	$455,819	$379,850	$325,585	$284,887
	Shipping/Receiving	$0	$0	$0	$0
	Other	$0	$0	$0	$0
	TOTAL	$2,630,241	$2,193,328	$1,881,247	$1,647,186
	Annual lbs VOC emitted	68,461	57,051	48,901	42,788
	Chromate in paint used (lbs)	480	400	343	300

Figure H-2: "Summary" worksheet with results

3.1 Costs

Capital Costs

The capital costs (illustrated in Figure H-1) are the one-time costs associated with implementation of the IRRIT technology. This consists of the cost of the IRRIT camera and associated systems, which is listed as $87,600 under "Labor/Equipment". The cost of training personnel to use the camera system is listed under "Other". The cost of Labor/Equipment under "Capital Costs" will remain constant regardless of user input, while the cost of "Other" under "Capital Costs" will vary based on the number of personnel selected for training. The baseline scenario, which does not include use of IRRIT, incurs no Capital Costs, because equipment is already owned and personnel are already trained.

Annual O&M Costs

The "Annual O&M" costs (also illustrated in Figure H-1) are the total costs to strip and repaint units of the weapon system each year. For the baseline scenario, this is the user-supplied baseline surface area (square footage) stripped per year multiplied by the costs per square foot calculated from the P-3 cost analysis. For the alternative scenarios, the alternative surface area stripped per year, which is calculated on the "Intro" worksheet, is used.

Annual VOC Emissions

The amount of VOCs emitted per P-3 aircraft stripped was calculated by first determining the volumes of paints, chemical strippers, and sealants used in stripped and repainting a single P-3 aircraft. These values were then multiplied by the VOC content for the chemical used in order to determine the total pounds of VOCs released during each P-3 strip and repaint activity. This number was calculated as "VOC emissions per sq. ft." based on the surface area of the P-3. For the baseline scenario, this is the user-supplied baseline square footage stripped per year multiplied by the VOC emissions per square foot calculated from the P-3 cost analysis. For the alternative scenarios, the amounts of surface areas stripped per year (calculated on the "Intro" worksheet) are used.

3.2 Savings/Loss

The third table (illustrated in close-up as Figure H-3 below) illustrates the savings or loss in dollars each year based on the maintenance interval reduction allowed by use of the IRRIT camera. This is calculated by subtracting the yearly O&M costs for the each alternative from the yearly O&M costs for the baseline. In the example given in Figure H-3 (based off the P-3), even a one-year extension in maintenance interval under Alternative 1 results in a cost reduction of $647,381 per year.

	Alt 1	Alt 2	Alt 3	Alt 4
Annual Savings/(Loss)	$608,887	$1,045,801	$1,357,882	$1,591,943
Simple Payback (yrs)	0.17	0.10	0.08	0.07
Annual VOC reduction (lbs)	17,115	28,526	36,676	42,788
Annual chromate use reduction	120	200	257	300

Figure H-3: Savings and Payback

This yearly savings is used to calculate the "Simple Payback", which estimates the number of years required for annual savings to recoup Capital Cost invested in the IRRIT system. In the example given for Alternative 1 (one-year maintenance interval extension), the IRRIT system pays for itself in 0.16 years. Note that this Simple Payback does not take into account inflation.

In addition, the annual reduction in VOC emissions and chromate use are calculated. Though this does not translate into a dollar savings unless the facility is near emissions limits and/or where permits are involved, it does quantify a significant potential environmental impact.

4.0 Summary

While this spreadsheet was developed using data, estimates, and assumptions from a P-3 OML application, variables that are significant drivers for coating application and removal (e.g., surface area, labor rate) have been "normalized" to allow use of this tool on other weapon systems. Therefore, other end users interested in using the IRRIT technology should be able to use this tool to asses the feasibility of implementing IRRIT it in their specific application(s) – whether on aircraft, other weapon systems, or support equipment.

However, the further the baseline process moves from P-3 OML application, the less accurate a predictor this tool will be. The costs included are the costs for chemically stripping the OML of an aircraft and repainting it with a specific prime and topcoat process. Stripping other varieties of vehicles or support equipment, even with a roughly similar surface area, may involve greatly varying amounts of labor and materials.

5.0 Spreadsheet Tool

Attached below is the tool for non-specific weapon systems.

IRRIT Analysis Spreadsheet

APPENDIX I APPLICABLE UNITED STATES PATENTS AND PATENT APPLICATIONS

US007164146B2

(12) **United States Patent**
Weir et al.

(10) **Patent No.: US 7,164,146 B2**
(45) **Date of Patent: Jan. 16, 2007**

(54) **SYSTEM FOR DETECTING STRUCTURAL DEFECTS AND FEATURES UTILIZING BLACKBODY SELF-ILLUMINATION**

(75) Inventors: **John Douglas Weir**, Huntington, NY (US); **Donald DiMarzio**, Northport, NY (US); **Steven Chu**, Ronkonkoma, NY (US); **Robert P. Silberstein**, New York, NY (US)

(73) Assignee: **Northrop Grumman Corporation**, Los Angeles, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 279 days.

(21) Appl. No.: **10/971,217**

(22) Filed: **Oct. 22, 2004**

(65) **Prior Publication Data**

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(51) **Int. Cl.**
G01N 21/86 (2006.01)

(52) **U.S. Cl.** **250/559.4**; 250/559.27; 250/559.45

(58) **Field of Classification Search** 250/559.4, 250/559.27, 559.45; 356/239.1, 239.2
See application file for complete search history.

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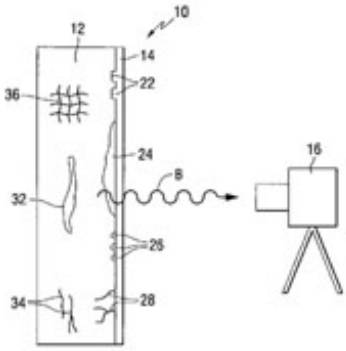
Primary Examiner—Que T. Le
(74) *Attorney, Agent, or Firm*—Alan G. Towner, Esq.; Pietragallo, Bosick & Gordon LLP

(57) **ABSTRACT**

A system is disclosed which utilizes the substantially steady-state temperature of a coated object, in conjunction with an optical detection system, to selectively view defects and features of the object below the coating without the necessity of transient heating or IR illumination and reflectance imaging. The optical detector, such as an IR camera, may be tailored for the wavelengths at which the coating material is substantially transparent, thereby maximizing the viewing clarity of the defects and features under the coating, and distinguishing them from any spurious features on the top surface of the coating. The present system enables the inspection of small or large areas in real time, without requiring complex image acquisition, storage and image processing equipment and software.

39 Claims, 15 Drawing Sheets



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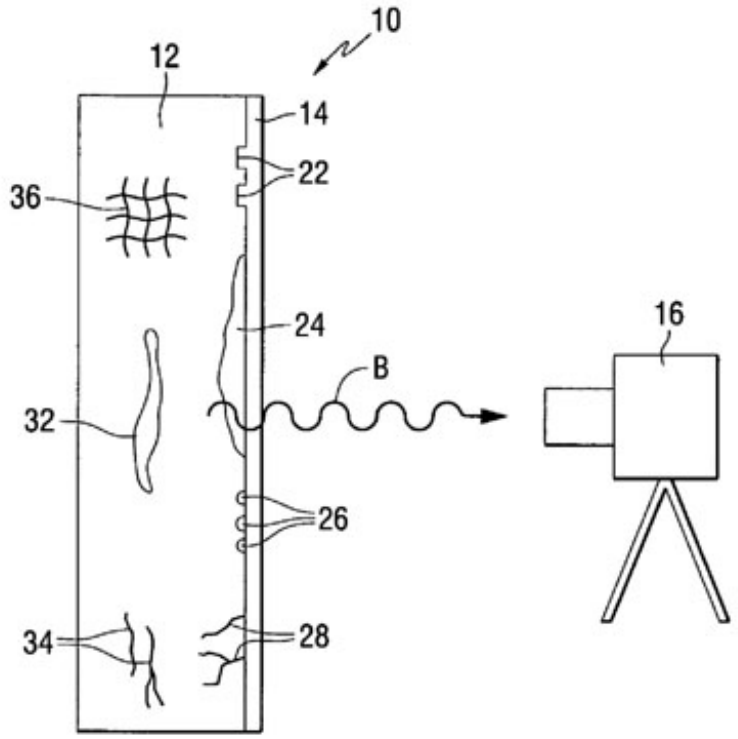
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FIG. 1

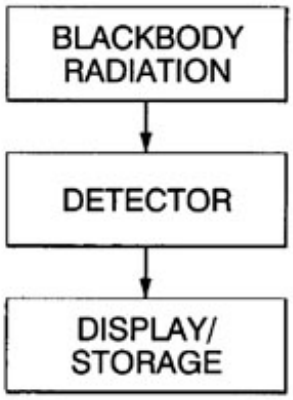
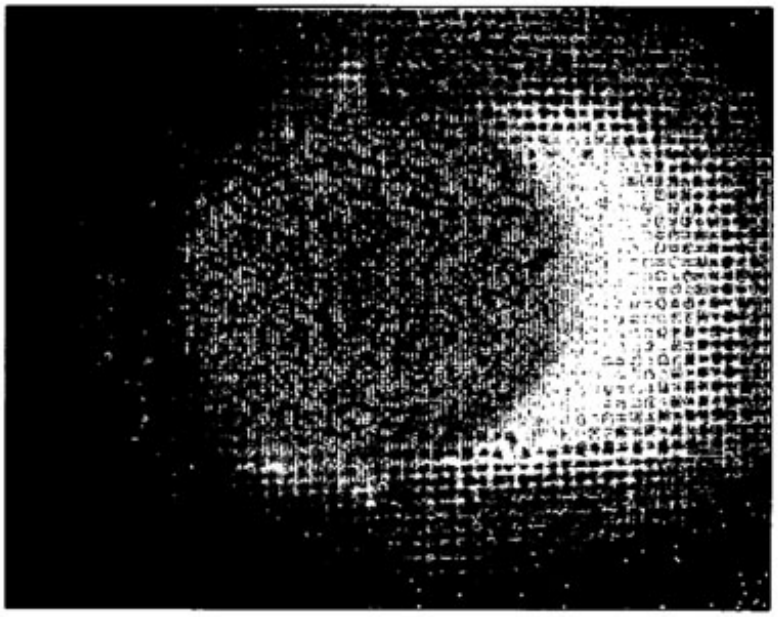
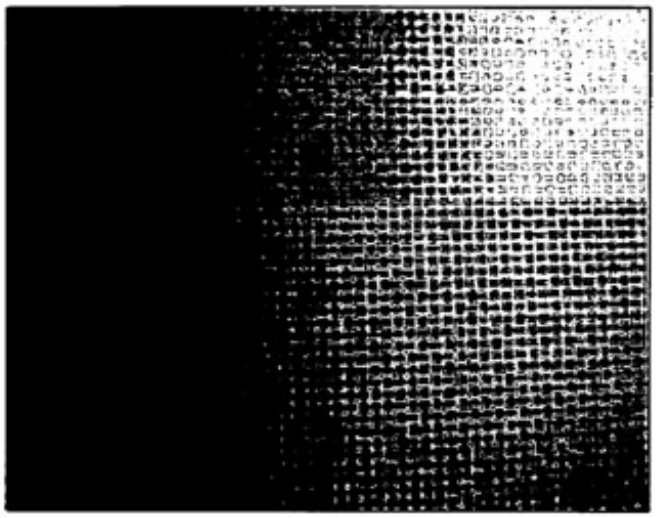

BLACKBODY RADIATION
DETECTOR
DISPLAY/ STORAGE

FIG. 2



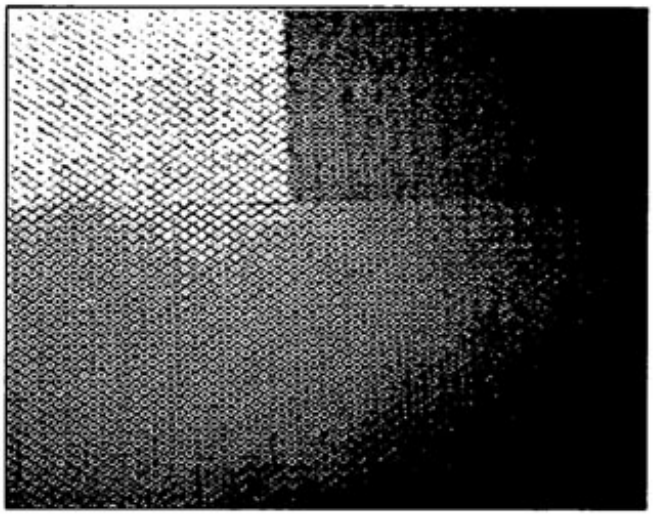
GRAPHITE PAINTED PANEL AT 89° F, RT-CALIBRATION

FIG. 3



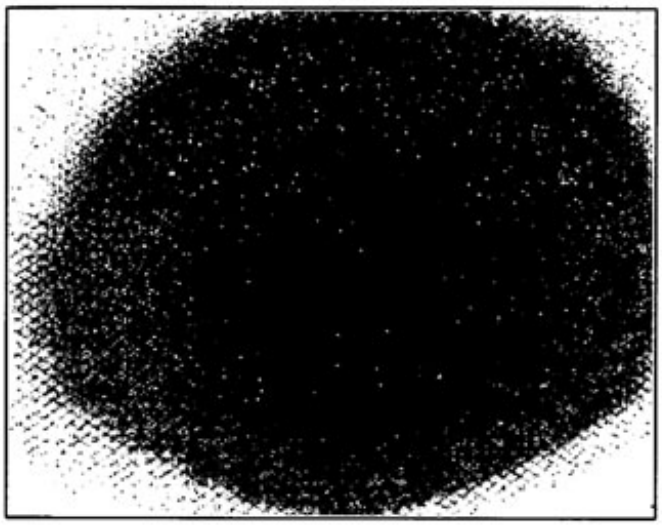
GRAPHITE PAINTED PANEL AT 90° F, 84° F HOT-CALIBRATION

FIG. 4



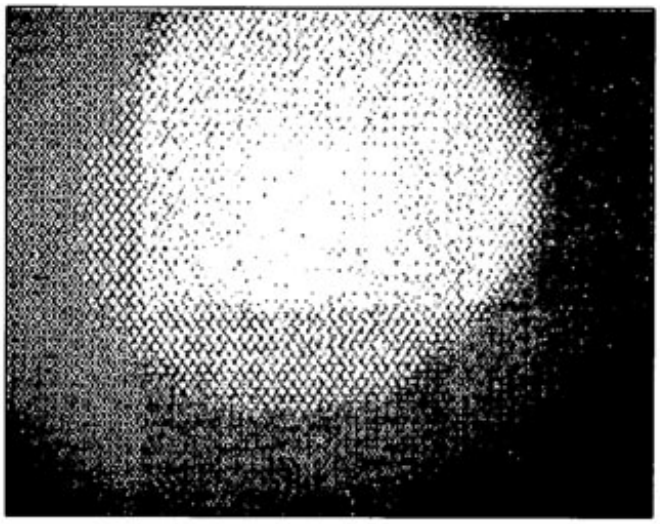
GRAPHITE WITH Cu FIBER PAINTED PANEL AT 90° F, 84° F HOT-CALIBRATION

FIG. 5



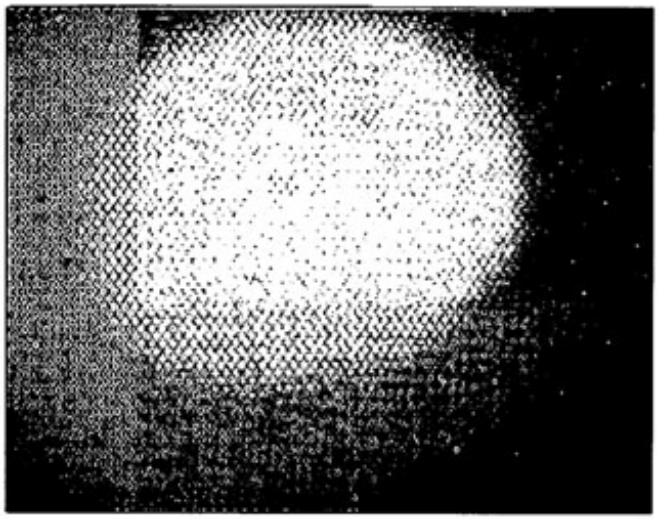
GRAPHITE WITH Cu FIBER PAINTED PANEL AT 74° F,
84° F HOT-CALIBRATION

FIG. 6



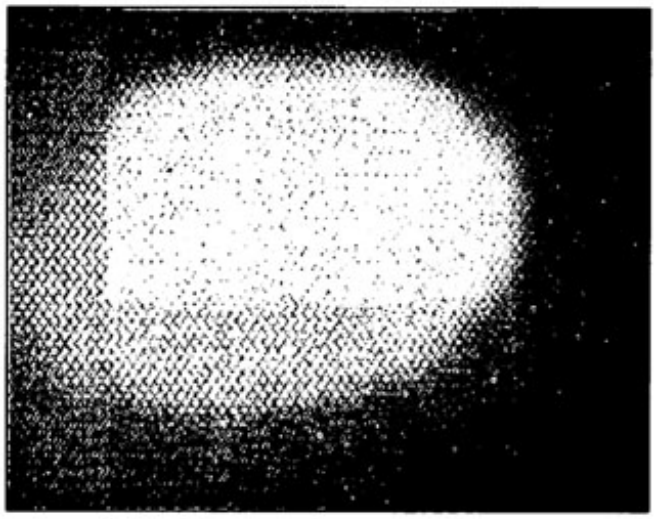
GRAPHITE WITH Cu WEAVE, PAINTED PANEL AT 91° F,
RT-CALIBRATION

FIG. 7



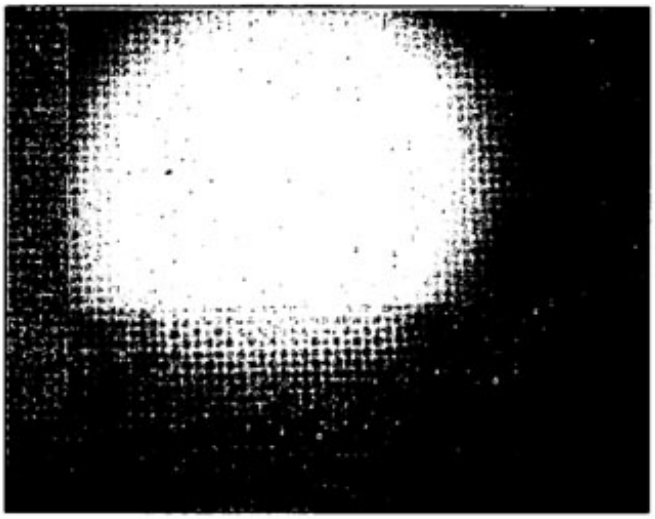
GRAPHITE WITH Cu WEAVE, PAINTED PANEL AT 87°F, RT-CALIBRATION

FIG. 8



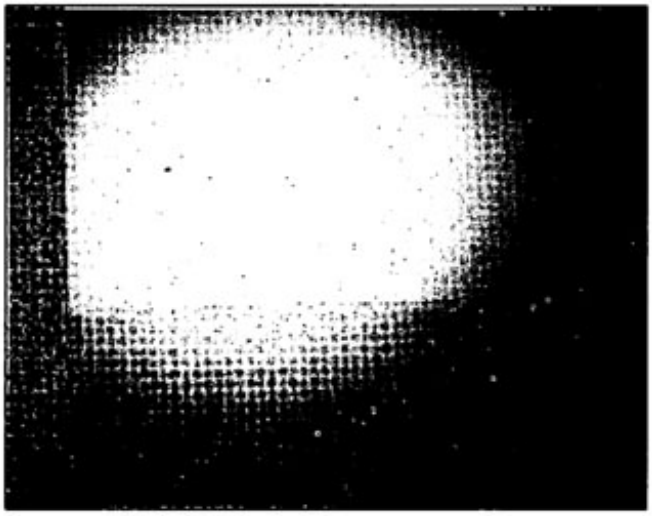
GRAPHITE WITH Cu WEAVE, PAINTED PANEL AT 82°F, RT-CALIBRATION

FIG. 9



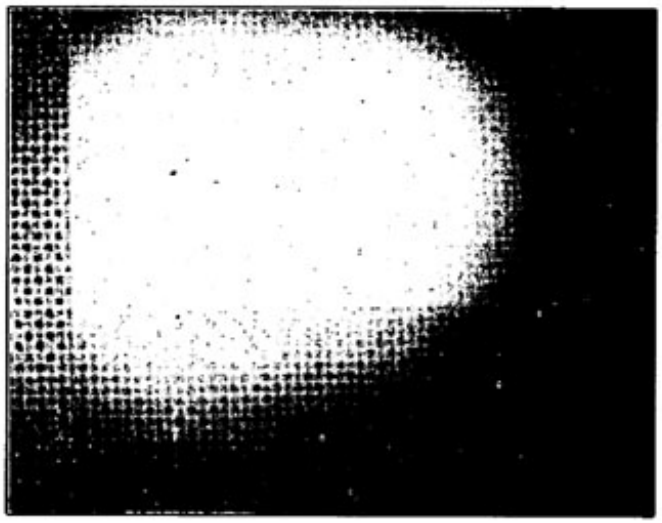
GRAPHITE, PAINTED PANEL AT 90°F, RT-CALIBRATION

FIG. 10



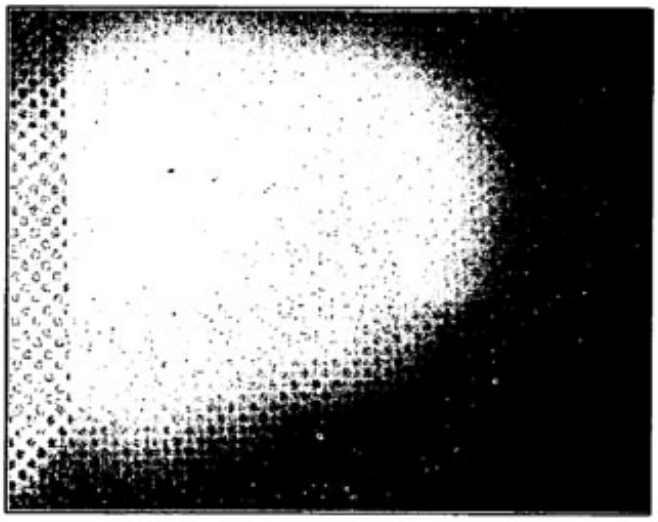
GRAPHITE, PAINTED PANEL AT 86°F, RT-CALIBRATION

FIG. 11



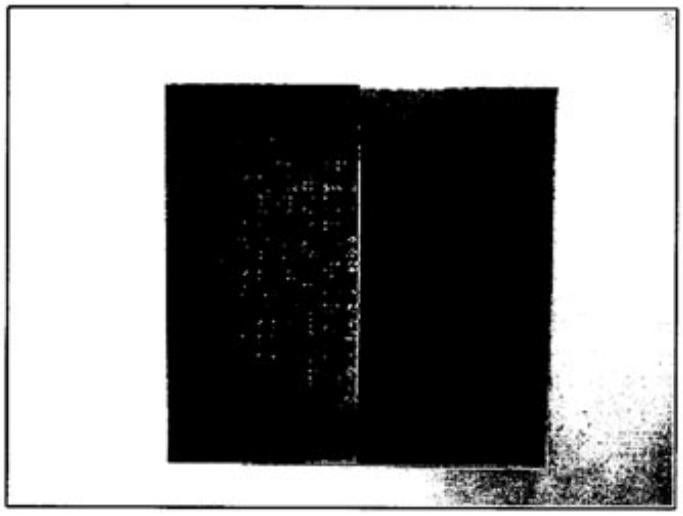
GRAPHITE, PAINTED PANEL AT 82°F, RT-CALIBRATION

FIG. 12



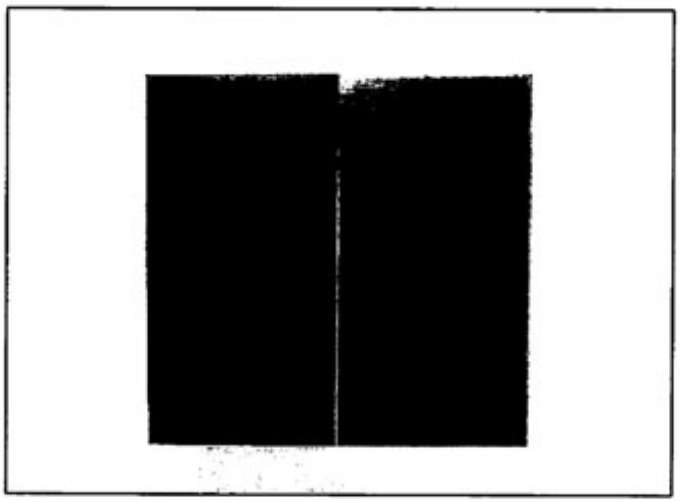
GRAPHITE, PAINTED PANEL AT 78°F, RT-CALIBRATION

FIG. 13



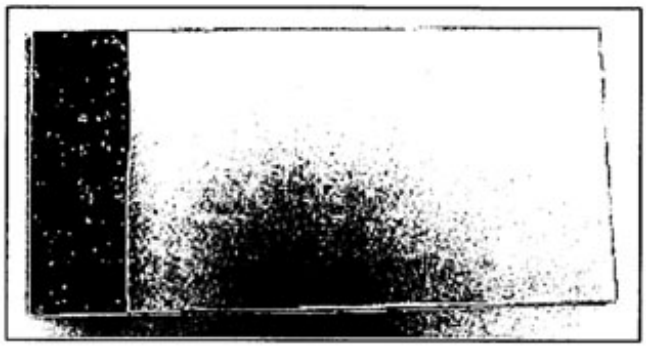
GRAPHITE, PAINTED AND PRIMED PANEL: VISIBLE IMAGE

FIG. 14



GRAPHITE WITH Cu WEAVE, PAINTED AND PRIMED PANEL: VISIBLE IMAGE

FIG. 15

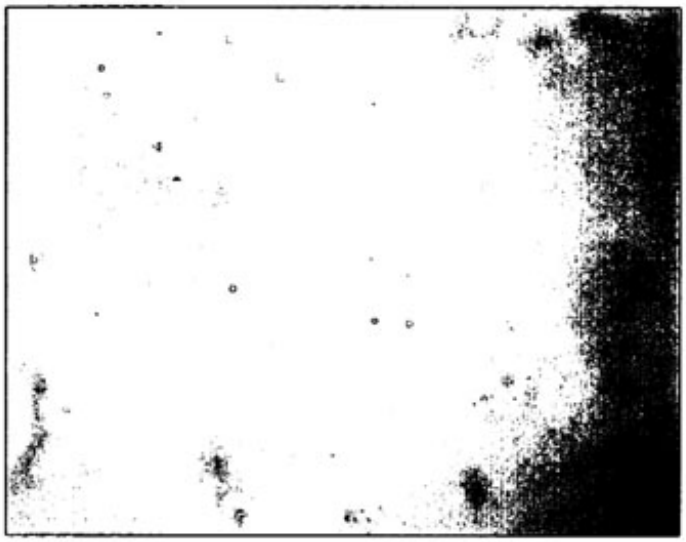


ALUMINUM C2: VISIBLE IMAGE

FIG. 16

ALUMINUM C2 1x MAG. AT 77°F, IR REFLECTANCE IMAGE

FIG. 17



ALUMINUM C2 1x MAG. AT 75°F, IR REFLECTANCE IMAGE

FIG. 18

ALUMINUM C2 1x MAG. AT 84°F, RT-CALIBRATION

FIG. 19

ALUMINUM C2 1x MAG. AT 78°F, RT-CALIBRATION

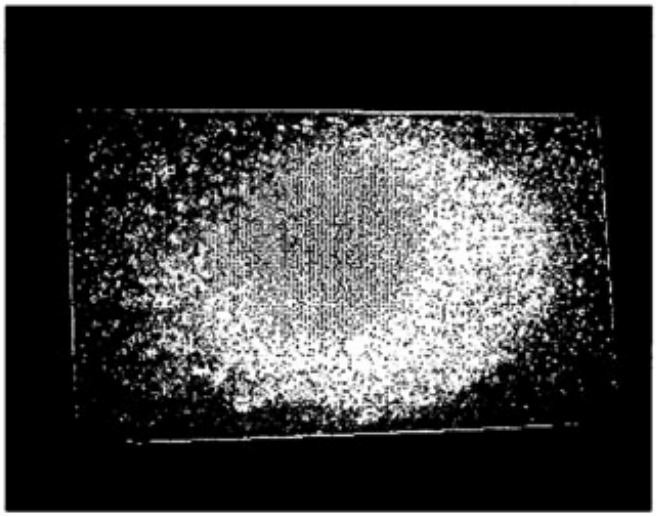
FIG. 20

ALUMINUM C2 1x MAG. AT 72°F, RT-CALIBRATION

FIG. 21

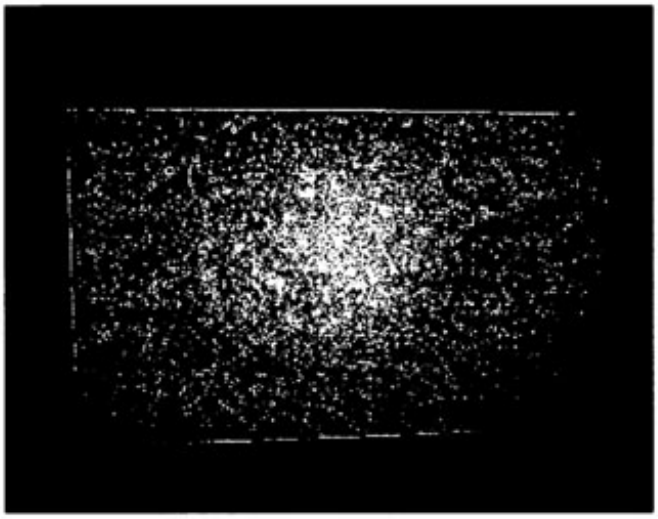
ALUMINUM C9 (LOW IR PRIMER) IR REFLECTANCE IMAGE

FIG. 22



ALUMINUM C9 (LOW IR PRIMER) AT 96°F,
78°F HOT-CALIBRATION

FIG. 23

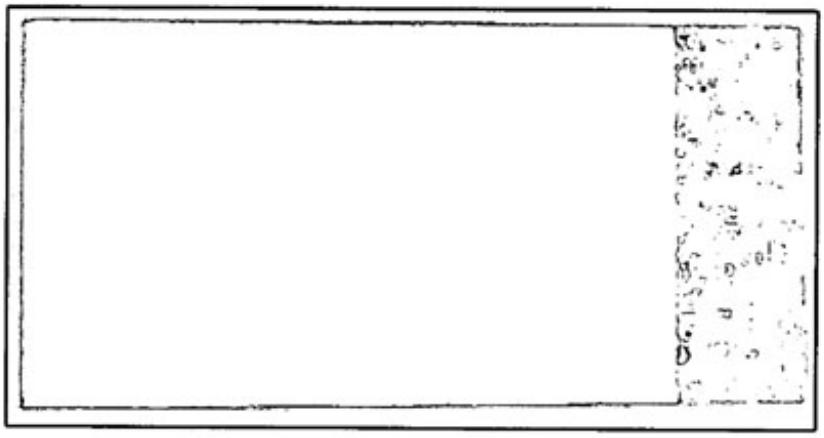


ALUMINUM C9 (LOW IR PRIMER) AT 86°F,
78°F HOT-CALIBRATION

FIG. 24

ALUMINUM C9 (LOW IR PRIMER) AT 79°F,
78°F HOT-CALIBRATION

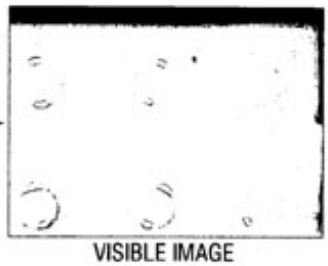
FIG. 25



ALUMINUM C9 (LOW IR PRIMER), VISIBLE IMAGE

FIG. 26

FIG. 27a

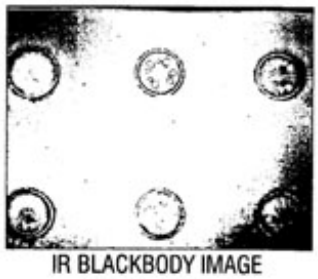


VISIBLE IMAGE

FIG. 27b

IR REFLECTANCE IMAGE

FIG. 27c



IR BLACKBODY IMAGE

FIG. 27d

SYSTEM FOR DETECTING STRUCTURAL DEFECTS AND FEATURES UTILIZING BLACKBODY SELF-ILLUMINATION

GOVERNMENT CONTRACT

The United States Government has certain rights to this invention pursuant to Contract No. DACA 72-99-C-011 awarded by SERDP.

FIELD OF THE INVENTION

The present invention relates to detection of structural features, and more particularly relates to a system which utilizes blackbody self-illumination to observe defects and other structural features of coated objects such as aircraft components.

BACKGROUND INFORMATION

Aircraft components are subject to constant degradation such as corrosion and cracking caused by environmental and operational conditions. Although the application of coatings, such as paints, reduces corrosion problems substantially, they typically cannot eliminate them entirely. Furthermore, stress experienced during flight can result in damage which a coating of paint cannot mitigate, such as stress defects and cracking. In order to ensure that aircraft are ready for flight, periodic inspections are necessary.

Inspection of aircraft components traditionally includes visual inspection. When visually inspecting aircraft components, the coating used to protect the components becomes an obstacle because it may hide structural defects or features beneath the coating. It is therefore necessary to strip the component assembly or aircraft in question of its paint before a proper visual inspection can be performed. Afterward, a new coating of paint must be applied. This process results in substantial expense in the form of labor and materials, raises environmental concerns, and requires a great amount of time.

Apart from the inefficiency of visual inspection methods, another problem is that visual inspection is not always effective. While a skillful eye may pick up most human-visible defects with a satisfactory degree of consistency, some defects may be very small or lie under the surface of the component. In many cases these defects will go unnoticed by visual inspection regardless of the skill and experience of the observer.

In addition to visual inspection, active thermography techniques have been proposed for inspection of various components. One such technique utilizes a transient heat source to heat the component, followed by detection of a transient heat signature on the surface of the component to determine the presence of anomalies or defects. However, such techniques require specialized equipment and controls to generate the necessary transient heating, and are inefficient because detection of the transient thermal signature can require a significant amount of time.

U.S. Published Patent Application No. US 2004/0026622 A1 discloses a system for imaging coated substrates which utilizes an infrared (IR) light source. The IR light shines on the object and is reflected to a focal plane array. While such a system may be useful for some applications, an IR light source is required and the incident IR radiation must make two passes through the coating. Furthermore, a portion of the incident radiation may reflect off the surface of the coating, thereby obscuring the image of the underlying substrate.

The present invention has been developed in view of the foregoing.

SUMMARY OF THE INVENTION

The present invention utilizes the substantially steady-state temperature of a coated object, in conjunction with an optical detection system, to selectively view defects and features of the object below the coating without the necessity of transient heating or IR illumination and reflectance imaging. The optical detector, such as an IR camera, may be tailored for the wavelengths at which the coating material is substantially transparent, thereby maximizing the viewing clarity of the defects and features under the coating, and distinguishing them from any spurious features on the top surface of the coating. The present system enables the inspection of small or large areas in real time, without requiring complex image acquisition, storage and image processing equipment and software.

An aspect of the present invention is to provide a method of inspecting a coated object. The method includes maintaining substantially steady state blackbody radiation from the object, and detecting structural features of the object under the coating based on the blackbody radiation.

Another aspect of the present invention is to provide a system for inspecting a coated object. The system comprises means for maintaining substantially steady state blackbody radiation from the object, and means for detecting structural features of the object under the coating based on the blackbody radiation.

A further aspect of the present invention is to provide a system for inspecting a coated object comprising a camera structured and arranged to detect structural features of the object under the coating based on substantially steady state blackbody radiation generated from the object.

These and other aspects of the present invention will be more apparent from the following description.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic illustration of a system for detecting structural features of a coated object utilizing blackbody self-illumination of the object.

FIG. **2** is a schematic flow diagram illustrating the detection of blackbody radiation from an object to be inspected in accordance with an embodiment of the present invention.

FIGS. **3**–**26** are blackbody infrared radiation images of coated graphite panels and coated aluminum panels in accordance with various embodiments of the present invention.

FIGS. **27***a*–*d* are visible, IR reflectance, and IR blackbody radiation images of a coated aircraft panel with rivets, showing features of the rivets underneath the coating in accordance with a blackbody self-illumination embodiment of the present invention.

DETAILED DESCRIPTION

FIG. **1** schematically illustrates a detection system in accordance with an embodiment of the present invention. A coated object **10**, such as an aircraft component, composite panel, painted panel, ship hull, ground vehicle, aircraft assembly, aircraft landing gear, metallic substrate, honeycomb bonded assembly or the like, includes a substrate or object **12** at least partially covered with a coating **14** such as paint, composite matrix material or the like. Examples of some specific coatings include coatings manufactured to the

following specifications: BMS 10-72; BMS 10-11; BMS-10-79, BMS 10-60; MiL-PRF-23377; MiL-PRF-85582; MiL-PRF-85285 and TT-P-2760. In accordance with the present invention, the object **12** emits blackbody radiation B toward a detector **16** such as an infrared (IR) camera, IR detector or the like.

In accordance with the present invention, the blackbody radiation B from the object **12** is generated in a substantially steady state. As used herein, the term "substantially steady state blackbody radiation" means the radiation naturally generated from the object to be inspected due to its maintenance at a temperature above zero degrees Kelvin, typically at room temperature or a slightly elevated temperature. Steady state blackbody radiation results from maintaining the object or a portion thereof at a substantially uniform temperature, i.e., in the absence of significant thermal gradients throughout the object or portion thereof being inspected.

Since the object **12** is at or near room temperature, it emits a significant amount of substantially steady state infrared (IR) blackbody thermal radiation B. In contrast, the coating **14** may be substantially transparent at some of the wavelengths at which the underlying object emits the blackbody radiation B. Many organic polymers that may be used in the coating **14** are significantly IR-transmissive in certain spectral bands. The blackbody radiation B of the object can penetrate the organic coating **14** covering the object **12** and reveal the surface condition of the object **12** under the coating **14**. The radiation B transmitted through the coating **14** is thus used to provide images from the self-illuminated object **12** that reveal any defects such as corrosion, cracks and pits, as well as other structural features under the coating **14**. The object **12** to be inspected becomes observable by its own IR radiation B, which is a function of the temperature of the object **12**.

As shown in FIG. **1**, the object **12** to be inspected may include various types of structural features. The structural features may be located on the surface of the object **12** under the coating **14**, or may be located below the surface of the object **12**. For example, surface features **22** may be provided on the surface of the object **12** below the coating **14**. Examples of surface features **22** include indicia such as alphanumeric symbols, marks, codes, part numbers, bar codes and the like. The object **12** may also include surface defects such as corrosion **24**, pits **26**, cracks **28**, gouges, and other structural defects. As shown in FIG. **1**, the object **12** may also include structural features below the surface of the object **12**, such as corrosion **32**, cracks **34**, composite reinforcements **36** and pits **26**.

FIG. **2** schematically illustrates a blackbody radiation detection process in accordance with an embodiment of the present invention. Blackbody radiation from an object such as the coated object **10** shown in FIG. **1** is transmitted to a detector such as an IR camera. After detection, an image of the coated object **12**, including structural features of the object **10** under the coating **14** may be displayed and/or stored. In addition, the image may be transmitted by any suitable means such as the Internet, wireless, cable or satellite for display and/or storage at any desired location.

In accordance with an embodiment of the present invention, the steady state blackbody radiation B from the object to be inspected may be generated by holding the object at room temperature. The entire object may be maintained at a substantially uniform temperature at or near room temperature. As used herein, the term "room temperature" means the surrounding ambient temperature found in an area such as a testing laboratory, production facility, warehouse, hanger, airstrip, aircraft cabin or ambient exterior temperature. Room temperatures are typically within a range of from about 60 to about 80° F. However, temperatures above or below such a range may exist. For example, in cold environments such as unheated hangers or warehouses in cold regions, the room temperature may be 32° F. or lower. In warm environments such as non-air-conditioned hangers and warehouses in desert or tropical regions, the "room temperature" may be well above 80° F., e.g., up to 100 or 110° F., or even higher.

In accordance with another embodiment of the present invention, the object to be inspected is held at an elevated temperature, e.g., above room temperature, to maintain the substantially steady state blackbody radiation. Such an elevated temperature may be up to about 120° F. or higher, typically in a range of from 80 to about 110° F. The elevated temperature may be maintained by any suitable means, such as exposure to sunlight, heat gun, heat lamp, thermal blanket, hot packs, human contact and the like.

The detector **16** may selectively detect radiation at certain wavelengths at which the coating **14** is substantially transparent. In this manner, the coating **14** does not substantially interfere with the image from the object **12**. The detector **16** may include any suitable device such as an IR camera, IR detector, IR focal plane or the like. For example, the camera may be an analog or digital camera, and may record still or video images. Infrared cameras may be used, for example, cameras which detect mid-infrared radiation, e.g., having wavelengths between about 3 and about 5 microns. Such mid-IR wavelengths have been found to produce relatively sharp images with minimal interference from several types of coatings. Other infrared cameras include near-infrared cameras which detect wavelengths between about 0.7 and about 3 microns, and far-infrared cameras which detect wavelengths between about 3 and about 12 microns.

In addition to the camera **16**, standard filters and/or polarizers (not shown) may be positioned in the optical path of the blackbody radiation B between the object **12** and the detector **16**. Such filters and/or polarizers may remove a portion of the blackbody radiation B having wavelengths at which the coating **14** is non-transparent.

The detector **16** may include a portable or movable camera such as a hand-held camera or a camera that may be mounted on a tripod or the like that can be moved by means of a pan feature and/or a tilt feature.

In accordance with an embodiment of the present invention, the detected image of the object **12**, including the detected structural features, may be compared with a reference image. For example, a reference image may be generated from another object similar to the coated object that is known to be substantially free of defects. By comparing a substantially defect-free reference object to the coated object being inspected, manual or automated evaluations may be performed. The reference image used as the standard could be preprogrammed into a database and a comparison made between the reference image and the image created from paint under test. Acceptability criteria could be preprogrammed as well, unacceptable areas could be highlighted in red and acceptable areas in green. Other colors could be selected, as well, such as gray for an area requiring more evaluation.

The following examples are intended to illustrate the various aspects of the present invention and are not intended to limit the scope of the invention.

EXAMPLE 1

As shown in FIG. **3**, a painted graphite panel comprising epoxy graphite with an epoxy primer and urethane top coat paint was imaged with a mid-IR camera at the wavelength of 3 to 5 microns. During the imaging process, the panel was held at 89° F. The panel was subjected to a room temperature calibration which involved adjusting pixel intensity to make focal plane uniform and linear within selected room temperature (RT) calibration.

EXAMPLE 2

As shown in FIG. **4**, a painted graphite panel comprising epoxy graphite and epoxy primer and urethane top coat paint was imaged with a mid-IR camera at a wavelength of 3 to 5 microns with the panel held at a temperature of 90° F. The panel was subjected to hot calibration at a temperature of 84° F. The hot calibration process involved adjusting pixel intensity to make focal plane uniform and linear within selected 84° F. calibration.

EXAMPLE 3

As shown in FIG. **5**, a composite panel comprising epoxy graphite and laminated copper fiber painted with epoxy primer and urethane top coat was imaged with a mid-IR camera at a wavelength of 3 to 5 microns, with the panel maintained at a temperature of 90° F. The panel was subjected to hot calibration at 84° F., as described above.

EXAMPLE 4

As shown in FIG. **6**, a painted graphite and copper fiber panel similar to the panel of Example 3 was imaged at a temperature of 74° F. The panel was subjected to hot calibration at 84° F.

EXAMPLE 5

As shown in FIG. **7**, a panel comprising epoxy graphite with a laminated copper weave painted with epoxy primer and urethane top coat was imaged at a temperature of 91° F. The panel was subjected to room temperature calibration.

EXAMPLE 6

As shown in FIG. **8**, a painted graphite and copper weave panel similar to that of Example 5 was imaged at 87° F. after room temperature calibration.

EXAMPLE 7

As shown in FIG. **9**, a painted graphite and copper weave panel similar to that of Examples 5 and 6 was imaged at 82° F. after room temperature calibration.

EXAMPLE 8

As shown in FIG. **10**, an epoxy graphite panel painted with epoxy primer and urethane top coat was imaged at 90° F. after room temperature calibration.

EXAMPLE 9

As shown in FIG. **11**, a painted graphite panel similar to that of Example 8 was imaged at 86° F. after room temperature calibration.

EXAMPLE 10

As shown in FIG. **12**, a painted graphite panel similar to that of Examples 8 and 9 was imaged at 82° F. after room temperature calibration.

EXAMPLE 11

As shown in FIG. **13**, a painted graphite panel similar to that of Examples 8–10 was imaged at 78° F. after room temperature calibration.

EXAMPLE 12

As shown in FIG. **14**, a panel comprising epoxy graphite was primed with epoxy primer and painted with epoxy primer and urethane top coat on the right side of the panel. FIG. **14** is a visible image of the painted and primed panel.

EXAMPLE 13

As shown in FIG. **15**, a panel comprising graphite with copper weave was primed with epoxy primer in lower right hand side and painted with urethane top coat in upper right of panel. In FIG. **15**, the left side of the panel is unprimed and unpainted, while the right side is primed and painted. FIG. **15** is a visual image of the panel.

EXAMPLE 14

FIG. **16** is a visible image of an aluminum panel comprising a corroded aluminum substrate coated with epoxy primer and urethane top coat.

EXAMPLE 15

FIG. **17** is an IR reflectance image of the panel of Example 14 at 77° F. The IR reflectanct image was generated by reflecting IR radiation off the aluminum substrate detecting the reflected energy in an IR camera or detector. The corrosion is indicated in dark areas.

EXAMPLE 16

FIG. **18** is an IR reflectance image of the panel of Example 14 taken 75° F. The corrosion is indicated in dark areas.

EXAMPLE 17

FIG. **19** is a blackbody radiation image made in accordance with the present invention of the coated aluminum panel of Example 14. The panel was maintained at a temperature of 84° F. with a room temperature calibration. The corrosion is indicated in light areas.

EXAMPLE 18

FIG. **20** is a blackbody radiation image made in accordance with the present invention of the coated aluminum panel of Example 14, at 78° F. with a room temperature calibration. The corrosion is indicated in light areas.

EXAMPLE 19

FIG. **21** is a blackbody radiation image made in accordance with the present invention of the coated aluminum panel of Example 14, at 72° F. with a room temperature calibration. The corrosion is indicated in light areas.

EXAMPLE 20

FIG. **22** is an IR reflectance image of a corroded aluminum panel coated with an epoxy low IR primer and urethane top coat. The IR reflectance image was made by reflecting IR radiation off the coated aluminum substrate and detecting the reflected energy in an IR camera. The corrosion is indicated in dark areas.

EXAMPLE 21

FIG. **23** is a blackbody radiation image produced in accordance with the present invention taken from the same primed and top coated aluminum panel described in Example 20. The blackbody radiation procedure was performed at 96° F. with a 78° F. hot calibration. The corrosion is indicated in light areas.

EXAMPLE 22

FIG. **24** is a blackbody radiation image produced in accordance with the present invention taken from the same primed and top coated aluminum panel described in Example 20. The blackbody radiation procedure was performed at 86° F. with a 78° F. hot calibration. The corrosion is indicated in light areas.

EXAMPLE 23

FIG. **25** is a blackbody radiation image produced in accordance with the present invention taken from the same primed and top coated aluminum panel described in Example 20. The blackbody radiation procedure was performed at 79° F. with a 78° F. hot calibration. The corrosion is indicated in light areas.

EXAMPLE 24

FIG. **26** is a visible image of the primed and top coated aluminum panel of Examples 20 to 23.

The foregoing examples demonstrate that blackbody type IR radiation is capable of passing through coatings and producing an image. External illumination is not required, i.e., the parts are self-illuminating.

EXAMPLE 25

A bolted aluminum aircraft panel was coated with Epoxy primer MIL-PRF-23377TYI and Urethane MIL-PRF-85285TYI paint, as shown in FIG. **27***a*. It was inspected using visible imaging (FIG. **27***b*), IR reflectance imaging (FIG. **27***c*), and IR blackbody imaging (FIG. **27***d*). The blackbody self-illumination image was made with a mid-IR camera at a wavelength of 3 to 5 microns. During the black body imaging process, the painted aluminum panel was held at a temperature of 85 to 95° F. As shown in FIG. **27***d*, details

An advantage of the present blackbody self illumination system is that an independent IR illumination source is not needed. In some cases, an object's IR radiation at ambient temperature may be sufficient to allow imaging of the object through the coating, while in other situations moderate heating of the object to a slightly elevated temperature may be desirable. Such heating can be achieved naturally, e.g., by sunlight, or by a heat gun, thermal blankets, an IR heat lamp, or by other means that produce a substantially steady-state temperature of the object.

Another advantage of the present blackbody system is that the IR radiation only has to make one pass through the coating. This is more efficient compared to IR reflectance techniques, in which IR radiation from an external illuminator must first penetrate the coating, reflect off the substrate or object and pass through the coating again. An additional advantage of the present blackbody method is the reduction or elimination of the coating surface reflection. In the reflectance method, IR energy is reflected off the coating surface partially obscuring the image from the substrate underneath.

Whereas particular embodiments of this invention have been described above for purposes of illustration, it will be evident to those skilled in the art that numerous variations of the details of the present invention may be made without departing from the invention as defined in the appended claims.

The invention claimed is:

1. A method of inspecting a coated object, the method comprising:

maintaining substantially steady state blackbody radiation from the object; and

detecting structural features of the object under the coating based on the blackbody radiation.

2. The method of claim **1**, wherein the object is held at room temperature to maintain the substantially steady state blackbody radiation.

3. The method of claim **2**, wherein the room temperature is from about 32 to about 80° F.

4. The method of claim **1**, wherein the object is held at an elevated temperature to maintain the substantially steady state blackbody radiation.

5. The method of claim **4**, wherein the elevated temperature is less than about 120° F.

6. The method of claim **4**, wherein the elevated temperature is from about 80 to about 110° F.

7. The method of claim **4**, wherein the elevated temperature is maintained by exposing the object to sunlight.

8. The method of claim **4**, wherein the elevated temperature is maintained by heating the object with a heat gun, a heat lamp and/or a thermal blanket.

9. The method of claim **1**, wherein the structural features of the object are detected using an infrared camera.

10. The method of claim **9**, wherein the infrared camera detects mid-infrared radiation having wavelengths between about 3 and about 5 microns.

11. The method of claim **9**, wherein the infrared camera detects near-infrared radiation having wavelengths between about 0.7 and about 3 microns.

12. The method of claim **9**, wherein the infrared camera detects far-infrared radiation having wavelengths between about 3 and about 12 microns.

13. The method of claim **1**, wherein the structural features

14. The method of claim **1**, wherein the structural features of the object are detected using a movable camera.

15. The method of claim **14**, wherein the movable camera is a hand-held camera.

16. The method of claim **14**, wherein the movable camera is mounted at a single location during the detection, and includes a pan feature and/or a tilt feature.

17. The method of claim **1**, wherein the structural features of the object are detected using a camera and a filter located in an optical path between the object and the camera.

18. The method of claim **17**, wherein the filter removes a portion of the blackbody radiation having wavelengths at which the coating is non-transparent.

19. The method of claim **1**, wherein the structural features of the object are detected using a camera and a polarizer located in an optical path between the object and the camera.

20. The method of claim **1**, wherein the structural features comprise defects.

21. The method of claim **1**, wherein the defects are on a surface of the object under the coating.

22. The method of claim **21**, wherein the surface defects comprise corrosion, cracks, pits and/or gouges.

23. The method of claim **20**, wherein the defects are under a surface of the object.

24. The method of claim **23**, wherein the defects comprise corrosion, cracks and/or voids.

25. The method of claim **1**, wherein the structural features comprise surface features on a surface of the object under the coating.

26. The method of claim **25**, wherein the surface features comprise indicia.

27. The method of claim **26**, wherein the indicia comprises alphanumeric symbols, marks or codes.

28. The method of claim **1**, wherein the structural features comprise features under a surface of the object.

29. The method of claim **28**, wherein the features comprise composite reinforcements and/or composite matrix materials.

30. The method of claim **1**, wherein the object comprises an aircraft component.

31. The method of claim **1**, wherein the coating comprises paint, a composite matrix material, primer, top coat and/or intermediate coatings.

32. The method of claim **1**, further comprising displaying an image of the object including the detected structural features.

33. The method of claim **1**, further comprising storing an image of the object including the detected structural features.

34. The method of claim **1**, further comprising transmitting an image of the object including the detected structural features.

35. The method of claim **34**, wherein the image is transmitted over the internet.

36. The method of claim **1**, further comprising comparing an image of the object including the detected structural features with a reference image.

37. The method of claim **35**, wherein the reference image is generated from another object similar to the coated object that is substantially free of defects.

38. A system for inspecting a coated object comprising:

means for maintaining substantially steady state blackbody radiation from the object; and

means for detecting structural features of the object under the coating based on the blackbody radiation.

39. A system for inspecting a coated object comprising a camera structured and arranged to detect structural features of the object under the coating based on substantially steady state blackbody radiation generated from the object.

* * * * *

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(54) SPECTRAL FILTER SYSTEM FOR INFRARED IMAGING OF SUBSTRATES THROUGH COATINGS

(75) Inventors: **Donald DiMarzio**, Northport, NY (US); **John Douglas Weir**, Huntington, NY (US); **Steven Chu**, Ronkonkoma, NY (US); **Nils Jakob Fonneland**, Lake Grove, NY (US); **Dennis John Leyble**, Great River, NY (US)

Correspondence Address:
Alan G. Towner
Pietragallo, Bosick & Gordon LLP
One Oxford Centre, 38th Floor
301 Grant Street
Pittsburgh, PA 15219 (US)

(73) Assignee: **Northrop Grumman Corporation**, Los Angeles, CA

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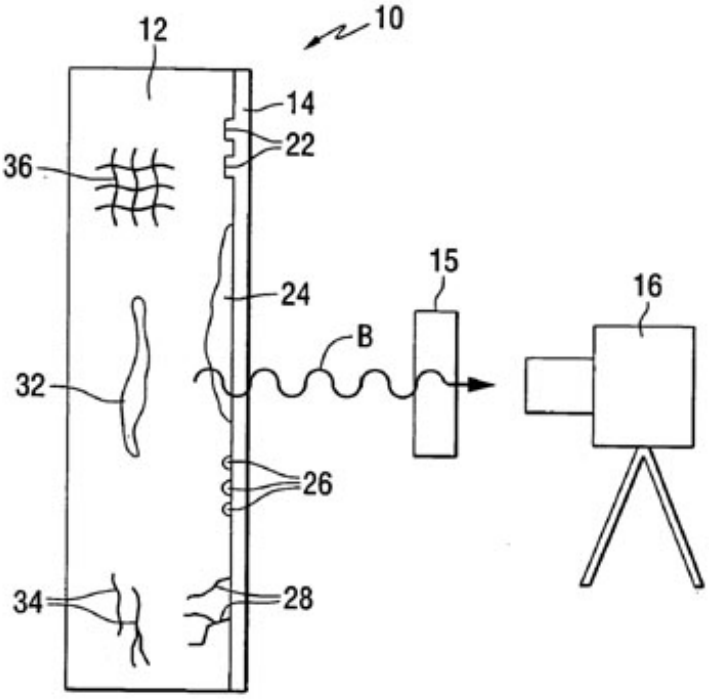
(52) **U.S. Cl.** **250/341.8**

(57) **ABSTRACT**

An improved system for visual inspection of substrates coated with paints and polymers is disclosed. Painted substrates can be inspected for environmental and physical damage such as corrosion and cracks without removing the paint. The present invention provides the ability to maximize paint thickness penetration. This is accomplished with a spectral bandpass filter that rejects reflected light from the coating opaque bands, while allowing light in the paint window to pass to an IR detector such as an IR camera focal plane. The narrow bandpass range enhances the ability for IR imaging to see through thicker paint layers and improves the contrast over standard commercial IR mid-wave cameras. The bandpass may be adjusted to coincide with the full spectral window of the paint, consistent with the ability of the imaging focal plane to detect light in the spectral region.



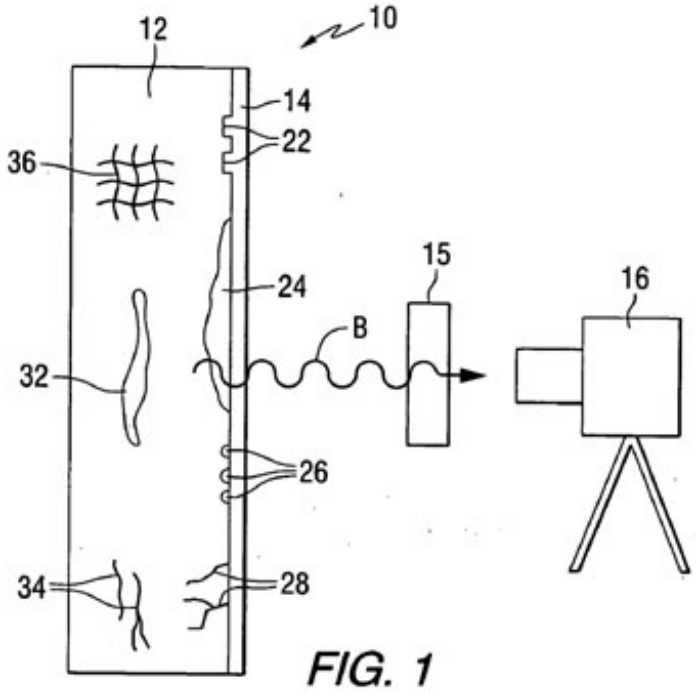

10
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FIG. 1

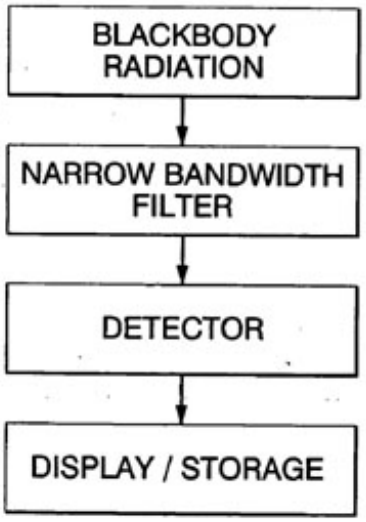

BLACKBODY RADIATION
NARROW BANDWIDTH FILTER
DETECTOR
DISPLAY / STORAGE

FIG. 2

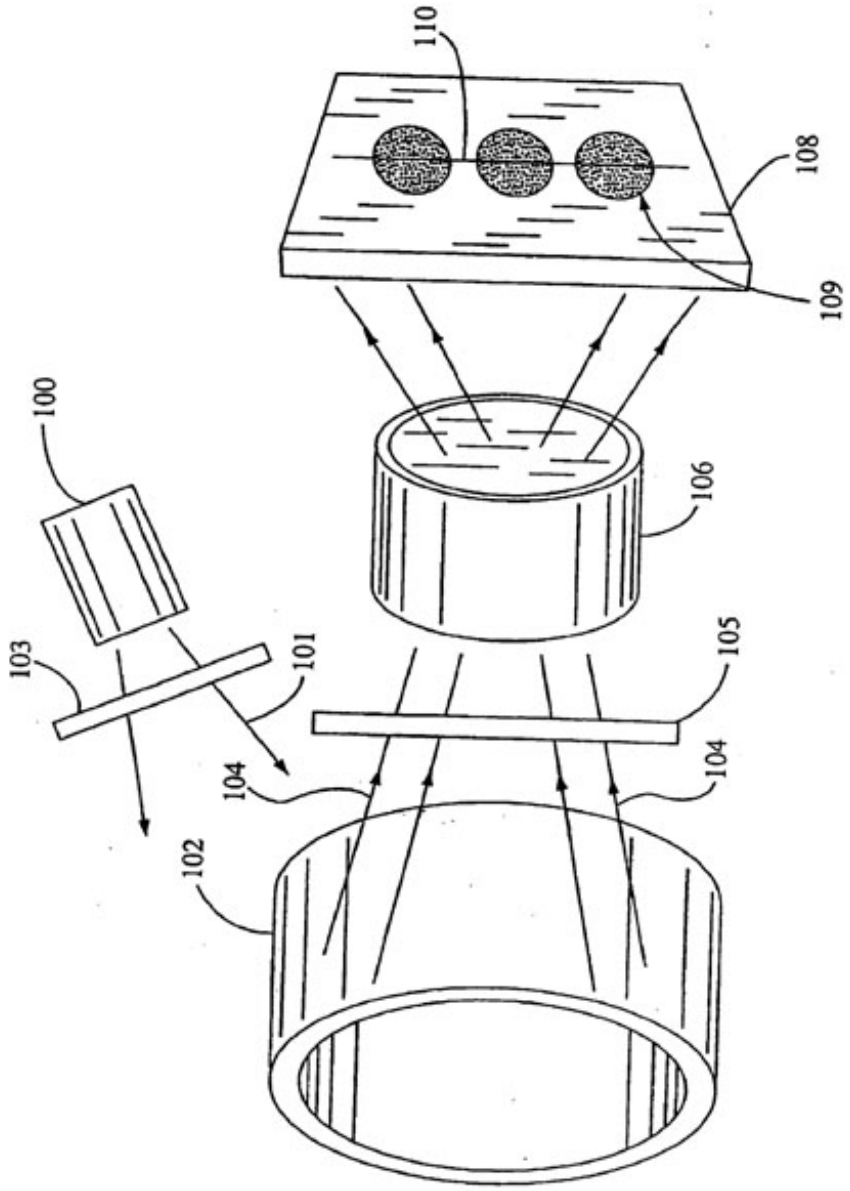
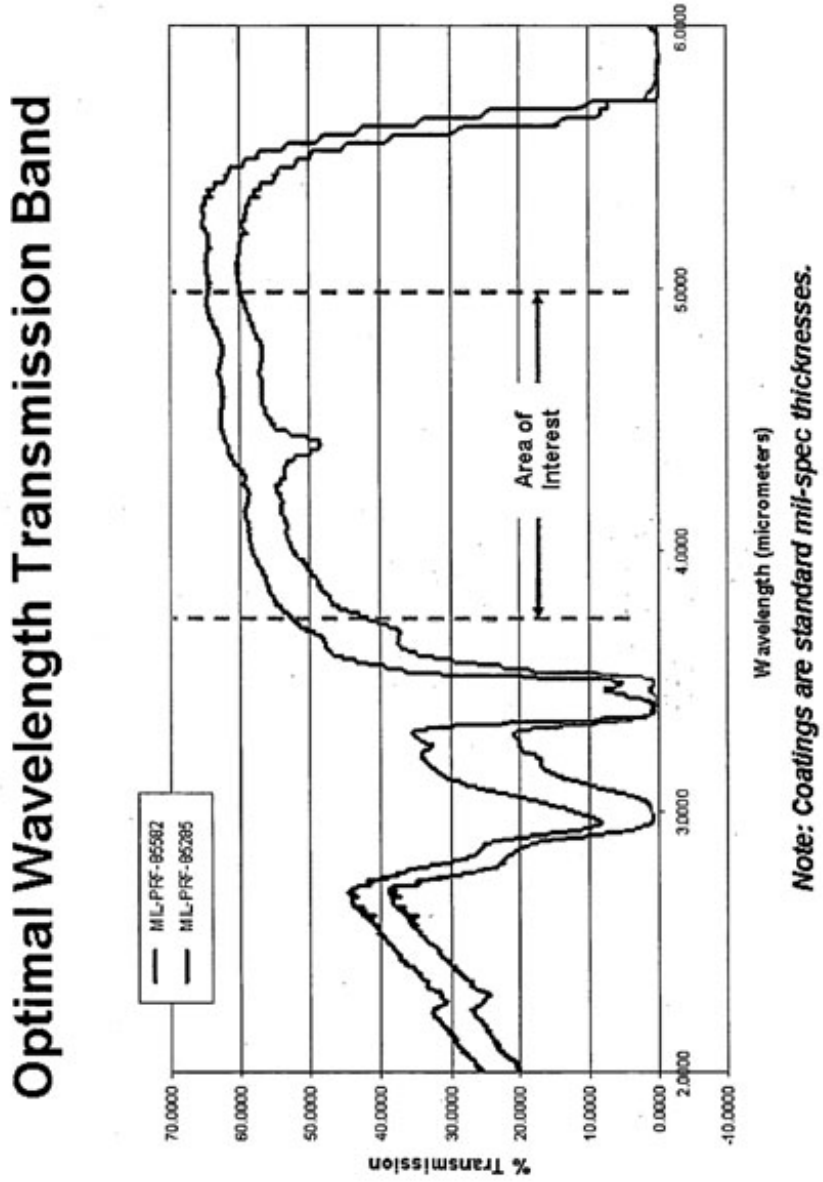


Fig. 3



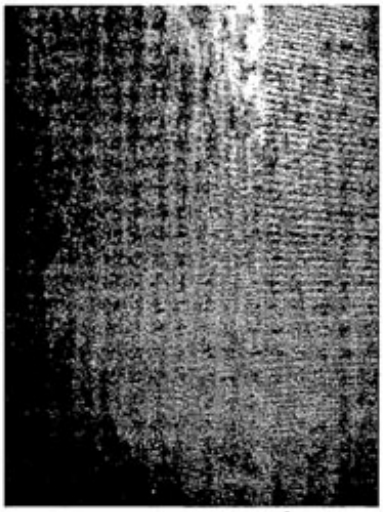
Note: Coatings are standard mil-spec thicknesses.

FIG. 4

Gloss P1T1 Sample

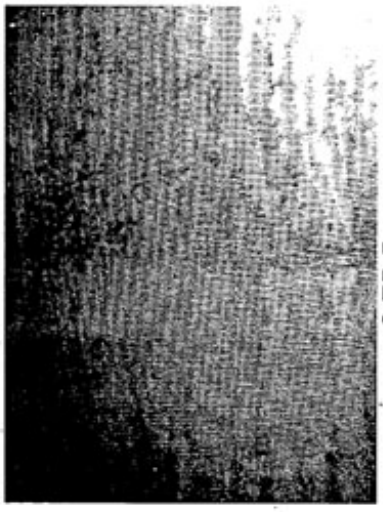
3-5 µm

FIG. 5



3.5-5 µm

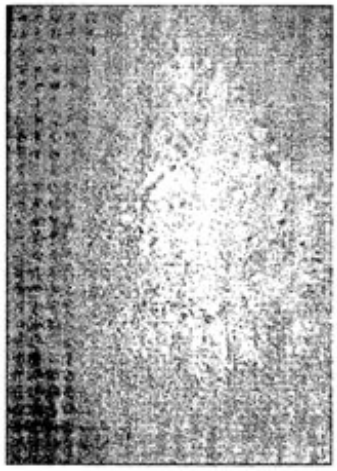
FIG. 6



3.75-5 µm

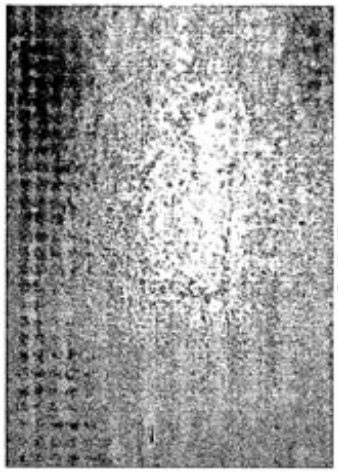
FIG. 7

Camo P2T2 Sample



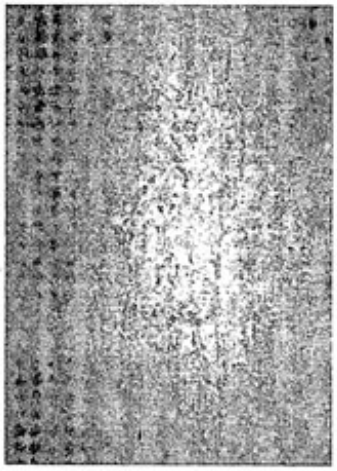
3-5 µm: STANDARD FILTER

FIG. 8



3.5-5 µm

FIG. 9



3.75-5 µm: *OPTIMIZED FILTER*

FIG. 10

SPECTRAL FILTER SYSTEM FOR INFRARED IMAGING OF SUBSTRATES THROUGH COATINGS

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application is a continuation-in-part of U.S. application Ser. No. 10/971,217 filed Oct. 22, 2004, which is incorporated herein by reference.

GOVERNMENT CONTRACT

[0002] The United States Government has certain rights to this invention pursuant to Contract No. DACA 72-99-C-011 awarded by SERDP.

FIELD OF THE INVENTION

[0003] The present invention relates to imaging of substrates through coatings, and more particularly relates to a spectral filter system for infrared imaging of defects and other structural features of coated objects such as aircraft components.

BACKGROUND INFORMATION

[0004] Aircraft components are subject to constant degradation such as corrosion and cracking caused by environmental and operational conditions. Although the application of coatings, such as paints, reduces corrosion problems substantially, they typically cannot eliminate them entirely. Furthermore, stress experienced during flight can result in damage which a coating of paint cannot mitigate, such as stress defects and cracking. In order to ensure that aircraft are ready for flight, periodic inspections are necessary.

[0005] Inspection of aircraft components traditionally includes visual inspection. When visually inspecting aircraft components, the coating used to protect the components becomes an obstacle because it may hide structural defects or features beneath the coating. It is therefore necessary to strip the component assembly or aircraft in question of its paint before a proper visual inspection can be performed. Afterward, a new coating of paint must be applied. This process results in substantial expense in the form of labor and materials, raises environmental concerns, and requires a great amount of time.

[0006] Apart from the inefficiency of visual inspection methods, another problem is that visual inspection is not always effective. While a skillful eye may pick up most human-visible defects with a satisfactory degree of consistency, some defects may be very small or lie under the surface of the component. In many cases these defects will go unnoticed by visual inspection regardless of the skill and experience of the observer.

[0007] In addition to visual inspection, active thermography techniques have been proposed for inspection of various components. One such technique utilizes a transient heat source to heat the component, followed by detection of a transient heat signature on the surface of the component to determine the presence of anomalies or defects. However, such techniques require specialized equipment and controls to generate the necessary transient heating, and are inefficient because detection of the transient thermal signature can require a significant amount of time.

[0008] U.S. Published Patent Application No. US 2004/0026622 A1, which is incorporated herein by reference, discloses a system for imaging coated substrates which utilizes an infrared (IR) light source. The IR light shines on the object and is reflected to a focal plane array.

[0009] U.S. application Ser. No. 10/971,217 discloses a system for detecting structural defects and features of coated substrates using a blackbody self-illumination technique.

[0010] The present invention has been developed in view of the foregoing.

SUMMARY OF THE INVENTION

[0011] One embodiment of the present invention utilizes the substantially steady-state temperature of a coated object, in conjunction with an optical detection system, to selectively view defects and features of the object below the coating without the necessity of transient heating or IR illumination and reflectance imaging. The optical detector, such as an IR camera, may be tailored for the wavelengths at which the coating material is substantially transparent. At least one narrow bandwidth spectral optical filter is positioned between the substrate and the detector. The filter significantly improves viewing clarity of the defects and features under the coating, and distinguishes them from spurious features on the top surface of the coating. The system enables the inspection of small or large areas in real time, without requiring complex image acquisition, storage and image processing equipment and software.

[0012] Another embodiment of the present invention provides a system including the use of IR illumination for imaging the surface of a substrate through a coating on the substrate. An infrared light source is positioned to cast infrared light upon the substrate to create reflected light. A detector such as a focal plane array may be positioned to receive the reflected light and generate an image therefrom. At least one narrow bandwidth spectral optical filter is positioned between the substrate and the detector to pass wavelengths of the reflected light which reveal structural features of the substrate.

[0013] An aspect of the present invention is to provide a system for imaging the surface of a substrate through a coating on the substrate. The system comprises a detector positioned to receive infrared radiation from the substrate surface, and at least one narrow bandwidth spectral optical filter between the substrate and the detector to pass infrared wavelengths from 3.75 to 5.0 micrometers to the detector.

[0014] Another aspect of the present invention is to provide a method for imaging the surface of a substrate through a coating on the substrate. The method comprises generating infrared light from the substrate, filtering the infrared light with a narrow bandwidth filter which passes wavelengths within a range from 3.75 to 5.0 micrometers, and receiving the filtered infrared light on a detector.

[0015] These and other aspects of the present invention will be more apparent from the following description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] **FIG. 1** is a schematic illustration of a system for detecting structural features of a coated object utilizing

blackbody self-illumination of the object and a narrow bandwidth filter positioned between the object and a detector.

[0017] **FIG. 2** is a schematic flow diagram illustrating the filtering and detection of blackbody radiation from an object to be inspected in accordance with an embodiment of the present invention.

[0018] **FIG. 3** is a schematic illustration of a system for detecting structural features of a coated object utilizing IR illumination of the object and a narrow bandwidth filter positioned between the object and a detector.

[0019] **FIG. 4** depicts the FTIR spectra of an Aircraft Coating System. A strong absorbance peak occurs at 3.4 micrometers, which causes the IR to scatter and increases spectral noise. By using a narrow bandwidth filter (3.75-5.0 micrometer) in accordance with the present invention, a large percentage of scattering is eliminated.

[0020] **FIGS. 5-7** are photographic images of a coated substrate, illustrating unexpectedly improved detection of substrate damage under the coating with a system including a narrow bandwidth filter of the present invention (**FIG. 7**) in comparison with systems having broader bandwidth filters (**FIGS. 5 and 6**).

[0021] **FIGS. 8-10** are photographic images of a coated substrate, illustrating unexpectedly improved detection of substrate damage under the coating with a system including a narrow bandwidth filter of the present invention (**FIG. 10**) in comparison with systems having broader bandwidth filters (**FIGS. 8 and 9**).

DETAILED DESCRIPTION

[0022] The present invention provides improved visual inspection of substrates that are coated with paints and polymers. Most paints and polymer coatings have a region of significantly reduced electromagnetic radiation absorption and scattering in the mid IR region as compared to the visible spectral region. This effectively opens a window of visibility where certain IR imaging cameras can see through coatings to the underlying substrates. Painted substrates can be inspected for environmental and physical damage such as corrosion and cracks without removing the paint.

[0023] The present invention provides the ability to maximize paint thickness penetration. This is accomplished with a spectral bandpass filter that rejects reflected light from the coating opaque bands, while allowing light in the paint window to pass to the IR camera focal plane. The narrow bandpass range results in the enhanced ability for IR imaging to see through thicker paint layers. The bandpass may be adjusted to coincide with the full spectral window of the paint, consistent with the ability for the imaging focal plane to detect light in the spectral region. In one embodiment, a suitable camera uses a cooled InSb focal plane array with a sensitivity to IR light which drops to zero for wavelengths longer than about 5.6 micrometers.

[0024] In accordance with the present invention, it has been found that extending the bandpass filter to wavelengths beyond 5.0 micrometers actually has a deleterious effect on the image that is produced by the IR camera. This unwanted effect can be explained by the significant increase in thermal radiative flux going to the focal plane in the spectral regions above 5.0 micrometers. For objects at or near room temperature, the natural thermal emission of radiation increases in the mid IR region as the wavelength increases. This means that regions of an object that have low reflectance (high emissivity) and look dark in the IR reflectance image, now start to look lighter since the regions are emitting more of their own radiation in the range above 5.0 micrometers. This results in reduced contrast between the low reflectance regions (e.g., corrosion on metal) and the higher reflectance regions (uncorroded). This reduced contrast makes it more difficult to visually detect regions of corrosion on metals covered with relatively thick paint.

[0025] As used herein, the term "narrow bandwidth filter" means that the spectral range for the bandpass filter for IR imaging lies between 3.7 and 5.0 micrometers, for example, between 3.75 and 5.0 micrometers. This applies to the use of active IR illumination of a coated substrate to create the image, or the use of the natural thermal emission of the coated substrate for self-illumination.

[0026] **FIG. 1** schematically illustrates a detection system in accordance with an embodiment of the present invention. A coated object **10**, such as an aircraft component, composite panel, painted panel, ship hull, ground vehicle, aircraft assembly, aircraft landing gear, metallic substrate, honeycomb bonded assembly or the like, includes a substrate or object **12** at least partially covered with a coating **14** such as paint, composite matrix material or the like.

[0027] Examples of some specific coatings include coatings manufactured to the following specifications: BMS 10-172; BMS 10-11; BMS-10-79, BMS 10-60; MIL-PRF-23377; MIL-PRF-85582; MIL-PRF-85285 and TT-P-2760. In accordance with the present invention, the coatings may be relatively thick while still allowing clear imaging of substrate defects below the coating. For example, the coating **14** may be approximately 0.5 to 12 mils thick.

[0028] The object **12** emits blackbody radiation B toward a detector **16** such as an infrared (IR) camera, IR detector or the like. A narrow bandwidth filter **15** is located between the coated object **10** and the detector **16**. The narrow bandwidth filter **15** can be single or multiple component filter to obtain the desired bandpass.

[0029] In accordance with an embodiment of the present invention, the blackbody radiation B from the object **12** is generated in a substantially steady state. As used herein, the term "substantially steady state blackbody radiation" means the radiation naturally generated from the object to be inspected due to its maintenance at a temperature above zero degrees Kelvin, typically at room temperature or a slightly elevated temperature. Steady state blackbody radiation results from maintaining the object or a portion thereof at a substantially uniform temperature, i.e., in the absence of significant thermal gradients throughout the object or portion thereof being inspected.

[0030] Since the object **12** is at or near room temperature, it emits a significant amount of substantially steady state infrared (IR) blackbody thermal radiation B. In contrast, the coating **14** may be substantially transparent at some of the wavelengths at which the underlying object emits the blackbody radiation B. Many organic polymers that may be used in the coating **14** are significantly IR-transmissive in certain spectral bands. The blackbody radiation B of the object can

penetrate the organic coating **14** covering the object **12** and reveal the surface condition of the object **12** under the coating **14**. The radiation B transmitted through the coating **14** is thus used to provide images from the self-illuminated object **12** that reveal any defects such as corrosion, cracks and pits, as well as other structural features under the coating **14**. The object **12** to be inspected becomes observable by its own IR radiation B, which is a function of the temperature of the object **12**.

[0031] As shown in **FIG. 1**, the object **12** to be inspected may include various types of structural features. The structural features may be located on the surface of the object **12** under the coating **14**, or may be located below the surface of the object **12**. For example, surface features **22** may be provided on the surface of the object **12** below the coating **14**. Examples of surface features **22** include indicia such as alphanumeric symbols, marks, codes, part numbers, bar codes and the like. The object **12** may also include surface defects such as corrosion **24**, pits **26**, cracks **28**, gouges, and other structural defects. As shown in **FIG. 1**, the object **12** may also include structural features below the surface of the object **12**, such as corrosion **32**, cracks **34**, composite reinforcements **36** and pits **26**.

[0032] **FIG. 2** schematically illustrates a blackbody radiation detection process in accordance with an embodiment of the present invention. Blackbody radiation from an object such as the coated object **10** shown in **FIG. 1** is transmitted through a narrow bandwidth filter to a detector such as an IR camera. After detection, an image of the coated object **12**, including structural features of the object **10** under the coating **14** may be displayed and/or stored. In addition, the image may be transmitted by any suitable means such as the Internet, wireless, cable or satellite for display and/or storage at any desired location.

[0033] In accordance with an embodiment of the present invention, the steady state blackbody radiation B from the object to be inspected may be generated by holding the object at room temperature. The entire object may be maintained at a substantially uniform temperature at or near room temperature. As used herein, the term "room temperature" means the surrounding ambient temperature found in an area such as a testing laboratory, production facility, warehouse, hanger, airstrip, aircraft cabin or ambient exterior temperature. Room temperatures are typically within a range of from about 60 to about 80° F. However, temperatures above or below such a range may exist. For example, in cold environments such as unheated hangers or warehouses in cold regions, the room temperature may be 32° F. or lower. In warm environments such as non-air-conditioned hangers and warehouses in desert or tropical regions, the "room temperature" may be well above 80° F., e.g., up to 100 or 110° F., or even higher.

[0034] In accordance with another embodiment of the present invention, the object to be inspected is held at an elevated temperature, e.g., above room temperature, to maintain the substantially steady state blackbody radiation. Such an elevated temperature may be up to about 120° F. or higher, typically in a range of from 80 to about 110° F. The elevated temperature may be maintained by any suitable means, such as exposure to sunlight, heat gun, heat lamp, thermal blanket, hot packs, human contact and the like.

[0035] The detector **16** may selectively detect radiation at certain wavelengths at which the coating **14** is substantially transparent. In this manner, the coating **14** does not substantially interfere with the image from the object **12**. The detector **16** may include any suitable device such as an IR camera, IR detector, IR focal plane or the like. For example, the camera may be an analog or digital camera, and may record still or video images. The detector **16** may include a portable or movable camera such as a hand-held camera or a camera that may be mounted on a tripod or the like that can be moved by means of a pan feature and/or a tilt feature. Infrared cameras may be used, for example, cameras which detect mid-infrared radiation, e.g., having wavelengths between about 3 and about 5 microns. Such mid-IR wavelengths have been found to produce relatively sharp images with minimal interference from several types of coatings.

[0036] In addition to the camera **16**, the narrow bandwidth filter **15** is positioned in the optical path of the blackbody radiation B between the object **12** and the detector **16**. The narrow bandwidth filter **15** removes portions of the blackbody radiation B having wavelengths at which the coating **14** is non-transparent, e.g., wavelengths below 3.7 or 3.75 micrometers are removed, and wavelengths above 5.0 micrometers are removed.

[0037] In accordance with an embodiment of the present invention, the filtered image of the object **12**, including the detected structural features, may be compared with a reference image. For example, a reference image may be generated from another object similar to the coated object that is known to be substantially free of defects. By comparing a substantially defect-free reference object to the coated object being inspected, manual or automated evaluations may be performed. The reference image used as the standard could be preprogrammed into a database and a comparison made between the reference image and the image created from paint under test. Acceptability criteria could be preprogrammed as well. For example, unacceptable areas could be highlighted in red and acceptable areas in green. Other colors could be selected, as well, such as gray for an area requiring more evaluation.

[0038] **FIG. 3** illustrates another system for detecting structural features of a coated object which utilizes IR illumination and a narrow bandwidth filter in accordance with an embodiment of the invention. An infrared light source **100** is used to cast infrared light **101** in the direction of a substrate **102** which is coated. Prior to reaching the substrate **102**, the infrared light **101** may optionally pass through a first polarizer **103**. The first polarizer **103** is operative to polarize the infrared light to a first selected polarity.

[0039] Light reflected by the substrate creates reflected light **104**. The reflected light **104** passes through an optional second polarizer **105**. The second polarizer **105** is operative to polarize the reflected light to a second selected polarity. For instance, the second polarizer **105** may be configured to polarize the reflected light **104** in a direction opposite to that of first selected direction, a method known as cross-polarity. In this case, light of the polarity modulated by the first polarizer **103** will not pass through the second polarizer **105**. Polarizers may not be necessary in many instances because most coatings are not polarized in any certain orientation.

[0040] The portion of the reflected light **104** which was reflected off of regular areas of the substrate **102** will retain the polarity modulated by the first polarizer **103** and there-

fore will not pass through the second polarizer **105**. However, the portion of the reflected light **104** which was reflected off of irregular areas, such as corrosion or rust, will have an altered polarity and will therefore pass through the second polarizer **105**. Additionally, this optional polarization technique can reduce scattering by pigments in the coating which results in a clearer image of the substrate. Thus, only the portion of the reflected light **104** which was reflected off of irregular areas of the substrate **102** will pass through the second polarizer **105**. The first polarizer **103** and second polarizer **105** may therefore operate in tandem to highlight the areas of the substrate **102** which are irregular because they are corroded or otherwise damaged. Additionally, the polarity modulated by the first polarizer **103** may be configured to allow viewing of the substrate **102** at various levels. This is because light of a polarity parallel to the substrate **102** will more easily reflect off of the coating, while light of a polarity perpendicular to the substrate **102** will more easily penetrate through the coating to the substrate beneath. Accordingly, it is possible to focus on either the surface of the substrate itself or on the surface of the coating. This methodology may be combined with the cross-polarity method described above in order to enhance particular features of the substrate at a particular level. It should be noted that although the first polarizer **103** and second polarizer **105** may be used in the fashion described and are therefore present in a potentially preferred embodiment, they are not necessary to the function of the present invention, and need not be included.

[0041] In accordance with the present invention, the reflected light **104** passes through a narrow bandwidth optical filter **106** similar to the narrow bandwidth filter **15** previously described. Coatings used on, for instance, aircraft components and assemblies are generally designed to be opaque in the visible range of light. Often, they are more transparent in the infrared range of light. Accordingly, certain wavelengths of light are more likely to pass through the coating to be reflected by the substrate beneath. The image created by the portion of the reflected light **104** having these wavelengths will represent an image primarily of the substrate **102** instead of the coating on the substrate. It is therefore desirable to focus on these wavelengths to the exclusion of others, and they become the selected wavelengths passed by the narrow bandwidth optical filter **106**. The filter **106** need not be a single filter, but could be a series of filters, in order to tailor the bandpass wavelength to a specific wavelength range.

[0042] Subsequent to passing through the filter **106**, the reflected light **104** reaches a detector in the form of a focal plane **108**. A focal plane array (not shown) is positioned at a focal plane **108** for the purpose of receiving an image by the reflected light **104** at the focal plane **108**. Structural features of the substrate **102**, such as cracks **110** and corrosion are visible in this image **109**. The focal plane array is operative to take this image generate it as a photograph, image on an LCD display, or otherwise represent it on a human-viewable medium.

[0043] The following examples are intended to illustrate the various aspects of the present invention and are not intended to limit the scope of the invention.

EXAMPLE 1

[0044] An aluminum panel coated with Military Grade Epoxy Primer, MIL-P-23377TY1 and Military Grade Polyurethane Top Coat, MIL-PRF-85285 TYI having a total thickness of approximately 2.1 to 3.3 mils (0.0021 to 0.0033 thousands of an inch) was imaged with a standard mid-wave Merlin™ IR Camera with the standard of detection limits of the focal plane in the mid-wave. The panel was illuminated with IR radiation. A filter comprising multiple filters having an adjustable bandwidth was used to produce images at settings of 3-5 micrometers, 3.5-5 micrometers, and 3.75-5 micrometers. During the imaging process, the panel was held at room temperature or approximately 70 to 75° F. **FIG. 5** shows the results with the 3-5 micrometer filter; **FIG. 6** shows the results with the 3.5-5 micrometer filter; and **FIG. 7** shows the results with the 3.75-5 micrometer filter. The figures show the improved effect of glare removal. **FIG. 5** shows the baseline image produced by the standard mid-wave Merlin™ IR Camera. This image has significantly increased brightness compared to the other images. The brightness is due in part to the reflection off the coating surface. This reflection is cut back by the moving the filter window from 3.0 to 3.5 microns, as shown in **FIG. 6**. Additionally moving the filter window up to 3.75 microns significantly enhances the window, as more glare is removed. The filter windows should be optimized not only for the camera and focal plane, but also for the IR transmission window of the coating. This process may be repeated until the IR energy reduction from the glare does not warrant any more glare removal from the image of the camera.

EXAMPLE 2

[0045] Example 1 was repeated, except the aluminum panel was coated with two coats of Military Grade Epoxy Primer, MIL-PRF-23377TYI and two coats of Military Grade Polyurethane Top Coat, MIL-PRF-85285TYI having a total approximate thickness of 4.2 to 6.6 mils (0.0046 to 0.0066 thousands of an inch). **FIG. 8** shows the results with the 3-5 micrometer filter; **FIG. 9** shows the results with the 3.5-5 micrometer filter; and **FIG. 10** shows the significantly improved results with the 3.75-5 micrometer filter.

[0046] **FIGS. 5-10** illustrate the improved contrast that can be seen after the incorporation of the narrow bandwidth filter of the present invention. In addition to self-illumination and IR-illumination techniques, the present narrow bandwidth filter is also applicable to active thermography to improve contrast and fidelity of images produced from the flash lamp process. The images produced by active thermography can also be of the reflectance mode or images produced from the thermographic cooling mode, as a function of time.

[0047] Whereas particular embodiments of this invention have been described above for purposes of illustration, it will be evident to those skilled in the art that numerous variations of the details of the present invention may be made without departing from the invention as defined in the appended claims.

1. A system for imaging the surface of a substrate through a coating on the substrate, comprising:

a detector positioned to receive infrared radiation from the substrate surface; and

at least one narrow bandwidth spectral optical filter between the substrate and the detector to pass infrared wavelengths from 3.75 to 5.0 micrometers to the detector.

2. The system of claim 1, wherein the infrared radiation from the substrate comprises blackbody radiation from the substrate.

3. The system of claim 1, wherein the infrared radiation from the substrate comprises reflected infrared radiation from the substrate.

4. The system of claim 1, further comprising a source of infrared radiation illuminating the substrate.

5. The system of claim 1, wherein the detector comprises an infrared camera.

6. The system of claim 6, wherein the infrared camera detects mid-infrared radiation having wavelengths between about 3 and about 5 microns.

7. The system of claim 1, wherein the structural features comprise defects.

8. The system of claim 1, wherein the object comprises an aircraft component.

9. The system of claim 1, wherein the coating has a thickness of 0.5 to 12 mils.

10. The system of claim 1, wherein the coating comprises paint, a composite matrix material, primer, top coat and/or intermediate coatings.

11. The system of claim 1, further comprising means for displaying an image of the object including the detected structural features.

12. The system of claim 1, further comprising means for comparing an image of the object including the detected structural features with a reference image.

13. The method of claim 12, wherein the reference image is generated from another object similar to the coated object that is substantially free of defects.

14. The system of claim 1, further comprising means for comparing an image of the object where the filter may be selected to maximize signal-to-noise ratio and contrast between reflective surfaces through a coating.

15. A method for imaging the surface of a substrate through a coating on the substrate, comprising:

generating infrared light from the substrate;

filtering the infrared light with a narrow bandwidth filter which passes wavelengths within a range of from 3.75 to 5.0 micrometers; and

receiving the filtered infrared light on a detector.

16. The method of claim 15, wherein the infrared radiation from the substrate comprises blackbody radiation from the substrate.

17. The method of claim 15, wherein the infrared radiation from the substrate comprises reflected infrared radiation from the substrate.

18. The method of claim 15, further comprising illuminating the substrate with infrared radiation.

19. The method of claim 15, wherein the coating has a thickness not to exceed 12 mils.

20. The method of claim 15, further comprising generating at least one image from the detector so as to visually reveal structural features of the substrate.

22. The device as claimed in claim 19, wherein the waveguide comprises two waveguide parts which enclose the component when said two waveguide parts are assembled.

23. The device as claimed in claim 19, comprising a static magnet whose field line inside the waveguide are oriented in the z direction.

24. The device as claimed in claim 19, wherein the waveguide comprises two waveguide parts which enclose the component when when said two waveguide parts are assembled and the magnetic field line are guided via the sides of one of the two waveguide parts into the adhesive joint.

* * * * *

US007193215B2

(12) **United States Patent**
DiMarzio et al.

(10) **Patent No.: US 7,193,215 B2**
(45) **Date of Patent: Mar. 20, 2007**

(54) **SYSTEM AND METHOD FOR IMAGING OF COATED SUBSTRATES**

(75) Inventors: **Don DiMarzio**, Northport, NY (US); **Robert Silberstein**, New York, NY (US); **John Weir**, Huntington, NY (US)

(73) Assignee: **Northrop Grumman Corporation**, Los Angeles, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **11/211,304**

(22) Filed: **Aug. 25, 2005**

(65) **Prior Publication Data**

US 2007/0012877 A1 Jan. 18, 2007

Related U.S. Application Data

(63) Continuation of application No. 10/213,599, filed on Aug. 6, 2002, now abandoned.

(51) **Int. Cl.**
G01N 21/35 (2006.01)

(52) **U.S. Cl.** **250/341.8**; 250/339.11

(58) **Field of Classification Search** 250/341.8, 250/339.03, 358.1

See application file for complete search history.

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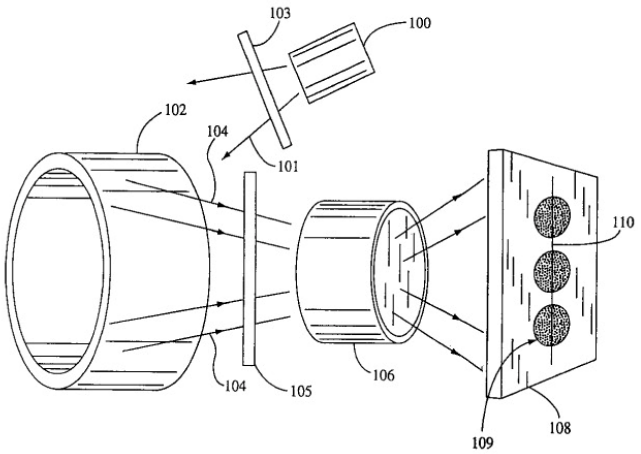
Primary Examiner—Otilia Gabor
(74) *Attorney, Agent, or Firm*—Stetina Brunda Garred & Brucker

(57) **ABSTRACT**

The present invention relates to a system for imaging the surface of a substrate through a coating on the substrate. The system includes an infrared light source positioned to cast an infrared light upon the substrate to thereby create reflected light. A focal plane array may be positioned to receive the reflected light and generate an image therefrom. At least one optical filter may be disposed between the substrate and the focal plane array so as to pass only coating transparent wavelengths of the reflected light along an optical path between the infrared light source and the focal plane array thereby visually revealing irregular structural features of the substrate as at least one image.

31 Claims, 4 Drawing Sheets
(2 of 4 Drawing Sheet(s) Filed in Color)



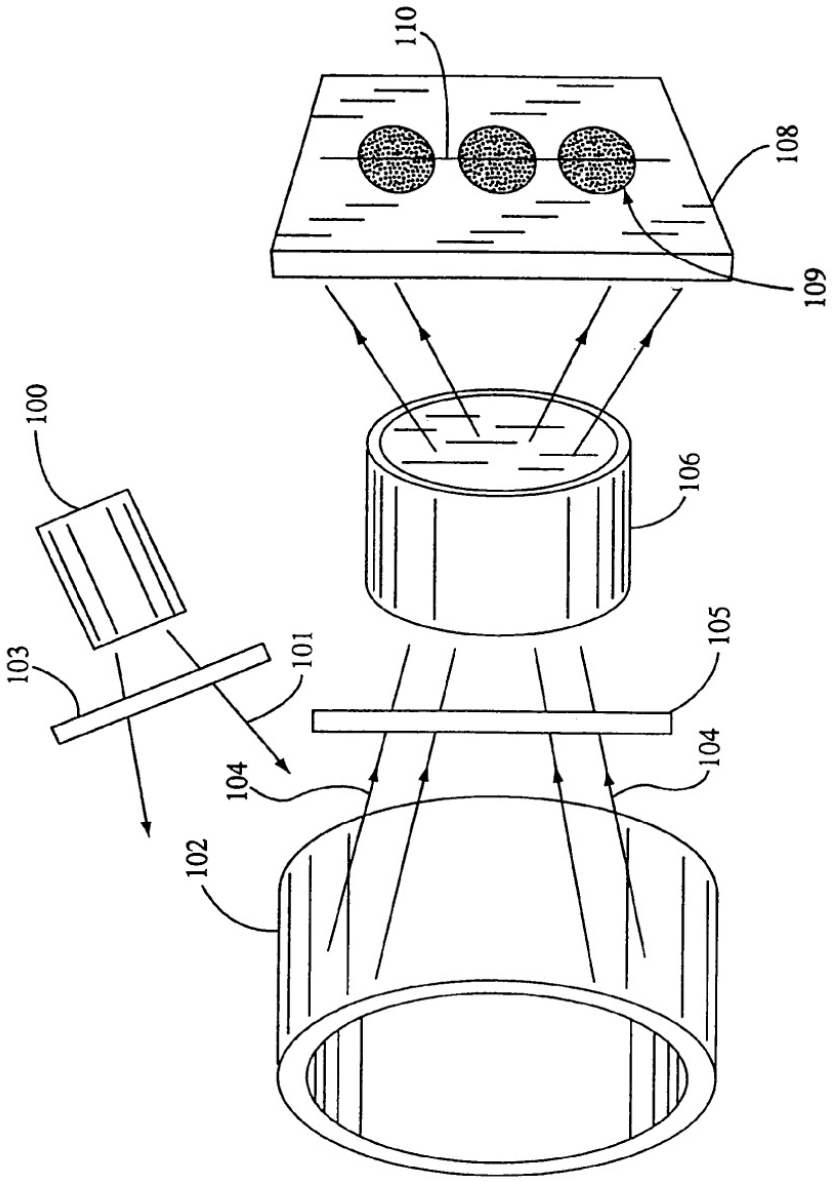


Fig. 1

Corrosion Under Paint

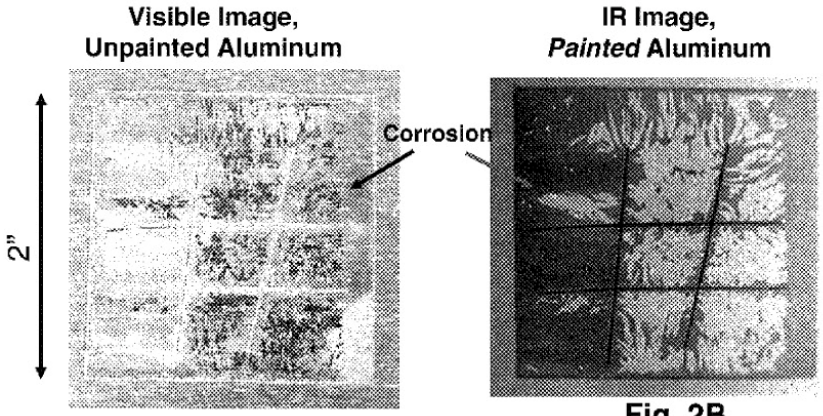


Fig. 2A

Fig. 2B

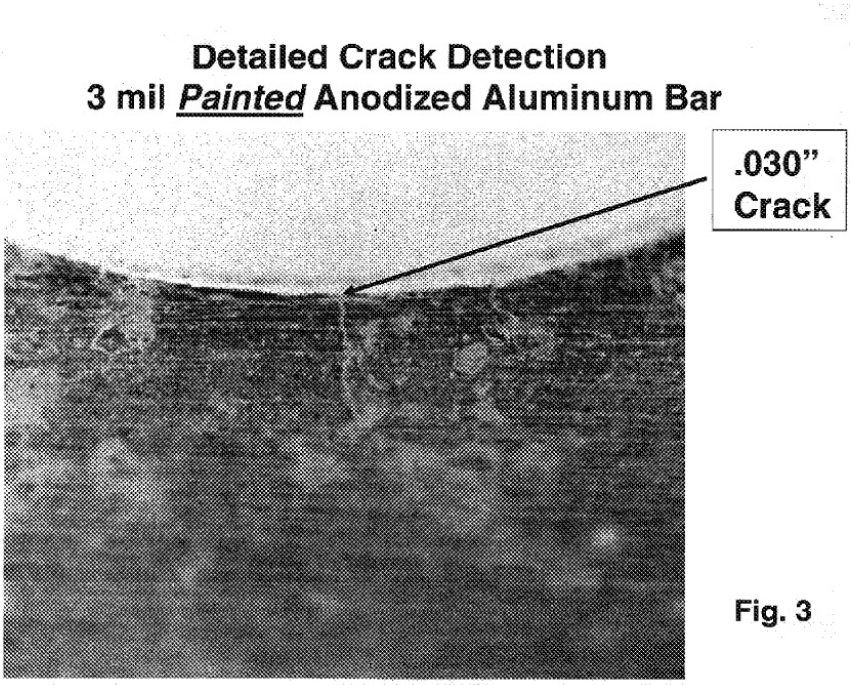

Detailed Crack Detection
3 mil Painted Anodized Aluminum Bar
.030"
Crack

Fig. 3

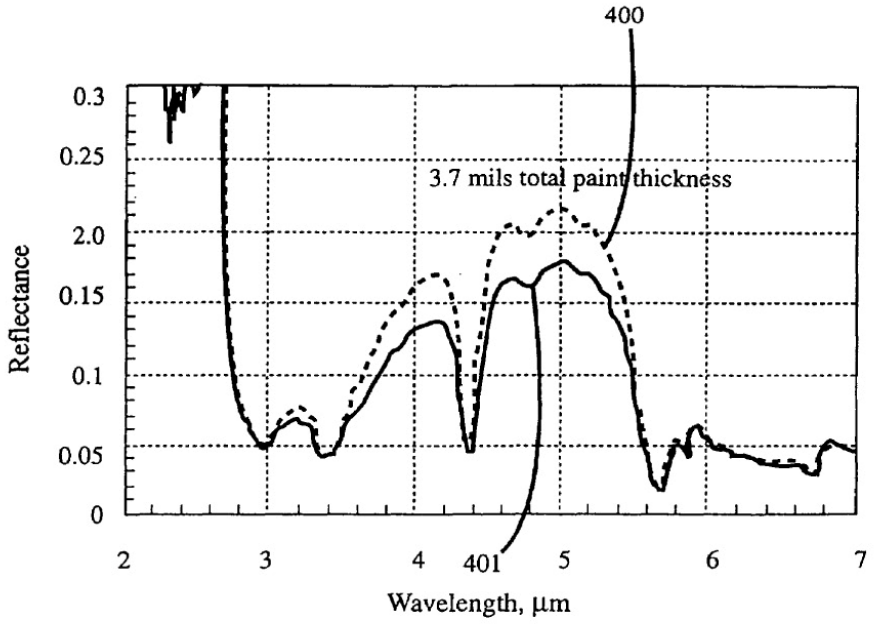

400
0.3
0.25
2.0
0.15
0.1
0.05
0
Reflectance
3.7 mils total paint thickness
2
3
4
401
5
6
7
Wavelength, µm

Fig. 4

SYSTEM AND METHOD FOR IMAGING OF COATED SUBSTRATES

CROSS-REFERENCE TO RELATED APPLICATIONS

The application is a continuation of U.S. patent application Ser. No. 10/213,599, filed Aug. 6, 2002 now abandoned.

STATEMENT RE: FEDERALLY SPONSORED RESEARCH/DEVELOPMENT

The U.S. Government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license to others on reasonable terms as provided for by the terms of Contract No. DACA 72-99-C-0011 awarded by SERDP.

BACKGROUND

The present invention relates generally to analysis of substrates which are coated, and more particularly to a system and method for imaging the surface of a substrate which is coated through the coating for the purposes of detecting rust, pitting, corrosion, cracks, scratches, gouges, and other structural imperfections.

Aircraft components are subject to constant degradation caused by environmental conditions. Various agents including moisture, dust, wind, solar radiation, and air pollutants cause damage to components in the form of rust or corrosion. Although the application of a coating, such as paint, reduces these problems substantially, it typically cannot eliminate them entirely. Moreover, other causes such as stress experienced during flight can result in damage which a coating of paint cannot mitigate, such as stress defects and cracking. While the occurrence of these forms of damage is to be expected, the particular rate at which any given aircraft's components degrade is highly dependent upon the particular environment of the aircraft and the circumstances under which it operates. This is readily apparent at aircraft maintenance depots, where maintenance personnel sometimes have the opportunity to view two aircraft of similar make and age. In many instances, the need for repair or replacement of components is much greater for one such aircraft than for the other. It is therefore impractical to rely upon projected maintenance schedules in determining when an aircraft will need repair. The only effective way to ensure that aircraft are ready for flight is through periodic inspection.

Using traditional methods, inspection of aircraft components is accomplished by means of visual inspection. When visually inspecting aircraft components, the coating used to protect the components becomes an obstacle because it may hide structural defects beneath. It is therefore necessary to strip the component assembly or aircraft in question of its paint before a proper inspection can be performed. Afterward, a new coating of paint must be applied. Obviously, this process results in substantial expense in the form of labor and materials, and likewise requires a great amount of time. It has been estimated that an aircraft spends twelve percent of its life in some form of maintenance or inspection, and billions of dollars are spent on aircraft maintenance every year. Apart from the inefficiency of visual inspection methods, another problem is the fact that visual inspection is simply not as effective as might be desired. While a skillful eye may pick up most human-visible defects with a satisfactory degree of consistency, some defects may be very

small or lie under the surface of the component. In many cases these defects will go unnoticed by the naked human eye, regardless of the skill and experience of the observer. It is therefore desirable to devise a method for analyzing damage to aircraft components without the need to strip paint from the component or rely upon the human eye alone. Some inventions offer insight into how this problem might be solved.

One such invention is described in U.S. Pat. No. 5,426,506 entitled OPTICAL METHOD AND APPARATUS FOR DETECTION OF SURFACE AND NEAR-SUBSURFACE DEFECTS IN DENSE CERAMICS issued to Ellingson, et al. The invention described therein employs a laser of a wavelength calculated to penetrate the surface of an object to be analyzed. The laser is passed through a polarizer before being reflected by the object, and through a second polarizer afterward. When striking the object, that portion of light which strikes irregularities is reflected at an altered polarity, while the portion which strikes regular features is reflected at its original polarity. The second polarizer is configured to detect this difference, and the system generates an image reflecting it. In order to generate an image of an area, the object to be analyzed is secured to a mount capable of translation and/or rotation and controlled by a computer or similar device. The object is moved about under the laser beam, to thereby be scanned. The most obvious disadvantage of this system is that in order to perform area analysis, a motorized mount typically must be used. This appears to preclude the possibility of a hand-held unit, and the system would be highly impractical when applied to components or assemblies already mounted on aircraft. Another obvious disadvantage is the method is not used to see surfaces under organic coatings and the wavelength of the laser light will not penetrate coatings or polymers.

A second related invention is disclosed in U.S. Pat. No. 4,682,222 entitled STIMULATED SCANNING INFRARED SYSTEM issued to Smith et al. The invention uses a collimated energy beam, such as a laser, to heat an object to be analyzed. Because objects radiate infrared light when they are warm, an infrared detector can then be used to detect the heat of areas of the object relative to each other. For instance, because areas which are cracked will heat at a different rate than other areas, they can thereby be distinguished. The obvious disadvantage of this system is that the object to be scanned must be heated. For various reasons, methods involving heating the object to be analyzed are not ideal. For instance, a thermal shielding component of an aircraft with a coating of paint would pose a particular problem for this system. The component is specifically designed to be difficult to heat, and any source powerful enough to heat the component would likely damage the coating of paint. This patent additionally utilizes a technique of thermography which does not relate to IR imaging of substrate surfaces under organic coatings.

Still another related invention is disclosed in U.S. Pat. No. 6,184,528 entitled METHOD OF SPECTRAL NONDESTRUCTIVE EVALUATION issued to DiMarzio, et al. The invention disclosed therein employs an infrared light source, such as an infrared laser, to cast infrared light upon a substrate. Reflected light is measured as a function of wavelength to obtain reflectivity data. The reflectivity data of the sample substrate is compared to reflectivity data of a control substrate. Correlations are then drawn between differences in order to determine the presence of corrosion. This invention achieves some of the objectives of the present invention, but will not detect the full range of structural

features detectable by the present invention and does not provide a visual image of the substrate.

It is therefore desirable to devise a system and method for analyzing substrates free of the aforementioned drawbacks and, further, improving upon previous systems in terms of effectiveness and resolution.

BRIEF SUMMARY OF THE INVENTION

In accordance with the present invention, there is provided a system for imaging the surface of a substrate through a coating on the substrate. Coatings typically found on substrates are designed to be opaque in the visible range of the spectrum, and are often more transparent in the infrared area of the spectrum. An infrared light source may be positioned to cast infrared light upon the substrate to thereby create reflected light. A focal plane array may be positioned so as to receive the reflected light and generate an image therefrom. At least one spectral optical filter may be disposed between the substrate and the focal plane array so as to pass only coating transparent wavelengths of the reflected light along an optical path between the infrared light source and the focal plane array thereby visually revealing structural features of the substrate as at least one image. A multiplicity of optical filters disposed between the substrate and the focal plane array may be employed which are operative to generate images in a plurality of selected wavelengths for imaging structural features of the substrate. A multiple imaging device may be placed into communication with the focal plane array for simultaneously imaging a plurality of structural features of the substrate.

Further, a computer may be employed which is combining and enhancing images generated by the system to thereby generate collective images of selected structural features of the substrate. A computer programmed with substrate patterns for color-coding selected structural features of the substrate within the image based on the substrate patterns may be provided so as to provide visual categorization of the structural features. Additionally, a position sensor may be employed to mark reference points on the surface of the substrate so as to store coordinates of structural features of the substrate. A computer formed to compare images generated at selected wavelengths in a feedback loop may be provided so as to automatically enhance image quality of irregular selected structural features of the substrate based upon preselected enhancement criteria. Advantageously, the infrared light source, the focal plane array and the at least one optical filter may be collectively formed with a hand-held device so as to be transportable by as single human operator.

The system may also include a first polarizer disposed between the infrared light source and the substrate for polarizing the infrared light to a first selected polarity. Additionally, a second polarizer may be disposed between the substrate and the focal plane array for polarizing the reflected light to a second selected polarity. The first selected polarity and the second selected polarity may be oppositely configured so as to prevent reflected light corresponding to regular features of the substrate from being received upon the focal plane array. The polarities of the first and second polarizers may be rotatable so as to selectably provide a plurality of polarities for imaging irregular structural features from the substrate.

In use, there is also provided a method for imaging the surface of a substrate through a coating on the substrate. The method includes directing infrared light upon the substrate. The infrared light may be reflected from the substrate to thereby create reflected light. Only coating transparent wavelengths of the reflected light may be filtered. The reflected light may be received on a focal plane array and an image may be generated from the focal plane array so as to visually reveal irregular structural features of the substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

The patent or application file contains at least one drawing executed in color. Copies of this patent with color drawing(s) will be provided by the Patent and Trademark Office upon request and payment of necessary fee.

FIG. **1** illustrates an embodiment of the system and method of the present inventions

FIG. **2**A is a visible image of an unpainted selectively corroded aluminum substrate on a chemical film treated (Ref. Mil-c-5541) aluminum coupon;

FIG. **2**B is an IR image of the same aluminum coupon as shown in FIG. **2**A. However, in this case the substrate or aluminum coupon has been tested with 0.006" (6 mils) of primer and top coat. The corrosiveness was made visible under the coating by means of the system and method of the present invention;

FIG. **3** is an IR Image taken of a fatigue crack on a hole radius and made visible under a coating by means of the system and method of the present invention; and

FIG. **4** illustrates the reflectivity principles behind the present invention in the form of a graph illustrating sample plots of reflectance versus wavelength for aluminum components.

DETAILED DESCRIPTION

Referring now to the drawings wherein the showings are for purposes of illustrating embodiments of the present invention only, and not for purposes of limiting the same, FIG. **1** illustrates an embodiment of the system and method of the present invention. An infrared light source **100** is used to cast infrared light **101** in the direction of a substrate **102** which is coated. In an embodiment of the invention, prior to reaching the substrate **102**, the infrared light **101** may pass through a first polarizer **103**. The first polarizer **103** is operative to polarize the infrared light to a first selected polarity.

Light reflected by the substrate creates reflected light **104**. In an embodiment, the reflected light **104** passes through a second polarizer **105**. The second polarizer **105** is operative to polarize the reflected light to a second selected polarity. For instance, the second polarizer **105** may be configured to polarize the reflected light **104** in a direction opposite to that of first selected direction, a method known as "cross-polarity." In this case, light of the polarity modulated by the first polarizer **103** will not pass through the second polarizer **105**. According to basic principles of optics, the portion of the reflected light **104** which was reflected off of regular areas of the substrate **102** will retain the polarity modulated by the first polarizer **103** and therefore will not pass through the second polarizer **105**. However, the portion of the reflected light **104** which was reflected off of irregular areas, such as corrosion or rust, will have an altered polarity and will therefore pass through the second polarizer **105**. Additionally, this polarization technique can reduce scattering by pigments in the coating which results in a clearer image of the substrate. Thus, only the portion of the reflected light **104** which was reflected off of irregular areas of the substrate **102** will pass through the second polarizer **105**. The first polar-

izer **103** and second polarizer **105** may therefore operate in tandem to highlight the areas of the substrate **102** which are irregular because they are corroded or otherwise damaged. Additionally, the polarity modulated by the first polarizer **103** may be configured to allow viewing of the substrate **102** at various levels. This is because light of a polarity parallel to the substrate **102** will more easily reflect off of the coating, while light of a polarity perpendicular to the substrate **102** will more easily penetrate through the coating to the substrate beneath. Accordingly, it is possible to focus on either the surface of the substrate itself or on the surface of the coating. Of course, this methodology may be combined with the cross-polarity method described above in order to enhance particular features of the substrate at a particular level. It should be noted that although the first polarizer **103** and second polarizer **105** may be used in the fashion described and are therefore present in a potentially preferred embodiment, they are not necessary to the function of the present invention, and need not be included.

Subsequent to passing through the second polarizer **105** (if present), the reflected light **104** passes through an optical filter **106**. The optical filter **106** is operative to filter out all except selected wavelengths of the reflected light **104**. Coatings used on, for instance, aircraft components and assemblies are generally designed to be opaque in the visible range of light. Often, they are more transparent in the infrared range of light. Accordingly, certain wavelengths of light are more likely to pass through the coating to be reflected by the substrate beneath. The image created by the portion of the reflected light **104** having these wavelengths will represent an image primarily of the substrate **102** instead of the coating on the substrate. It is therefore desirable to focus on these wavelengths to the exclusion of others, and they become the selected wavelengths passed by the optical filter **106**. The optical filter **106** need not be a single filter, but could be a series of filters.

Subsequent to passing through the second polarizer **105** (if present) and optical filter **106**, the reflected light **104** reaches a focal plane **108**. A focal plane array (not shown) is positioned at a focal plane **108** for the purpose of receiving an image **109** created by the reflected light **104** at the focal plane **108**. Structural features of the substrate **102**, such as cracks **110** are visible in this image **109**. The focal plane array is operative to take this image **109** and generate it as a photograph, image on an LCD display, or otherwise represent it on a human-viewable medium.

FIGS. **2**A, **2**B, and **3** demonstrate the effectiveness of the system and method of the present invention. FIG. **2**A is a visible image of an unpainted substrate, in this case a chemical film treated (Ref mil-c-5541) aluminum coupon. The structural features of the substrate are visible to the human eye. FIG. **2**B is an image of the same Alodined aluminum coupon. However, in this case the substrate has been coated with a 0.006" thickness (6 mils) of primer and a top coat. The structural features of the substrate are only visible because this image was generated using the system and method of the present invention. FIG. **3** is an image of a fastener hole, with a crack in it made visible by means of the system and method of the present invention. Experiments proved detectability of cracks as small as 0.030" in length and pits as small as 0.001" in diameter.

FIG. **4** illustrates the reflectivity principles behind the present invention in the form of a graph illustrating sample plots of reflectance versus wavelength for aluminum components. The first plot **400** is for an uncorroded aluminum component with a layer of primer and paint having a total thickness of 0.0037" (3.7 mils). The second plot **401** is for a corroded aluminum component with the same layer of paint and primer. By comparing the plots **400** and **401** a difference will be seen between the two plots **400** and **401** in the area between approximately a wave length of 3.5 microns (higher reflectance) and a wave length of 5.5 microns, with a dip at approximately a wave length of 4.4 microns. The first plot **400** is stronger than the second plot **401** because the uncorroded aluminum reflects a higher portion of the infrared light passing through the paint than the corroded aluminum does.

The above describes a basic implementation of the present invention. The invention may take a variety of embodiments designed to provide additional features. For instance, dependent upon the coating used on the substrate or upon the particular structural features in which an operator has interest, it may be expedient to view the substrate in a variety of wavelengths. The system may therefore include a multiplicity of optical filters which may be manually or automatically changeable in order to accomplish this objective. Likewise, the polarity of the polarizers may be rotatable in order to provide imaging of the substrate in a variety of combinations of polarities. As an additional modification, the provision of imaging at a variety of wavelengths and/or combinations of polarities could be accomplished by means of a multiple imaging device. This would allow the system to create a plurality of images simultaneously for rapid processing. In this respect, the multiple imaging device could process and generate images at several different wavelengths and polarities.

Following the above line of additions, the system could include a computer for processing the images provided by the system in order to provide improved images of selected irregular structural features of the substrate. As will be recognized by those in the art, a given structural feature of the substrate will be more readily observable in certain wavelengths and/or combinations of polarities than in others. The computer could contain a database of information with respect to which combinations were effective for viewing, for instance, corrosion. The operator would then simply indicate to the computer that he desired to view corrosion, and the computer would automatically select the combination or combinations appropriate to so doing. Additionally, images or signal taken in the IR from the surface or internal to the coating may be substrated out as background signals to enhance images taken on the substrate to be inspected for an improved composite image of the substrate surface.

The computer could additionally be programmed to recognize selected structural features of the substrate. As will be apparent to those in the art, this can be accomplished by means of software operative to search for substrate patterns. Such substrate patterns may include specific corrosion characteristics, extrusions and inclusions of the surface and other characteristics which indicates that the substrate is damaged in some manner. Once identified, the features could be labeled for the user. For instance, the computer could provide color-coded images of the substrate. The color-coding could operate as a function of feature type or level of structural integrity. In the former case, the computer could assign, for instance, red to corrosion and black to cracking. In the later case, the computer could assign, for instance, red to undamaged portions of the substrate, yellow to moderately damaged portions of the substrate, and blue to seriously damaged portions of the substrate. In any event, the computer operates to perform a preliminary analysis which may be useful to the operator.

The system could incorporate an automatic feedback loop driven by hardware or software, operative to rapidly find the

best combinations of wavelengths and/or polarities for viewing the substrate, or selected structural features of the substrate. The computer would experiment with various combinations and use the above mentioned identification techniques in order to determine which combinations were working most effectively. It could then rapidly determine which combination or combinations were most appropriate for the task at hand, and automatically employ those combinations.

Furthermore, the system could comprise an automatic pointer device operative to generate an alarm or automatic notification when selected structural features are observed. This could take the form of software operative to impose a crosshair on the image or software or hardware operative to automatically zoom on selected structural features of the image, for instance. The latter would be highly useful in applications where it is necessary to analyze large objects for potentially subtle signs of damage. The operator could move the view of the system over the object and, when the system detected a defect of below a preset visibility threshold, it would automatically zoom in on the defect in question to ensure identification of the defect.

In further keeping with the above line of improvements, a position sensor could be included in order to store coordinates on the substrate for future reference. The coordinates could be identified, for instance, with respect to a reference point on the substrate. In this example, the position sensor could record the coordinates of the system on the substrate as a function of distance to and direction from the reference point. Marking by the position sensor could be accomplished automatically by a computer, or could be performable by the operator.

Still a further embodiment of the invention would provide a communications device, such as a communications port or transmitter, operative to put the system in communication with an external device or network. Including a communications device could enhance the usefulness of the system in many ways. For instance, an external computer could contain a database of coatings available on the market. In order to inspect the substrate, the operator would first identify its coating and send a query to the external computer. The external computer could then provide the system with information as to which combination of wavelengths and/or polarities was appropriate in order to effectively view the substrate. A further improvement would use the system's own imaging system to automatically assess features of the coating and send values with respect to these features to the external computer. The external computer could compare these values to values in its own database and identify the coating itself before sending the relevant data. This would eliminate the need of the operator to identify the coating in question.

Another use of communications capability would be to allow an operator to call up remotely stored control images. The control images could be either images of an undamaged substrate of the same design or the same substrate at an earlier time. The control image could be displayed on the same screen as the image then being generated in order to allow convenient comparison by the operator. The generated image could additionally be compared to the control image by hardware or software operative to identify discrepancies, in order to further clarify which structural features of the substrate were irregular. This latter method would be particularly helpful in situations in which the substrate has, in its undamaged form, peculiar features which may otherwise appear to be damage. The computer could use the control image as a mask to eliminate all structural features expected to be in the substrate in order to ensure that physically irregular but appropriate features were not identified as damage.

It will additionally be apparent to those in the art that the images generated by use of the system and method of the present invention may be further operated upon in order to provide additional information. For instance, a database could be established for the purpose of storing images taken of a given substrate over time. The images so stored could be compared, for instance by a computer, in order to assess the rate at which damage was occurring to the substrate. The approximate time at which the substrate would become unsuitable for use could therefore be extrapolated, and projected repair and maintenance schedules developed.

Still a further embodiment of the invention would use the infrared light source to cause the substrate to emit light. This could be more easily accomplished if the infrared light source were a laser. Certain structural features of the substrate will have different chemical compositions than the undamaged portion of the substrate. They will therefore emit light of different wavelengths than the undamaged portion of the substrate. The system could therefore be configured to view, for instance, corrosion by means of selecting the selected wavelengths with respect to the wavelength of light emitted by corrosion on the substrate. A filtered IR light source (spectral/polarized) could also be used in the embodiment as just described.

Obviously, any of the above described features could be combined. For instance, the aforementioned damage-over-time analysis method described would be particularly useful in combination with a position sensor as described further above. Additionally, while the present invention has been described in connection with inspection of substrates for damage, it is understood that the invention may be employed in a variety of applications. For instance, the present invention could be used to read serial codes or other identifying marks on substrates.

Additional modifications and improvements of the present invention may also be apparent to those of ordinary skill in the art. Thus, the particular combination of elements described and illustrated herein is intended to represent only certain embodiments of the present invention, and is not intended to serve a limitation on systems and methods within the spirit and scope of the invention.

What is claimed is:

1. A system for imaging the surface of a substrate through a coating on the substrate, comprising:

a) an infrared light source positioned to cast infrared light upon the substrate to thereby create reflected light;

b) a focal plane array positioned to receive the reflected light off the substrate surface and generating an image therefrom; and

c) at least one spectral optical filter disposed between the substrate and the focal plane array so as to pass only coating transparent wavelengths of the reflected light along an optical path between the infrared light source and the focal plane array thereby visually revealing structural features of the substrate as at least one image.

2. The system of claim **1**, further comprising a multiplicity of optical filters disposed between the substrate and the focal plane array for generating images a plurality of selected wavelengths and for imaging structural features of the substrate.

3. The system of claim **1**, further comprising a multiple imaging device in communication with the focal plane array for simultaneously imaging a plurality of structural features of the substrate.

4. The system of claim **1**, further comprising a computer combining and enhancing images generated by the system to thereby generate collective images of selected structural features of the substrate.

5. The system of claim **1**, further comprising a computer programmed with substrate patterns for color-coding selected structural features of the substrate within the image based on the substrate patterns so as to provide visual categorization of the structural features.

6. The system of claim **1**, further comprising a position sensor for marking reference points on the surface of the substrate so as to store coordinates of structural features on the substrate.

7. The system of claim **1**, further comprising a computer comparing images generated at selected wavelengths in a feedback loop so as to automatically enhance image quality of selected structural features of the substrate based upon preselected enhancement criteria.

8. The system of claim **1**, where in the light source, the focal plane array and the at least one optical filters are collectively formed within a hand-held device transportable by a single human operator.

9. The system of claim **1**, further comprising:

a) a first polarizer disposed between the infrared light source and the substrate for polarizing the infrared light to a first selected polarity; and

b) a second polarizer disposed between the substrate and the focal plane array for polarizing the reflected light to a second selected polarity.

10. The system of claim **9**, wherein the first selected polarity and second selected polarity are oppositely configured so as to prevent reflected light corresponding to selected structural features of the substrate from being received upon the focal plane array.

11. The system of claim **9**, further comprising a multiplicity of optical filters providing imaging at a plurality of selected wavelengths so as to form an image of a plurality of structure features from the substrate.

12. The system of claim **9**, wherein the polarities of the first and second polarizers are rotatable so as to selectably provide a plurality of polarities for imaging structural features from the substrate.

13. The system of claim **9**, further comprising a multiple imaging device in communication with the focal plane array for simultaneously imaging a plurality of structural features of the substrate.

14. The system of claim **9**, further comprising a computer combining and enhancing images generated by the system to thereby generate collective images of selected structural features of the substrate.

15. The system of claim **9**, further comprising a computer programmed with substrate patterns for color-coding selected structural features of the substrate within the image based on the substrate patterns so as to provide visual categorization of the irregular structure features.

16. The system of claim **9**, further comprising a position sensor for making reference points on the surface of the substrate so as to store coordinates of structure features of the substrate.

17. The system of claim **9**, further comprising a computer comparing images generated at a plurality of selected wavelengths and selected polarities in a feedback loop so as to automatically enhancing the image quality of selected structural features of the substrate based upon selected criteria.

18. The system of claim **9**, wherein the infrared light source, the focal plane array and the at least one optical filter are collectively formed within a hand-held device transportable by a single human operator.

19. The system of claim **1**, further comprising a communication device for transferring the revealed structure features to a remote human viewable medium.

20. The system of claim **1**, further comprising a communication device for transferring the revealed structure features to a database.

21. The system of claim **1**, further comprising a communication device for transferring the revealed structural features to a database.

22. A method of imaging the surface of a substrate through a coating on the substrate, comprising:

a) directing infrared light upon the substrate;

b) reflecting the infrared light from the substrate to thereby create reflected light;

c) filtering to pass only coating transparent wavelengths of the reflected light;

d) receiving the filtered reflected light on a focal plane array; and

e) generating at least one image from the focal plane array so as to visually reveal structural features of the substrate.

23. The method of claim **22**, further comprising comparing a plurality of images generated upon the focal plane array as a function of time to thereby establish a rate of degradation for the substrate.

24. The method of claim **22**, further comprising selecting the coating transparent wavelengths from a database storing reflectivity characteristics of coatings found on substrate.

25. The method of claim **22**, further comprising comparing the generated images with a pre-selected control image to thereby identify irregular structural features of the substrate.

26. The method of claim **22**, further comprising:

a) directing the infrared light through a first polarizer before the infrared light reaches the substrate so as to polarize the infrared light to a first selected polarity; and

b) directing the reflected light through a second polarizer before the infrared light reaches the focal plane array so as to polarize the reflected to a second polarity.

27. The method of claim **26**, wherein the first selected polarity and the second polarity are oppositely features of the substrate from being received upon the focal plane.

28. The method of claim **26**, further comprising comparing a plurality of images generated upon the focal plane array as a function of time to thereby establish a rate of degradation for the substrate.

29. The method of claim **26**, further comprising selecting the selected wavelengths and first and second selected polarities from a database storing reflectivity and characteristics of coatings found on substrates.

30. The method of claim **26**, further comprising comparing the generated images with a pre-selected control image to thereby identify irregular structural features of the substrate.

31. The method of claim **22**, further comprising transferring the generated images to a remote human viewable medium.

* * * * *

APPENDIX J NDI CERTIFICATION

NON-DESTRUCTIVE INSPECTION (NDI)

1. General

a. Ensure each trainee has a current work record that documents the method(s) in which they are receiving training. Daily entries are required unless the work is repetitive in nature. When work is of a repetitive nature, one entry per week is sufficient.

b. Certification/re-certification for levels I, II and III shall be IAW references (a), (t) and (u) and the American Society for Non-Destructive Testing (ASNT) for the following: liquid penetrant (LT), magnetic particle (MT), eddy current (ET), ultrasonic (UT), radiography (RT) temper etch (TE) and infrared (IR) inspection methods recommended practices.

2. Certification Requirements, Education, Training and Work Experience. Individuals considered for certification shall receive sufficient formal training to become proficient with principles and practices of the applicable test method IAW reference (v). The training program shall include instruction in introduction to defects in materials; basic NDI principles, products, equipment, operating procedures and test techniques encountered in a specific assignment; applicable local instruction, specifications and codes. The following are minimum requirements for training and experience:

a. Level I. Shall have sufficient training and indoctrination in the applicable method to have passed the applicable qualification exams IAW the following: classroom, general NDI work experience hours and OJT are the minimum requirements for level I certification.

METHOD	CLASSROOM	OJT IN METHOD	GENERAL NDI WORK IN EXPERIENCE ANY METHOD
PT	16 hours	130 hours	65 hours
MT	16 hours	65 hours	65 hours
ET	40hours	400 hours	65 hours
UT	40 hours	400 hours	200 hours
RT	40 hours	400 hours	200 hours
TE	4 hours	30 hours	130 hours
IR	4 hours	24 hours	130 hours

b. Level II. Individuals shall have completed the following total hours in training (including any level I training) for the applicable method and general NDI work experience:

METHOD	CLASSROOM Level I experience	CLASSROOM Direct access (Without Level I experience)	OJT IN METHOD Level I experience	GENERAL NDI WORK IN EXPERIENCE ANY METHOD (No level I cert)
PT	16 hours	32 hours	270 hours	400 hours
MT	16 hours	32 hours	400 hours	530 hours
ET	40 hours	80 hours	1200 hours	1600 hours
UT	40 hours	80 hours	1200 hours	1600 hours
RT	40 hours	80 hours	1200 hours	1600 hours
*TE	4 hours	8 hours	60 hours	400 hours
*IR	4 hours	8 hours	48 hours	400 hours

*Individuals must be certified in two other methods.

c. Level III

(1) Individuals shall have completed one of the following level II or equivalent work experience (non-current) in the applicable method and in conjunction with the level of education attained as shown in the below chart.

LEVEL II METHOD	METHOD (+) METHOD WITH NO COLLEGE DEGREE	METHOD (+) TECHNICAL ASSOCIATE'S DEGREE	MIN THREE YR WITH ACCREDITED SCI/ENGRG DEGREE
PT	4 years exp	2 years exp	1-year exp
MT	4 years exp	2 years exp	1-year exp
ET	4 years exp	2 years exp	1-year exp
UT	4 years exp	2 years exp	1-year exp
RT	4 years exp	2 years exp	1-year exp
TE	4 years exp	2 years exp	1-year exp
IR	4 years exp	2 years exp	1-year exp

(2) Level III candidates shall be examined and certified by ASNT. Exceptions to this requirement are when no ASNT certification for an NDI method exists. In those cases, local procedures will be developed.

d. NDI Instructor. Individuals must at a minimum meet one of the following criteria in order to be designated as an NDI instructor:

(1) Be certified to Level III in the method for which they will be designated instructors.

(2) Possess the equivalent of a Bachelor of Science (B.S.) degree in engineering, physical science, or

technology and have sufficient knowledge in the method for which they will be designated instructors.

(3) Possess an associate's degree in physical science or technology and have a minimum of five years' experience, or equivalent, as a level II in the method for which they will be designated instructors.

(4) Possess a minimum of 10 years' experience as a level II, or equivalent, in the method for which they will be designated instructors.

e. Candidates for NDI certification shall receive instruction in the following prior to being certified:

(1) Standardization and calibration.

(2) Operation of applicable test equipment.

(3) Specific test procedures.

(4) Interpretation/evaluation of test results.

(5) Safety.

(6) Applicable codes, specifications and standards.

f. Training Final Examinations. An individual must pass a final exam (minimum score of 70) in order to receive credit for a block of training hours. Such examinations given in conjunction with training shall not be used to satisfy any of the qualification examination requirements. This requirement is applicable to all training whether for initial qualification, remedial, or continuing education.

g. Previous Experience/Training. Previous experience or training at other facilities must be substantiated and verified in writing by the previous employer(s) and the individual tested to determine competence at previously certified levels within a given NDI method. As a minimum, individuals must pass the applicable written, practical and physical examinations.

(1) Certification Examinations. Exams to verify both physical and technical qualifications shall consist of physical, visual acuity, general, specific and practical exams. The examination questions for each level shall be representative of the knowledge and proficiency required. The candidate for certification must achieve a minimum grade of 70% on the general and specific qualification exams. They must detect all discontinuities or conditions specified by the level III during the practical exam and achieve a minimum score of 70% on the remainder of the practical exam. The candidate must have an overall average score of no less than 80% in order to be eligible for certification. All exam scores shall be of equal weight in determining the average score. Materials Engineering Division (code 4.9.7) may call for re-examination of NDI personnel and may recommend certification be revoked, or that personnel receive additional training and re-examination.

(2) Physical. Annual physical exams consist of radiation physicals IAW NAVAIRINST 5100.8A Radiological Affairs Support Program, urine testing, blood count, Prostate Specific Antigen (PSA), hearing and vision as directed by the attending physician. Exam required for re-certification.

(3) Visual Acuity. Yearly examination conducted to ensure natural or corrected vision meets the following minimum requirements:

(a) Near Vision. At least one eye, Jaegar 1 at not less than 12 inches.

(b) Color Perception. Must be capable of distinguishing and differentiating between colors used in the method(s) to be certified.

(4) General. This examination shall be closed book for all levels. It shall consist of questions covering the cross-section of the applicable method at the appropriate level. Questions, answers and references in the applicable supplement or other sources may be used in developing examinations. A minimum of 40 questions shall be used to test each level of certification. For level III, the general exam questions shall address general knowledge of other methods as well as the method for which certification is sought.

(5) Specific. This examination for all levels shall be closed book and cover the specifications, codes, equipment, operating procedures and test techniques the candidate may use in the performance of their duties. A minimum of 30 questions shall be used for the specific examination at each level.

(6) Practical. This examination shall consist of a demonstration of proficiency by the candidate in performing tasks that are typical of those to be accomplished in the performance of his/her duties. Test samples used in the examination may be actual hardware if the candidate is required to demonstrate proficiency in the application of the process and interpreting results or interpretation of images only. Written checklists covering the topics detailed below shall be developed by the level III to ensure adequate coverage and to assist in the administration and grading of the examination.

(a) Level I. Candidate shall demonstrate proficiency by using the appropriate method to examine at least one test sample for each technique to be used and document the results. Test samples shall represent products normally processed. Checklist shall address proficiency in the use of procedures and equipment or materials, adherence to procedural details, and the documentation of the results. If the candidate is to accept products, then the checklist shall also include proficiency in the interpretation and evaluation of indications.

(b) Level II. Candidate shall demonstrate proficiency by using the appropriate method to examine at least one test sample for each technique. Candidate shall interpret, evaluate, and document the results of the examinations of test samples. At least two test samples shall be evaluated for each method. Test samples shall be representative of the products normally processed. Checklist shall include proficiency in the use of the procedures and equipment or materials, adherence to procedural details, and the accuracy and completeness of interpretations and evaluation of indications.

(c) Level III. Candidate shall demonstrate proficiency by preparing an NDI procedure appropriate to employer's requirements. Candidates required to inspect or evaluate products shall demonstrate proficiency in performing such tasks. Checklist shall

address the practical and technical adequacy of the procedures prepared by the candidate and, when applicable, the adequacy of the interpretation and evaluation of indications. If the candidate has previously developed satisfactory procedures, it is not necessary to develop another one for the practical exam. The results of practical exams shall be documented. Procedures developed for a previous employer can be used to satisfy this requirement if their adequacy can be verified and documented.

3. Re-Certification Requirements

a. Level I and Level II Re-Certification Requirements

(1) Maintain certification currency.

(2) Pass annual physical and vision screening requirements.

(3) Pass general, specific and practical exams (test to be administered no sooner than 30 days prior to re-certification).

(4) Re-certify every five years.

(5) Complete the following number of continuing education (CE) hours prior to re-certification:

METHOD	REQUIRED CE HOURS
PT	4
MT	4
ET	8
UT	16
RT	16
TE	4
IR	4

(6) Continuing education hours may be completed any time during the five-year re-certification cycle. Continuing education curricula shall provide/ensure NDI certified personnel are provided timely and useful information relative to current NDI practices, procedures and equipment. Where possible, enhance the skills and abilities of NDI certified personnel, and to continually improve the process of NDI.

b. Level III Re-Certification Requirements

(1) Maintain certification currency for ASNT/local requirements.

(2) Re-certify every five years.

(3) Re-certify via ASNT or local requirements where no ASNT requirements exist.

(4) Pass annual vision screening requirements.

4. Procedures

a. Materials Engineering Division (code 4.9.7) NDI Program Manager

(1) Approve written and practical exams.

(2) Provide technical expertise.

(3) Provide signature authority for granting NDI certification.

(4) Maintain level III ASNT certifications.

(5) Provide engineering support as necessary, see reference (v).

b. Candidate's Supervisor

(1) Ensure NDI candidates complete all certification requirements.

(2) Request re-certification via memorandum to the Industrial Quality Management Division (code 6.4.1) NDI Certification Program Manager.

(3) Ensure NDI Work Records, NAVAIRDEPOTJAX 4855/65, are completed by NDI personnel and forwarded to the Common Industrial Programs Division (code 6.2.5).

(4) Ensure each trainee has a current work record.

(5) Ensure artisans perform/ document one job in each NDI method (Level I and Level II) every three months at a minimum to remain current.

c. Industrial Quality Management Division (code 6.4.1) NDI Certification Program Manager

(1) Review certification documentation for quality requirements.

(2) Sign applicable certification documentation.

(3) Maintain NDI Special Process Certification in TMS/EC+ database.

d. Common Industrial Programs Division (code 6.2.5) Non-Destructive Examination Shop (code 6.2.5.2.25) NDI Instructor

(1) Provide continuing education training and OJT for level I and level II certifications.

(2) Provide remedial training when the results of general, specific, or practical exams indicate the need for additional training or as required due to feedback.

(3) Administer and evaluate general, specific and practical exams.

(4) Revise (with the concurrence of the NDI Program Manager) general, specific and practical exams every five years.

(5) Maintain certification/re-certification records IAW reference (u).

APPENDIX K MID WAVE INFRARED INSPECTION OF CORROSION UNDER PAINTED AIRCRAFT COMPONENTS

MID WAVE INFRARED INSPECTION OF CORROSION UNDER PAINTED AIRCRAFT COMPONENTS

GENERAL THEORY AND INSTRUCTIONS

Reference Material

Aircraft Weapons System Cleaning and Corrosion Control ..... NAVAIR 01-1A-509
Infrared Training Center ..... ITC Level I Course Manual
FLIR Systems MilCAM RECON Operators Manual ..... 17485-000 Rev C

Index

Subject — Page
Infrared Thermography Defined 2
Infrared Thermography Techniques 2
Passive Thermography 2
Reflectance Thermography 2
Flash Thermography 2
Thermal Energy Concepts 2
Energy 2
Heat 2
Temperature 2
IR Science Fundamentals 2
The Electromagnetic Spectrum 2
IR Waves 2
Visible Light 3
Conservation of Energy 3
Absorption 3
Transmissivity 3
Reflectance 3
Emissivity 3
Corrosion 3
Corrosion Defined 3
Effect on Military Aircraft 3
Infrared Inspection of Corrosion 4
IRRIT 4
IRRIT Background 4
Inspection Intervals 4
Recommendations Based on Inspections 5
Strip and Repaint Entire Aircraft 5
Scuff-Sand and Topcoat Small Areas 5
Spot Strip and Repaint Small Areas 5
Strip and Repaint Large Local Areas 5
Managing and Monitoring vs. Repairing Corrosion 6
Materials Compatibility 6
Aluminum Substrate 6
Procedure 6
Health, Safety, and Environmental Considerations 7
Appendix 7
Glossary of Terms 7

1. **Introduction**. This work package provides information for the use of infrared thermography (mid-IR reflection) for the detection of metallic corrosion through organic paint systems applied to aircraft, components and avionics equipment. This inspection technique is applicable for use at Organizational, Intermediate, and Depot levels.

2. **Infrared Thermography Defined**. Infrared thermography is the process of acquisition, analysis, and interpretation of infrared (thermal) energy radiating from a surface.

3. **Infrared Thermography Techniques**.

a. Passive Thermography. Passive thermography involves the use of an IR camera to detect thermal energy from any material above 0 Kelvin.

b. Reflectance Thermography. Reflectance thermography involves the use of external IR emitters to generate IR reflectance energy from a metal substrate, quite often through organic coatings.

c. Flash Thermography. Flash thermography involves the use of a flash bulb to impart heat on an object. As the heat is absorbed into and emitted from the part, an IR camera records the heat transfer.

4. **Thermal Energy Concepts**.

a. Energy. Energy is the ability to do work. There are many different forms of energy and each one can be converted to a different form of energy.

b. Heat. Heat is the thermal energy that people sense. It is the result of a temperature difference between two materials.

c. Temperature. Temperature is the measurement of the random movements or dissociation of the atoms and molecules of a material. As the molecular dissociation increases in a material, the temperature of the material increases. If the molecules of a material are moving, the material is said to have thermal energy. The lowest possible temperature is absolute zero, or 0 Kelvin, where no atoms or molecules are moving. Nothing exists at 0 Kelvin, therefore all objects emit some form thermal energy.

5. **IR Science Fundamentals**.

a. The Electromagnetic Spectrum. The electromagnetic spectrum comprises all forms of energy. The spectrum spans from low energy radio waves to high energy gamma-rays. Visible light that human beings see is near the middle of the spectrum at roughly 400 nm to 750 nm (0.400 µm to 0.750 µm). Infrared light or radiation exists at longer wavelengths than visible light between approximately 0.700 µm to 12.0 µm. Refer to figure 1 for the spectrum.

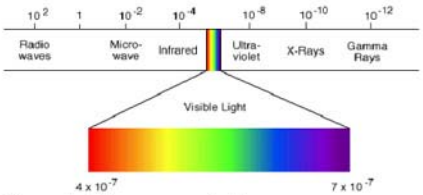


Figure 1: Electromagnetic Spectrum

b. IR Waves. Generally, IR waves are classified as either mid wave or long wave. Mid wave IR radiation is found around the 3 µm to 5 µm range. Long wave IR radiation is found around the 8 um to 12 µm. Most thermography systems are designed to measure in the long wave IR band. However, recent emphasis has been placed on mid wave IR due to the ability of the energy to transmit through certain opaque materials.

c. Visible Light. Visible light is different than infrared light in that the latter can not be seen with the naked eye. Infrared cameras only detect infrared energy and not visible light energy.

d. Conservation of Energy. The first law of thermodynamics states that energy can neither be created nor destroyed. This means that any incident infrared energy on a materials surface must be absorbed, reflected, or transmitted by that material. The following equation states the relationship:

$$\alpha + \rho + \tau = 1 \qquad (1)$$

e. Absorption (α). Absorption is the fraction of incident infrared radiation absorbed by a material.

f. Reflectance (ρ). Reflectance is the fraction of incident infrared radiation reflected off a surface.

g. Transmissivity (τ). Transmissivity is the fraction of incident infrared radiation transmitted through a material.

h. Emissivity. Emissivity is equal to the absorption of a material. The amount of energy a material emits is dependent upon this property. In general, materials that do not have a high emissivity are shiny, smooth metals. Measuring the correct emissivity is critical to obtaining quantitative accuracy.

Certain materials may be opaque but have a very high transmissivity. This property of some organic coatings comes in handy when inspecting metallic substrates for corrosion. As it is explained later, corrosive products and non-corroded metal substrates have different emissivities, which allow mid wave thermal imaging systems to detect corrosion underneath certain organic coatings.

6. **Corrosion**.

a. Corrosion Defined. Corrosion is the electrochemical deterioration of a material or its properties due to its chemical reaction with the surrounding environment. This reaction occurs because of the tendency of metals to return to their naturally occurring state, usually oxide or sulfide ores. For example, iron in the presence of moisture and air will return to its natural state, iron oxide or rust. Aluminum and magnesium form corrosion products that are white oxides or hydroxides. When a water solution containing soluble salts is present, corrosion of many alloys can occur easily at ambient temperatures. This type of corrosion can be effectively treated by maintenance personnel as discussed in this manual. Corrosion can also occur in the absence of water but only at high temperatures, such as those found in gas turbine engines. However, the most common type of corrosion (and the one that can be most effectively treated by maintenance personnel) is electrochemical corrosion.

b. Effect on Military Aircraft.
Maintenance of military aircraft and avionic equipment requires knowledge of why metals corrode and materials degrade. The theory lies in the definition and description of mechanisms that cause equipment to fail in field service. Corrosion is the chemical or electrochemical deterioration of a material. This deterioration is complex in nature because of the various types of corrosion, the frequent simultaneous presence of several types of corrosion, and the design characteristics and maintenance/environmental factors that make aircraft and avionic systems susceptible to corrosion.

Corrosion can cause complete failure of equipment or undesirable changes in electrical characteristics. It is a process that is active on a 24 hour basis. Equipment does not necessarily have to be installed, operated, or resident in a particularly harsh environment. Some form of corrosion will take place even in near ideal environments. All personnel should recognize that corrosion is the natural continuing process of materials returning to their normal state. Inadequate corrosion prevention and control will ultimately affect equipment life cycles, downtime, and overall system reliability.

7. **Infrared Inspection of Corrosion**.

a. IRRIT. Current NDI methods are inadequate in detecting relatively small concentrations of corrosion products at the metal/paint interface through an intact coating system. Most common methods are useful for crack detection, however they tend to concentrate on detecting significant amounts of bulk corrosion and defects in structural members and require coating removal. The infrared reflectance imaging technique (IRRIT) provides an alternative method that would enhance or replace other corrosion inspection methods by its ability to detect relatively small concentrations of corrosion through the coating system.

b. IRRIT Background. IRRIT was successfully developed under a previous Government contract managed by the Strategic Environmental Research and Development Program (SERDP) Project PP-1137 under the Secretary of Defense Office with Northrop Grumman Corporation (NGC) as the prime contractor. The technology exploits the difference in infrared reflection properties between corroded and non-corroded metallic surfaces. Infrared (IR) radiation from maintenance facility lights, the sun, or a low-wattage IR heater illuminates the area to be observed. The IR passes directly through the

coating and then reflects off the metallic substrate back through the coating and into an IR camera. Since the corroded areas do not reflect the IR energy as well as the non-corroded areas, a picture or image is generated by the IR camera much the same as observing the corrosion under standard visual techniques.

c. Inspection Intervals. Inspection intervals, methodology, and equipment are prescribed in applicable maintenance manuals, (derived from commercial, depot engineering data, and end-user input) inspection work cards or checklist. All requirements pertaining to inspections are normally accomplished concurrently to avoid complication in scheduling and controlling the required maintenance. The typical inspection concepts for aerospace vehicles are periodic, phase, isochronal, phased depot maintenance (PDM) and aerospace vehicle manufacture maintenance. The weapon system manager establishes the necessary controls to ensure that the periodic, phase, or isochronal inspections are accomplished at or near the scheduled due time as authorized in applicable technical manuals or approved waivers. System engineers and the using activity have the primary responsibility for the safe operation of aerospace vehicles, systems, and components. Systems managers and engineers with authority may increase the frequency or scope of scheduled inspections or individual inspection requirements for temporary situations. Scheduled deviations beyond what is authorized in weapon system specific technical manuals must be approved through the weapon system program office.

All activities are responsible for properly phasing the accomplishment of additional or replacement inspection requirements resulting in changes to scheduled inspections and maintenance manuals. Determine the interval for accomplishment of any new inspection requirements by comparing and aligning the aerospace vehicles, systems, and components inspection cycle with the interval prescribed for the new requirement/process.

8. **Recommendations Based on Inspection**.

a. Strip and Repaint Entire Aircraft. After analyzing data collected from IRRIT inspections, system managers can enhance current inspection methods, eliminating unnecessary stripping and repainting. System managers can shift paint intervals, for example from 6 years to 7 years, defer or reduce maintenance to large sectional repairs/small spot repairs, or shift from schedule based maintenance to conditional based maintenance, stripping and repainting as needed, on case by case basis.

b. Scuff-Sand and Topcoat Small Areas. Recent advances in coating technology created by new performance standards has led towards the application of more durable coatings with an extended service life (10+years). As the aircraft painted with extended life coatings approach their PDM cycles, IRRIT provides technicians with a reliable and rapid method to ascertain the condition and integrity of the coatings and substrate without stripping of the coatings. Managers have the option of scuff-sanding and top coating instead of a full strip and repaint.

c. Spot Strip and Repaint Small Areas. IRRIT's ability to detect relatively small amounts of corrosion through coatings, will lead to reduced maintenance through early detection and treatment of corrosion in its infancy stages. Technicians can selectively sand, spot repair, and locally touch-up affected areas.

d. Strip and Repaint Large Local Areas. Use IRRIT to inspect coatings on aerospace vehicles, systems, and components during PDM, field level maintenance, or at any phase or juncture in an inspection cycle that requires coating removal to ascertain substrate condition. Coatings conforming to the latest military specifications are formulated to resist fading and chalking making it possible to seamlessly paint large sections of the aircraft while able to match existing paint.

9. **Managing and Monitoring Versus Repairing Corrosion**. The unique ability of IRRIT to image corrosion through coatings in real time, display, and store images enables technicians to make immediate decisions, or send images for engineering disposition. Properly identified and cataloged inactive corrosion sites encapsulated under an intact coating system may

not require repairs, only increased monitoring using IRRIT.

In some instances the corrosion removal process of grinding and sanding, especially on critical substrates, may actually cause more damage and stress to the substrate than the corrosion. Engineers using continuously updated IRRIT data to determine disposition may decide to hold maintenance for PDM (if aircraft is close to PDM), or impose flight restrictions until proper repair/replacement can be accomplished, enabling aircraft to remain in service.

10. **Materials Compatibility**. During demonstration and validation of IRRIT, topcoats and primers were evaluated for compatibility with the IRRIT system. Table 1 shows the materials tested. The

Table 1. Materials and IRRIT Compatibility

Compatibility ↓	**Topcoat** MIL-PRF-85285, Ty I Hentzen Color 16440 DEFT Color 36375 03-GY-292, Color 35237 03-BL-159, Color 36320 03-GY-287 MIL-C-27725 Fuel Tank Coating	**Primer** MIL-P-23377 MIL-PRF-85582 Ty I Epoxy Primers Deft 44-GN-7/ Deft 44-GN-7	Compatibility ↓
	APC	TT-P-2760 Elastomeric Polyurethane Primer	

top row indicates the materials with the highest compatibility with IRRIT.

11. **Aluminum Substrate**. Aluminum and its alloys are the most widely used materials for aircraft construction. Aluminum is highly anodic as evidenced by its position in the galvanic series. However, the formation of a tightly adhering oxide film offers increased resistance under mild corrosive conditions. The corrosion products of aluminum are white to gray powdery materials (aluminum oxide or hydroxide), which can be removed by mechanical polishing or brushing with abrasive. It is anodic to most other metals and, when in contact with them, galvanic corrosion of the aluminum will occur.

Aluminum alloys are subject to pitting, intergranular corrosion, intergranular stress corrosion cracking, and corrosion fatigue cracking. In some cases, the corrosion products of the metal in contact with aluminum are corrosive to aluminum. Therefore, it is necessary to clean and protect aluminum and its alloys to prevent corrosion. Since pure aluminum is more corrosion resistant as well as being more anodic than most alloys, aluminum alloy sheet stock is often covered with a thin layer of nearly pure aluminum called alclad.

While fully intact, the alclad layer is very resistant to corrosion because a very adherent oxide film rapidly forms on its surface to protect it. Alclad is easily removed by harsh treatment with abrasives and tooling, exposing the more corrosion susceptible aluminum alloy base metal surface. If the break in the alclad layer is small, the alclad will sacrificially corrode and protect the exposed base metal alloy because it is more anodic than the alloy. In such areas, chemical conversion coatings, paints, and corrosion preventive compounds are especially important. In a marine environment, all aluminum surfaces require protection.

12. **Procedure**. Corrosion inspection shall be performed utilizing mid-IR (3 – 5 µm) infrared imaging cameras. Inspection shall be performed on surfaces free of external contamination, such as, dirt, grease, oil, etc. When possible an aircraft wash should be scheduled prior to the inspection process. Camera operation shall be in accordance with the equipment manufacturer's instructions and guidelines. Corrosion identification shall be performed in accordance with NA 01-1A-509. Disposition of corrosion shall be in accordance with NA 01-1A-509 or other program specific technical data packages.

IR Illumination – Illuminators must supply sufficient illumination in the 3-5 micrometer range. Sufficient illumination is defined as enough illumination to penetrate the coating system and reflect off the substrate to the camera system detector array.

Acquisition System – Includes the IR Camera, IR Illumination source, and a data acquisition system, which can be a digital video camera capable of storing still and video images onto recording media.

Once IRRIT system is operating, make necessary adjustments according to inspection environment. IRRIT Operation Standard: A standard is required to check operational ability of IRRIT, and to ensure all internal camera settings are appropriate. Recommended operational standard

is the use of a commercially available camera resolution standard (Air Force Target Standard) coated with the applicable coating system representative of the material for inspection.

13. **Health, Safety, and Environmental Considerations**. While the methods, applications, and processes described or referenced in this document may involve exposure to hazardous materials, this document does not address the handling of hazardous materials. It is the sole responsibility of each user to ensure familiarity with the procedures for safe and proper exposure, handling, or use of any hazardous materials and to take necessary precautionary measures to ensure the health and safety of all personnel involved.

Wear appropriate Personal Protective Equipment (PPE), (clothing, gloves, apron, eye protection, etc.) approved for materials, procedures, and tools being used. Contact supervisor for guidance. If necessary, contact the local Bioenvironmental Engineering or Safety Office for guidance.

14. **Appendix**

15. **Glossary of Terms**.

Atmospheric Attenuation**.** The amount of radiated IR energy that is absorbed by the atmosphere. It is a function of the temperature and humidity, particles in the air (i.e. fog, smoke, smog, etc.) and wavelength, among other factors.

Critical Dimension. The dimension of a target used in calculating the DRI performance. It is a function of length, width and height, as well as what face of the target is presented to the imager.

DRI (Detection-Recognition-Identification). A method of characterizing the range performance of a thermal imager according to a standard set of criteria using a standard atmospheric model, and a target of alternating black and white stripes (cycles) at different temperatures.

Detection. The minimum distance at which an imager can reproduce a single cycle (black/white stripe) of a target. Typically used to represent the distance at which the imager can first detect a given target. In addition to the imager, the detection range is also a function of the target size and temperature difference form the background.

Field of View (FOV). The area in space that is seen by the lens of a thermal imager. Usually expressed in degrees, and specified for both horizontal and vertical dimensions. The FOV is a function of the lens.

FLIR92. A set of standards defined by the Night Vision Laboratories for calculating DRI information.

Focal Plane Array (FPA). An integrated circuit with a two dimensional matrix of detector elements that sits in the focal plane of the thermal imager. An imager that uses an FPA is referred to as a staring imager because the entire array stares at the scene to collect IR energy to make an image.

Hyperfocal Distance. The distance beyond which all objects are in focus when an imager's focus adjust is set to infinity.

Infrared Imager. An Instrument that collects infrared energy and produces a video image where the gray scale values correspond to differences in temperature.

Infrared. The portion of the electromagnetic spectrum located just above visible light. The infrared spectrum extends from just above red (0.7 micrometers) to about 12 micrometers.

Instantaneous Field of View. A measure of the spatial resolution of an IR detector. It is defined as the angle seen by an individual pixel in the FPA.

Kelvin Temperature Scale. Absolute temperature scale related to the Celsius (or Centigrade) scale. 0° Kelvin (absolute zero) is equal to -273° C. The units of Kelvin are equal to Centigrade degrees. Therefore, room temperature (23°C) is equal to 296° K.

Long Wave Infrared (LWIR). The section of the infrared band from
7 micrometers to 12 micrometers.

Micro-Cooler. A miniature Sterling Cycle cooler used to provide cryogenic temperatures for the Focal Plane Array.

Micrometer (μm) or Micron. One millionth of a meter (10-6 m). Units are used to express the wavelength of light.

Milliradian (mr). A measure of angle equal to one thousandth of a radian (1 radian = 180°/pi). Typically used to express the IFOV of an imager. 1 mr = 0.0573°.

Mid wave Infrared (MWIR). The portion of the infrared spectrum from 3 to 5 micrometers.

Minimum Resolvable Temperature Difference (MRTD). A figure of merit for a particular FPA based imager, it defines the minimum temperature difference that can be resolved by the detector.

Narrow Field of View (NFOV). In a dual field of view lens, the NFOV is the smaller of the two fields (more magnification) and is used for detection at longer ranges.

Noise Equivalent Temperature Difference (NETD). A figure of merit for an FPA based imager, it defines the temperature difference that produces a signal just equal to the RMS noise signal.

Non-Uniformity Correction. A built in correction routine that calculates a set of field correction coefficients to apply to each pixel in the array to normalize their response for a given scene temperature.

Pixel. Abbreviation for Picture Element, or each individual element that comprises a picture. Typical FPAs are arrays of 320 x 480 pixels, or 256 x 256 pixels.

Radian. The angular measurement equal to the ratio of the arc length of a circle divided by the radius. A circumference of a complete circle is 2 pi times the radius, so a complete circle (360°) equal 2 pi radians, and pi radians = 180°. 1 radian = 57.3°.

Recognition. The distance at which an imager can resolve three cycles across a given target. Typically used to define the distance at which an imager can distinguish between a truck and a tank or a car. In addition to the imager, the recognition range is also a function of the target size and temperature difference from the background.

Short Wave Infrared (SWIR). The portion of the infrared spectrum from 0.70 micrometers to 3 micrometers.

Wide Field of View (WFOV). In a dual field of view lens, the WFOV is the wider of the two fields (less magnification) and is used for observing a wider field of view.

APPENDIX L SUPPLEMENTAL EVALUATION OF ADDITIONAL COMMONLY USED COATINGS

L.1 Introduction

In a supplemental effort, the IRRIT system was applied to an additional set of commonly used coatings to determine, in the laboratory, the performance of a MWIR camera on these coatings. The list of coatings tested is as follows:

- Corrosion Preventative Compound (CPC), SO SURE® MIL-C-85054B Type I Class 134A
- CPC, LEKTRO-TECH, Inc., MIL-L-87177A Type I Grade B
- CPC, SO SURE®, MIL-C-81309E Type II Class 2 Grade 134A
- CPC, LHB Industries, MIL-PRF-32033
- Rain Erosion Coating, LORD Corporation, Lord M 1433 (MIL-C-85322)
- Low Temperature Cure Powder Coat, Crosslink Powder Coatings, Inc.
- Self-Priming Topcoat, Deft TT-P-2756 Type I (3 colors)
- Advanced Polyurethane Coating (APC), Polyurethane Topcoat, Deft, MIL-PRF-85285 Type I (3 colors)
- Anti-Chafe Coating, PRC-DeSoto

L.1.1 Background

This expanded investigation is a result of an October 2005 visit to the Warner Robins Air Logistics Center (WR-ALC). At WR-ALC, it was determined that the existing IRRIT system had some difficulty with thicker darker outer mold line (OML) coatings (refer to Appendix B for details on the WR-ALC trip). Specifically, the FED-STD-595 colors 36173, 36118, and 36375 of the APC or Extended Life Topcoat (ELT) version of MIL-PRF-85285 Type I.

One product of the WR-ALC visit was an investigation of free-standing films based on typical USAF OML paint schemes by FTIR transmission analysis (detailed in Appendix E). The FTIR transmission analysis of the free-standing films proved that insufficient MWIR is transmitted through the USAF OML paint schemes (refer to Appendix E.3). This led to redirecting the USAF OML effort to a USAF inner mold line (IML) at Oklahoma City Air Logistics Center (OC-ALC) and the feasibility of using the KC-135 IML and B-52 IML as candidate aircraft for IRRIT inspection.

In addition to the films studied following the WR-ALC visit, other films were identified for future investigation. This appendix details the results of that follow-on investigation. ESTCP provided additional funding for this supplemental effort.

L.1.2 Selected Coatings

Table L-1, below, illustrates new coating systems that were tested with the IRRIT following the submittal of the final report. Table 2-3 in the main body includes the original list of examined coating systems and their performance, while Appendix B lists some of the coatings identified for future investigation. Associated discussion about the general performance of MWIR (3-5 micrometers) with respect to typical organic coatings is found in Section 2.4.2 of the main body.

The coatings listed in Table L-1 were selected because they represent coatings that generate substantial waste material when removed, and thus a maintenance scenario based on IRRIT can generate substantial pollution reduction benefits. These coatings were also selected because they demonstrate the utility of IRRIT, and thus aid in the transfer of IRRIT technology into service.

The APC or ELT version of MIL-PRF-85285 was selected for this study because these topcoats are currently used on USAF aircraft. The APC coatings are widely used OML coatings and thus produce a large quantity of waste when stripped. Demonstrating that IRRIT can effectively see through APC coatings would greatly expand the applications for which IRRIT may be applied. Figure L-1, below, shows the potential pollution savings accrued by being able to expand IRRIT use beyond those coatings previously identified as compatible to include OML APCs.

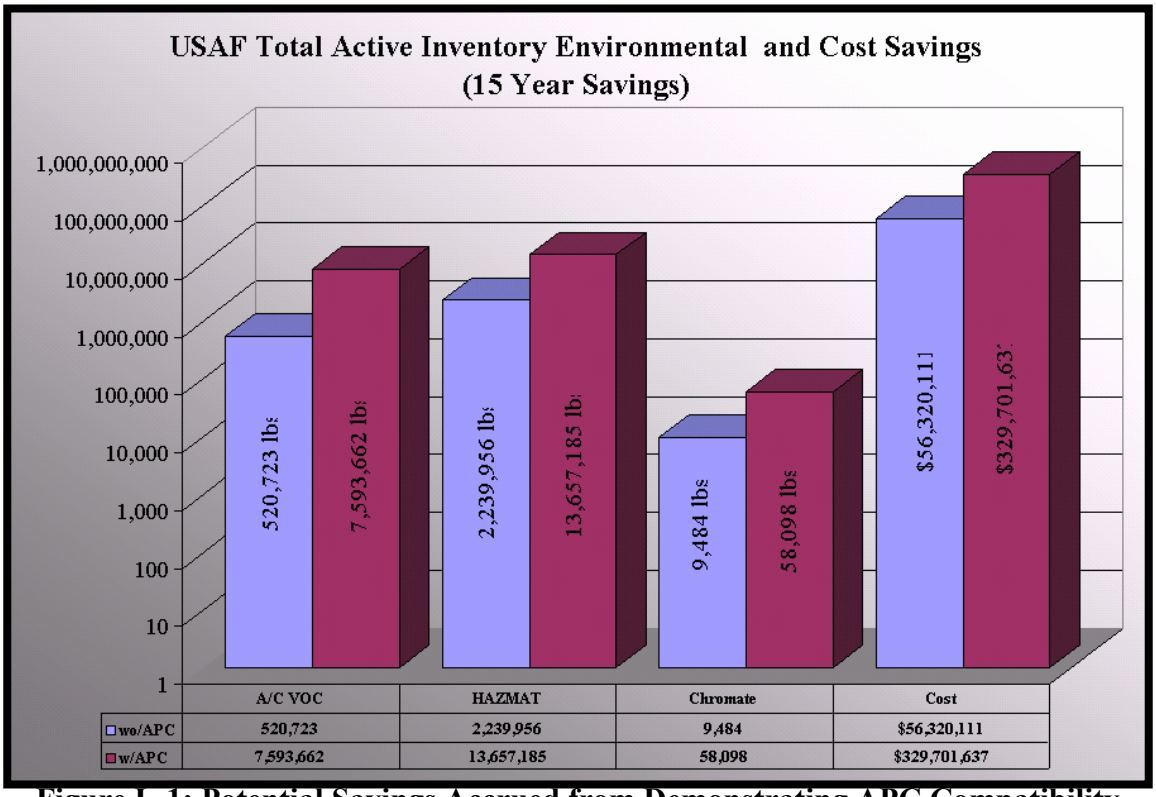


Figure L-1: Potential Savings Accrued from Demonstrating APC Compatibility

NAVAIR is currently evaluating COTS low temperature cure powder coatings for aerospace applications and requested that IRRIT's performance against such powder coatings be assessed. Should the powder coatings be accepted and IRRIT able to view through the coatings, this would offer an additional expansion in IRRIT applications.

The anti-chafe coating was examined because of its widespread use in aerospace applications.

Table L-1: Additional Paint and Coating Systems Tested with IRRIT

Type	Manufacturer	Specification	Color # (FED-STD-595)	Part #	Thickness (mils)	Section
CPC	SO SURE®	MIL-C-85054B Type I Class 134A	N/A	NSN: 8030-01-347-0979	N/A*	L.2.1
	LEKTRO-TECH, Inc.	MIL-L-87177A Type I Grade B	N/A	NSN: 6850-01-328-3617	N/A*	L.2.2
	SO SURE®	MIL-C-81309E Type II Class 2 Grade 134A	N/A	NSN: 8030-00-938-1947	N/A*	L.2.3
	LHB Industries	MIL-PRF-32033	N/A	NSN: 9150-00-458-0075	N/A*	L.2.4
Rain Erosion Coating	LORD Corporation	Lord M 1433 (MIL-C-85322)	N/A	NSN: 8010-01-054-7228	~20	L.2.5
Powder Coat	Crosslink Powders, Inc.	N/A	Gloss White	6191-61003	5.2	L.2.6
Self-Priming Topcoat	Deft	TT-P-2756 Type I	Gloss Gray 16440	03-TY-400	1.34	L.2.7
					2.82	
					4.34	
			Flat Light Gray 36375	03-GY-369	1.84	L.2.8
					3.30	
					4.96	
			Flat Dark Gray 36118	03-GY-381	1.62	L.2.9
					2.92	
					4.74	
APC Polyurethane Topcoat	Deft	MIL-PRF-85285 Type I	Flat Medium Gray 36173	99-GY-001	1.44	L.2.10
					2.88	
					4.84	
			Flat Dark Gray 36118	99-GY-13	1.66	L.2.11
					2.66	
					5.54	
			Flat Light Gray 36375	99-GY-003	1.84	L.2.12
					2.76	
					5.22	
Anti-Chafe Coating	PRC-DeSoto	N/A	Light Flat Gray	N/A	1.62**	L.2.13
					2.1	
					2.1**	

Green Shading = IRRIT had success with this thickness of coating
Red Shading = IRRIT had no success with this thickness of coating
*The CPCs had no measured thickness; it was evaluated while on 2.8-mil polyethylene.
**This anti-chafe coating had an additional "Post-It" note sheet between the test standard and camera.

L.2 COATINGS RESULTS

In Sections L.2.1 through L.2.13, two forms of results are presented: plots of the percentage of IR light transmission through a freestanding film of the specified coating in the range of 3-5 micrometers and, in some cases, IRRIT images were taken of freestanding films suspended partly in front of a standard U.S. Air Force glass resolution target. Such a target is shown without an obscuring coating in Figure L-2.

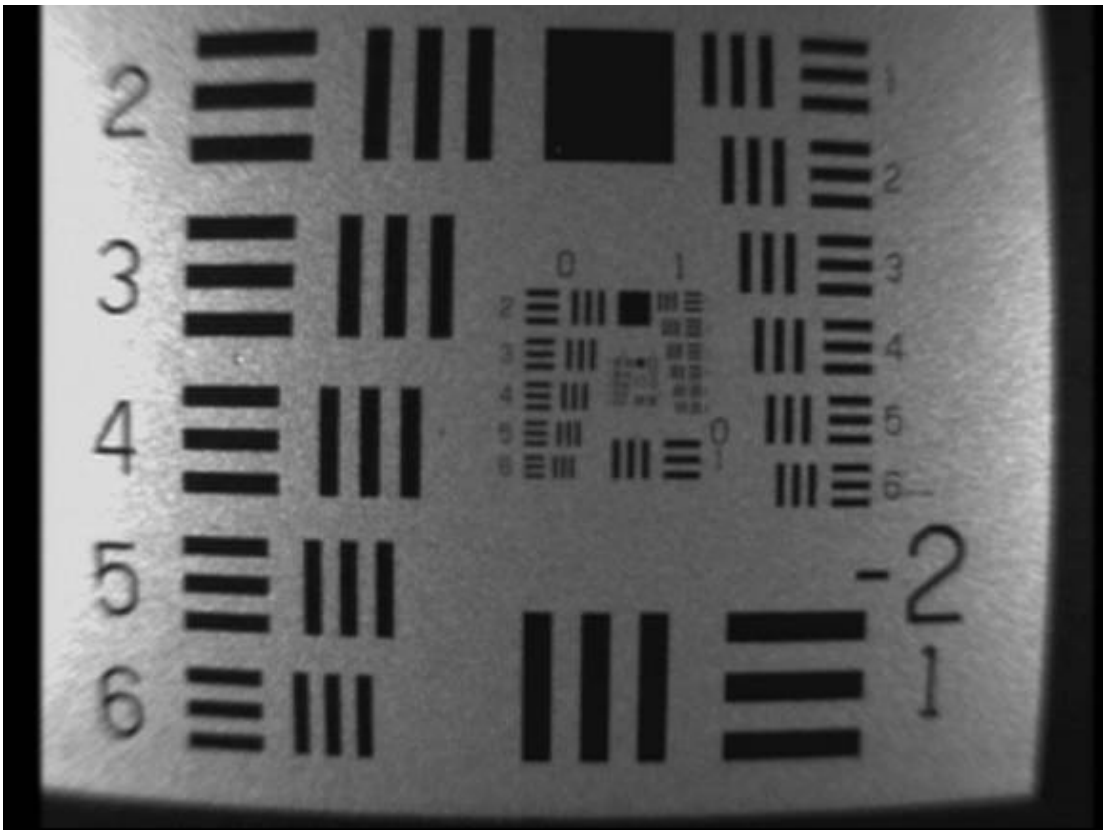


Figure L-2: IRRIT Image of a USAF Glass Resolution Calibration Target.

L.2.1 SO SURE® MIL-C-85054B Type I Class 134A CPC

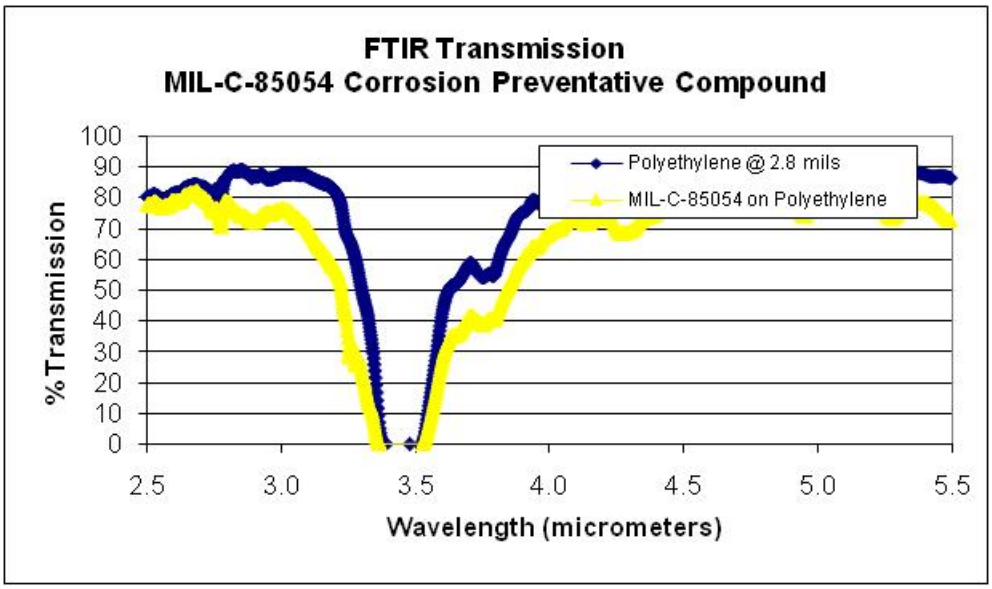


Figure L-3: FTIR Transmission Through SO SURE® MIL-C-85054B Type I Class 134A CPC on 2.8 Mils Polyethylene, and 2.8 Mils Polyethylene Baseline

L.2.2 LEKTRO-TECH, Inc. MIL-L-87177A Type I Grade B CPC

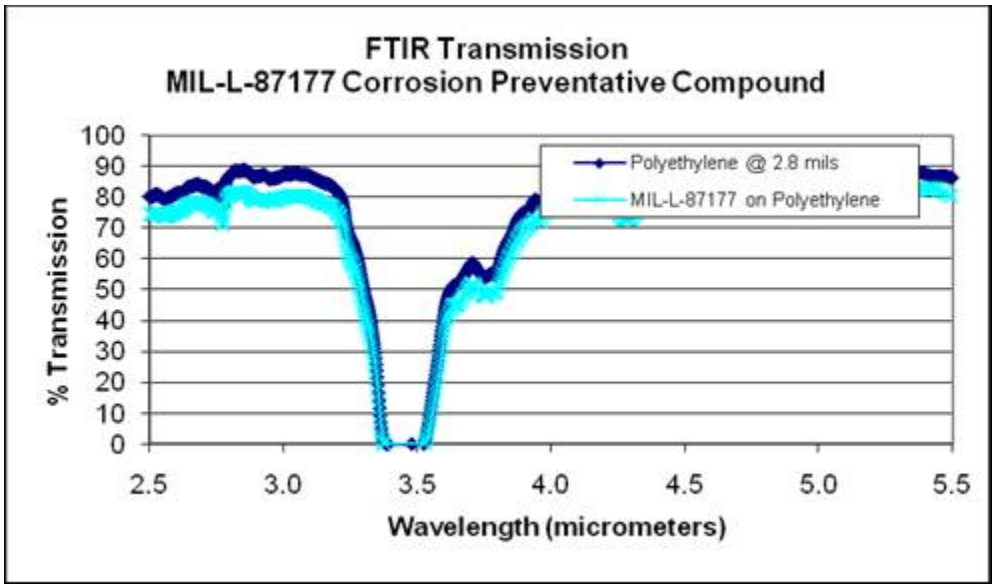


Figure L-4: FTIR Transmission Through LEKTRO-TECH, Inc. MIL-L-87177A Type I Grade B CPC on 2.8 Mils Polyethylene, and 2.8 Mils Polyethylene Baseline

L.2.3 SO SURE® MIL-C-81309E Type II Class 2 Grade 134A CPC

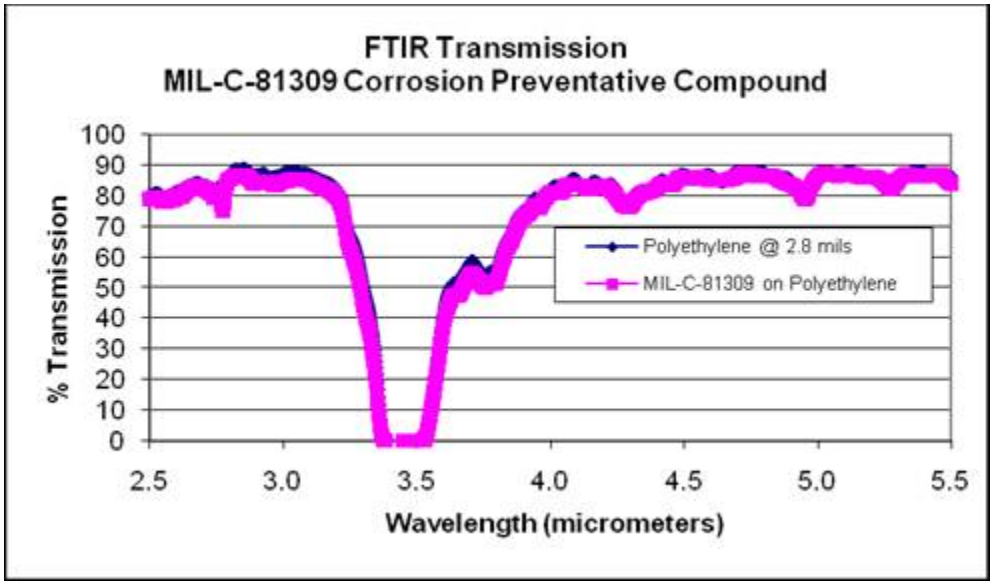


Figure L-5: FTIR Transmission Through SO SURE® MIL-C-81309E Type II Class 2 Grade 134A CPC on 2.8 Mils Polyethylene, and 2.8 Mils Polyethylene Baseline

L.2.4 LHB Industries MIL-PRF-32033 CPC

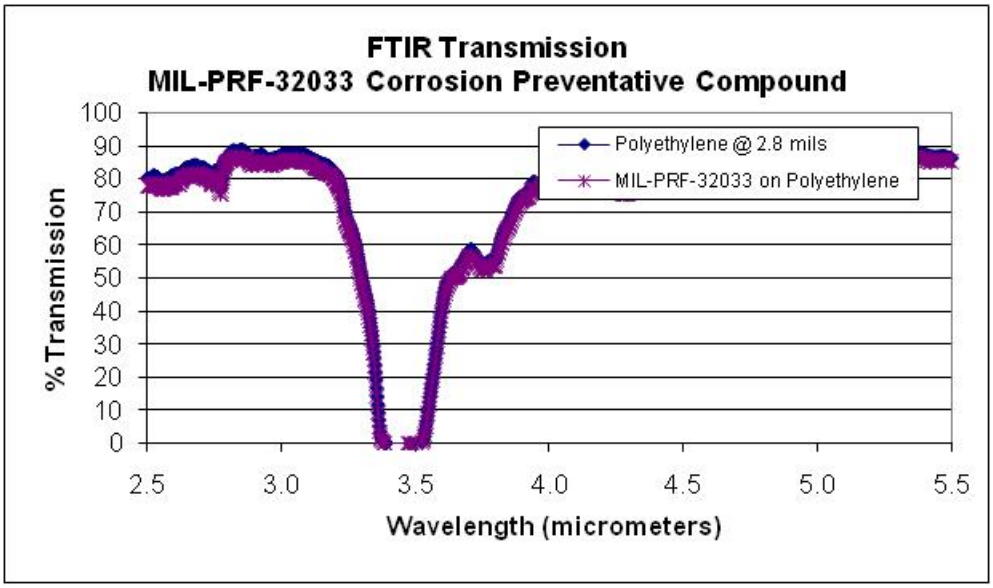


Figure L-6: FTIR Transmission Through LHB Industries MIL-PRF-32033 CPC on 2.8 Mils Polyethylene, and 2.8 Mils Polyethylene Baseline

L.2.5 LORD Corporation Lord M 1433 (MIL-C-85322) Rain Erosion Coating

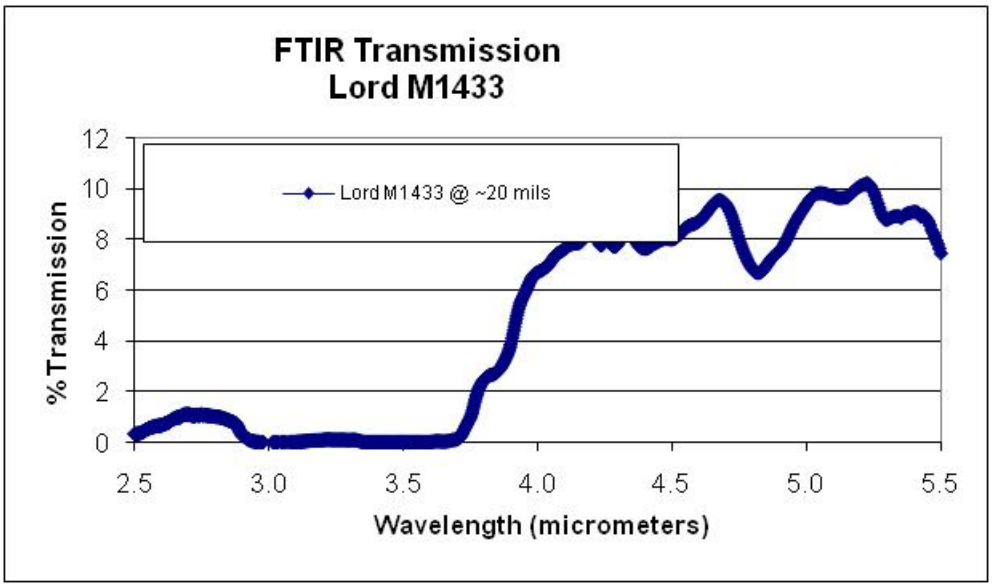


Figure L-7: FTIR Transmission Through LORD Corporation Lord M 1433 (MIL-C-85322) Rain Erosion Coating

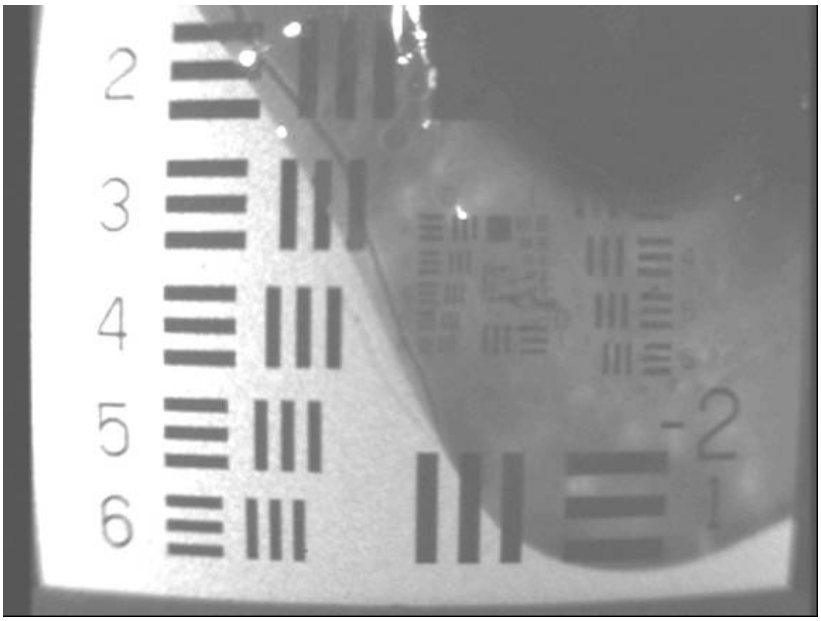


Figure L-8: IRRIT Image of Target Through ~20-mil Lord M 1433 Rain Erosion Coating

L.2.6 Crosslink Powders, Inc., Low Temperature Cure Powder Coat

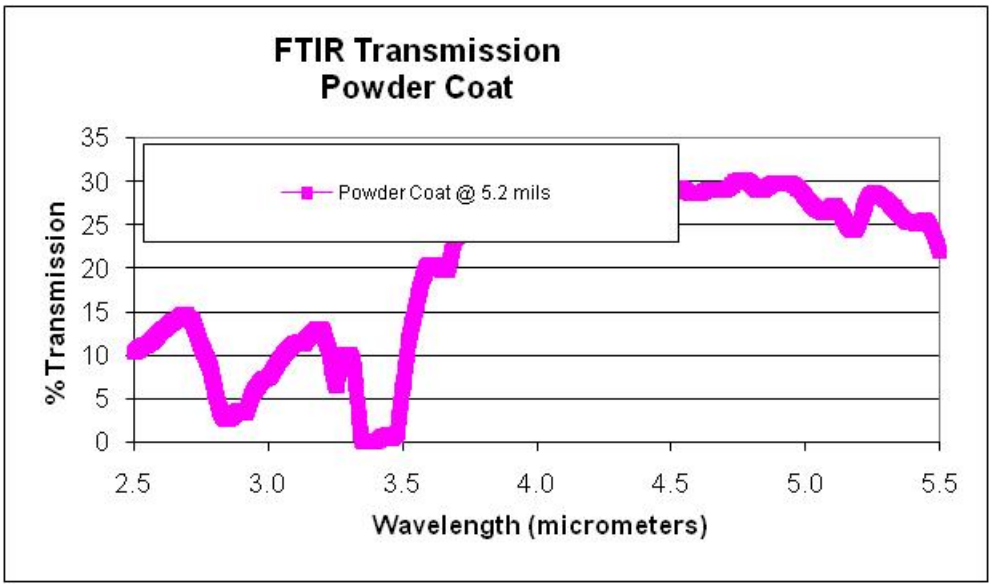


Figure L-9: FTIR Transmission Through 5.2-mil Crosslink Powders, Inc., Powder Coat, Gloss White

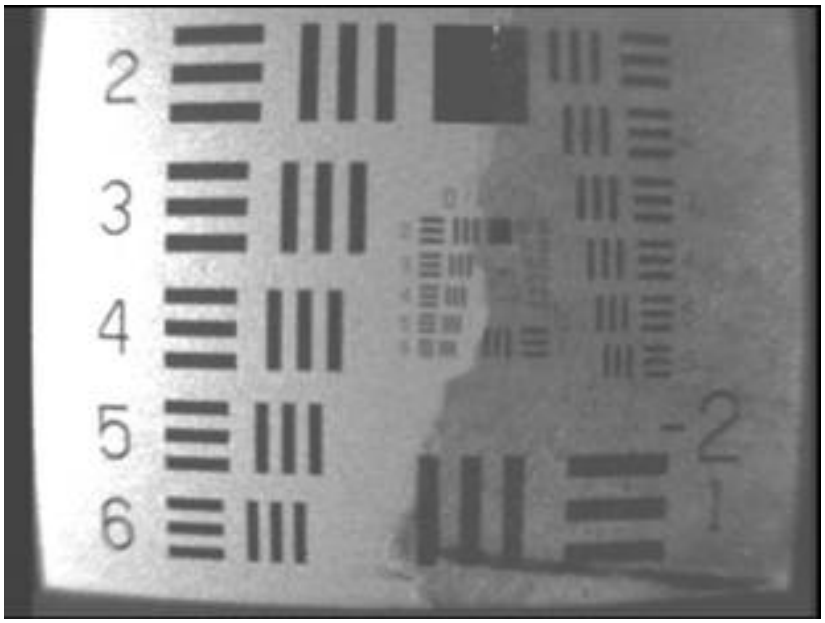


Figure L-10: IRRIT Image of Target Through 5.2-mil Crosslink Powders, Inc., Powder Coat, Gloss White

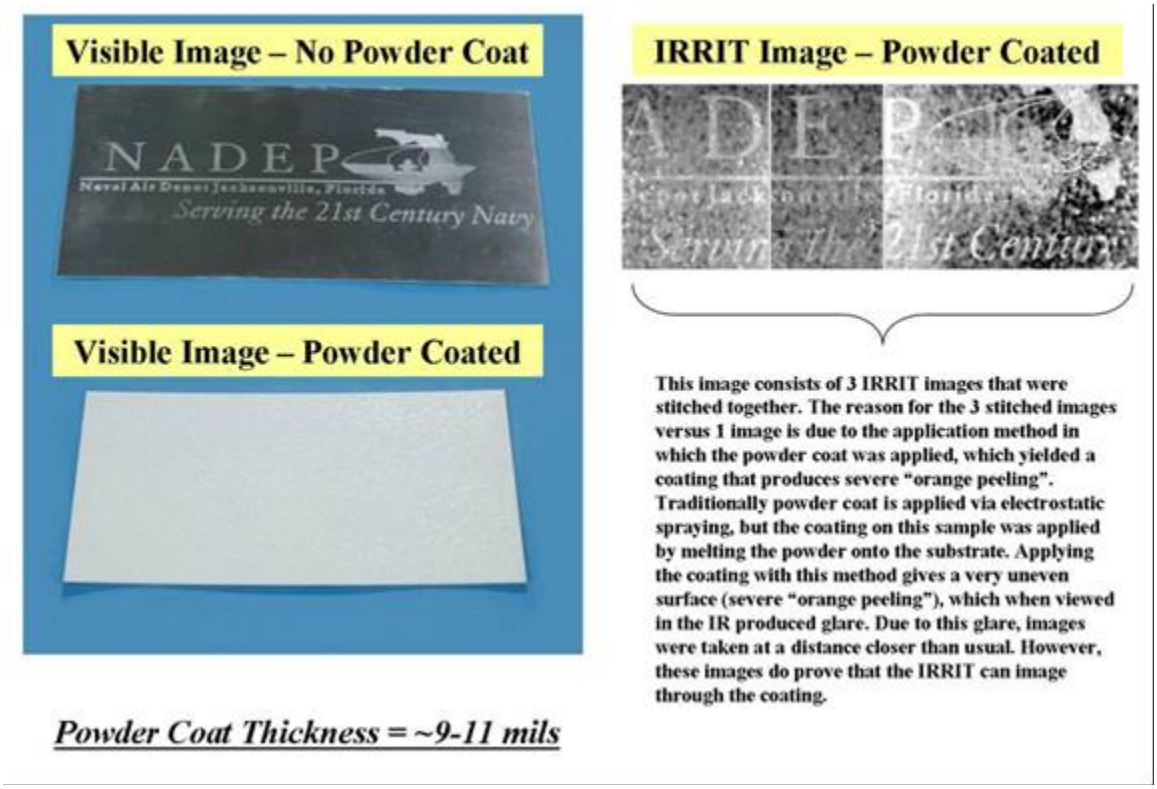


Figure L-11: IRRIT images surface in high detail under thick powder coat

L.2.7 Deft TT-P-2756 Type I Self Priming Top Coat, Gloss Gray

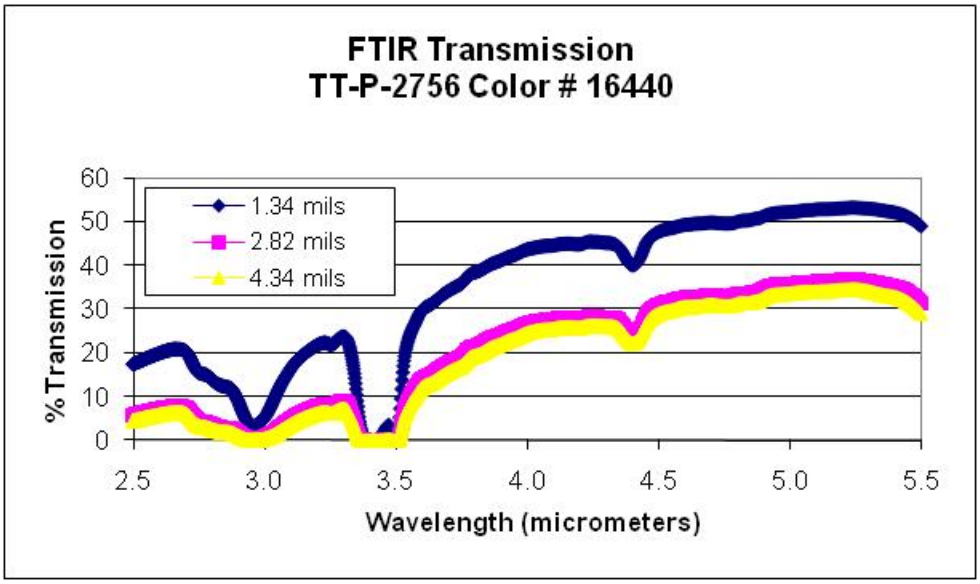


Figure L-12: FTIR Transmission Through Deft TT-P-2756 Type I Self Priming Top Coat, Gloss Gray

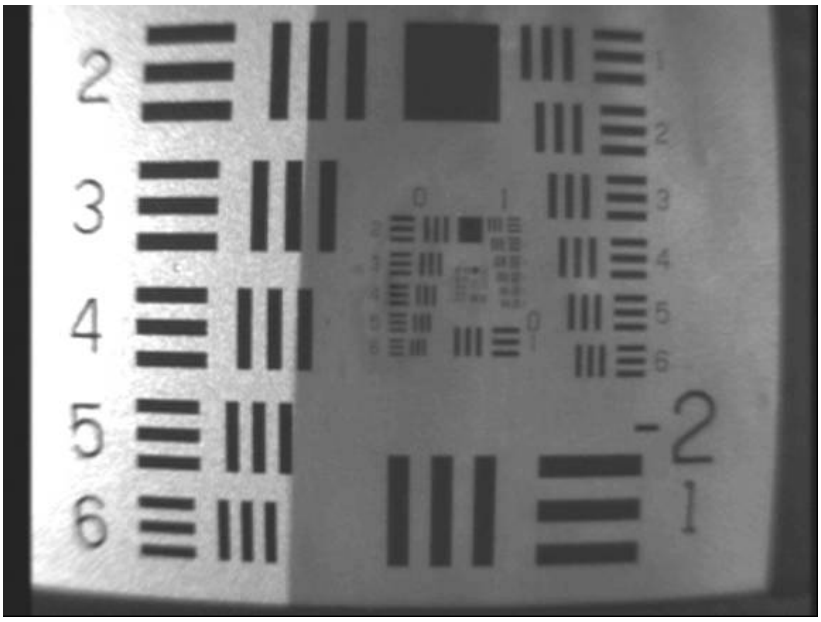


Figure L-13: IRRIT Image of Target Through 1.34-mil Deft Self-Priming Topcoat, Gloss Gray

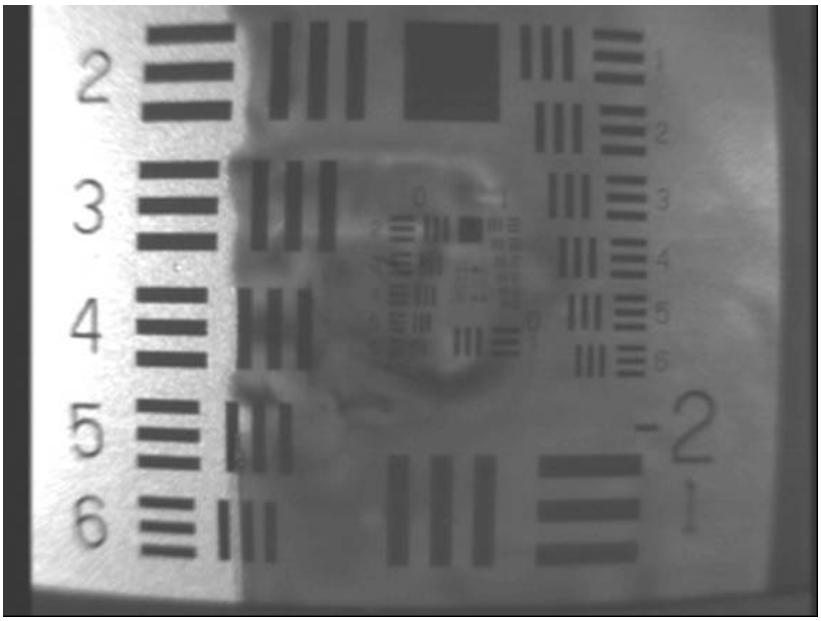


Figure L-14: IRRIT Image of Target Through 2.82-mil Deft Self-Priming Topcoat, Gloss Gray

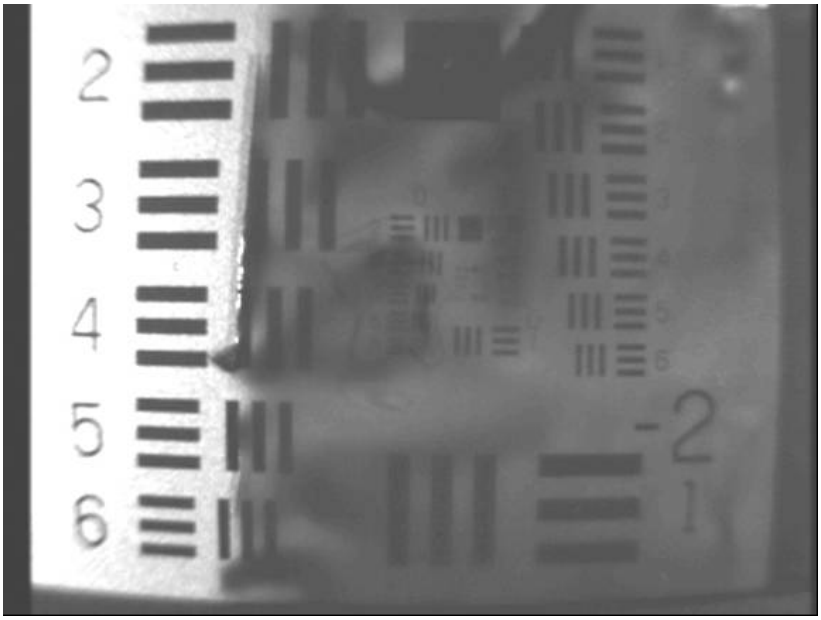


Figure L-15: IRRIT Image of Target Through 4.34-mil Deft Self-Priming Topcoat, Gloss Gray

L.2.8 Deft TT-P-2756 Type I Self Priming Top Coat, Flat Light Gray 36375

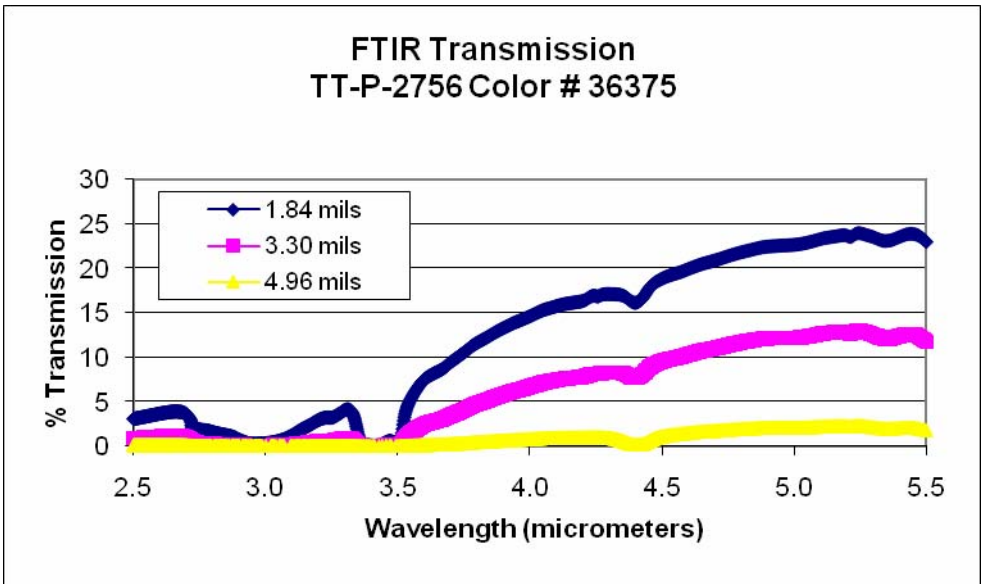


Figure L-16: FTIR Transmission Through Deft TT-P-2756 Type I Self Priming Top Coat, Flat Light Gray 36375

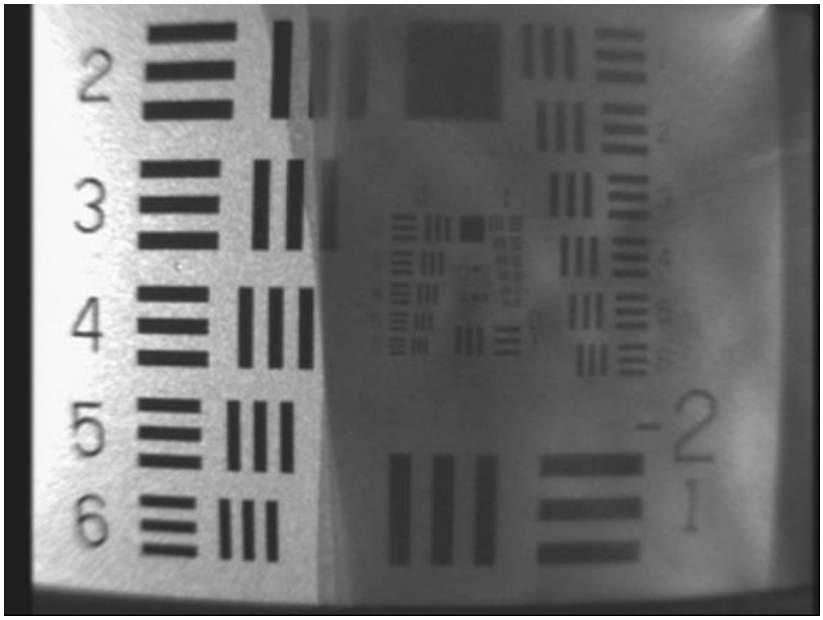


Figure L-17: IRRIT Image of Target Through 1.84-mil Deft Self-Priming Topcoat, Flat Light Gray

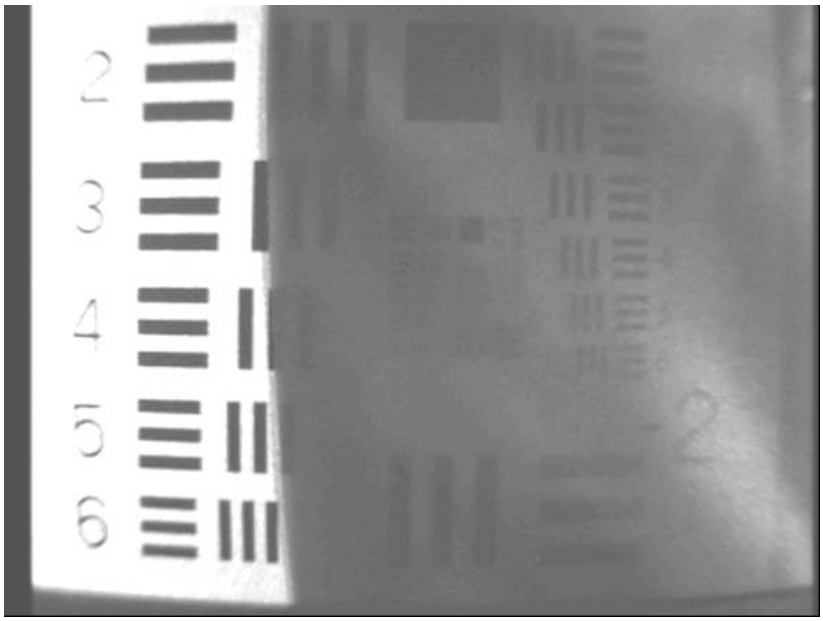


Figure L-18: IRRIT Image of Target Through 3.30-mil Deft Self-Priming Topcoat, Flat Light Gray

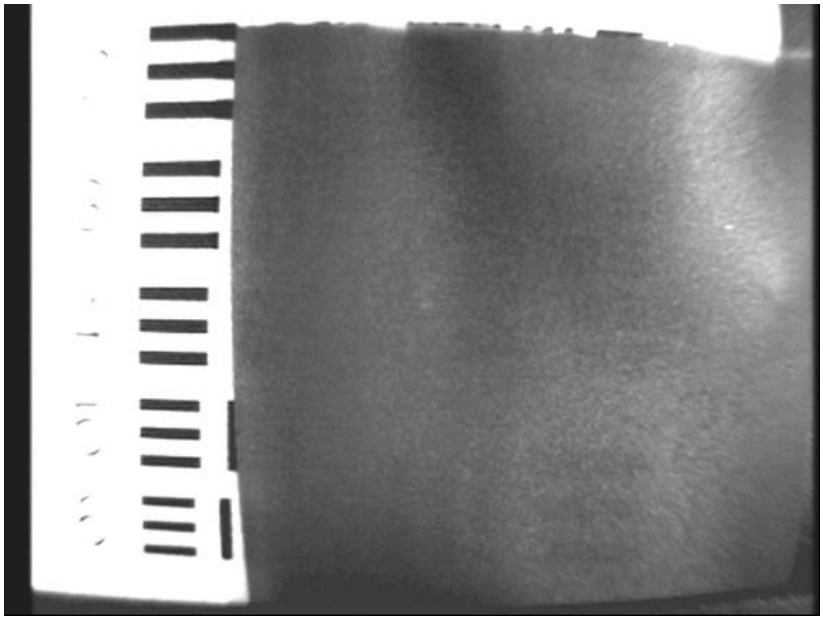


Figure L-19: IRRIT Image of Target Through 4.96-mil Deft Self-Priming Topcoat, Flat Light Gray

L.2.9 Deft TT-P-2756 Type I Self Priming Top Coat, Flat Dark Gray 36118

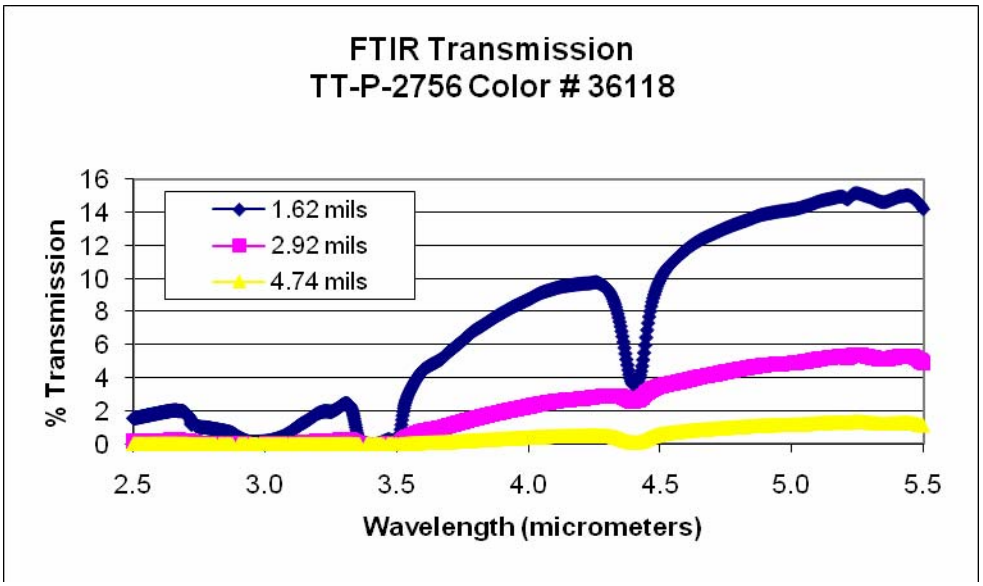


Figure L-20: FTIR Transmission Through Deft TT-P-2756 Type I Self Priming Top Coat, Flat Dark Gray 36118

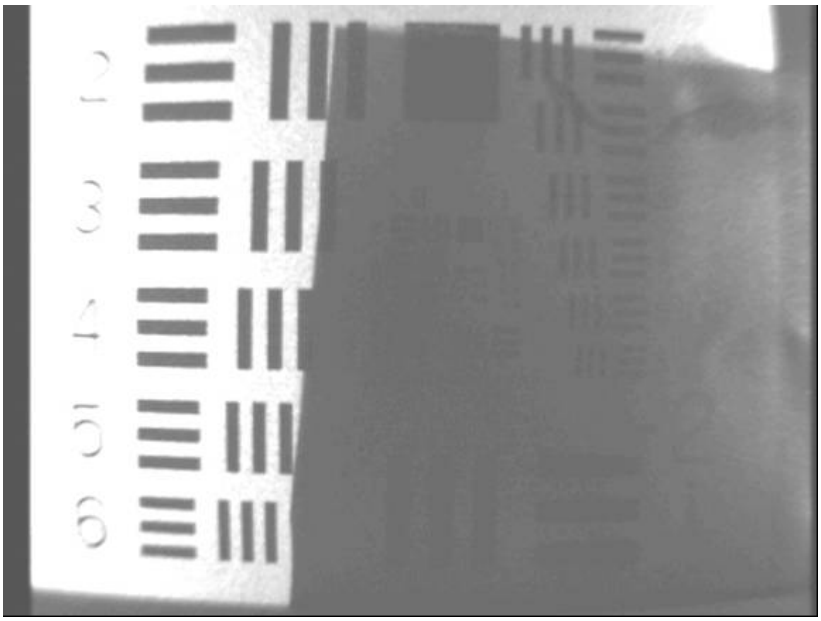


Figure L-21: IRRIT Image of Target Through 1.62-mil Deft APC Topcoat, Flat Dark Gray

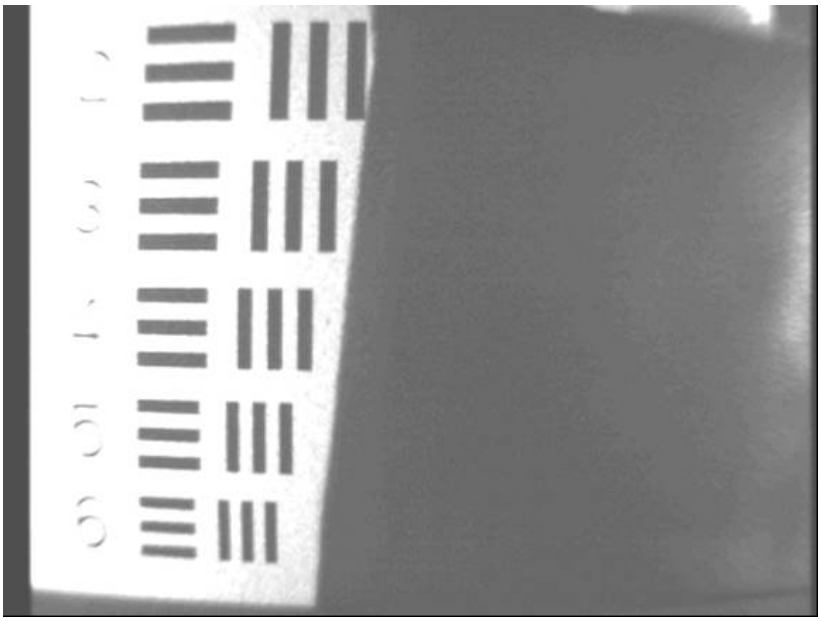


Figure L-22: IRRIT Image of Target Through 2.92-mil Deft APC Topcoat, Flat Dark Gray

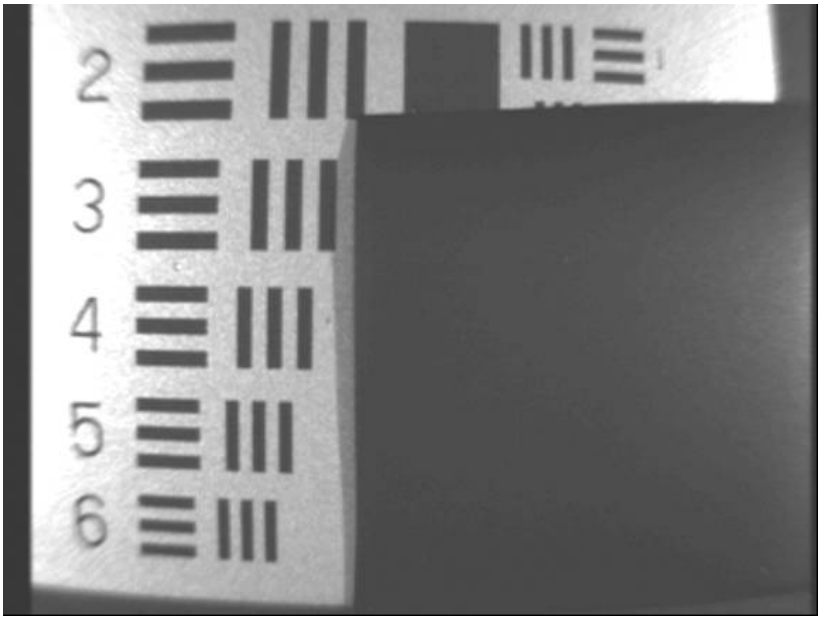


Figure L-23: IRRIT Image of Target Through 4.74-mil Deft APC Topcoat, Flat Dark Gray

L.2.10 Deft APC Topcoat, MIL-PRF-85285 Type I, Flat Medium Gray 36173

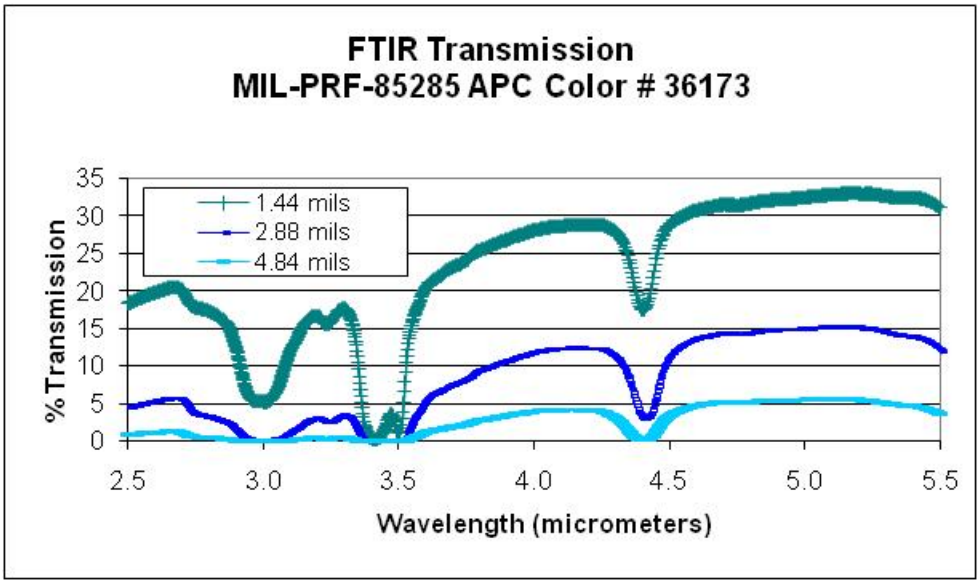


Figure L-24: FTIR Transmission through Deft APC Topcoat, MIL-PRF-85285 Type I, Flat Medium Gray 36173

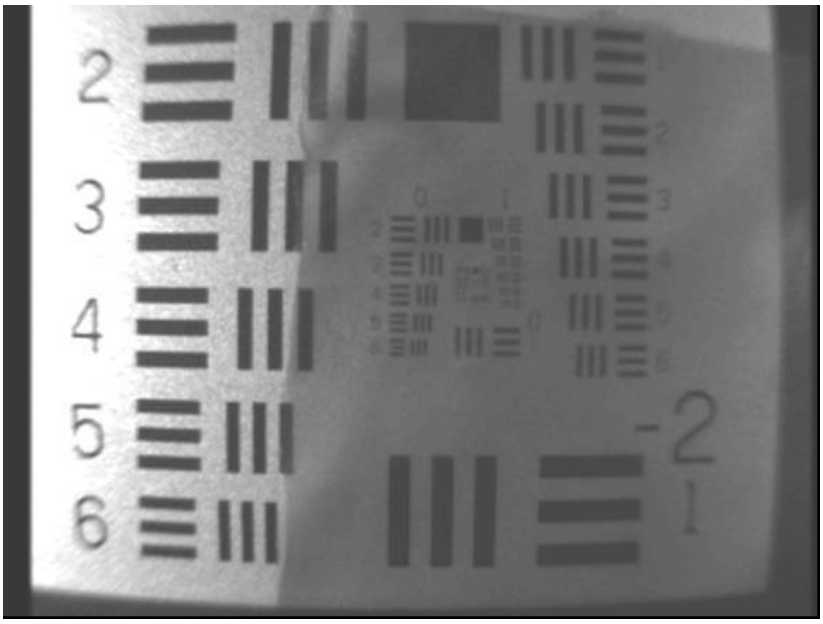


Figure L-25: IRRIT Image of Target Through 1.44-mil Deft APC Topcoat, Flat Medium Gray

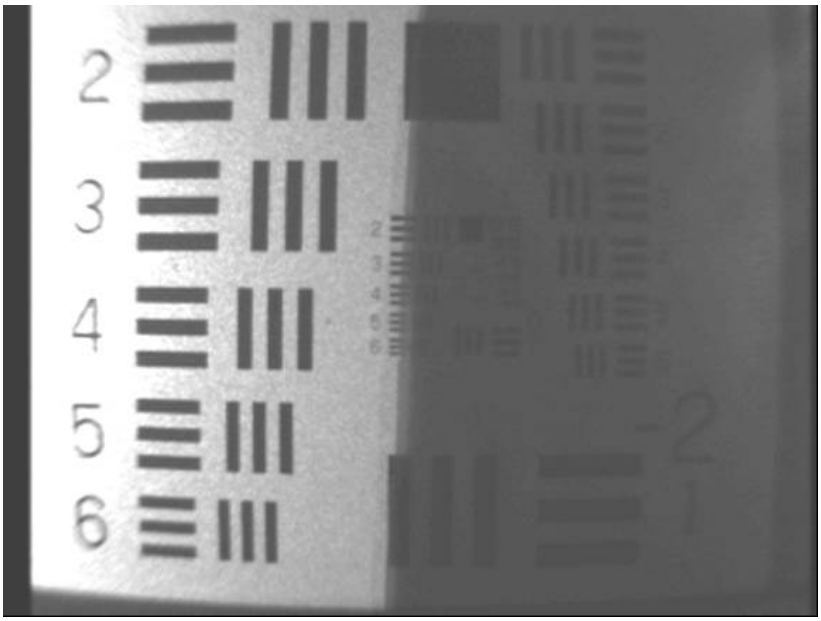


Figure L-26: IRRIT Image of Target Through 2.88-mil Deft APC Topcoat, Flat Medium Gray

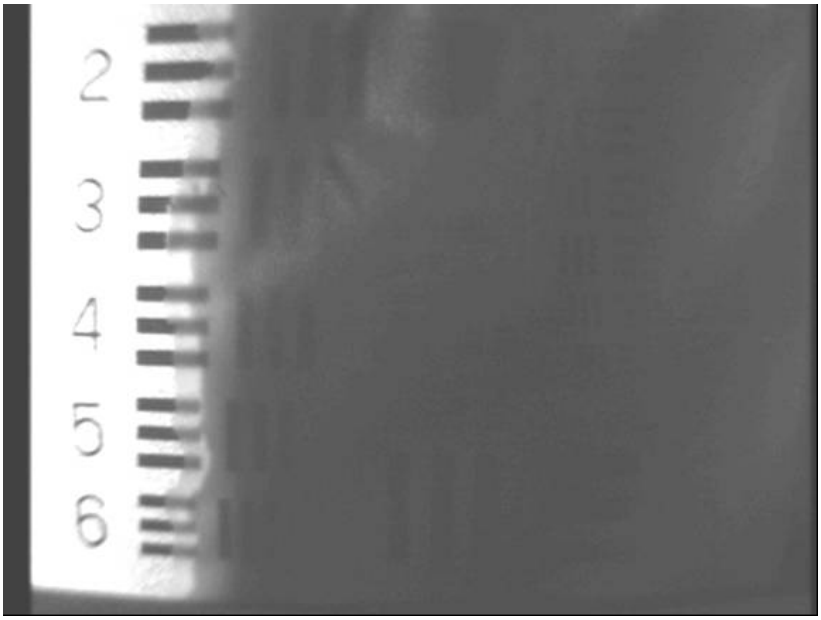


Figure L-27: IRRIT Image of Target Through 4.84-mil Deft APC Topcoat, Flat Medium Gray

L.2.11 Deft APC Topcoat, MIL-PRF-85285 Type I, Flat Dark Gray 36118

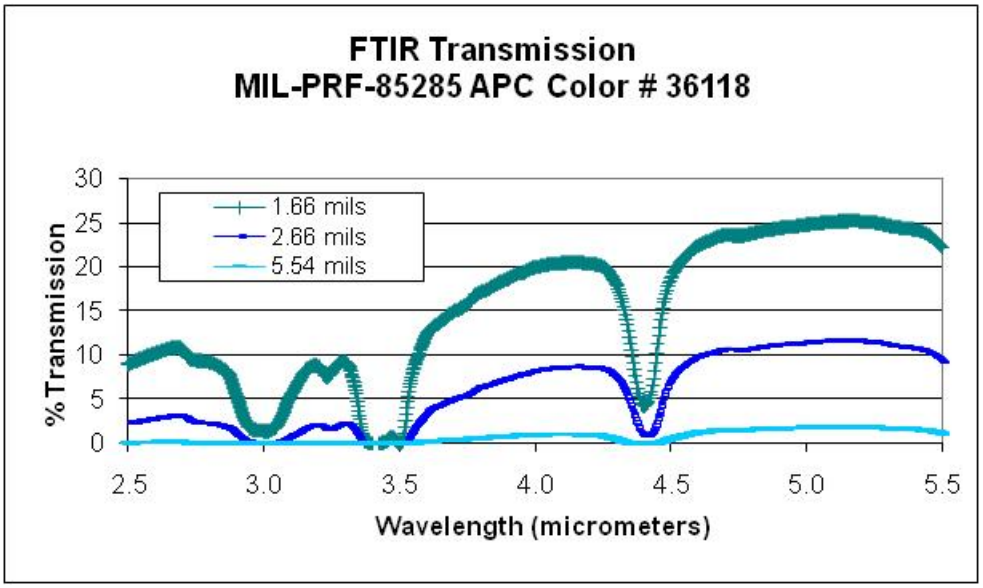


Figure L-28: FTIR Transmission through Deft APC Topcoat, MIL-PRF-85285 Type I, Flat Dark Gray 36118

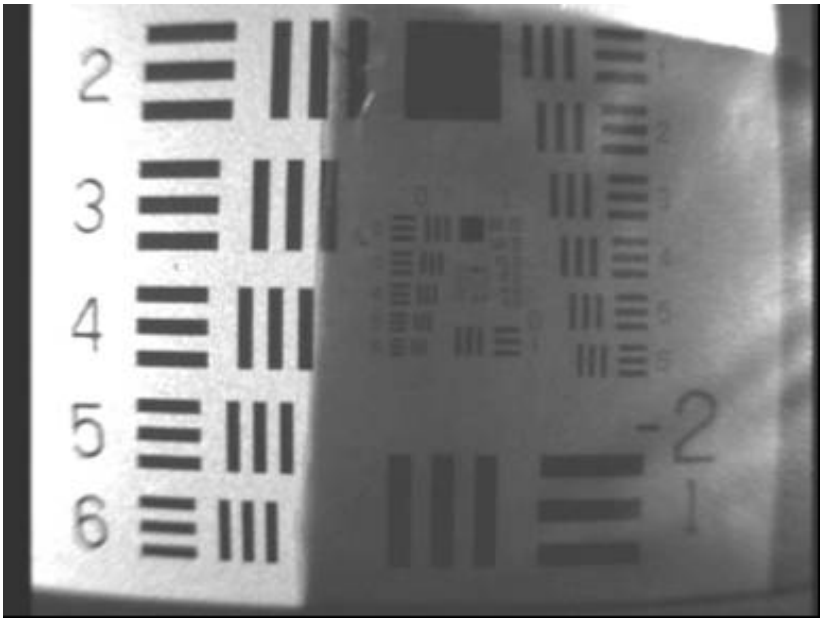


Figure L-29: IRRIT Image of Target Through 1.66-mil Deft APC Topcoat, Flat Dark Gray

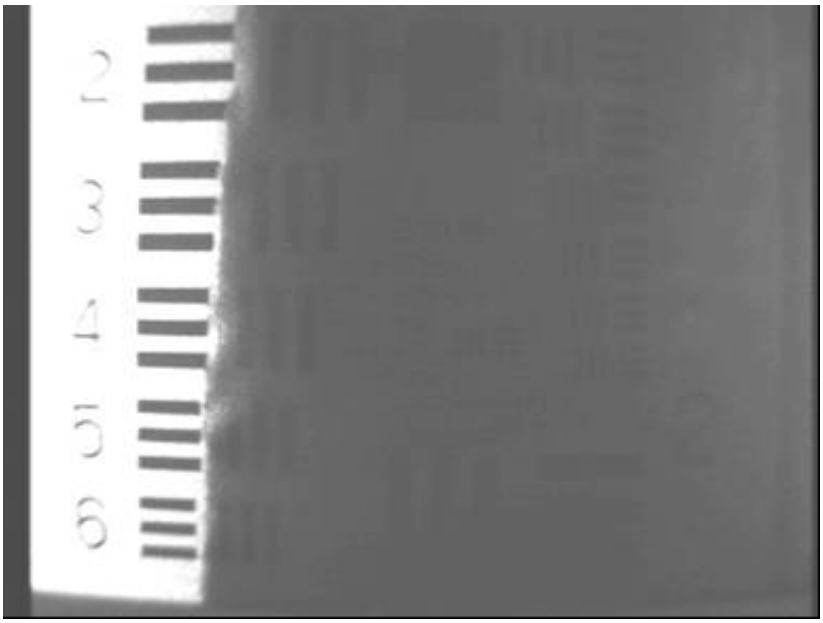


Figure L-30: IRRIT Image of Target Through 2.66-mil Deft APC Topcoat, Flat Dark Gray

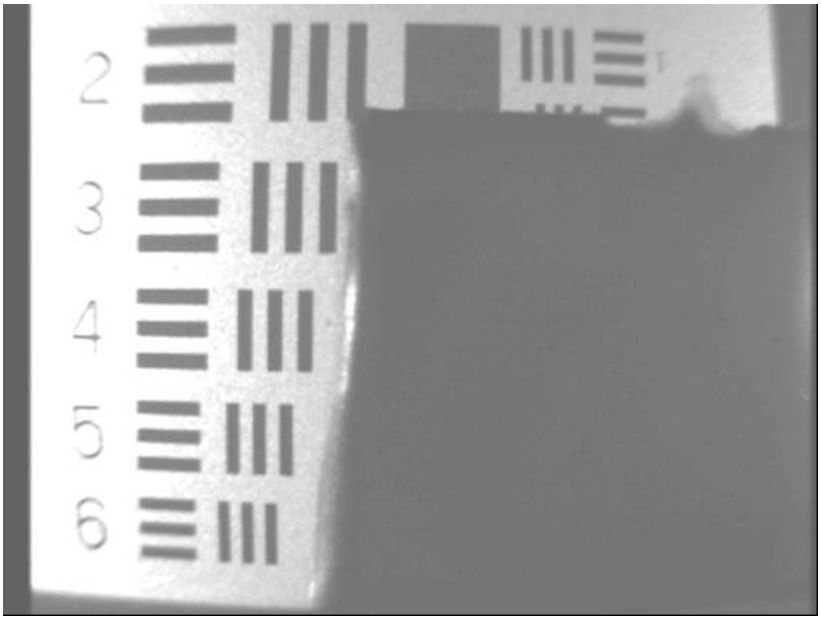


Figure L-31: IRRIT Image of Target Through 1.66-mil Deft APC Topcoat, Flat Dark Gray

L.2.12 Deft APC Topcoat, MIL-PRF-85285 Type I, Flat Light Gray 36375

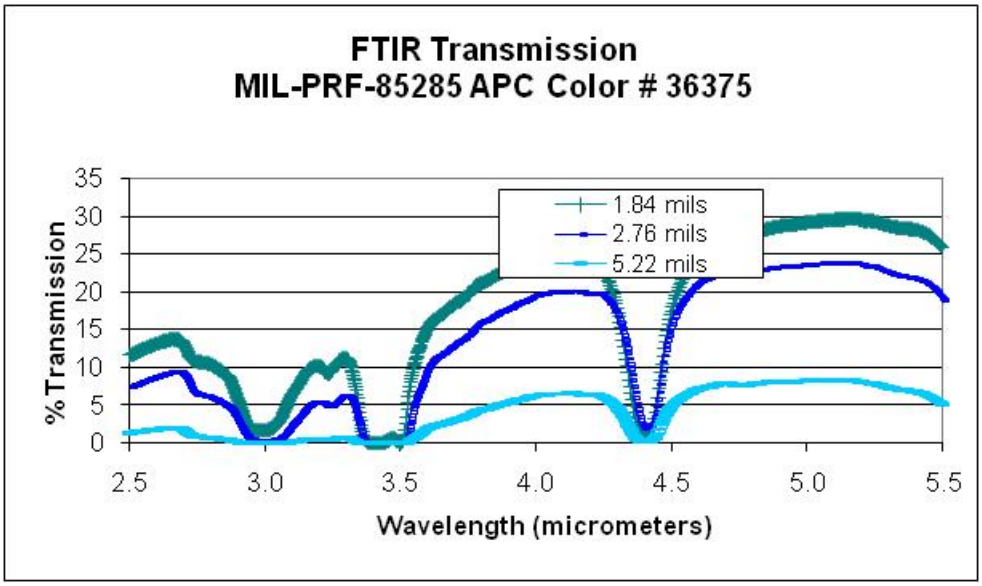


Figure L-32: FTIR Transmission Through Deft APC Topcoat, MIL-PRF-85285 Type I, Flat Gray 36375

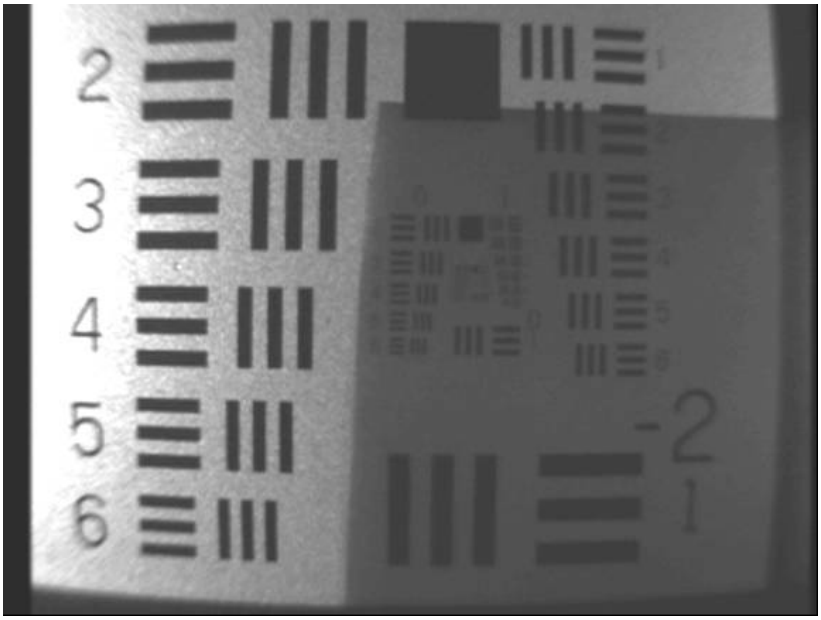


Figure L-33: IRRIT Image of Target Through 1.84-mil Deft APC Topcoat, Flat Light Gray

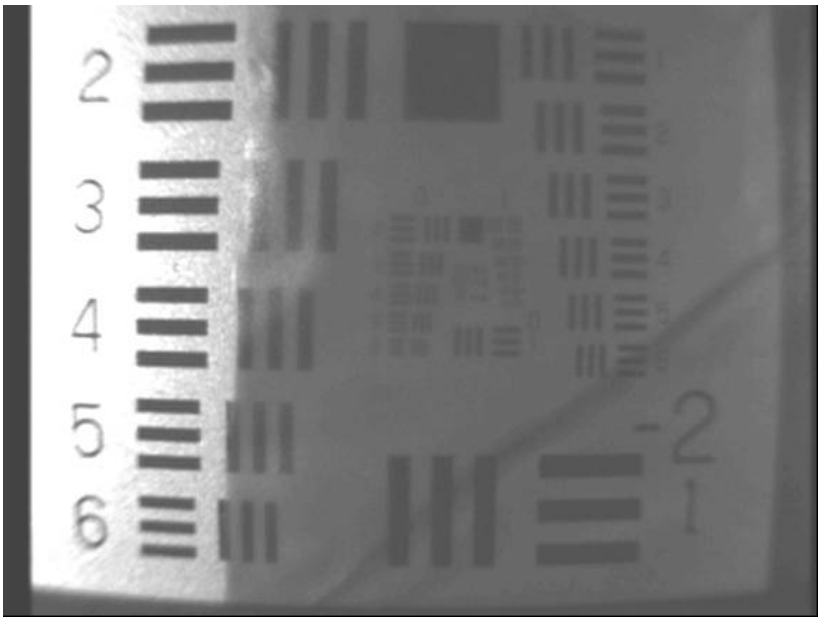


Figure L-34: IRRIT Image of Target Through 2.76-mil Deft APC Topcoat, Flat Light Gray. Note Diagonal Wrinkle in Film.

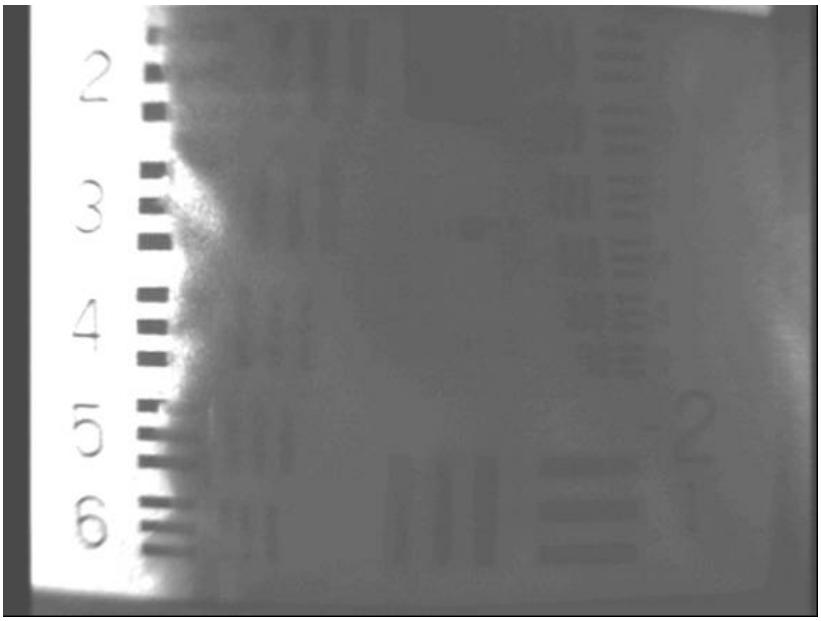


Figure L-35: IRRIT Image of Target Through 5.22-mil Deft APC Topcoat, Flat Light Gray

L.2.13 PRC-DeSoto CA8110 Anti-Chafe Coating, Flat Light Gray

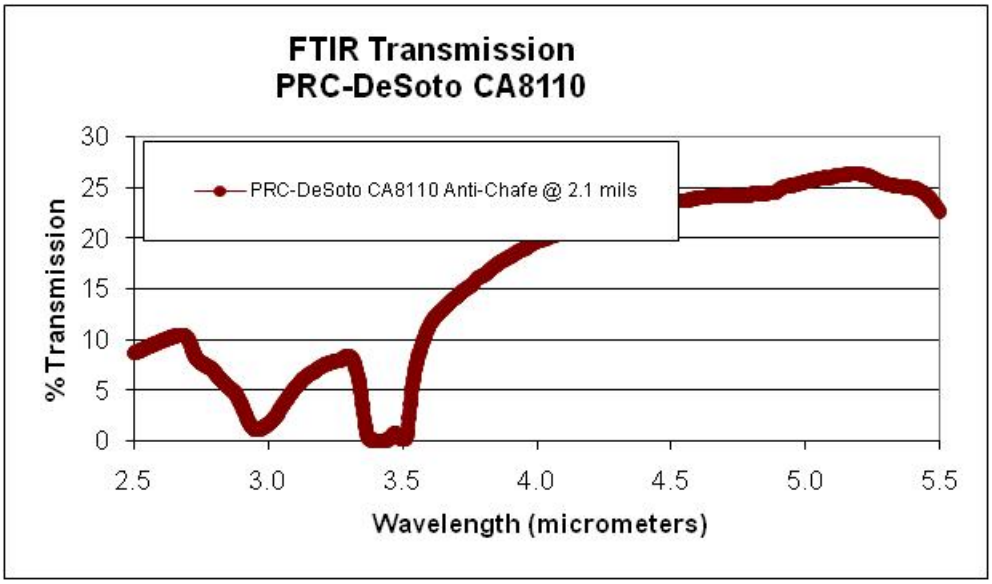


Figure L-36: FTIR Transmission PRC-DeSoto Anti-Chafe Coating, Flat Light Gray

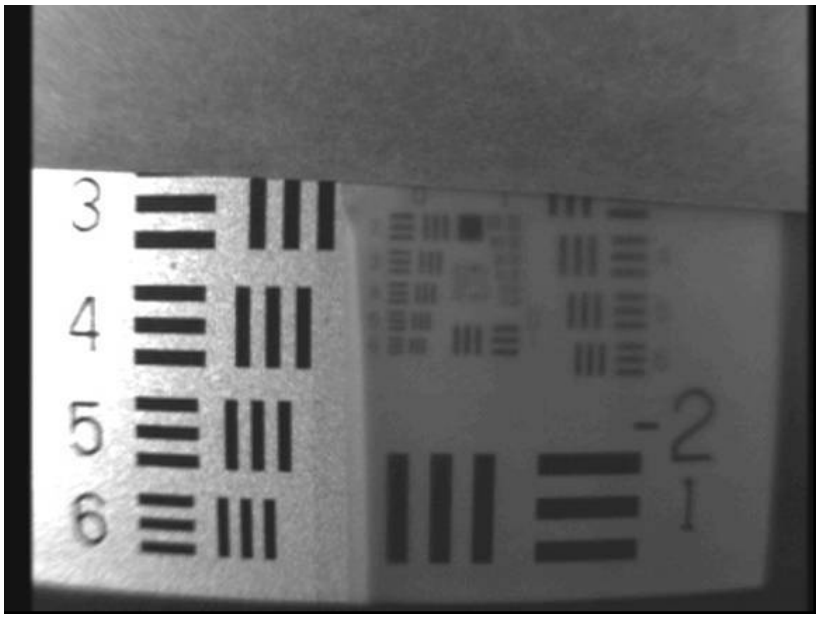


Figure L-37: IRRIT Image of Target Through 1.62-mil PRC-DeSoto Anti-Chafe Coating, Flat Light Gray (Lower Right) and PostIt™ Note (Top)

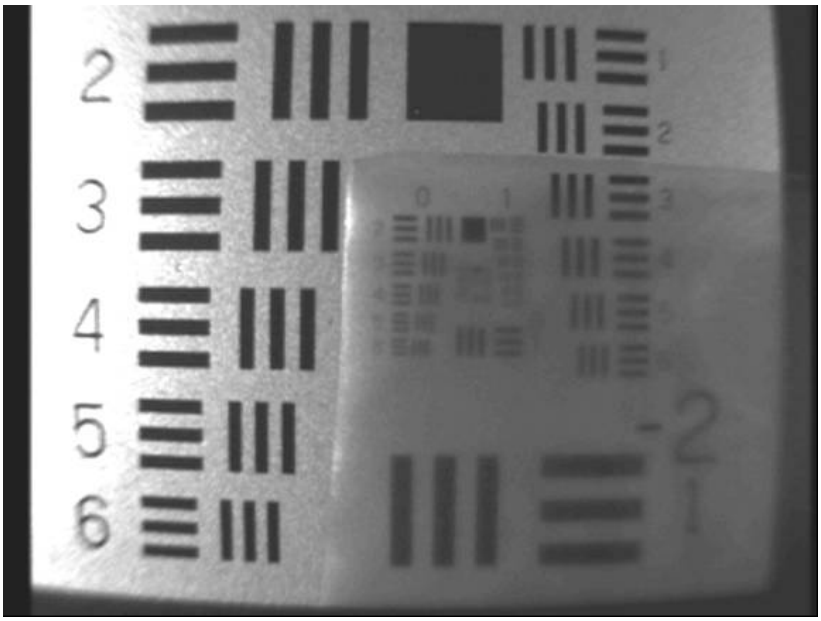


Figure L-38: IRRIT Image of Target Through 2.1-mil PRC-DeSoto Anti-Chafe Coating, Flat Light Gray

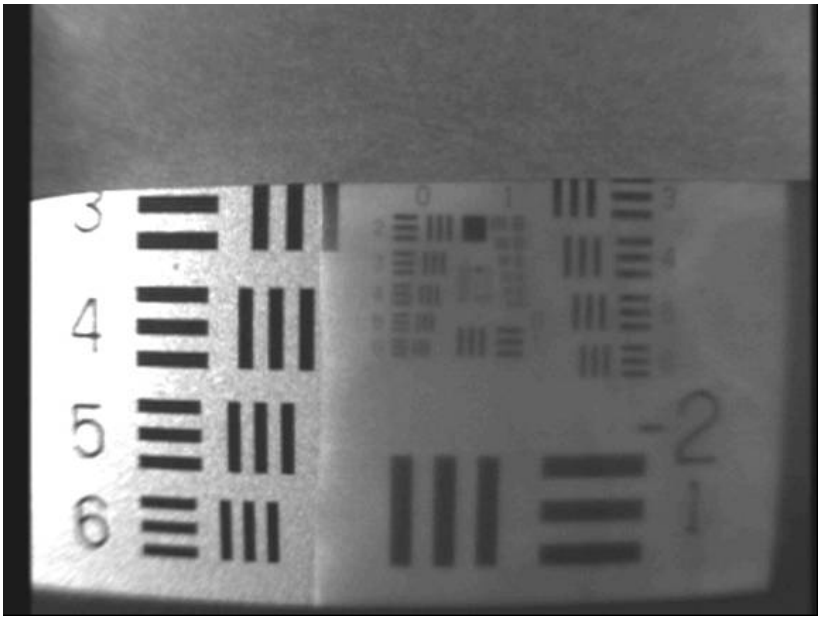


Figure L-39: IRRIT Image of Target Through 2.1-mil PRC-DeSoto Anti-Chafe Coating, Flat Light Gray (Lower Right) and PostIt™ (Top)

L.3 CONCLUSIONS

Based on the data acquired from the free-standing films (both the IR transmission scans and the IRRIT images), it has been concluded that the IRRIT system had success in imaging through all of the coatings tested when applied to the proper military specification thickness (i.e., 1.7 to 2.3 mils for MIL-PRF-85285 Type I). These coatings include the following:

- Corrosion Preventative Compound (CPC), SO SURE® MIL-C-85054B Type I Class 134A
- CPC, LEKTRO-TECH, Inc., MIL-L-87177A Type I Grade B
- CPC, SO SURE®, MIL-C-81309E Type II Class 2 Grade 134A
- CPC, LHB Industries, MIL-PRF-32033
- Rain Erosion Coating, LORD Corporation, Lord M 1433 (MIL-C-85322)
- Low Temperature Cure Powder Coat, Crosslink Powder Coatings, Inc.
- Self-Priming Topcoat, Deft TT-P-2756 Type I (3 colors)
- Advanced Polyurethane Coating (APC), Polyurethane Topcoat, Deft, MIL-PRF-85285 Type I (3 colors)
- Anti-Chafe Coating, PRC-DeSoto

However, on USAF aircraft the thickness of the APC's (or ELT's) were sometimes seen in the range of 2-3 times the proper military specification thickness (based on coating thickness measurements that were obtained at WR-ALC and OC-ALC). Therefore, in scenarios where the coating thickness is above the proper military specification thickness, the IRRIT system compatibility must be evaluated on a case-by-case basis. In the case of APC Color # 36173 and APC Color # 36375, the IRRIT system had success in imaging a thickness of up to 5 mils. Although, the darkest of the APC's tested, Color # 36118 only showed success up to 2.66 mils. The IR transmission data illustrates that the thicker and darker coatings do not allow high percentages of MWIR to transmit through them, these same coatings also when imaged with the IRRIT system act as filters, sometimes blocking either all or a large percentage of the MWIR. It should also be noted that the coatings tested were in the form of free-standing films. In the case of the APC's or ELT's which require a primer, the addition of the primer would lower the percentage of the MWIR transmission.

In conclusion, this appendix illustrates that the IRRIT system could be used for inspecting aircraft that utilize these specific coatings when applied to the proper military specification. In this scenario, the IRRIT system stands to offer a substantial amount of pollution reduction.