What is AFIRM?

- **AFIRM = ASIP + FSIP**
  - ASIP = Aircraft Structural Integrity Program
  - FSIP = Functional Systems Integrity Program

- **Marriage of Structures and Systems Methodologies ensures the most cost-effective means of Reliability Management.**
  - (A systems component time-changed during PDM is much more cost effective than having an aircraft stranded at a remote base waiting for parts)

- **Effective management of aging aircraft requires an aggressive maintenance plan coupled with comprehensive fleet data.**
  - ASIP and FSIP Managers have access to real-time and archival data
  - Data can be used to manage the entire fleet as well as an individual aircraft
Goals of AFIRM

- Ensure Flight Safety
- Improve Mission Reliability
- Reduce Operation and Maintenance Costs
- Provide a source for an expanding knowledge base
- Consolidate everything needed to manage the fleet into one place
Consolidation of Information

Daily Status Updates

Usage Data

AFIRM

Technical Manuals

Analyses

Historical Databases

Bulletin Boards
C-5 Fleet Summary

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Total A/C in Service: 112  17,715

- "A" Models: 60  19,357
- "B" Models: 50  15,813
- "C" Models: 2  16,002

9 A/C are currently at Robins AFB
5 A/C are currently at LM Aero
64 A/C are currently NMC or PMC
2 A/C have been reassigned in last 90 days
14 A/C are retired

Monthly Flying Hours Report: By A/C | By Base

Copyright 2005 Lockheed Martin Corporation
### Monthly Flying Hours Report

#### By A/C

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#### By Base

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AFIRM = ASIP + FSIP
FSIP Integrated Database

- MTBF
-Serialized Tracking
- ISO / HSC Evaluations
-Top NMC Drivers
-WUC Alerts
-Air Abort Data
-Bulletin Boards
-In-Depth Analyses
• Reference Items

  - Major Reports

    • ASIP Master Plan

    • Force Structural Maintenance Plan (FSMP)

    • Durability & Damage Tolerance Analysis (DADTA)

    • Annual LM Aero ASIP Reports

    • All Major Reports can be searched by keywords
<table>
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<tr>
<th>Report</th>
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• Reference Items (continued)

  – TO 1C-5A-6 (Scheduled Inspection and Maintenance Requirements)

  – Work Unit Code (WUC) Diagrams (-06)

  – Work Unit Code (WUC) Master List
• **Databases**

  - AFTO95 Historical Data
  - -6 Special Inspection & Time Change Items
• Databases (continued)
  
  • Structural Audit Program
  
  • Teardown
  
  • Torque Deck Replacement Status
• Analysis

  • Durability and Damage Tolerance Analysis
• Analysis (continued)

• Individual Aircraft Tracking (IAT)
ASIP Menu Options - Usage

• Usage
  • Force Usage Monitoring Diagram
  • L/ESS Aircraft Summary (Loads Environment Spectra Survey)
  • Quarterly Fleet Usage Summary
  • Tinker L/ESS Program
• **Bulletin Boards**
  • Structures
  • Corrosion
  • Miscellaneous
What’s Ahead?

• Maintenance Data Collection System
  – Consolidates the following data
    • NDI Log
    • AFMC 202’s (Technical Assistance Requests)
    • T.O. 00-25-107 (Tech Manual for Requesting Maintenance Assistance)
    • AFTO 349
    • AFTO 95 Corrosion Data
    • AFTO 427 Integral Fuel Cell Repairs
    • Structural Audit Findings

  – Repairs will eventually be accessed through graphical user interface
Summary

• The AFIRM web site has become a valuable tool in C-5 community

• Helps control costs, increase reliability, and improve fleet safety

• Combines everything needed to manage the fleet in one place

• Provides a user-friendly interface to USAF data such as G081.

• The site is constantly expanding and will continue to improve in order to meet the changing needs of the ASIP / FSIP managers.
Updating the C-130 Force Structural Maintenance Plan For Improved Fleet Management

ASIP 2005
01 December 2005

Kenneth L. Taylor, PhD
Mercer Engineering Research Center

Peter Christiansen
USAF, Warner Robins Air Logistics Center
Acknowledgements

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  – Mr. Brian Harper
  – Robert McGinty, PhD
  – Ms. Mary Schleider, PE
  – Mr. Greg Wood
Agenda

- Overview of FSMP
- Rebaselining ASIP critical inspection intervals
- Crack history database
- IATP (AIRCAT)
- Continuing efforts

FSMP = Force Structural Maintenance Plan
ASIP = Aircraft Structural Integrity Program
IATP = Individual Aircraft Tracking Program
AIRCAT = Automated Inspection, Repair, Corrosion, and Aircraft Tracking
  • AIRCAT is the USAF’s IATP for the C-130 fleet
Agenda

- Overview of FSMP
- Rebaselining ASIP critical inspection intervals
- Crack history database
- IATP (AIRCAT)
- Continuing efforts
Overview of FSMP

- Aircraft Structural Integrity Program (ASIP) requires a Force Structural Maintenance Plan (FSMP) * to drive:
  - Inspections (when, where, how)
  - Force structure planning
  - Maintenance planning
  - Capture aging/damage data
  - Analytical Condition Inspection program
  - Structural teardown program
  - Repair criteria
- Update as required

* MIL-STD-1530C, Section 5.4.3

MIL-STD-1530 C (01 November 2005) defines the goals, objectives, and tasks of an ASIP program.

Noteworthy sections include:

- **5.1.1** ASIP Master Plan
- **5.4.3** FSMP.
  - **5.4.3.1** Structural Maintenance Database
  - **5.4.3.2** Inspections, intervals, methods
  - **5.4.3.3** Surveillance (ACI and structural tear down)
  - **5.4.4** Loads/Environmental Spectra Survey
  - **5.4.5** IATP
- **5.5** Force Management Execution, including the role of the IATP
Overview of FSMP

• MERC engaged in activities to update elements of the C-130 FSMP in accordance with ASIP requirements
  – Rebaselining ASIP critical inspection intervals
  – Crack history database
  – IATP (AIRCAT)
Agenda

- Overview of FSMP
- Rebaselining ASIP critical inspection intervals
- Crack history database
- IATP (AIRCAT)
- Continuing efforts
Rebaselining ASIP critical inspection intervals

- ASIP tracking points are critical locations that are the focus of:
  - Damage Tolerance Analysis (DTA) crack growth curves
  - Non-Destructive Inspection (NDI) procedures

- Baseline DTA sets NDI intervals in equivalent baseline hours (EBH)
  - Initial inspection occurs at half the baseline safety limit
  - Recurring inspections occur at half the remaining baseline time

- Actual flights are categorized with a spectrum and DTA
  - Each flight has duration (AFH) and a baseline equivalent (EBH)
  - Aircraft tracking point history is plotted as AFH vs EBH (cumulative)
  - Severity Factor (SF) is the slope of the AFH vs EBH curve

- Rebaselining process establishes NDI intervals in AFH
  - Determine a stable, accurate method for determining SF
  - Evaluate SF for all aircraft, all tracking points
  - Set inspection intervals per MDS groups

MIL-STD-1530-C, Section 5.5.1, requires the IATP to determine EBH for each aircraft, and to adjust the inspection, maintenance, and replacement schedules for each component accordingly.

EBH is the standard or baseline measurement of the tracking point status
AFH is the actual airframe flight hour accumulation
SF is the conversion between EBH and AFH
Inspection intervals are derived in theoretical time (EBH) and scheduled in directly measurable time (AFH).
The rebaselining process for a given inspection translates the EBH interval into customized AFH intervals based on considerations of the specific mission history severity for each aircraft within the MDS.
Rebaselining ASIP critical inspection intervals

- Develop better inspection intervals with accurate severity factors

Each flight possesses a known AFH increment and a derived EBH increment for each ASIP tracking point, based on the mission parameters of that flight.

- The history may be summarized by the cumulative EBH vs AFH plot
- The SF is the slope of this plot
- The plot is not a straight line for all time, due to variation in mission types

Rebaselining requires a reliable, robust method of calculating severity factor from the EBH vs AFH plot.

- The efficacy of a SF calculation method can be tested by going back to a given point in time and evaluating the error when forecasting forward from that point
- Lookback window defines how much of the total historical data to use in the SF calculation.
- Prediction window defines how far forward in time the forecast is to be made.
Multiple methods were considered candidates for SF calculation. Multiple look-back window sizes were considered for each calculation method.

- Shorter windows respond to trends faster, but also over react to transients
- Longer windows are slow to detect trend changes, but tend to attenuate the effects of spurious transients

To ensure the method was not customized for an outlier:

- Data from multiple tails were considered (representative of various MDS in the fleet)
- Data from multiple tracking points were considered
- Multiple projection points were considered (i.e. the point defining the end of the lookback window and the beginning of the forecast window)
To compare results, the forecasting error was normalized for each choice of tail, component, method, lookback window, forecast window, and choice of projection point.

- A root mean square value of the normalized error was determined for the range of projection points and tails
- The result is an error metric encompassing the effects of different tails and points in history
- Plotting this metric as a function of the lookback window enables comparison of the different methods
Rebaselining ASIP critical inspection intervals

- Secant method using 1500 AFH lookback window chosen as prediction method for individual aircraft SF
  - Most robust predictor based on minimal normalized error and stability

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The error metric results were renormalized and averaged across the tracking points at a given lookback window value.

The result was a single metric value that encompasses not only the different tails but the different components as well.
Rebaselining ASIP critical inspection intervals

- Rebaselining ASIP critical inspection intervals
  - SF’s calculated with 1500hr secant method for all component zones, all active aircraft
  - Representative component zone SF chosen for each MDS group
  - Inspection interval ranges established for each NDI procedure

The SF values for a component zone and all the tails within an MDS group was examined. The max value was noted, as well as the mean plus three sigma value. The representative value was selected to be the smaller of the two.

The representative value was then used to convert the inspection interval from EBH to AFH.
Rebaselining ASIP critical inspection intervals

Severity factor distribution for all C-130E, Component Zone OW-1

The choice of a representative value facilitates scheduling inspection by MDS group.
It is customized for that MDS group because it only considers those tails within the group.
It is conservative in that it forces early inspections for the majority of the tails in the MDS group.
The inspection method and area being inspected establishes the crack probability of detection (POD), and a maximum crack size that can go undiscovered (aNDI).

The baseline DTA defines a time tNDI (in EBH) that corresponds to aNDI.

The recurring interval (in EBH) is defined as half of time between tNDI and the safety limit. This is accordance with MIL-STD-1530-C 5.4.3.2.1.

This recurring interval is converted to AFH using the representative SF.

For scheduling purposes, this time will need to be rounded. To provide a measure of the sensitivity of the interval to rounding, lower and upper bounds may be calculated using 40% and 60% of the time between tNDI and the safety limit.
Agenda

• Overview of FSMP
• Rebaselining ASIP critical inspection intervals
• Crack history database
• IATP (AIRCAT)
• Continuing efforts
Crack history database

- Database for logging crack findings
- Embedded within AIRCAT
- Crack findings mined from multiple sources:
  - Engineering assistance requests (107s, 202s)
  - Failure analysis reports
  - Wing durability reports
  - CW teardown reports
- Specific information sought:
  - Tail number/serial number
  - Date of discovery
  - Crack size/location/orientation
  - Multi-element-damage/multi-site-damage assessment
  - Documentation, images, photos, etc.
- AIRCAT determines AFH, EBH, SF at time of discovery

MIL-STD-1530-C 5.4.3.1 prescribes a database for capturing aging process information.

Advantages of embedding the crack history database within AIRCAT:
- Web-based, accessible worldwide by authorized users for analysis and for entry of new crack events
- Linked to flight history data for updated assessment of AFH, EBH, SF
Web-based form guides user through data entry for complete information capture. Information recorded includes crack size, location, orientation details. The crack record may be linked to other records if it is a part of a multi-site damage (MSD) or multi-element damage (MED) event. Other documentation, photos, etc. may be electronically attached to the form.
The crack data is available for analysis via numerical and graphical methods. Shown here is a 3-D plot of the center wing lower surface crack discovery locations, the locations of the DTA points, and the areas covered by the NDI procedures. This permits evaluation of the inspections and DTA locations with respect to where the cracks are actually occurring.
In this plot, information for cracks for a specific component zone have been extracted from the crack history database. Each crack may be plotted using its length and EBH at time of discovery as coordinates. The DTA crack growth curve used to track the component zone is then superimposed on the data.

For a given crack length, the ratio of the DTA curve EBH to the EBH at the time of discovery is a measure of the effectiveness of the analysis. Here, the ratios are less than unity. The DTA is conservative, because the crack sizes at the time of discovery are smaller than the DTA predicts.

A cumulative distribution function plot of the error ratio shows the probability of the analysis being conservative.
Agenda

- Overview of FSMP
- Rebaselining ASIP critical inspection intervals
- Crack history database
  - IATP (AIRCAT)
- Continuing efforts
IATP (AIRCAT)

- **AIRCAT (Automated Inspection, Repair, Corrosion and Aircraft Tracking)**
  - USAF C-130 IATP (Individual Aircraft Tracking Program)
- **Oracle database tracking all active, inactive, retired tails**
  - 1.7 million flight records
  - Series-Command-Base-Wing assignment (SCBW)
  - Mission Design Series (MDS), configuration/component history
  - Retirement status
  - Inspection history
  - ASIP critical point fracture growth tracking data

MIL-STD-1530C sections 5.4.5 and 5.5.1 prescribe the functionality of the IATP. Specific aspects include providing flight data for the purposes of adjusting maintenance intervals and component replacement intervals.

Every USAF C-130 flight is logged into AIRCAT. Flight data includes the date, take-off and landing time, tail number. Additionally, parameters describing the various flight segments is also entered (airspeed, altitude, etc.). AIRCAT evaluates these parameters and categorizes the flight with one of several hundred predetermined mission codes. For each mission code, every tracking point has an incremental damage associated with it. The tracking point EBH is determined by summing the increments over the entire flight history and multiplying by the baseline safety limit. In this manner, AIRCAT computes both the airframe hours and equivalent baseline hours for each aircraft, according to the unique flight history of each aircraft.
IATP (AIRCAT)

- AIRCAT is comprehensive database enabling robust analysis for implementing ASIP, FSMP concepts
- Current reporting processes data in AIRCAT to evaluate
  - Airframe hours, equivalent baseline hours
  - FGT (Fracture Growth Tracking), i.e. normalized time accumulation
  - Rates (severity factors, usage rates) for forecasting future events (inspection due, component end of service life)
  - Inspections due, accomplished
  - Grounding, restriction decisions
  - Daily flying rates
  - Squad-based performance

AIRCAT algorithms process the flight data to provide comprehensive, up-to-date usage parameters (flying rates, SF, EBH) for individual tails and ASIP tracking points.

The parameters can be used to forecast when the next inspection is due, or when a component is expected to reach a targeted EBH value that signals the end of its economic service life.

The trends of current flight data can also be used to re-evaluate the inspection intervals. For example, if current flights have shifted towards more severe missions, then the inspections intervals may shorten.
This is an example of an inspection forecasting report. This is run for a specific tail, and can show the status for multiple zones of a given component (in this case, the aft fuselage).

The AIRCAT database can retrieve aircraft fracture growth tracking information at the time the last inspection was accomplished, and based on the inspection interval, usage, and severity factor, make a forecast regarding the next inspection.
IATP (AIRCAT)

- AIRCAT improvements:
  - All flight record chronology from 1987 forward was verified with Air Force Knowledge System (AFKS) data
    - Repaired keying, rounding errors that created extraneous makeup flights
    - Affirmed high confidence levels in AIRCAT usage rates
  - Reviewed base and command history with AFKS records
    - Anomalies identified
  - Verification of inspection and end-of-service life forecasting algorithms
  - Update of inspection accomplishments via TCTO
  - Added capability/framework for embedding ASIP Master Plan and FSMP documents within AIRCAT

AFKS flight data consists of dates and flight hours. These inputs are independent of the AIRCAT flight data inputs and are generally believed to enjoy a higher reporting rate. The AFKS hours are accepted as the defacto correct flight hour records. Synchronizing the AIRCAT history with the AFKS hours brings maximum accuracy and minimal flight rejection to the AIRCAT data. (Note: The other flight parameters required by AIRCAT to categorize each flight are not recorded in AFKS, and are found only in AIRCAT.)

TCTO records (applicability and accomplishment status) are also logged in AFKS. Those TCTOs enacting an ASIP critical inspection were identified, and their accomplishment status extracted from AFKS. The data was reformatted for updating the AIRCAT records of inspection accomplishment.
Agenda

- Overview of FSMP
- Rebaselining ASIP critical inspection intervals
- Crack history database
- IATP (AIRCAT)
- Continuing efforts
Continuing efforts

• Increased automation of fleet management tools, task updates
  – ASIP Master Plan and FSMP document content finalization with automated update capability via links to AIRCAT data
  – 3D graphical depiction of crack, fleet management data
  – Modularity for future data analysis tools
  – Report customization
  – Maintenance data collection
C-130
Inspection Developments

ASIP 2005
01 December 2005

W. Darin Lockwood, PhD
Mercer Engineering Research Center

Peter Christiansen
USAF, Warner Robins Air Logistics Center

Darren Fritz
USAF, Warner Robins Air Logistics Center
Acknowledgements

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  – Mr. Bob Bailey
  – Mr. Daniel Edwards
The purpose of the talk is to provide a look at the current state of the C-130 inspection program and highlight ongoing developments that are being incorporated as a result of current service findings as well as examination of historical data.

Characterize the C-130 inspection program through its components.
Identify current and historical fatigue cracking issues.
Highlight developments being incorporated into an updated inspection manual.
C-130 Inspection Program

- Identification and analysis of critical structure:
  - Durability and Damage Tolerance Assessment (DADTA)
  - Determine baseline Safety Limit
  - Define initial inspection interval (0.5*Safety Limit)

First component of the inspection program is identification of critical structure. Historically, this is done through durability and damage tolerance assessments.

The critical structural element is identified and crack growth analysis is performed.

Results of the crack growth analysis used to define:
- Safety Limit - time for the crack to grow to critical length
- Initial inspection interval - computed as half of the safety limit
C-130 Inspection Program

• Tracking damage growth in critical structure

  – **AIRCAT** is the C-130 IATP
    • Tracks individual flights and categorizes each by FTP code
    • Primary structure organized into component zones (ASIP Tracking points)
    • Each component zone is driven by a DTA which characterizes damage accumulation
      – DTA provides baseline growth rate
      – FTP code assigns growth coefficient for each flight
      – Accumulated growth expressed as EBH
        • EBH = growth / baseline rate

  – **AIRCAT** uses this information to determine inspection intervals

Second component of the inspection program is tracking damage growth in the critical structure. The aircraft contains numerous components that are considered critical from a structural integrity standpoint and these components are tracked on a fleet wide basis via the USAF C-130 Individual Aircraft Tracking Program (IATP) known as AIRCAT (Automated Inspection Repair Corrosion and Aircraft Tracking).

AIRCAT is a web based database system used to track and monitor the fleet on a flight by flight basis. Individual flights are recorded and categorized by a FTP (Fracture Tracking Program) code that essentially describes the type of mission the flight represents.

Critical structure is organized into component zones, where the component defines the major structure (i.e. center wing) and the zones represent further subdivisions of the component (i.e. lower surface spanwise splices). The collection of component zones represents the ASIP tracking points.

Each component zone is driven by a corresponding DTA which characterizes the damage accumulation. DTA provides the baseline growth rate. The FTP code assigns a growth coefficient for flight and the accumulated growth is expressed as Equivalent Baseline Hours (EBH), where EBH is effectively the actual growth divided by the baseline rate.
C-130 Inspection Program

• Inspection Intervals
  – Initial inspection occurs when \( G_{\text{init}} = 0.5 \)
    • \( a_{\text{NDI}} = \) max undetectable crack length
    • For inspection purposes, growth is reset to \( g_{\text{NDI}} \)
  – Recurring inspection interval = \( 0.5 \times (1 - g_{\text{NDI}}) \)

Previously, the initial inspection interval was determined from the crack growth curve as one half the safety limit. On a normalized scale, this translates to when the accumulated growth equals 0.5.

The technique used to perform the inspection has a corresponding \( a_{\text{NDI}} \), associated with a given POD, which describes the largest undetectable crack length. This \( a_{\text{NDI}} \) value is then used to determine the remaining life from which the recurring interval is computed. For inspection purposes, accumulated growth is reset to \( g_{\text{NDI}} \) (determined from \( a_{\text{NDI}} \)) and the recurring inspection interval is set to one half the remaining life (1-\( g_{\text{NDI}} \)) to allow for two inspections prior to the crack going critical.
The third component of the inspection program is the inspection of the critical structure.

AIRCAT currently tracks 91 component zones, which comprise the ASIP tracking points.

The tracking zones are typically representative of the structure associated with the DTA driver and generally cover large areas including the DTA location.

Inspection procedures are assigned to cover the component zones and are tailored to finding expected service cracking.
The relationship between identification of critical structure (DTA), monitoring (AIRCAT), and inspection (NDI) is shown here visually for reference.

AIRCAT tracking zones are defined to monitor damage growth in critical structure.

Ideally:

- AIRCAT utilizes a DTA, from representative structure, as the driver for damage growth in the component zone.

- An inspection procedure is employed that completely covers the intent of the tracking zone and includes the DTA driver.
C-130 Inspection Program

- Review of AIRCAT-NDI-DTA relationship
  - Identification of cases where following criteria not met:
    - Inspection procedure assigned to tracking zone?
    - Inspection covers tracking zone and DTA driver?
  - MERC providing update of existing procedures and development of new procedures as required

- Inspection Schedules and Procedures
  - TO 1C-130A-6 (Scheduled Inspection and Maintenance Instructions)
    - Lists the scheduled inspection intervals for tracking points
  - TO 1C-130A-36 (Nondestructive Inspection Procedures)
    - Schedule not included
    - Instructions and artwork

MERC conducted a thorough review of the relationships between the three components of the inspection program for all of the ASIP tracking points.
The goal of the review was to identifying cases where the following criteria were not met:
- Is there an inspection procedure assigned to the tracking zone?
- Does the inspection procedure adequately cover the tracking zone and include the location for the DTA driver.
As a result of the review, MERC is providing an update of existing procedures and development of new procedures as required.

The inspection schedules and procedures are contained in the following tech orders:
1C-130A-6 contains inspection schedules and maintenance instructions
1C-130A-36 contains the NDI procedures
Fatigue Cracking Issues

- Recent service cracking
  - Increased number and severity of cracks found in lower wing panels, rainbow fittings, spar caps, corner fittings
  - Center wing crack findings led to the grounding of ~30 A/C and the restriction of 60 A/C in early 2005

Recent findings of in-service cracking have identified both an increased number and severity of cracks found in several areas of the center wing box. These areas include flight critical structure such as the lower wing panels, rainbow fittings, spar caps and corner fittings.

The figures at the bottom of the chart represent (from left to right) crack findings in the lower wing panels and the rainbow fitting at the wing joint; corner fitting cracks; and cracks in the lower wing panels under the engine drag fitting and nacelle attach angle.

As a result of these findings, the AF grounded roughly 30 aircraft and placed approximately 60 additional aircraft on restricted flight status.
Fatigue Cracking Issues

• Review of historical data
  – MERC developed Crack History database feature for AIRCAT
    • Utilize AIRCAT’s existing field/depot maintenance and inspection records
    • Include all historical maintenance / test data sources
      – Requests for engineering assistance (107’s, 202’s)
      – Wing Durability Test
      – Wing Teardown Reports
  – Provide ASIP manager with fleet management tool
    • Identify trends
    • Highlight deficiencies

In addition to the current service cracking issues, MERC examined historical data made available through the Crack History database feature in AIRCAT.

The Crack History database is a feature developed by MERC that has been added to AIRCAT as part of the task to update the Force Structural Maintenance Plan (FSMP). It utilizes the existing field and depot maintenance and inspection records that reside within AIRCAT in addition to crack related data mined from historical maintenance and test data sources. The historical data sources used to mine crack data included all available requests for engineering assistance (AF Forms 107’s and 202’s), wing durability test reports and wing teardown reports.

The Crack History database provides the ASIP manager with a valuable tool, which can be used to both identify trends and highlight deficiencies pertinent to the C-130 fleet management in general and the inspection program in particular.
Fatigue Cracking Issues

- Data sample generated from Crack History database
  - Location and distribution of cracks
  - Used to identify potential problem locations and components

The plot shown on this chart provides a sample of the type of information now readily available from the crack history database.

Shown here are crack findings from the C-130 wing durability test plotted over a contour of the center wing boundary. The plot provides a graphical view of the individual crack locations, as well as, the distribution of cracks (colored solid lines) along the aircraft coordinate axes.

This data may be used to identify locations and components of interest.
Fatigue Cracking Issues

• Implications
  – ASIP manager relies on inspection program for comprehensive and thorough coverage of C-130 primary structure
  – Service cracking and extended analysis of historical data have identified need for updating the current inspection program
  – Inspection program update to include:
    • Review of all ASIP critical inspection procedures
    • Procedure modification to improve coverage and confidence in the inspection
    • Development of new procedures to cover problem locations that currently have no inspection

In light of the current inspection program and current trends within the fleet, it is evident that:

(1) The ASIP manager relies on the inspection program to provide comprehensive and thorough coverage of the aircraft primary structure.

(2) Examination of current service cracking and historical data have identified a need for updating the C-130 inspection program.

The inspection program update is to include a review of all ASIP critical inspection procedures with the goal of updating existing procedures to improve coverage and confidence in the inspection, and developing new procedures to cover problem locations that currently have no inspection.
The focus of the inspection program update and the subsequent inspection developments is on providing a revision to the -36 Inspection manual for all ASIP critical inspections. Revisions will include updating all equipment callouts to reflect equipment currently used by the USAF, tailoring of the inspection scope, and improving the instructions and detail in the artwork. Priority is given to center wing inspections, however, this is a work in progress and will eventually include all ASIP critical inspections.

The following slides highlight a few of the developments made in the center wing inspection procedures for the lower surface panels, rainbow fittings, and spar caps.
The center wing contains 3 panels on the lower surface that extend the entire length of the wing box and present an extensive inspection area.

Service cracking has been identified at multiple locations including the panel cutout radii at the wing joint (shown in the figure on the left), panel to rainbow fitting attachments (shown in the figure on the right), and under the engine drag fittings and nacelle attach angles. The existing procedures employed to inspect these areas required updates to address the current findings.

As a result of the crack findings, suspicions arose about the remaining portions of the lower wing panel which were not being inspected. This represents a large inspection area (in terms of number of fasteners) and the AF required a relatively quick response, so MERC developed an inspection procedure utilizing MOI technology to satisfy these requirements.
Inspection Developments

• Lower Surface Panels at Rainbow Fittings
  – Scan all panel fasteners outboard of nacelle attach angle
  – Scan all panel finger radii
  – Scan panel cutouts at corner fittings

• Improved coverage to capture service cracking

The procedure for inspecting the lower wing panels at the wing joint fitting is demonstrated in the figure. Detailed drawings of the structure including fastener and cutout locations landmark references, and actual service cracking locations were incorporated as enhancements.

Eddy current scan paths were added to cover the all fastener holes outboard of the nacelle attach angle, all panel cutout radii, and panel cutouts at the corner fittings.

Resulting procedure provides improved coverage to capture actual service cracking.
Inspection Developments

• Lower Surface Panels under Engine Drag Fittings
  – SEC scan along inboard and outboard edges of drag fittings and nacelle attach angles
  – UT scan all fasteners common to drag fittings and nacelle attach angles

• Improved inspection coverage and capability for detecting hidden cracks

The lower surface panels in the area under the engine nacelles presents challenges in the inspection due to obstructions of the engine drag fittings and nacelle attach angles.

Service crack locations have been added to the drawings as well as detailed fastener locations to provide specific guidance for the inspection.

The procedure has been enhanced with the addition of SEC scans along the inboard and outboard edges of the drag fittings and nacelle attach angles and the addition of ultrasonic scans on all fasteners common to the drag fittings and nacelle attach angles resulting in improved inspection coverage and capability for detecting hidden cracks.
Inspection Developments

- MOI Inspection of Lower Surface Panels
  - Magneto-Optic-Imaging (MOI) system
  - HUD with signal output for image/video capture
  - Fast and effective inspection of major portion of lower surface
  - Allowed USAF to make quick assessment regarding restricted aircraft

The lower panel service cracking caused concern about the remaining portions of the lower wing panels and the AF requested the development of a procedure for examining a large section of the lower wing skin.

A procedure was developed utilizing the MOI system for inspecting a major section of the wing skin from the armpit fairing to the engine nacelle. The MOI system is an eddy current system that allows for visualization of cracks around fastener holes. The unit comes with a heads up display (HUD) as well as signal output for image and video capture capability.

The figures on the right represent the type of crack and no crack images produced using the MOI.

This procedure offers fast and efficient inspection of large portions of the lower surface and allowed the AF to make quick assessment regarding restricted aircraft.
Inspection Developments

- Rainbow fittings, splice angles and attachments
  - Service cracking at multiple locations in wing joint area
  - Rainbow fittings and attachments transfer panel and stringer loads from OW to CW
  - Existing procedures updated

The next location deals with the rainbow fittings, splice angles and stringer attachments in the area of the wing joint.

This structure transfers panel and stringer loads from the outer wing to the center wing and has exhibited service cracking at multiple locations including the scalloped portion of the fitting (shown in the figure on the right) and in radii of the external tangs of the fitting (shown in the figure on the left).
Inspection Developments

• Rainbow fittings, splice angles and attachments
  – Added edge scan along cutouts
  – Expanded inspection to include entire length of attach angles
  – Enhanced images clarify inspection areas

• Improved inspection coverage and capability in detecting service cracks

The inspection procedure for the rainbow fittings, splice angles and attachments is shown in the figures on the right.

The rainbow fitting is a complex component and the inspection procedure required enhancements to the images in order to identify specific inspection locations such as the spotface region shown in the middle figure.

EC scans along the edges of the cutouts were added and the scan of the attach angles was expanded to include the entire length of the angle. Detailed scan paths were added to the inspection as well as the locations of service crack findings resulting in improved inspection coverage and capability.
The final location deals with the wing spar caps. The spar caps run the entire span of the wing box and provide connections for the upper and lower surfaces the front and rear beams of the center wing.

The figure on the left, viewed from inside the wing box, shows cracking in the horizontal and vertical flanges of the spar cap and the figure on the right shows an external view of a crack in the exposed bulb of the spar cap.

Service cracks have been found at multiple locations along the lower forward and aft spar caps and necessitated updates for several procedures.
The procedure for inspecting the lower forward spar caps in the engine dry bays (from wing station 178 to 214) is shown on this slide. It is an internal scan performed inside the wing box.

The inspection procedure was modified to show service crack locations, provide enhanced images for identifying landmarks, and provide better guidance for inspecting around obstructions. EC scans were added to include edge scans at the termination of the spar cap which is obstructed by the corner fitting resulting in expanded and improved inspection coverage.
Inspection Developments

- Lower Spar Caps at WS 80.5
  - Original inspection scanned 6 inboard/outboard of WS 80.5
  - Expanded coverage due to service cracking and historical data analysis
  - Enhanced images reflect accurate geometry and provide landmarks for inspectors

- Improved inspection coverage and detail

A separate procedure for inspecting the lower forward and aft spar caps in the vicinity of wing station 80.5 also required modification.

The original procedure called for EC scans approximately 6 inches inboard and outboard of WS 80.5 However, indicated service cracking and examination of historical findings in this area indicated a need for expanding the inspection area. Analysis of wing durability and teardown reports identified a large portion of the crack findings fell within the range from WS 61 to WS 108.

In addition to expanding the coverage area, new drawings were created to accurately reflect the geometry changes in the structure and provide additional landmarks for the inspectors resulting in improved inspection coverage and detail.
Summary

- Review of C-130 Inspection Program in progress and focusing on ASIP critical tracking points
- Examination of historical and recent findings indicate need for updated inspection program
- MERC teaming with WR-ALC to provide updated NDI manual
- New and improved inspection procedures have enhanced the capabilities of inspectors and reliability of inspections
- Updated inspection program provides the ASIP manager with increased confidence in ability to manage the fleet
Ogden Air Logistics Center

Converting A-10A DTA to AFGROW

December 1, 2005

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- **Hill AFB A-10 SPO and Engineering & Analysis Branch**
Overview

- Objectives
- AFGROW Specifics
- Challenges & Successes
- Precautions and Pitfalls
- Summary
Objectives

Why?
- Extended service life requirement
  - 16,000 hours (Current design = 8000 hours)

Where’s the beef?  
*(What does USAF get out of this effort?)*
- Organic capability with A-10 validated crack growth tool (AFGROW)
- Eliminate reliance on OEM legacy tools

Damage Tolerant Analysis (DTA) & Force Structural Maintenance Plan (FSMP)
- Updated usage *(last update 1993...)*
- Required by MIL-STD-1530 & OSS&E
AFGROW Input

- Material model (da/dN vs. ∆K)
- Spectrum
- Model geometry
- Retardation model
- Others...

Retardation when $r_{ep} > r_p$
Material Model

WHICH MATERIAL MODEL???

- Forman equation
  - Used historically for A-10
- NASGRO equation
  - Built into AFGROW
  - Newer NASGRO updated
- Tabular lookup files
  - Tailored to tested data
    - A-10 materials tested
  - Other available data
    - DTDH
    - MMPDS-HNDBK (MIL-HNDBK-5)
    - USAF data
      - T-37
      - T-38
**Challenges**

- **Forman & NASGRO Equations**
  - Does not account for specific behaviors (i.e., double knee)
  - Curve shifts when $K_c$ changed

- **Tabular Input Files**
  - Pulling $da/dN$ vs. $\Delta K$ data together
    - Large amount of data
    - Variety of sources [M(T), C(T), NaCl, Lab Air, Hz, etc.]
    - Increase in confidence
    - Too little data
      - Did not increase confidence
    - Vary $K_c$ with model thickness without curve shift

\[
da/dN = C\Delta K^n / ((1-R)K_c - \Delta K)
\]

Forman Equation
Material Model

Successes

- Tabular Input Files
  - 76% of control points (CPs)
    - a.k.a: FCLs
  - Increase in confidence
  - Specific A-10 data
  - Stable material models

- Forman Equation
  - Used as default

Material Models Utilized

<table>
<thead>
<tr>
<th>7 Tabular Input Files</th>
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<tbody>
<tr>
<td>2024-T3, 2024-T351, 2024-T3511, 4340 Steel, 7075-T6, 7075-T7351, and 7175-T74 (7175-T736)</td>
</tr>
<tr>
<td>(76% of CPs)</td>
</tr>
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<table>
<thead>
<tr>
<th>8 Forman Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024-T42, AMS 6526, 17-7PH, 7075-T6511, 7075-T73, 7075-T76, 7075-T7651, 7075-T76511</td>
</tr>
<tr>
<td>(24% of CPs)</td>
</tr>
</tbody>
</table>
Material Model Example

Crack Growth-Rate Data
R = 0.1 (2024-T3511 EXT L-T)

Da/dN (inches/cycle) vs. Delta K (ksi sqrt-inch)

- SwRI A-10, R=0.1, Spec LCP-2A
- SwRI A-10, R=0.1, Spec LCP-2B
- SwRI A-10, R=0.1, Spec LCP-4A
- SwRI A-10, R=0.1, Spec LCP-4B
- SwRI A-10, R=0.1, Spec LCP-7A
- SwRI A-10, R=0.1, Spec LCP-7B
- SwRI A-10, R=0.1, Spec LCP-7C
- 2024-T3511 R=0.1 Fit
- NASGROW R=0.1
- Forman R=0.1
- SwRI T-37B (Spec 3-LT-9)
- SwRI T-37B (Spec 3-LT-1)
- SwRI T-37B (Spec 3-LT-1)
- SwRI T-37B (Spec 3-LT-2)
- DTDH-Extrusion, R=0.1
AFGROW standard solutions
- Covered most analyses (97%)

AFGROW user defined
- Requires Beta solutions (3%)

Attention to:
- Aspect ratio for corner crack
  - Constant A/C for analysis
    - A-10 DTA history
- Oblique through thickness cracks
  - Not used for analysis
  - When used with A/C constant
    - Caused AFGROW to hiccup
Retardation Model

AFGROW offers:

- Generalized Willenborg
  - Shutoff Over Load Ratio (SOLR)
  - Default accounts for compression effects.
- Wheeler
- Closure
- Fastran
- Hsu

Generalized Willenborg selected due to previous study by NGC showing it to be the most suitable retardation model within AFGROW to compare with legacy (OEM) crack growth results.

Retardation when \( r_{ep} > r_p \)
General Approach for SOLR Correlation:

- **Coupon tests**
  - Select materials and spectra (CP specific)
  - Varied material thickness and peak stress level
- Not all CPs were tested
- SOLRs were assigned for non-tested CPs based upon engineering judgment and similar testing
- For SOLRs where no like-testing was performed, the SOLR values were back-calculated using the previous DTA results \( \text{[This was done to correlate SOLR with legacy results.]} \)
Retardation Model

- **SOLR Correlation Challenges**
  - **Fracture Mechanics Models:**
    - Testing was performed using a single corner crack at a hole.
      - After a period of growth, a second crack formed at the opposite side of the hole.
    - Since AFGROW does not have an applicable model for this geometry, the SOLR correlations were performed using only the single crack data.

- **Aspect Ratio Variance:**
  - The aspect ratio of the part through crack varied significantly.
  - Because AFGROW does not allow user-specified aspect ratio variance, beta values were determined in NASGRO and StressCheck. These beta values were then entered into AFGROW (user-defined beta option).
SOLR Correlation Challenges

- AFGROW Newman-Raju equation limitations:
  - Part through crack aspect ratio cannot be greater than 2:1
  - Thickness cannot be greater than the hole diameter.
  - Both of these limitations were exceeded by the some specimen coupon tests.
    - These limitations were discovered post test.

- To investigate the effect of exceeding the N-R limitations, the “a” and “c” crack tip betas were compared using AFGROW and StressCheck
  - Ideally, the betas should be the same in both directions

- Stress-Check betas matched, AFGROW did not.
  - This indicated that the N-R limitations may have affected the SOLR correlation.
Things were progressing well...
  - Reconfigured Post Desert Storm (RPDS) spectrum...up to mid 90s
  - Results in the same ballpark as previous spectrum on WCP and OWP

Lower longeron tossed up a RED FLAG!!!
For Lower Longeron Steel Strap @ FS 405 (CP48)
- New spectrum was more severe than previous
- Previous analysis predicted ~12,000 hours of crack growth life
- RPDS was predicting greater than 32,000 hours
- Off by more than 250%
Was not observed on wing analyses…

- RPDS wing spectrum was slightly less severe than previous spectra
- Previous analysis predicted ~10,000 hours
- New analysis predicted 13,700 hours
  - (within expectation)
Typical A-10 Spectrum
- Base-Peak-Base format
  - *Three points define a cycle*
    - Established because of stress sensitivity to aircraft speed.
  - Extra Midpoints
    - AFGROW see more cycles with lower $\Delta K=\text{slower } da/dN$

AFGROW Requirement
- Peak-Base format
  - *Two points define a cycle*

SwRI developed processing software
- Eliminates mid points and redundant bases
- Generates AFGROW specific files
Spectrum

**Lower Auxiliary Longeron**

Steel Strap @ FS 405 (CP48)

- Base stress varied significantly
  - Due to changes in speed

**No Processing**

- Midpoints remain
- Lower $\Delta K$ calculated

**Post Processing**

- Midpoints removed
- Higher $\Delta K$ calculated

**CP48 Equivalent Spectra**

*(No Processing and Post Processing)*

- No Processing
- Post Processing

**Cycle Count**

0 0.2 0.4 0.6 0.8

1 3 5 7 9 11 13 15 17 19 21 23 25

BE AMERICA’S BEST
- **Lower Wing Skin @ WS23 (CP7)**
  - Tension dominated
    - Base stress around 0.12
  - 240 hour block

- **Lower Auxiliary Longeron Steel Strap @ FS 405 (CP48)**
  - Base stress varied significantly
    - Due to changes in speed
  - 240 hour block
Spectrum Issues Solved

- Non Compatible Format Processed and Converted
- Software Developed to Process Spectra Files and Create AFGROW Specific Files
- Results Now within Expectations

![Graph showing crack growth comparison between no processing and post processing.](image)
Precautions & Pitfalls

- Understand Input Files
  - Spectra
    - Formatting a critical requirement
  - \( \frac{da}{dN} \) vs. \( \Delta K \)
    - More or less
  - Retardation
    - SOLR correlation time intensive
      - Note AFGROW (Willenborg) default: accounts for compressive cycles

- Establish Ground Rules
  - Common practices
  - Guides new analysts
Successes

- Strong Technical Team
  - USAF / NGC / SwRI
- Resolved Spectrum Mystery
- Compiled many sources of da/dN vs. ΔK data
- Updated DTA and FSMP to reflect more modern usage
  - Framework exists digitally...
- Increased Organic Capability
  - Digital database of current CPs
  - Improved warfighter support
    - Depot and field support (quick response)
    - Assess usage variations

The A-10 Team
Planning for the Future

- Testing & Experimentation
  - Attention to model constraints
  - Supplement existing data
    - Aircraft specific
    - Lack of previously available data

- Extending Analysis...
  - Repairs
    - Fleet wide
    - Individual aircraft

- Regular Updates
  - Reflecting Updated Usage
Summary

- Objectives Accomplished
  - Organic Capability
  - Updated DTA & FSMP
- AFGROW Requirements Defined
  - Material Model
  - Geometry Model
  - Retardation
  - Spectrum
- Precautions & Pitfalls
- Challenges & Successes
QUESTIONS?

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