330th Aircraft Sustainment Group

Combat Ready, Anytime, Anywhere

C-130 Center Wing Fatigue Cracking Lessons Learned: Application to ASIP Force Management Execution

Peter Christiansen

USAF C-130 ASIP Manager

Outline

- Acknowledgements
- Background
- Center Wing Box
- C-130 ASIP Status through April 2003
- C-130 ASIP Status June 2004
- Center wing independent Review Team and actions taken
- Fleet Sustainment
- Lessons Learned
- Recommendations/Considerations

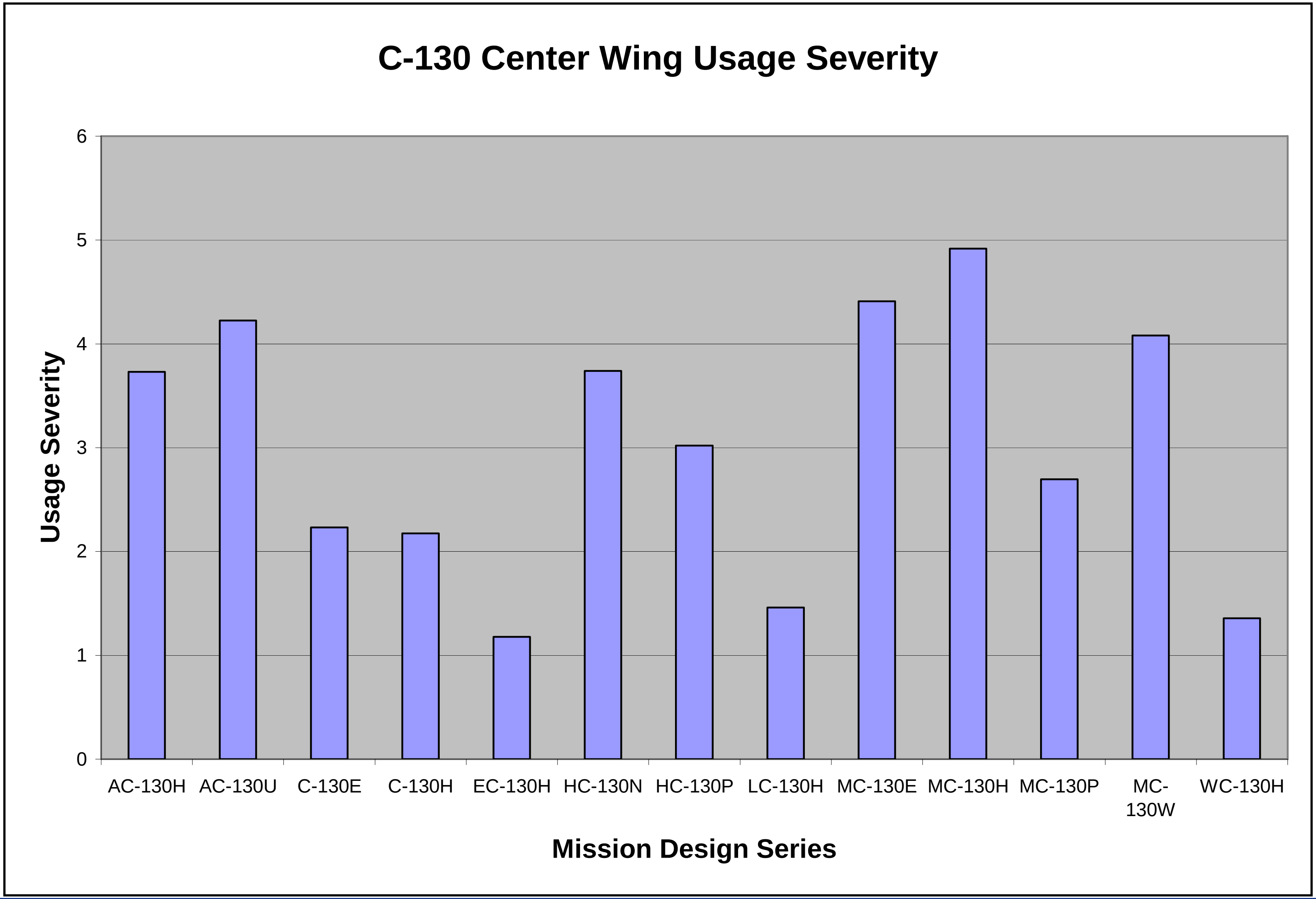
Acknowledgements

- C130 Center Wing Independent Review Team
- Lockheed Martin Aeronautical Systems
- Mercer Engineering Research Center
- CACI
- Center for Aircraft Structural Life Extension
- C-130 ASIP/Center Wing Team (Robins AFB)
- USAF C-130 maintainers and flight crews

C-130 Force Management

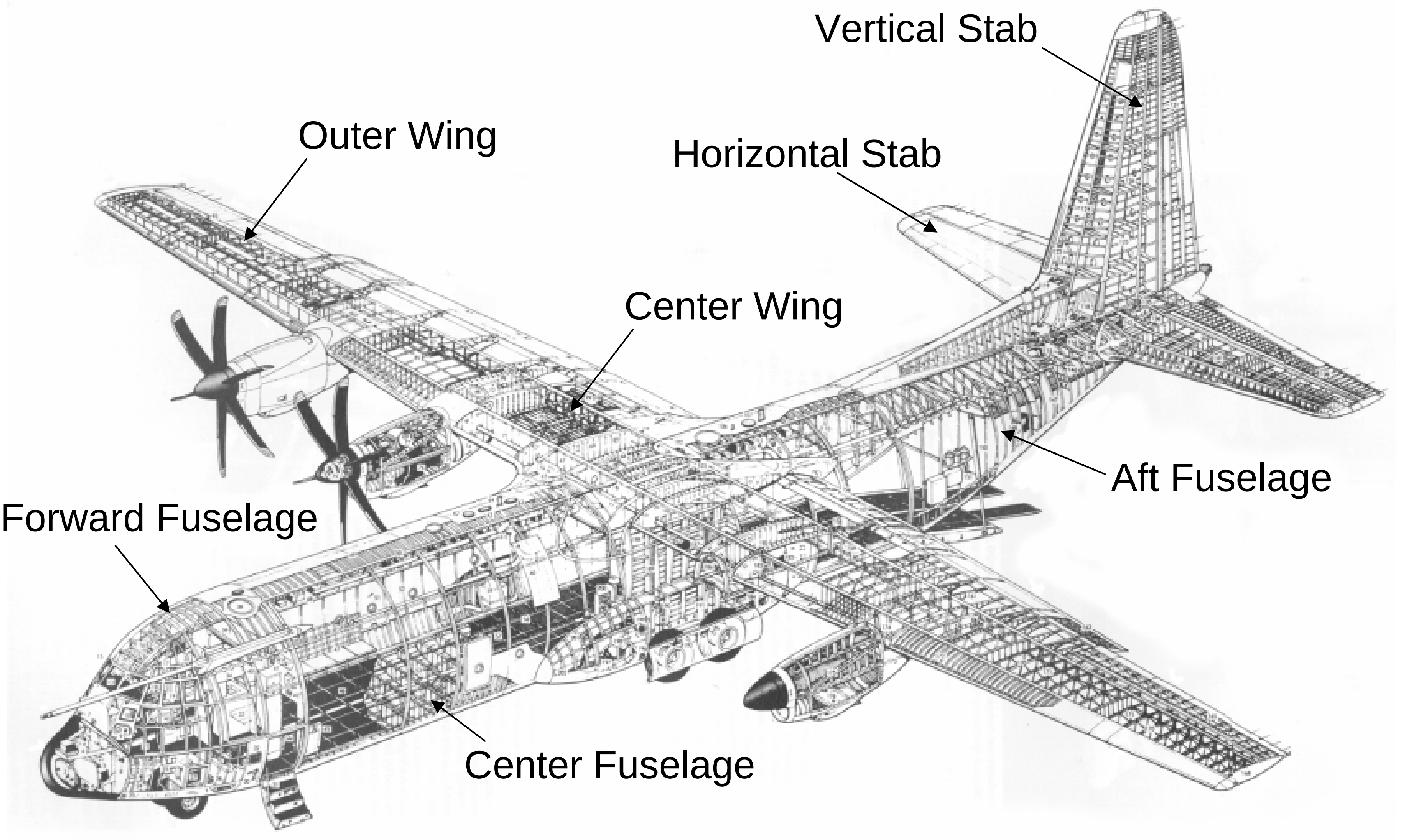
- The USAF C-130 Challenge
  - 47 permanent operating locations
    - Forward operating locations from Antarctica to Iraq
  - 9 Major Commands
  - 18 Mission Design Series
    - C-130E, C-130H, C-130J, AC-130H, AC-130U, EC-130H, EC-130J, HC-130N, HC-130P, LC-130H, MC-130E, MC-130H, MC-130P, MC-130W, NC-130H, TC-130H, WC-130H, WC-130J
  - 600+ active aircraft
    - Aircraft age varies from the first production C-130E (1961) to newly delivered C-130Js
  - Varied usage
    - Unit average flight hour consumption varies from 250 to 950 FH/yr
      - Usage of individual aircraft can vary more significantly
    - Varied Usage Severity

Usage Severity

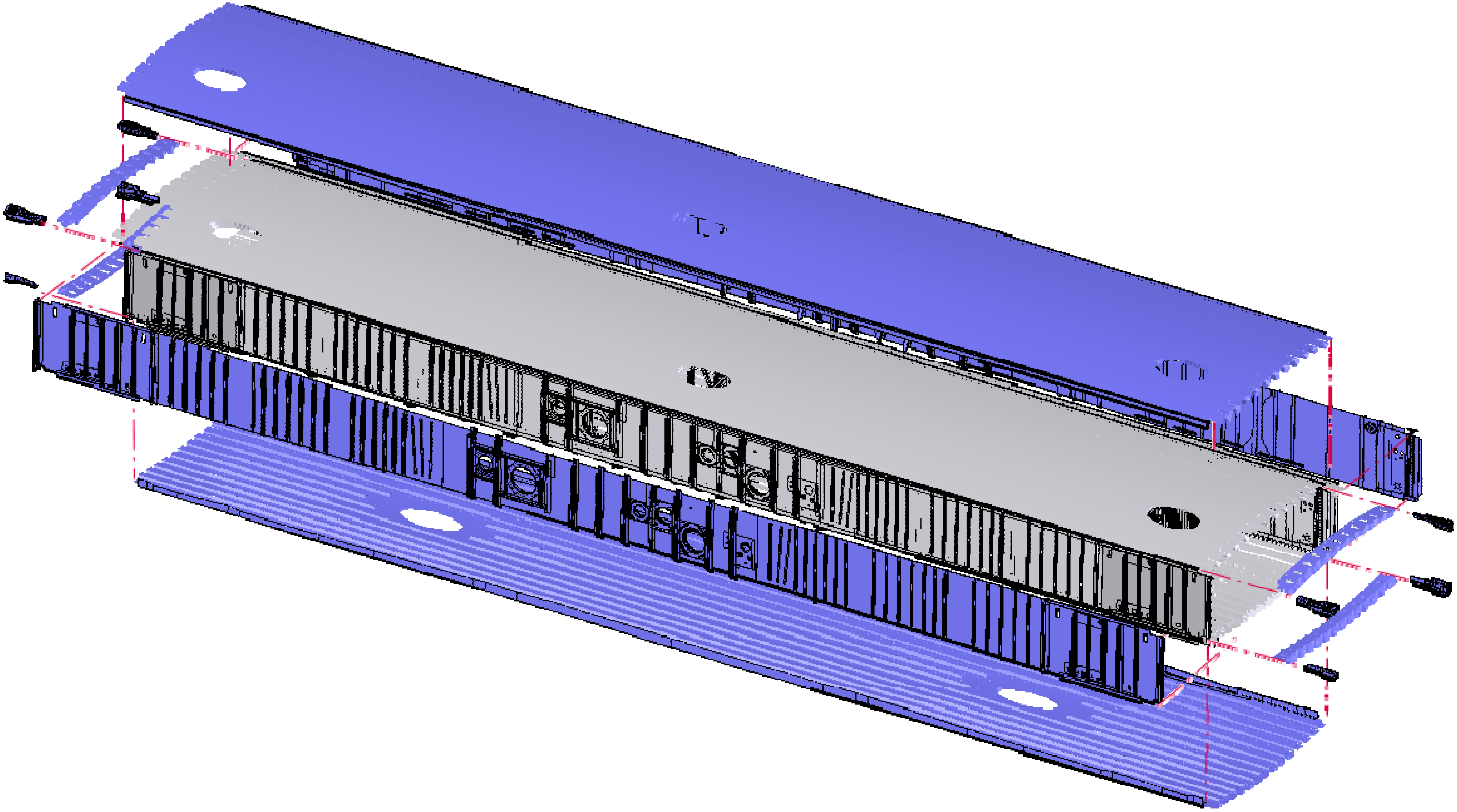


C-130 Center Wing

C-130 Structure



Center Wing Box Structure



Center Wing Box Structure

- Original C-130E center wing found with significant center wing cracking at low flight hours during Vietnam conflict
- Center wing redesigned in 1968 to increase service life
  - Redesigned wing retrofitted to all C-130's worldwide starting in 1968 (except C-130A)
  - Basis for all production wings after 1968 including C-130J
  - Design goal 10K flight hours of Vietnam usage – 27K EBH
  - Thickness of wing panels and stringers increased to reduce overall stress
  - Redesign led to 1150 lb weight increase (from 3800 lbs)

ASIP History prior to April 2003

C-130 IATP History

- Fatigue Life Monitoring – 1968-1986
  - Fatigue based IATP using Palmgren-Miner method
    - Flights categorized in terms of 9 representative missions
- Fracture Tracking Programs
  - DADTA performed 1979-1985
    - Basis for introduction of crack growth based tracking
  - 1986-1999 – IATP maintained on VAX mainframe
    - System discontinued in 1999 due to mainframe obsolescence and Y2K
  - Current system – Oracle based relational database
    - Mission categorization – 1621 missions
      - Gust and maneuver criteria based on L/ESS data (1980-90's data)
    - Initial capability in 2002
      - Numerous deficiencies identified 2002-03
      - System reached required maturity in 2004

Flight Data Reporting

- Flight data reporting prior to 2000
  - Flight engineer completed “bubble” sheet
  - Sheet mailed to ASIP office and scanned via optical scanner
  - Assessment
    - ✓ 80%-90% reporting rate - Minimal effort required to mail sheets
    - X Quality - No opportunity to validate/correct erroneous data
- Flight data reporting 2000 – Present
  - Flight engineer (FE) completes worksheet
  - FE enters flight data into database via internet
  - Assessment
    - ✓ Quality - Input data is validated against various parameters
    - X Reporting Rate - Reporting reduced due to additional effort

Durability Testing

- **C-130 Wing Durability Test (WDT) conducted in 1989-1993**
  - **Flight by flight spectrum (previous testing used block spectrum)**
  - **Test conducted to 60K Cyclic Test Hours (CTH)**
    - **Spectrum developed to produce a severity of 2 (CTH/Baseline)**
      - **At 26K CTH, identified applied loads had overshot targets**
        - Severity believed to be 3 for this period of testing
        - Problem corrected
    - **Center wing loading decreased after 44K CTH due to damage**
  - **Visual inspection predominate inspection method used during testing**
    - **Numerous cracks not identified until end of test**
  - **Selected areas of test article removed, disassembled, and analyzed**
    - **Complete teardown not performed**

Service Life Assessment

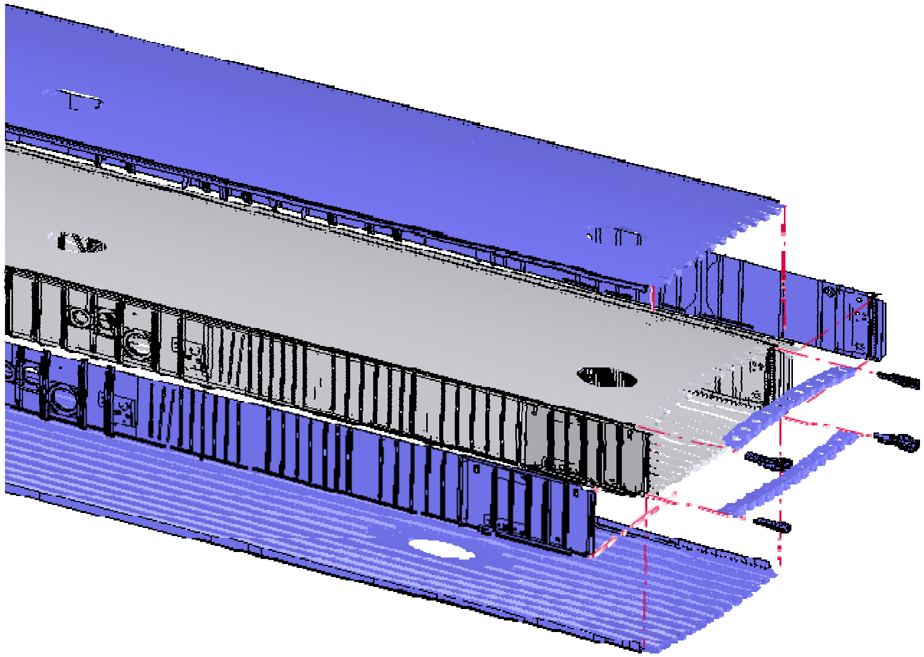
- Service life assessment performed in 1995-1997
  - Economic service life determined by comparison to durability test
    - 50% Probability of Significant Localized Cracking as Determined from Full Scale Durability Testing
      - Localized cracking does not affect safety if inspections are performed at correct intervals and repairs are accomplished
  - Center Wing service life determined to be 60K EBH

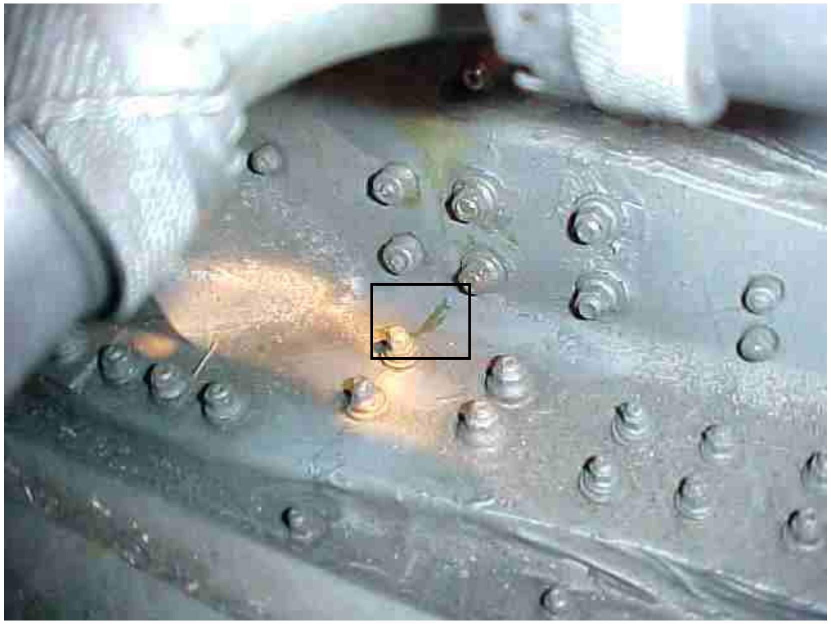
Inspection Program

- USAF C-130s utilize calendar based maintenance program
  - Isochronal inspections
    - Generally required on a yearly basis
      - Inspections accelerated for squadrons experiencing above average flying rates
    - Four work decks with annual, biannual, and 4 year intervals
    - ASIP requirements placed in work decks based upon average flight hours and severity
  - Programmed depot maintenance (PDM)
    - Depot level maintenance program required every 5 years
      - Initial PDM for new aircraft is 15 years (set by Controlled Interval Extension program on C-130H)
    - ASIP inspections performed for difficult to access areas
  - TCTOs issued as required to inspect locations with long recurring inspection intervals

Early Indicators

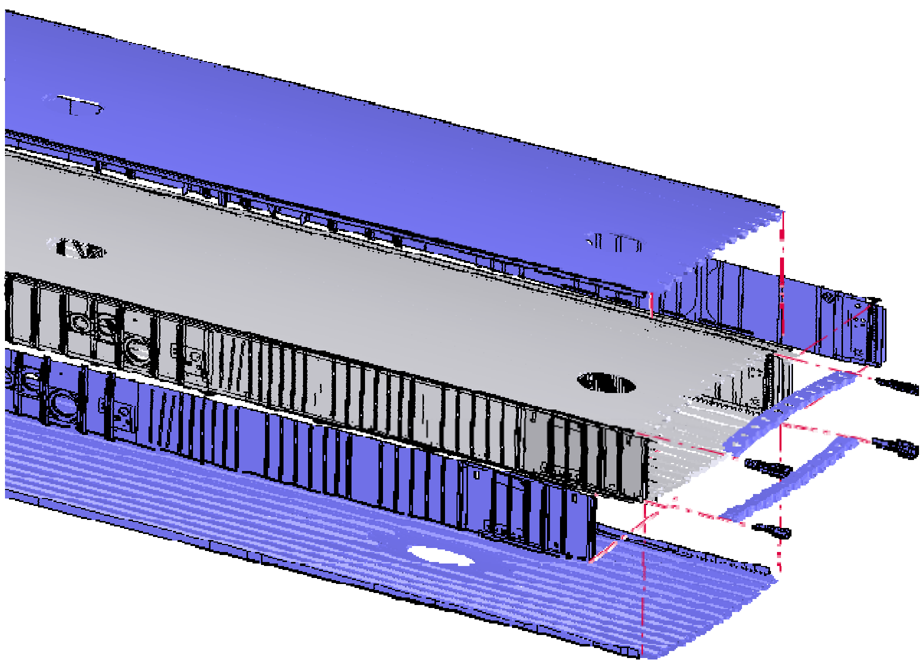
- **15 aircraft found with cracked corner fittings – 2001-2002**
  - **6 corner fittings severed**

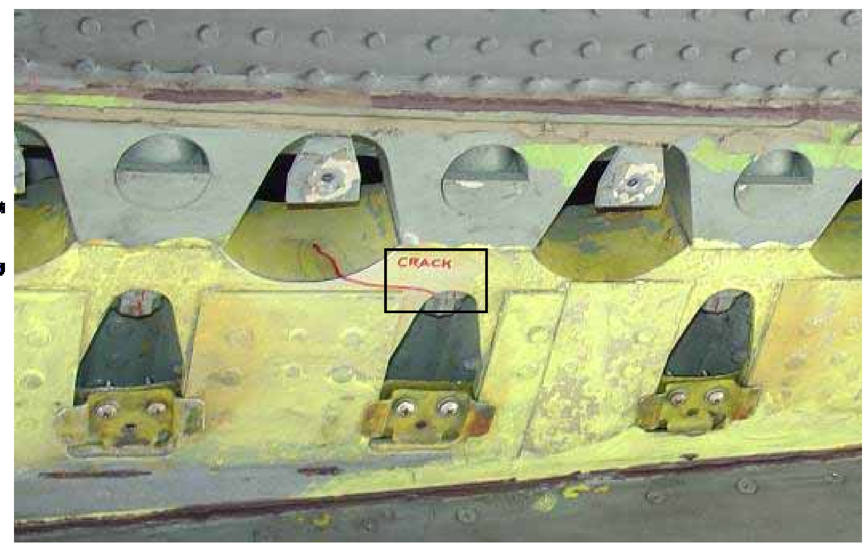




Early Indicators

- Cracked Rainbow fittings
  - First crack on wing durability test
    - Wing fail-safe for a single node crack
  - Replacements not tracked





ASIP Status as of April 2003

- ✓ Established Economic Center Wing Service Life – 60K EBH
  - ✓ Center wing replacement completed (2000) on 50 Special Ops A/C
  - ✓ High time C-130E aircraft scheduled for retirement
- ✓ Completed a full scale wing durability test (WDT)
- ✓ New Individual Tracking Program had just come online
- X Flight Data reporting had declined
- X L/ESS program cancelled (1990s) due to higher priority modifications
- X DADTA not updated since 1980s
  - X WDT results not used to update DADTA
- X Inspection program not flexible to changes in usage
- X Severe cracking discovered on center wing Corner Fitting
- X GWOT

Discovery – April 2003

- Aircraft found with 1.2” crack in center wing spar cap in April 2003
  - Crack longer than expected (based upon safety limit and previous inspection history)
  - Lockheed tasked to update DTA
    - Revised DTA included updated methodology and WDT results
    - Safety limit decreased from 73K to 19K EBH
- Urgent Action TCTO issued
  - A_{NDI}>2.0”
  - 8 additional aircraft found with cracks
  - ✓ Flight hour based inspection program instituted leading to more findings

Actions Taken

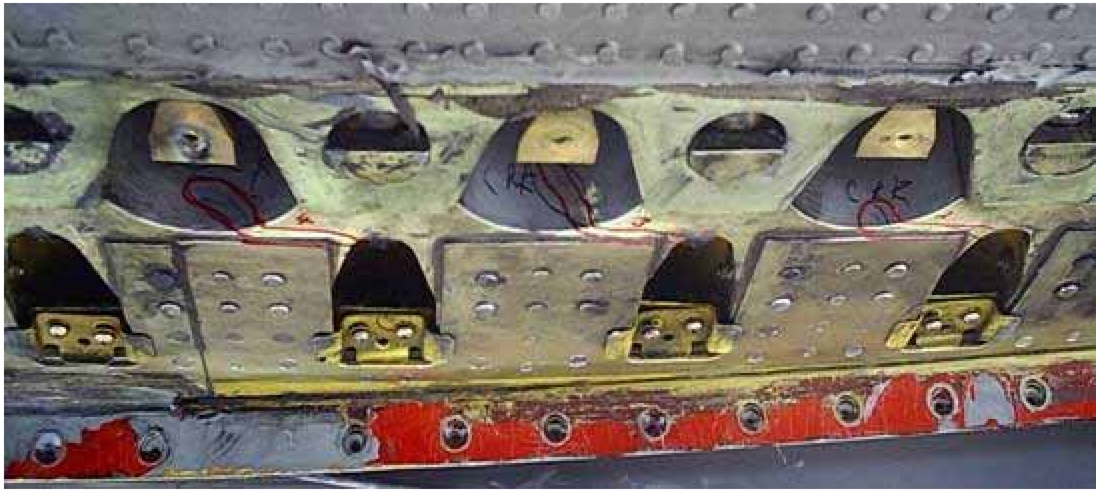
- Internal review of ASIP program
  - Lockheed tasked to provide interim DTA updates for all Center Wing and Outer Wing fatigue critical locations
  - ✓ Critical areas prioritized based upon risk and probability of cracking

Zones		Risk	Freq	Test	In Service	Comments
CW-1	**L/S General Spanwise Splice at WS 185.5**	**High**	**Low**	**Y**	**N**	**Lockheed reports in service cracking**
CW-2	**L/S Panel Stringer Attachments**	**Med**	**Low**	**Y**	**Y**	
CW-3	**L/S Panel 2 Drain holes at WS 56.4**	**High**	**Low**	**Y**	**N**	
CW-4	**L/S - Panel 1 at Drag Fitting, WS 178.0**	**High**	**Med**	**Y**	**Y**	
CW-8	**L/S - Panel 2 at Rainbow Fitting, WS 214.0**	**High**	**High**	**Y**	**Y**	
CW-9	**LWR Rainbow Fitting at WS 214.0**	**Med**	**Med**	**Y**	**Y**	
CW-10	**LWR FWD Corner Fitting at WS 214.0**	**Med**	**High**	**Y**	**Y**	**Inspected by TCTO's 1819/1828**
CW-11	**LWR FWD Spar Cap at WS 210**	**Med**	**Low**	**Y**	**N**	
CW-12	**LWR FWD Spar Cap at Web Stiff, WS 101**	**High**	**Low**	**Y**	**Y**	
CW-15	**LWR FWD Spar Cap at Web Stiff, WS 79**	**High**	**Low**	**Y**	**N**	**Lockheed reports in service cracking**
CW-16	**LWR Rear Spar Cap at Web Stiff, WS 80**	**High**	**Low**	**Y**	**N**	**Lockheed reports in service cracking**

  - TCTOs issued to inspect portions of Special Operations fleet and critical areas on high time aircraft

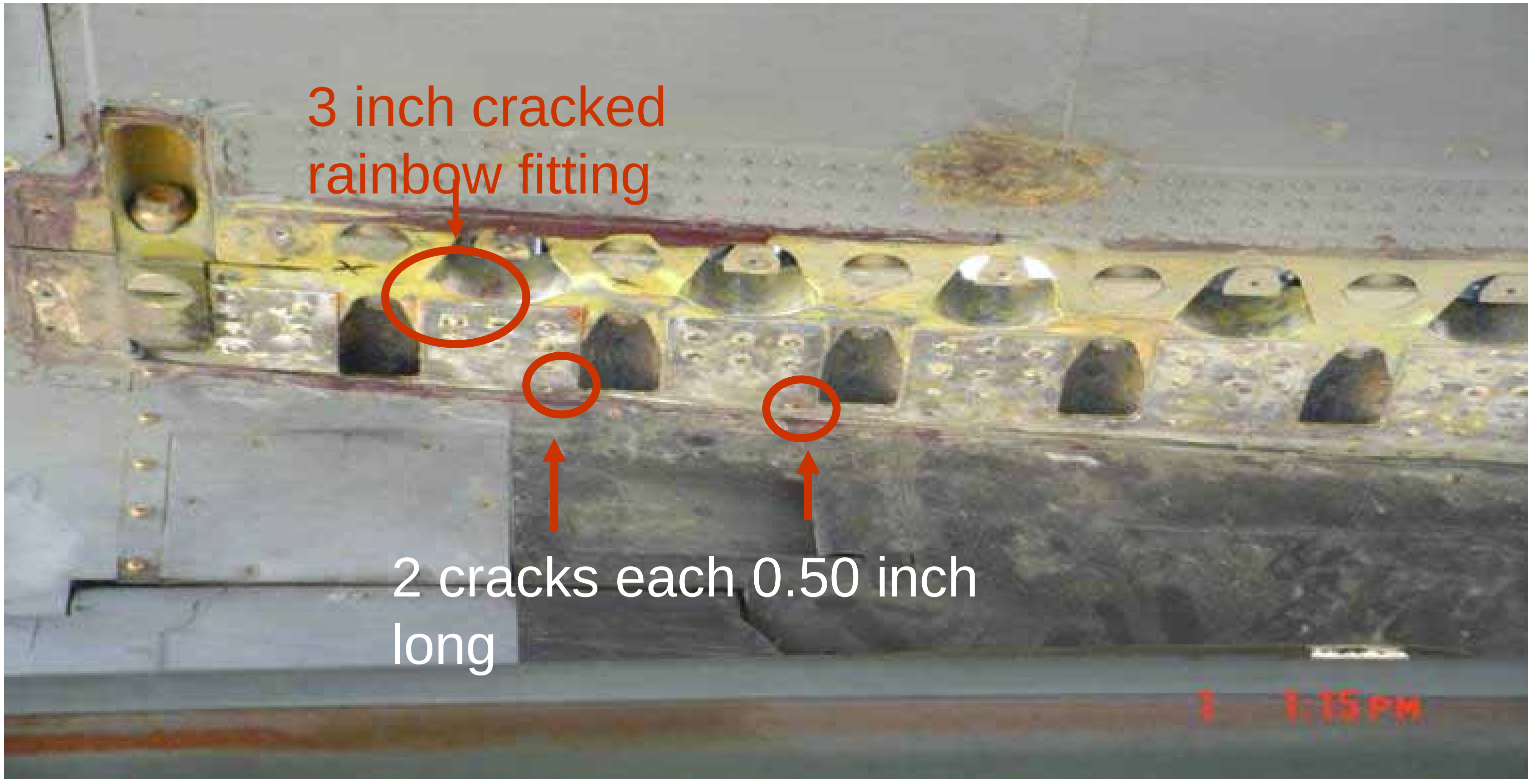
Discovery – March 2004

- TCTO 1875 issued to inspect Special Ops (SOF) aircraft that had not entered PDM cycle
  - 15 year initial PDM interval based upon standard C-130H usage
  - More severe usage of SOF led some locations to be beyond safety limit without inspection
  - SOF aircraft found with 3 consecutive nodes cracked on Rainbow fitting



Discovery – May/June 2004

- **TCTO 1882 issued to inspect prioritized areas on high time aircraft**
  - **Over 100 cracks discovered in wing panels and rainbow fittings**
  - **Significant Multi-Site and Multi-Element damage discovered**



ASIP Status as of June 2004

- ✓ TCTOs had succeeded in identifying critical cracking allowing aircraft to be repaired and return to service
- X 60K EBH service life (SL) considered to be an economic SL
  - X Significant safety of flight cracking discovered below 60K EBH
  - X Cracking rates 5-10 higher than predicted in 1995 Service Life Assessment
  - X 4 aircraft had reached SL without retirement
- X Severe cracking discovered on corner fittings, wing panels, and rainbow fittings
- X GWOT

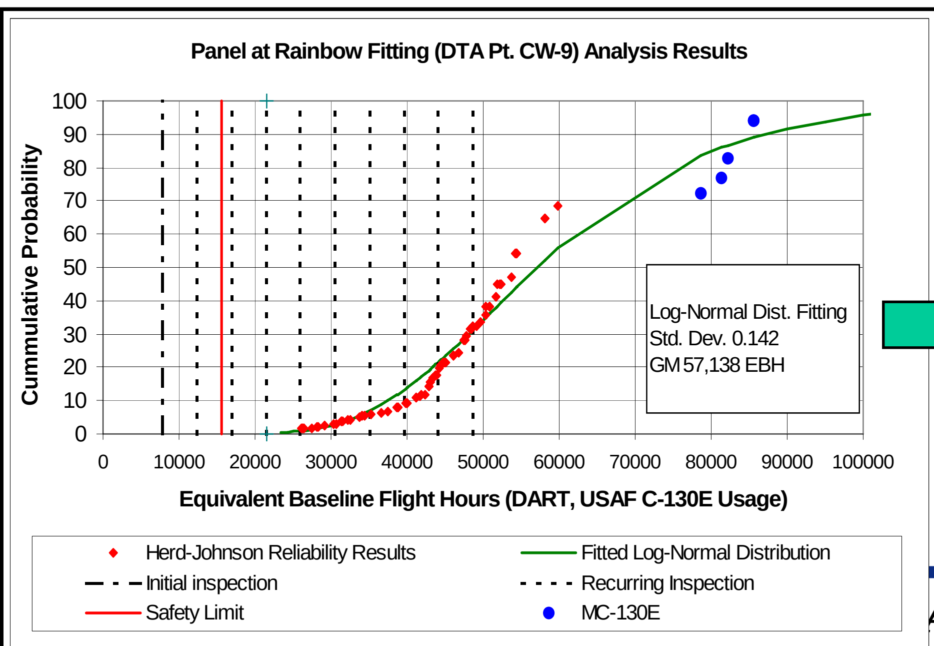
Needed Quantitative Method to Assess Service Life and Risk

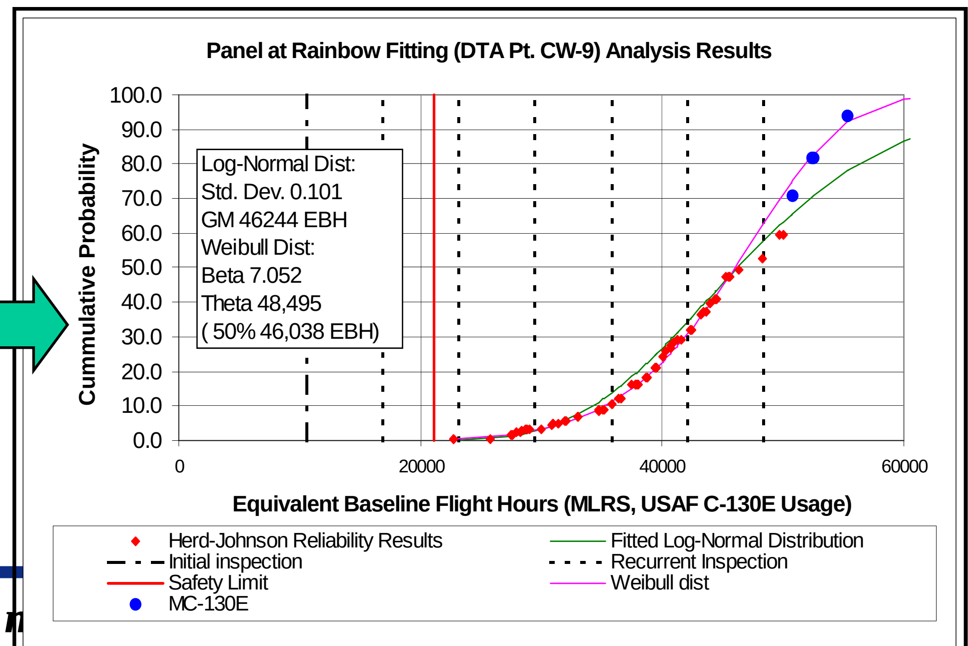
Center Wing
Independent Review Team (IRT)

- **SEP 2004 – Center Wing Independent Review Team Formed**
  - **To validate C-130 Service Life**
  - **To provide guidance on determining risk**
  - **Focused on 3 Center Wing FCL Zones**
  - **Concern over un-inspected area (95% of lower surface)**
- **Lead by Dr Gallagher, USAF ASIP Manager**
- **Lockheed Martin Aeronautical Systems**
  - **Developed unique analysis software and models which were required due to prevalence of MSD and MED**
  - **Reference 2005 and 2006 ASIP conference briefings by G.R. Bateman (Lockheed)**

Results

- Correlation analysis performed by Lockheed indicated that tracking program was over-predicting severity for low level operations
  - Tracking program rebaselined
    - ✓ Previously developed loads system and IAT updates allowed for quick implementation
  - 60K EBH service life rebaselined to 50K EBH
  - WDT Severity of first 26K CTH actually 2 (ILO 3)





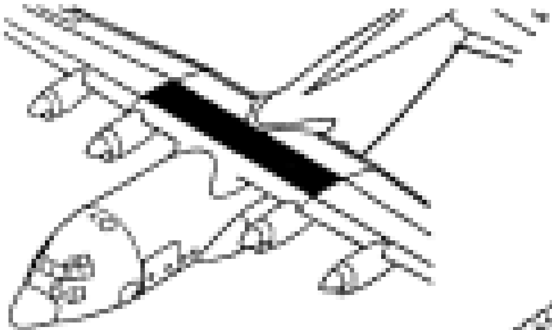
Results - continued

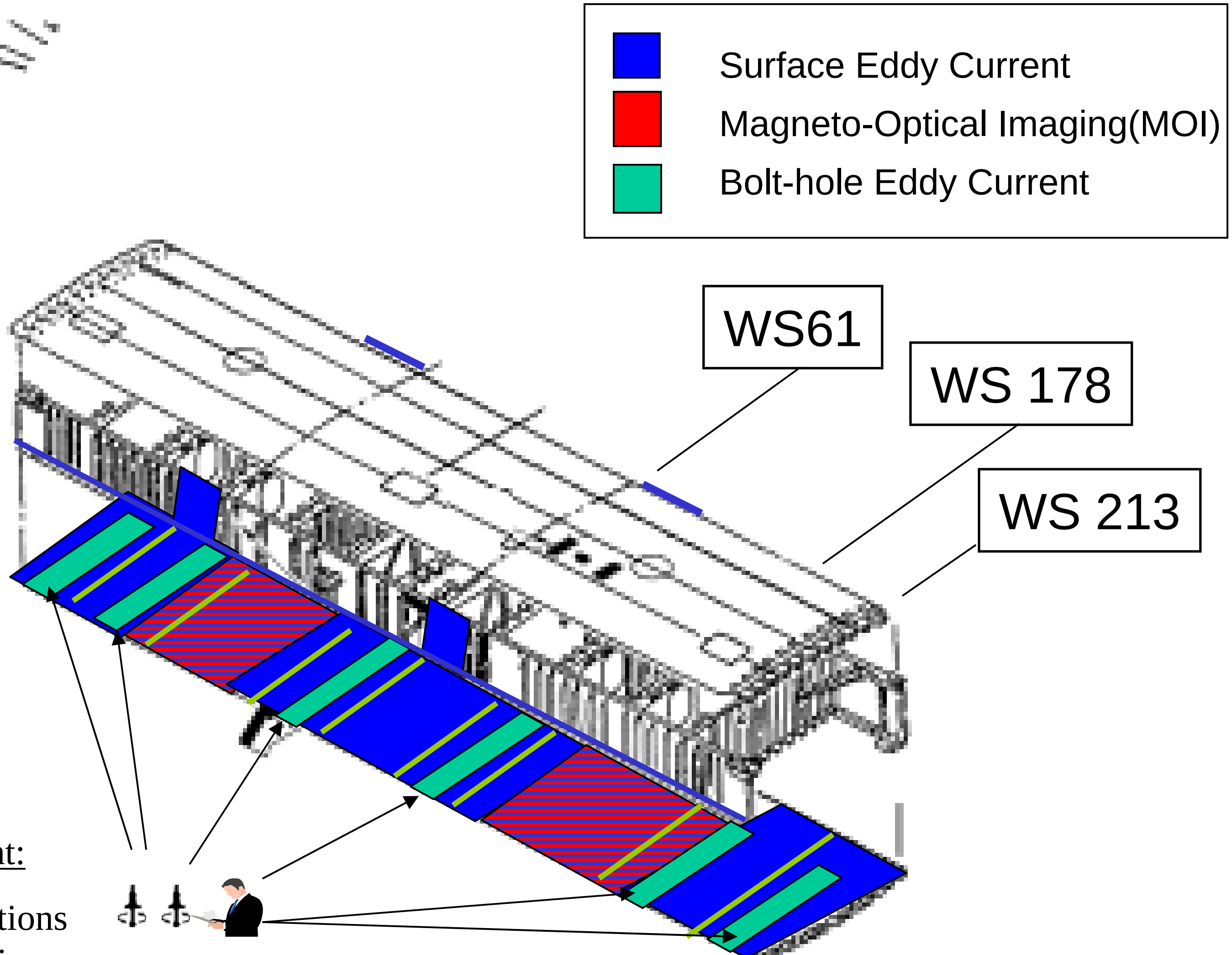
- Grounding and Restriction thresholds established/implemented - Feb 2005
  - Aircraft restricted at 38K EBH – 60 A/C restricted
  - Aircraft grounded at 45K EBH – 30 A/C grounded
- TCTO 1908 inspection developed to perform complete lower surface inspection
  - Successful completion of inspection and repair allows restrictions to be removed
  - Does not allow aircraft to operate beyond the grounding threshold

Discovery – March 2005

- Aircraft discovered with wing panel cracking 30 flight hours after TCTO 1882 inspection had been completed
  - Revised TCTO issued with updated inspection procedures
    - Results suggested that as much as 50% of cracks were missed during initial inspection
  - Team assembled to perform Root Cause Analysis
  - AFMC Tiger team and Action team assembled
  - Not just a C-130 issue
- Implication to Center Wing problem
  - ✓ Second independent inspection added for most critical areas during TCTO 1908 inspection of lower surface

Finalized Inspection Requirement



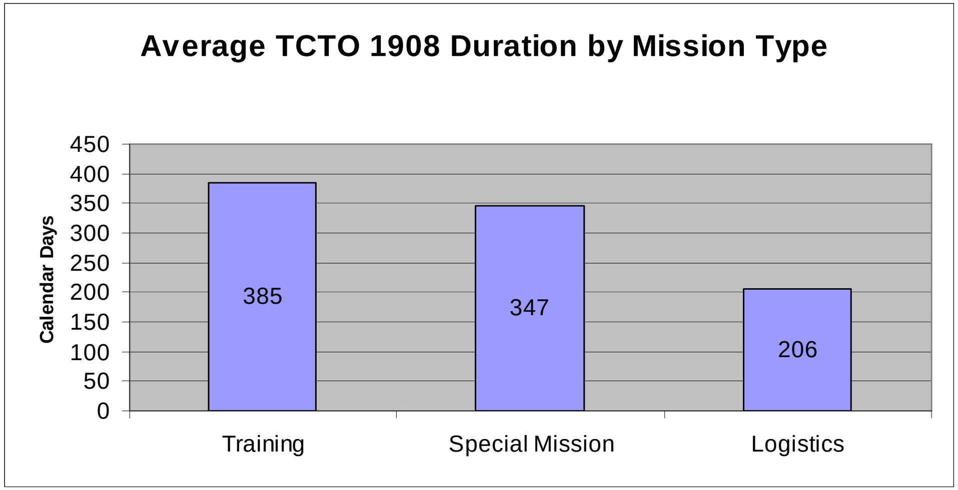


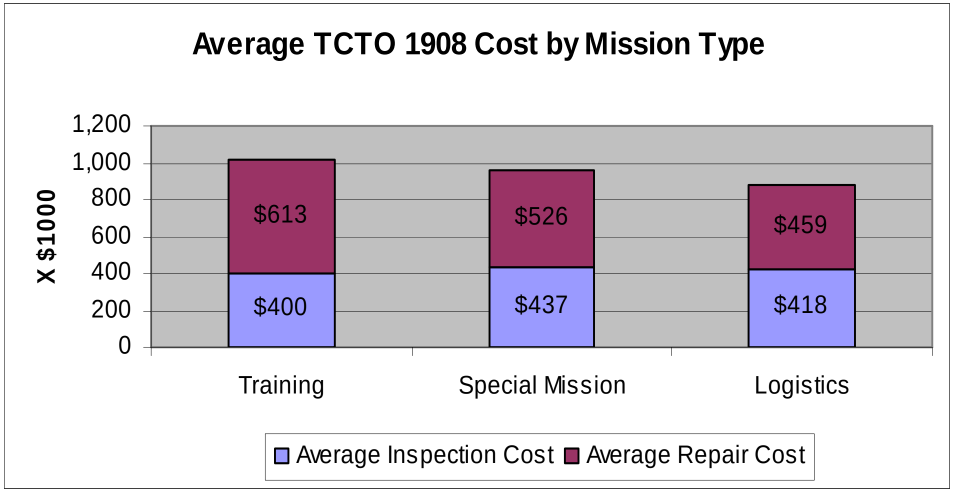
Finalized Requirement:

Two independent inspections required at critical locations

TCTO 1908 Inspection Results

- Inspection results
  - 39 aircraft have been completed, 17 aircraft in-work
    - All aircraft found with fatigue cracking
  - 37 of the 39 were repairable
    - 2 aircraft with damage beyond economical repair

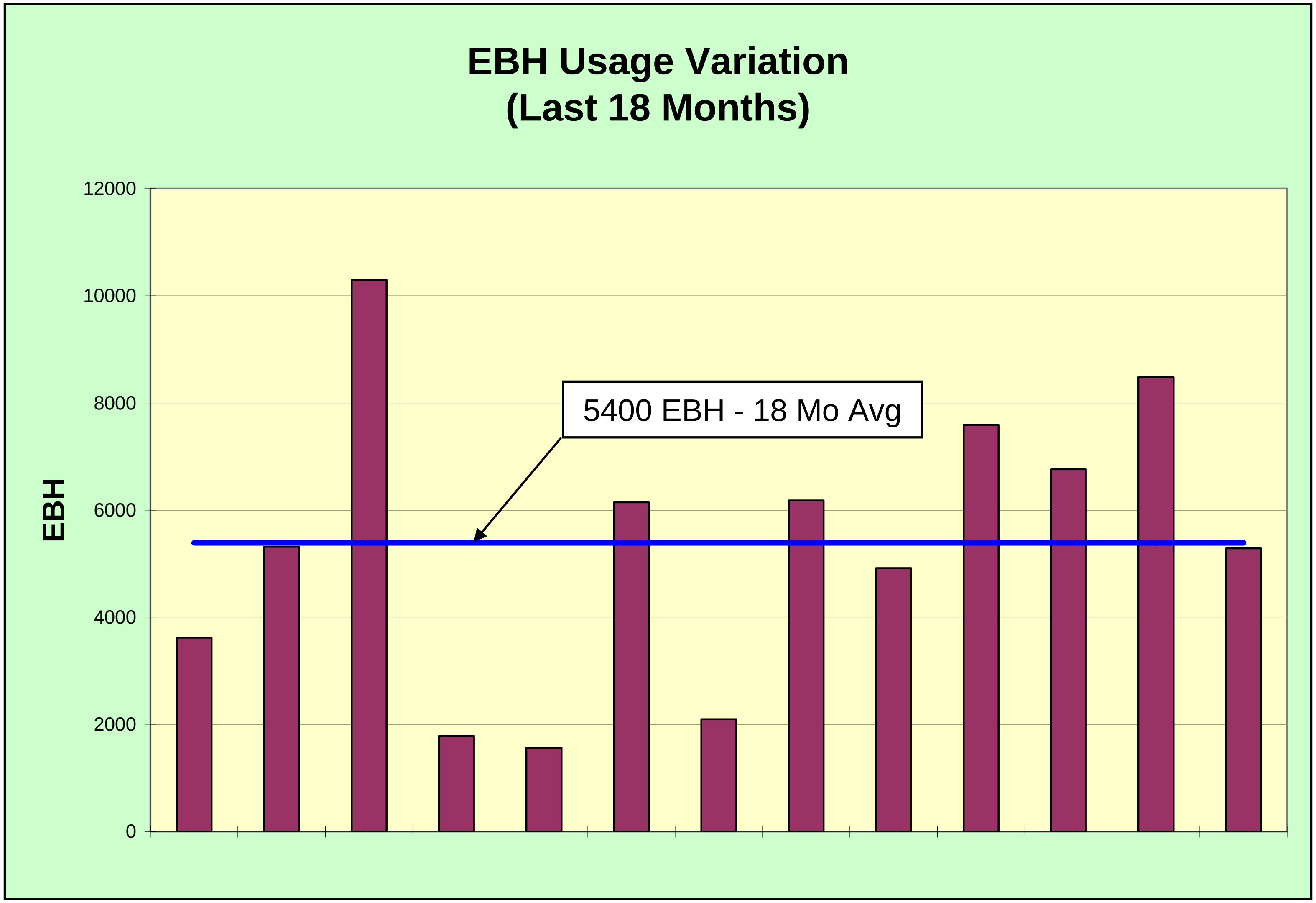




Sustaining the Fleet

- Center wing cracking has decreased aircraft available to perform missions
  - Force realignment
    - Aircraft reassigned from ARC to active duty
    - Squadron sizes reduced to minimum requirement
    - Aircraft transferred between bases
  - Projections for future groundings and restrictions published on a weekly basis
    - Assumes uniform distribution of flight hours and severity across a squadron
  - Unrestricted aircraft performing multiple deployments to meet operational requirements
    - EBH consumption rates beyond projected levels
      - Deployed usage up to 4x home station usage

Effect of Repeated Deployment



Service Life Management

- CW Service Life Management tool developed to allow MAJCOM and unit level visibility into the effect of aircraft scheduling
  - Schedule deployments and aircraft non-flying periods
  - Account for TCTO 1908 accomplishment
  - Look at the effectiveness of force structure changes
  - Identify potential aircraft shortfalls in the out years
  - Manage aircraft effectively until retirement or CW replacement

Lessons Learned

- Individual flight data
  - Reporting rates now exceed 95%
    1. Educate the data providers on the importance of the data
    2. Provide up-to-date feedback on reporting quality and timeliness
    3. Human factors need to be considered
- Maintenance data
  - Extensive crack history database developed
    1. Collect crack data at time of discovery
    2. Categorize cracking by location
    3. Collect all inspection data – cracks and no cracks
    4. Document all repairs and part replacements

Crack History Database

AIRCAT C-130 Crack History

Return to Main Menu

00287	00289	00326

CRACK HISTORY RECORD #	ORIGINATED BY	ORIGINATED DATE	LAST UPDATED BY	UPDATED DATE
00326	Christiansen, Peter	1/24/2005	,	4/23/2007

Aircraft Information

TAIL NUMBER	LMSN	STRUCTURAL CONFIG.
		Logistics (FY '61)

ASSIGNED UNIT AT TIME OF DISCOVERY

BASE	MAJCOM	SQUADRON
Ramstein Air Base	USAFE	37

	Zone Status at Time of Discovery	FM Status at Time of Discovery
COMPONENT INFORMATION:	C-130E	C-130E
COMPONENT HOURS:	19535	19535
EQUIVALENT BASELINE HOURS:	39285	38374
SEVERITY FACTOR:	2.01	1.96

Discovery Information

DATE OF DISCOVERY (MM/DD/YYYY)
2/23/1998

AIRCRAFT LOCATION AT TIME OF DISCOVERY:
Ramstein Air Base

MAINTENANCE OCCURING AT TIME OF DISCOVERY:
Unknown

COMMENT:
Information based upon fax from Ramstein AB

Discrepancy Information

COMPONENT SERIAL NUMBER	PART NUMBER
1200062	398827-2

- [ ] MULTI-SITE-DAMAGE
- [x] MULTI-ELEMENT-DAMAGE

(•) SHOW COMPONENT ZONE

( ) SHOW FM ZONES

AIRCAT COMPONENT	AIRCAT ZONE
Center Wing	37 - Lwr Rainbow Ftg Nodes

DTA COMPONENT
CW-11C - Lwr Rainbow Ftg Nodes

CRACK LOCATION WITHIN THE ZONE
Cracking from counterbore

STATION	STATION NBR	SIDE	CRACKING FROM
Wing Station	218.9	Right	Radius
		ELEMENT	**CAUSE OF CRACK**
Fuselage Station	545.5	Wing Joint Fitting (Rainbow)	Fatigue
		CRACK ORIENTATION	**CRACK LENGTH**
Water Line	255.9	Aft	2

COMMENT:
Crack at node 16. Crack length is not reported on the fax, but it is assumed to be at least 2" since it was found with the wing bolt still installed.

Attachments

Lessons Learned

- Service Life Assessment
  - Risk based assessment performed
    1. Risk based inspection intervals appropriate for decreasing deterministic inspection intervals (not increasing)
    2. Document all inspections including no crack findings
- Performance and reliability of NDI
  - Comprehensive inspections required to maintain safety of flight
    1. Inspection of large areas difficult
    2. Human factors affect NDI reliability
    3. Multiple inspections may be required in critical areas
- Hole drilling and fastener installation
  - Majority of cracks from holes occurred at manually drilled holes
    1. Minimize fastener counts
    2. Maximize use of automated tooling

Lessons Learned

- Inspection scheduling
  - Calendar based requirements not responsive to usage changes
    1. Inspection requirements to field need to be on FH/EBH basis
- Fiscal constraints
  - Fiscal constraints can limit ASIP Force Management updates
    - L/ESS, DADTA updates, Teardown inspection of WDT article
    - Minimal damage in early life tends to “lull” focus on maintaining ASIP capabilities
    1. Communicate long term implications
    2. USAF prioritize ASIP requirements appropriately

Lessons Learned

- Replacement versus inspection
  - Large scale inspection requires significant aircraft downtime
    1. From aircraft availability standpoint, replace is more advantageous than inspection
       - CW Replacement ~1/2 downtime of lower surface inspection
       - Replacement will "Zero Time" the structure
- Replacement versus refurbishment
  - Refurbishment (selective replacement) proposed as a alternative to complete replacement
    1. No cost benefit to refurbishment
    2. Higher program risk
    3. Higher life cycle costs

Lessons Learned

- Unscheduled versus scheduled maintenance
  - Unscheduled maintenance limits ability of warfighter to complete missions
    - Aircraft found with cracking while deployed
    - Some aircraft required 2+ years to implement repairs
    1. Consider limited replacement during scheduled maintenance (PDM)
- Maintaining aircraft structure near end of service life
  - Substantial manpower and financial costs required near end of life
    1. Economic service life needs to consider aircraft availability requirement and manpower constraints

Recommendations/Considerations

- Consider replacement/retirement before established service life
  - Increasing costs and diminishing aircraft availability near end of life
  - When sufficient crack data is available to perform detailed risk assessment, opportunity to schedule “orderly” replacement/retirement may be past
  - Consider performing residual strength tests on removed structure
- Ease of replacement of fatigue critical components should be considered during aircraft design
  - Aircraft continue to be used beyond initial design limits and more severely than originally intended
  - Do all fatigue critical components need to be designed to meet the original design life of the aircraft? Could overall life cycle costs be reduced by reducing weight and replacing components 2-3 times within the life of the aircraft?
- Consider minimizing reliance on inspection to insure safety of flight
- Worst case scenarios can happen