Intrusive Inspection Project

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Intrusive Inspection Working Group

FAA Inspectors/Engineers EAPAS Workshop

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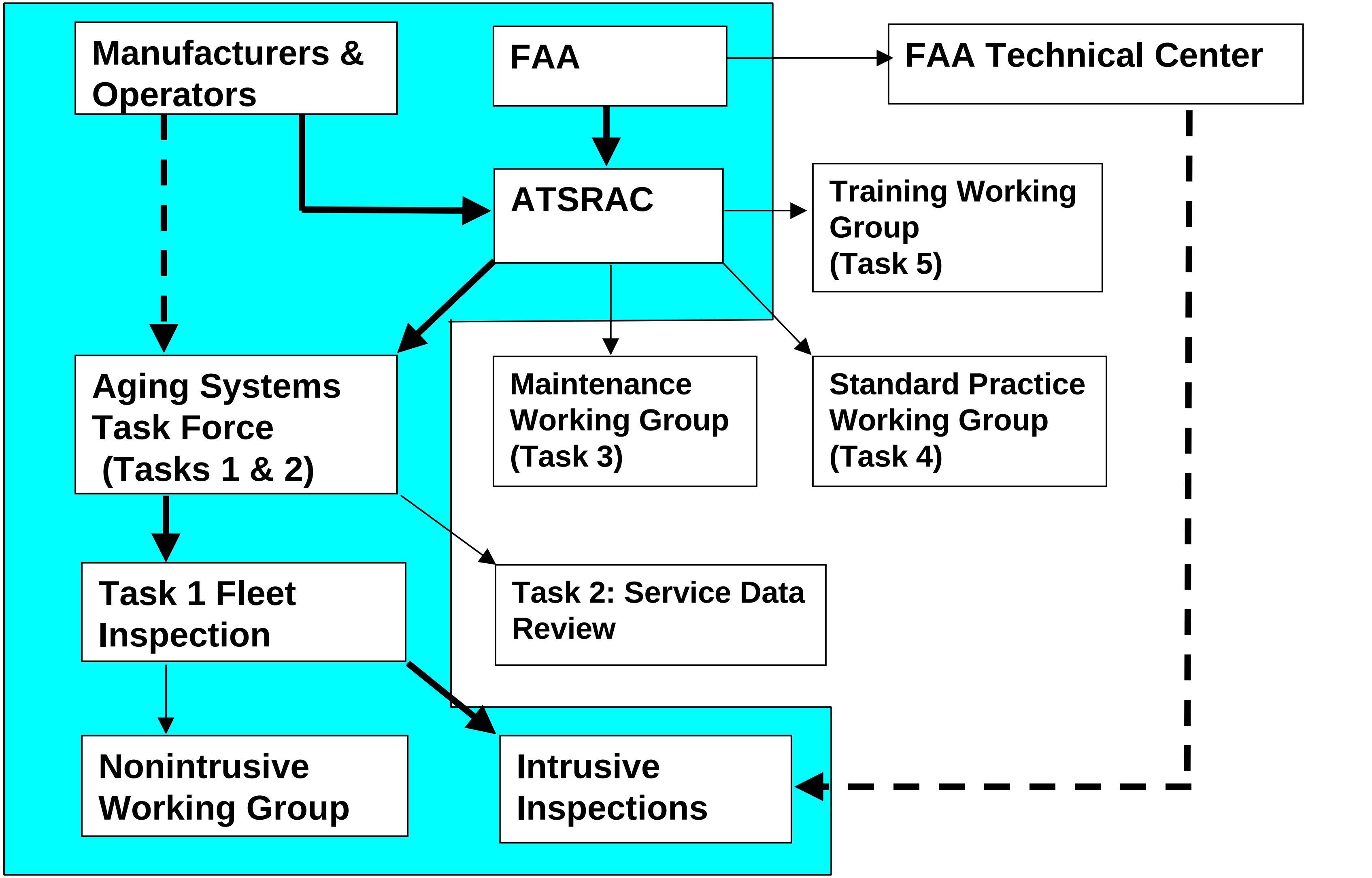
Presentation Overview

- Background
- Project Description
- Results
  - Inspection Results
  - On-Aircraft Testing Results
  - Laboratory Results
  - Results Summary
- Data Analysis
- Threat Assessment
- Recommendations

Intrusive Inspection Context



Premise and Objectives

Premise

- By their nature, ASTF's non-intrusive inspections were unable to collect certain data necessary to fully assess the state of wire in aged aircraft. In particular, a detailed assessment of wire-specific, degenerative flaws was beyond the scope of that project.

Objectives of the Intrusive Project

- To assess the state of wire in aged aircraft.
- To assess the adequacy of visual inspection.

Working Group Membership

Pall Arnason	**Navy, NAVAIR**
David Johnson	**Air Force, Air Force Research Lab**
Issa Ghoreishi	**Boeing Commercial Aircraft**
Jean Luc Ballenghien	**Airbus**
Dominique Mazzarino	**Airbus**
Larry Stevick	**Northwest Airlines**
Hank Zuberer	**United Airlines**
Edward Block	**National Air Disaster Alliance**
Walter Cinibulk	**Raychem**
Ian McLellan	**Transport Canada**
Frederick Sobeck	**FAA, Flight Standards (AFS 300)**
Robert McGuire	**FAA, Airworthiness Assurance R&D (AAR 430)**

Working Group Support

Raytheon	**Rex Beach, Joe Kurek**
Sandia	**Roberto Mata, Robert Bernstein, Roger Clough, Kenneth Gillen, Gerry Langwell**
Lectromec	**Bill Linzey, Armin Bruning, Noel Turner, Vince Press**
Eclypse	**Alan Ferguson, Kevin Steidel**
Wire Producers	**Raychem, Alcatel, Tensolite**
Airframers	**Boeing (several), Airbus (several)**
Operators	**Northwest, United, FedEx, DHL, SwissAir**
Government	**FAA, NTSB, Transport Canada**
ATSRAC	**several**

Project Overview

- Rigorous protocol addressing 14 characteristic locations across several aircraft types. (Where possible locations correspond with non-intrusive inspection protocol.)
- Enhanced inspections to assess insulation electrical properties, insulation mechanical properties, other degradation related parameters.

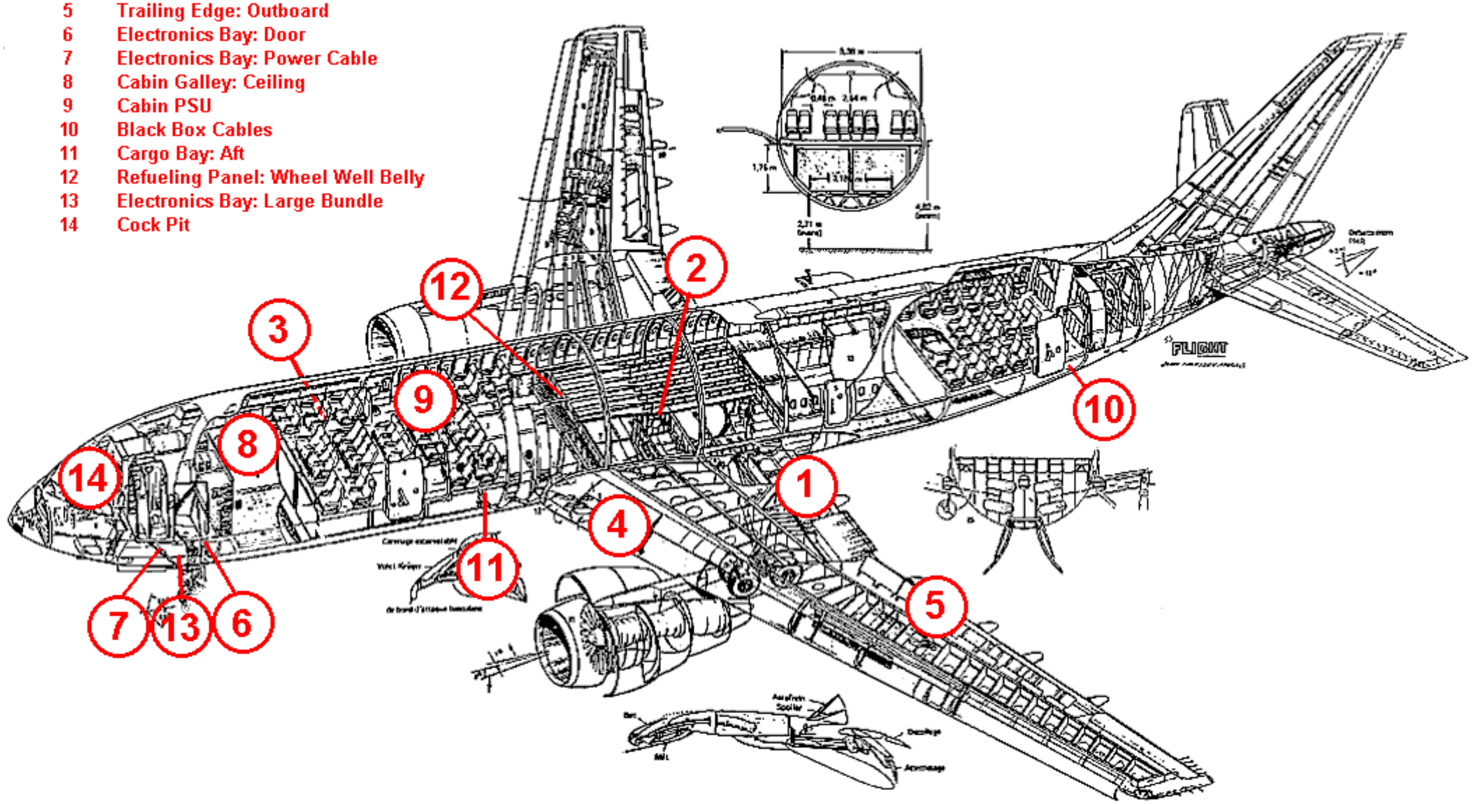
Specimen Types

- Interior and Exterior of Pressure Vessel
- Bilge and Crown Areas
- High/Low Maintenance Locations and Installations
- Bundles Exposed and In Conduit
- Straight Runs and Complex Harnesses
- Small and Large Bundles
- Small Gage and Large Gage Wire (Power Feeders)

Specimen Location Examples

Airbus Industrie A300

1 Trailing Edge: Inboard
2 Wheel Well: Ceiling
3 Cargo Bay Door: Floor
4 Leading Edge: Power Cable
5 Trailing Edge: Outboard
6 Electronics Bay: Door
7 Electronics Bay: Power Cable
8 Cabin Galley: Ceiling
9 Cabin PSU
10 Black Box Cables
11 Cargo Bay: Aft
12 Refueling Panel: Wheel Well Belly
13 Electronics Bay: Large Bundle
14 Cock Pit



Aircraft Information

All six aircraft have been subject to the detailed visual inspection and on-aircraft nondestructive testing:

Aircraft	A300	DC-9	747	DC-9	L1011	MD-10
Inspection	9/99	11/99	1/00	5/22/00	6/12/00	6/25/00
Year Mfr	1978	1967	1973	1971	1972	1979
Hours	40,000	75,000	100,000	66,800	63,600	61,300
Cycles	27,100	100,000	20,300	75,400	26,300	18,800
Retired	7/99	8/99	5/99	12/99	6/99	5/00*
Wire	PI	P/G/N	PolyX	P/G/N	PI	XL-ETFE

- **Aircraft temporarily decommissioned**

red – oldest by this measure

green – youngest by this measure

Caveat

All data and statistics are derived from six aircraft. Though the statistics may suggest the possible presence of a phenomenon, they should not be considered indicative of typical wire performance in any absolute or relative sense. These statistics are a starting point for analysis not its conclusion. Consolidated statistics (totals) assume some similarity across aircraft or specimen types. These statistics are indicative only to the extent that this assumption is true.

Visual Inspection Results

7 findings forwarded to the OEM for follow-up

Aircraft	Location	Part	Finding	Possible Cause
DC-9	Wing tip	Wire to tip lights	Burnt wire	Resistive heating
DC-9	Tail cone stair	Wire in spiral wrap	Burnt wire	Chafing
DC-9	Near cabin fluorescent lights	Wire ties	Severe embrittlement	Ultraviolet light
DC-9	Tail cone	Power feeder in conduit	Breached and possibly burnt wire	Chaffing
747	Forward cargo bay	Power feeder cables	Wire-to-wire chafing	Mis-installation of cables
A300	bilge area forward of electronics bay	Large bundle on left side	Delaminated wire	Contamination
L1011	Cockpit	Overhead circuit breaker panel wires	Traumatic damage to wires	Proximity to closure point

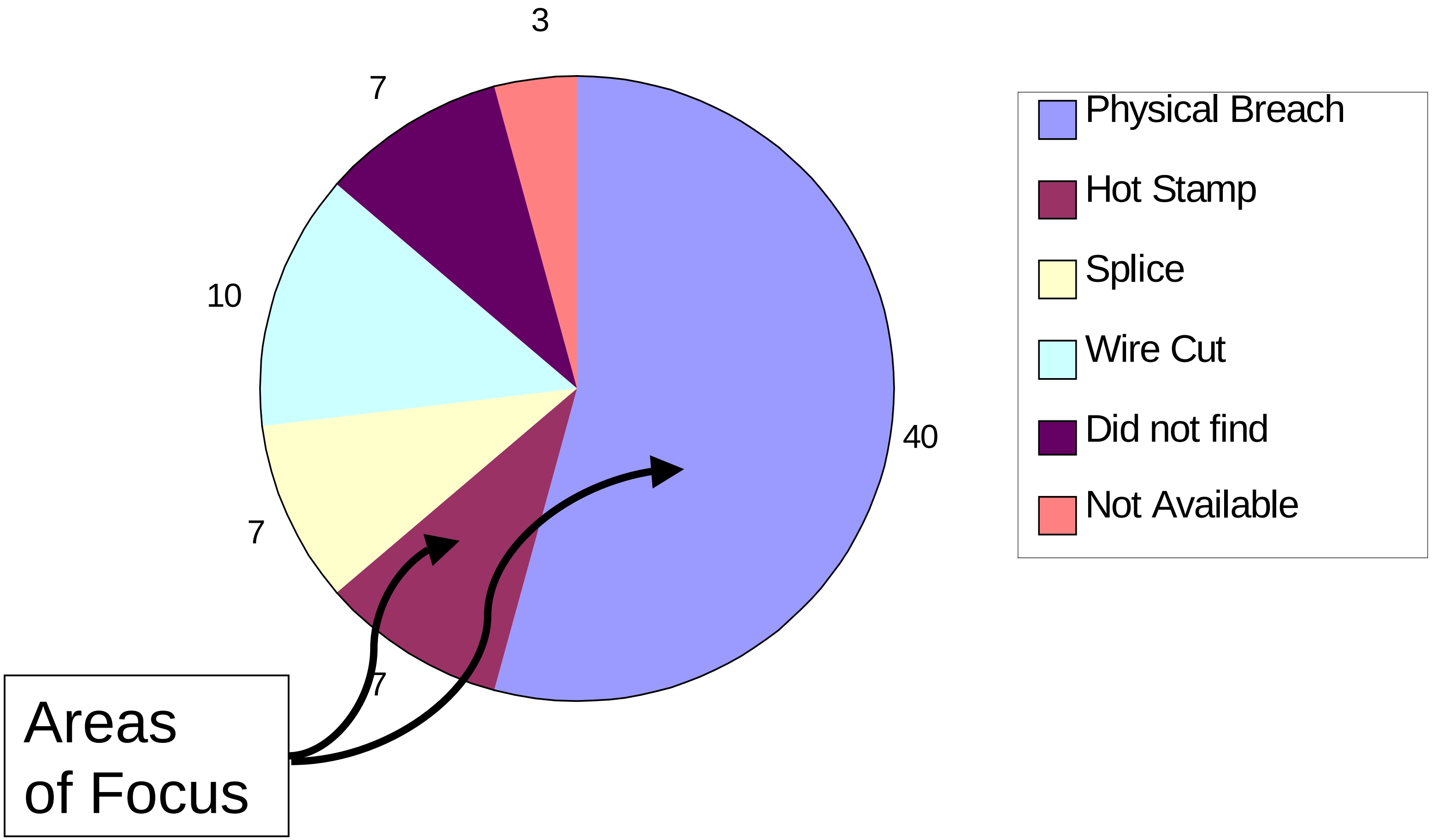
Intrusive/Non-Intrusive Comparison

Intrusive Inspection Finding Categories - Wire	**Non-Intrusive Finding Categories - Wire**
Inadequate Repair	Previous Repairs, Condition of
Degraded Repair	
Heat Damage	Heat/Vibration Damage
Vibration Damage	
Collateral Damage	Indirect Damage
Cracked Insulation	Cracked/Abraded Insulation
Non-traumatic Abrasion	
Traumatic Damage	
Broken Shield	Broken Shield/Conductor
Broken Conductor	
Exposed Shield	Exposed Shield/Conductor
Exposed Conductor	
Fluid or Chemical Contamination	Fluid or Chemical Contamination
Wire Corrosion	Wire Corrosion
Arcing	Other Wire Conditions
Other Wire Conditions	

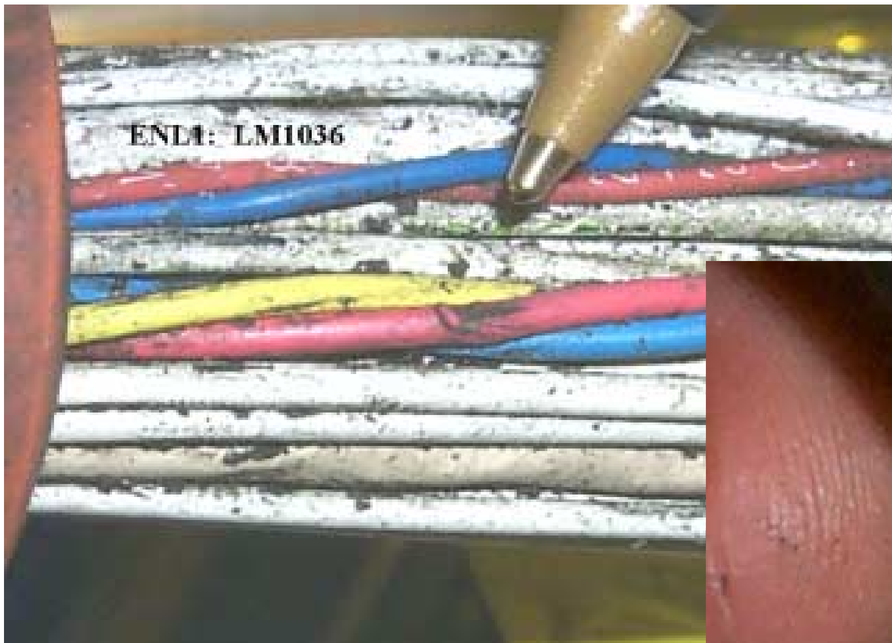
Visual Findings By Aircraft

	Inadequate Repair	Degraded Repair	Heat Damage	Arcing	Vibration Damage	Collateral Damage	Cracked Insulation	Abraded Insulation	Traumatic Damge	Broken Shield	Broken Conductor	Exposed Shield	Exposed Conductor	Fluid or Chemical Contamination	Wire Corrosion	Other Wire Condition
A300-1	4	0	0	0	0	0	1	3	1	0	1	0	1	10	0	7
DC-9-1	1	1	1	0	4	1	18	12	1	0	1	1	2	7	3	0
747-1	2	2	0	1	3	2	12	6	3	1	1	2	4	9	0	0
DC-9-2	5	0	14	1	4	2	26	18	4	0	2	0	9	4	0	4
DC-10	1	0	0	0	0	1	0	5	0	2	0	0	0	9	0	2
L1011	6	1	0	0	0	0	6	3	2	1	0	1	4	14	0	7
Totals	19	4	15	2	11	6	63	47	11	4	5	4	20	53	3	20
Significant	12	2	15	2	10	6	48	41	9	1	4	2	20	31	2	5
Totals Pre-selected	4	0	7	0	4	1	19	6	1	0	0	1	5	6	0	2
Pre-selected Significant	2	0	7	0	3	1	16	6	1	0	0	1	5	2	0	1

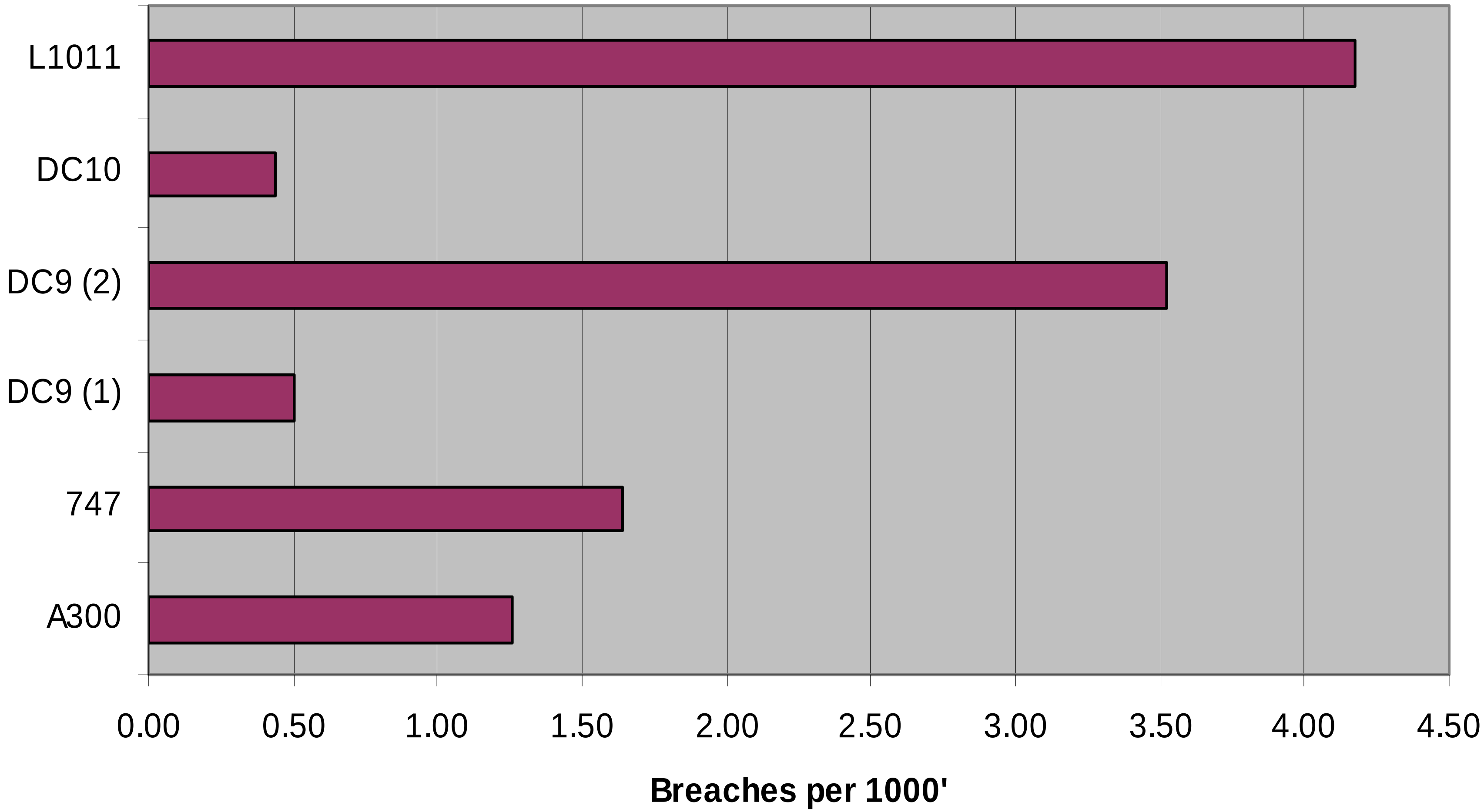
DelTest Results By Finding Type



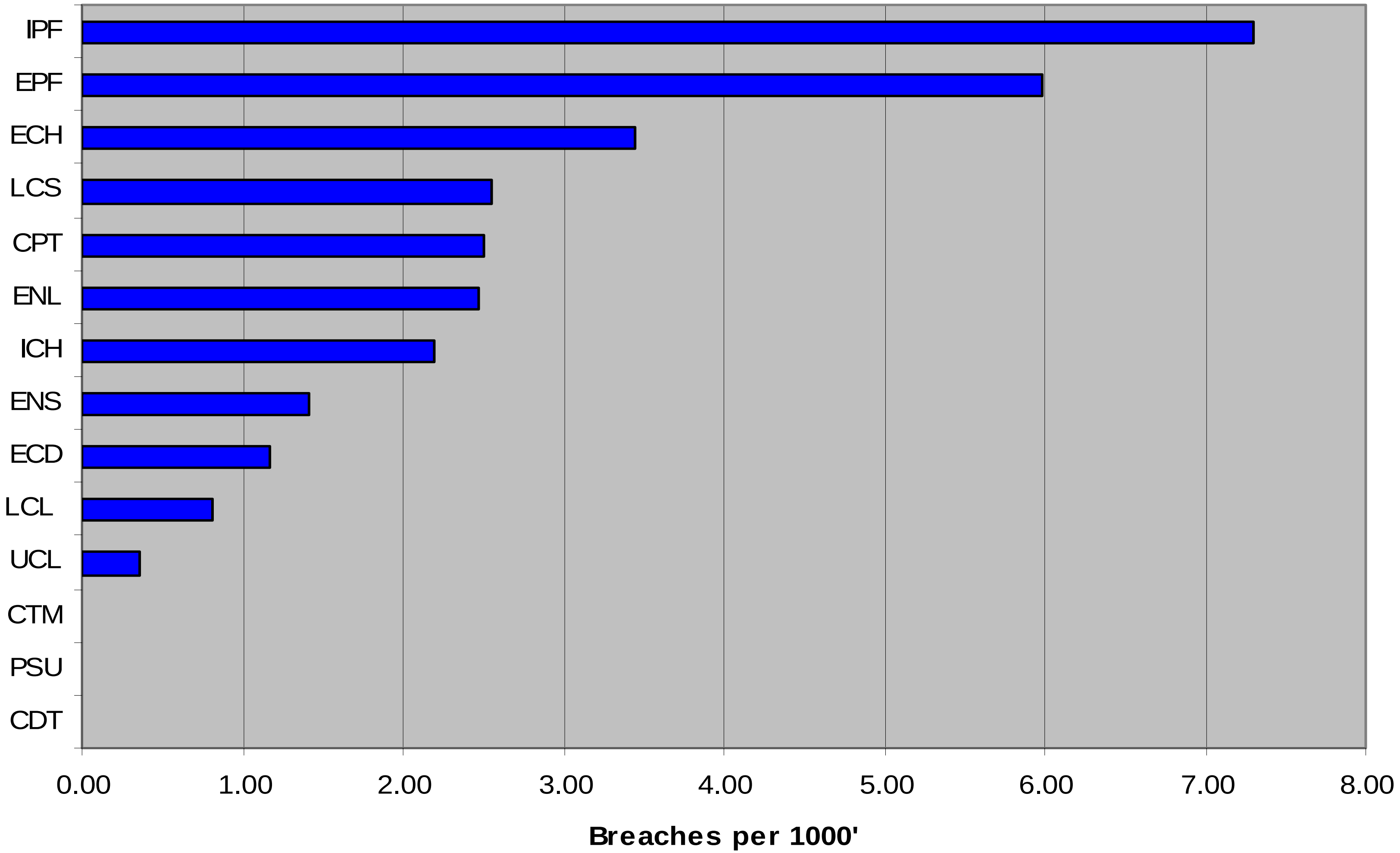
Typical Lectromec Findings



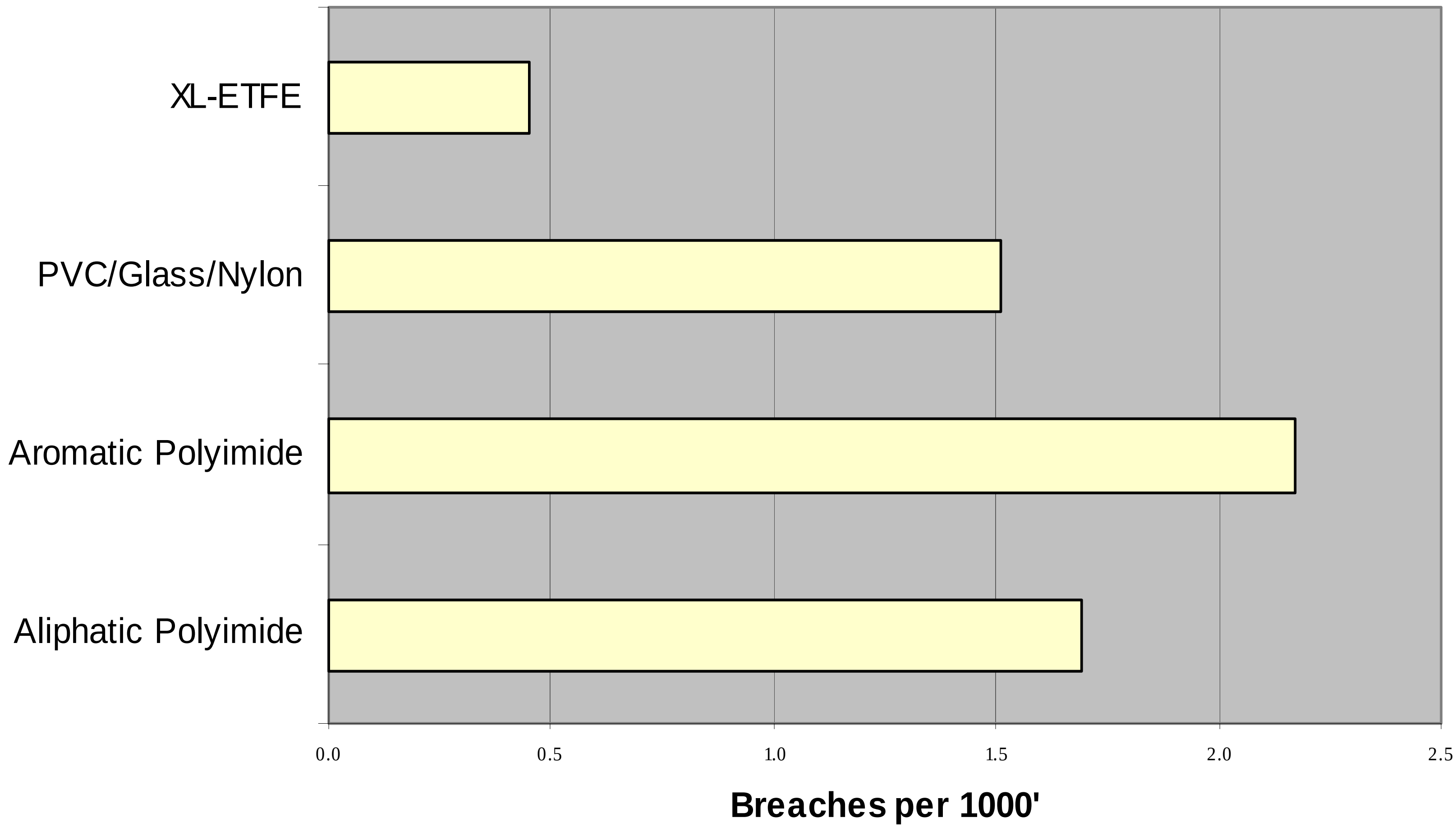
Deltest Results by Aircraft



Deltest Results by Specimen Type



Deltest Results by Wire Type

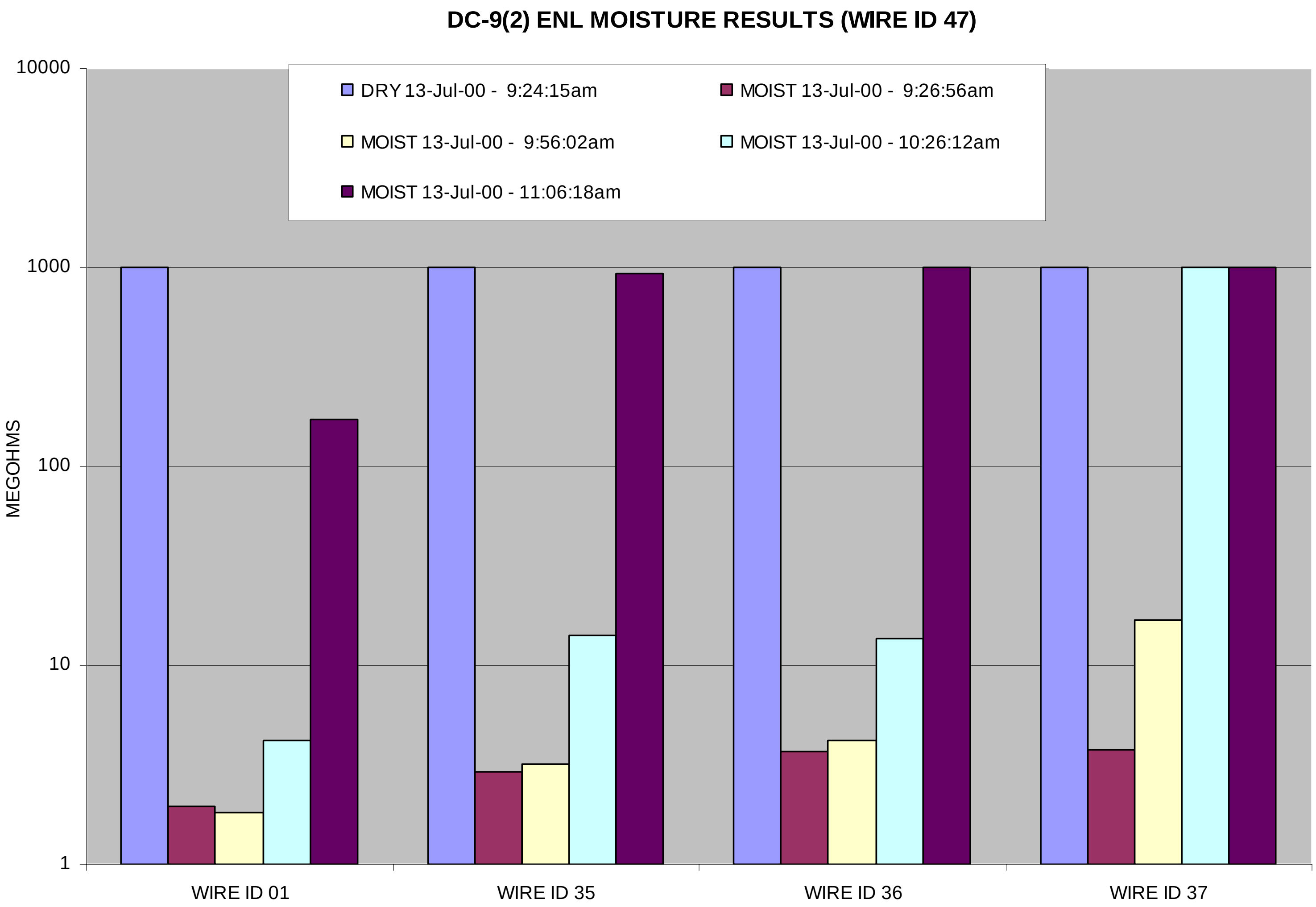


Eclype Results

A/C	Damage †	Conductor Integrity‡		Insulation Resistance‡	Grounds‡		Mosture‡	
		2 Wire	4 Wire		Resistance To Ground	Isolation From Ground	Dry	Wet
A300	0/19	0/583	0/583	0/583	0/0	0/583	0/0	0/0
DC-9(1)	0/13	0/542	3/542	0/542	9/25	53/517	0/0	0/0
747	0/18	0/485	0/485	7/485	11/15	1/470	0/114	11/114
DC–9(2)	0/15	0/311	4/311	4/311	11/30	2/281	0/84	18/84
TOTAL	0/65	0/1921	7/1921	11/1921	31/70	56/1851	0/198	29/198

†Number of Findings / Number of Specimens Tested
‡Number of Findings / Number of Wires Tested

Eclypse Moisture Test Results



NDT Observations

- Deltest is simple, objective, and accurate (but limited to breached insulation).
- Eclypse testing is subjective but potentially indicative of failure precursors.
- Eclypse testing requires
  - Detailed knowledge of installation
  - Baseline for comparison
  - Sophisticated interpretation of results

Laboratory Testing

Sandia National Labs

Optical Microscopy

Mandrel Bend screening

Density Measurements

Modulus Profiling

Insulation Tensile S And E

Solvent Swelling

Infrared Spectroscopy

Raytheon

Optical Inspection

Wrap Test

Wet Dielectric – Voltage Withstand

Conductor Resistance

Insulation Resistance

Inherent Viscosity Test

Dynamic Cut-Through, Notch Propagation

Lamination Sealing

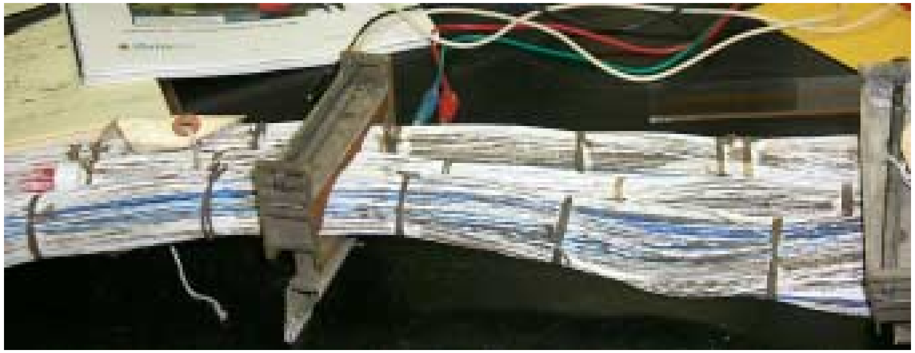
Cross Link Proof Test, Life-cycle

Dry/Wet Arc Tracking

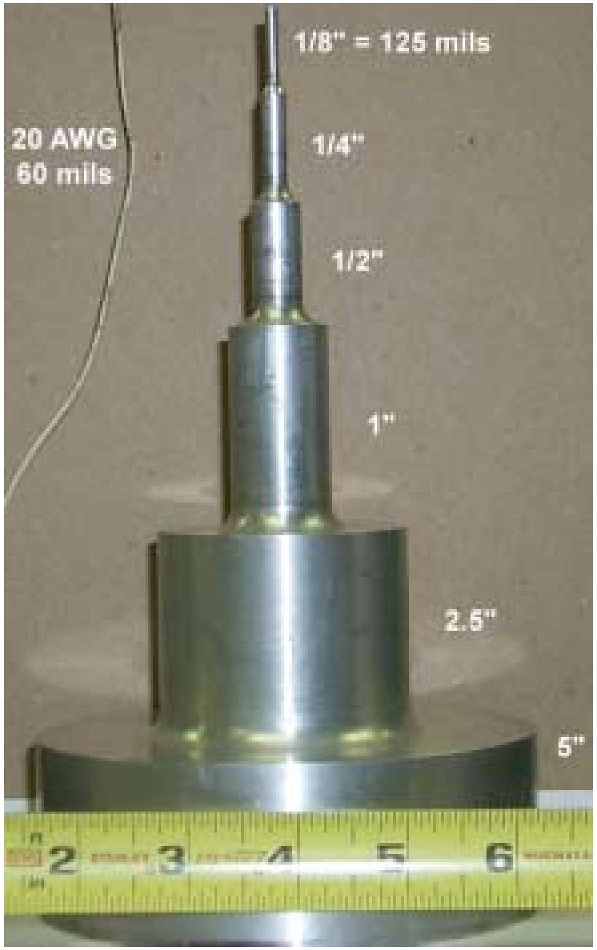
Flammability

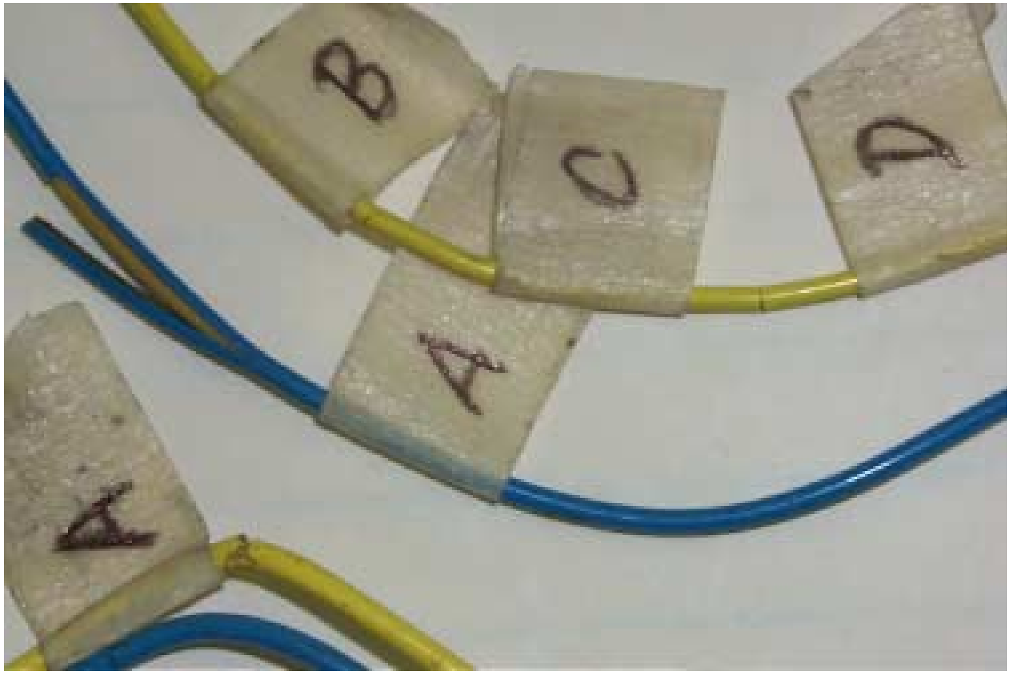
USAF Wright Labs will be doing some additional X-ray testing of connectors

Directed Visual Examination

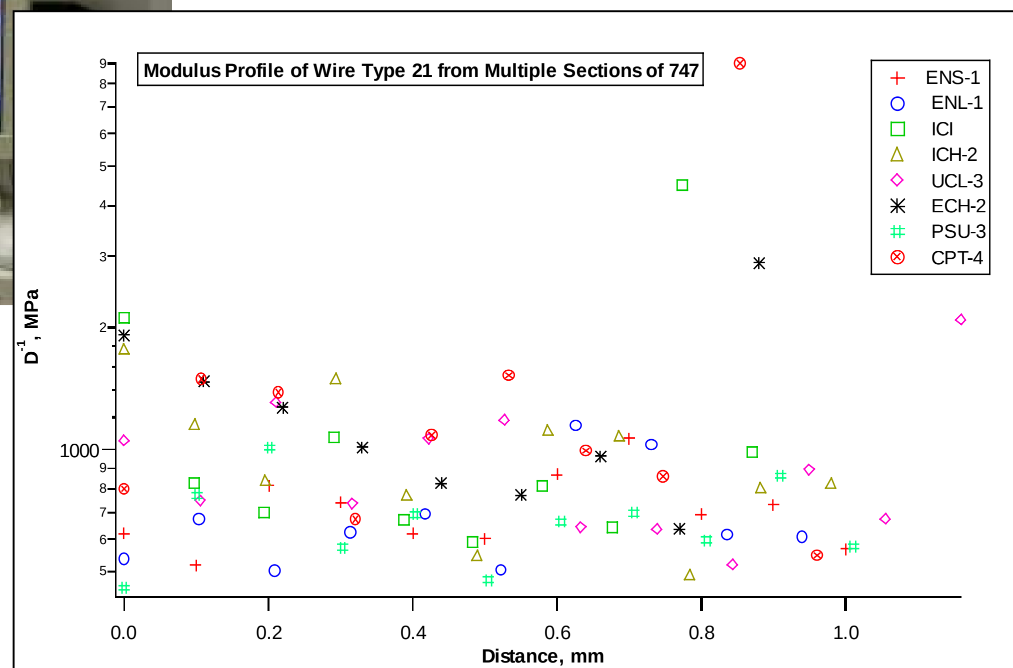


Mandrel Bend Testing

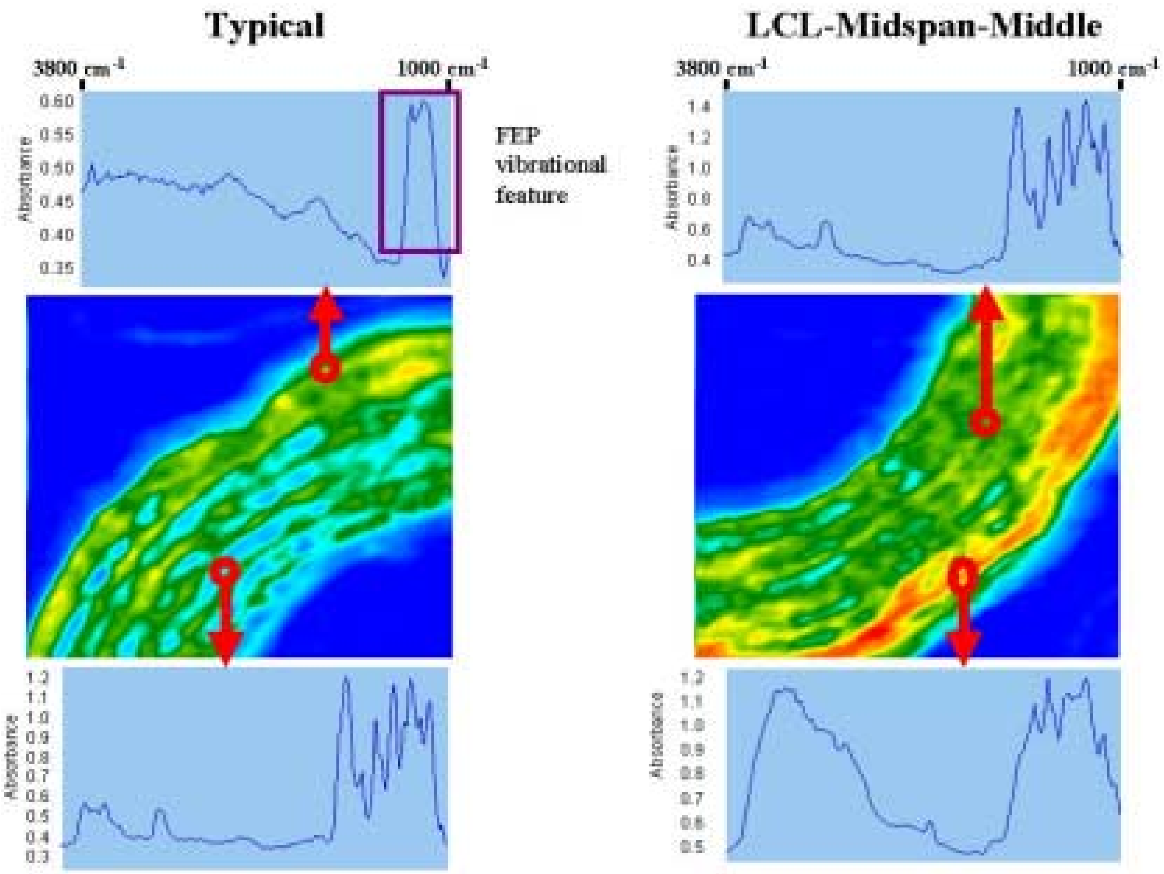




Modulus Profiling



Infrared Spectroscopy



Wire Conditions

Wire Condition	Degenerative	Fire Hazard	Cmn Mode
Inadequate Repair		✓	
Degraded Repair or Splice	✓	✓	
Heat Damage/Burnt Wire	✓	✓	
Arcing	✓	✓	✓
Vibration/Chafing	✓	✓	
Collateral Damage		✓	
Traumatic Damage		✓	
Cracked Insulation	✓	✓	✓
Wire Corrosion	✓		
Broken Shield			
Broken Conductor			
Exposed Shield			
Exposed Conductor		✓	✓

Select Age-Related Conditions

Deteriorated Repair: A currently dysfunctional wire splice assumed to have met requirements when established (e.g. a splice originally established to be environmentally sealed but no longer so). Does not include inappropriate or unacceptable repair practice.

Heat Damage or burnt wire: Thermal damage to insulation resulting from the presence of elevated temperature.due to internal or external heating.

Vibration Damage/Chafing: Insulation wear (material loss) resulting from the repeated application of a force which if applied only once would not result in noticeable damage.

Cracked Insulation: A breach in the wire insulation that does not include breaches resulting from the direct physical contact or traumatic force (e.g. knife cut, or tears).

Arcing: One or more instantaneous electrical discharges evidenced by burnt spot on one or more wires and melted conductors

Delamination: The unraveling of a tape-wrapped insulation. The separation of layers of insulation in a multilayered construction.

Cracking

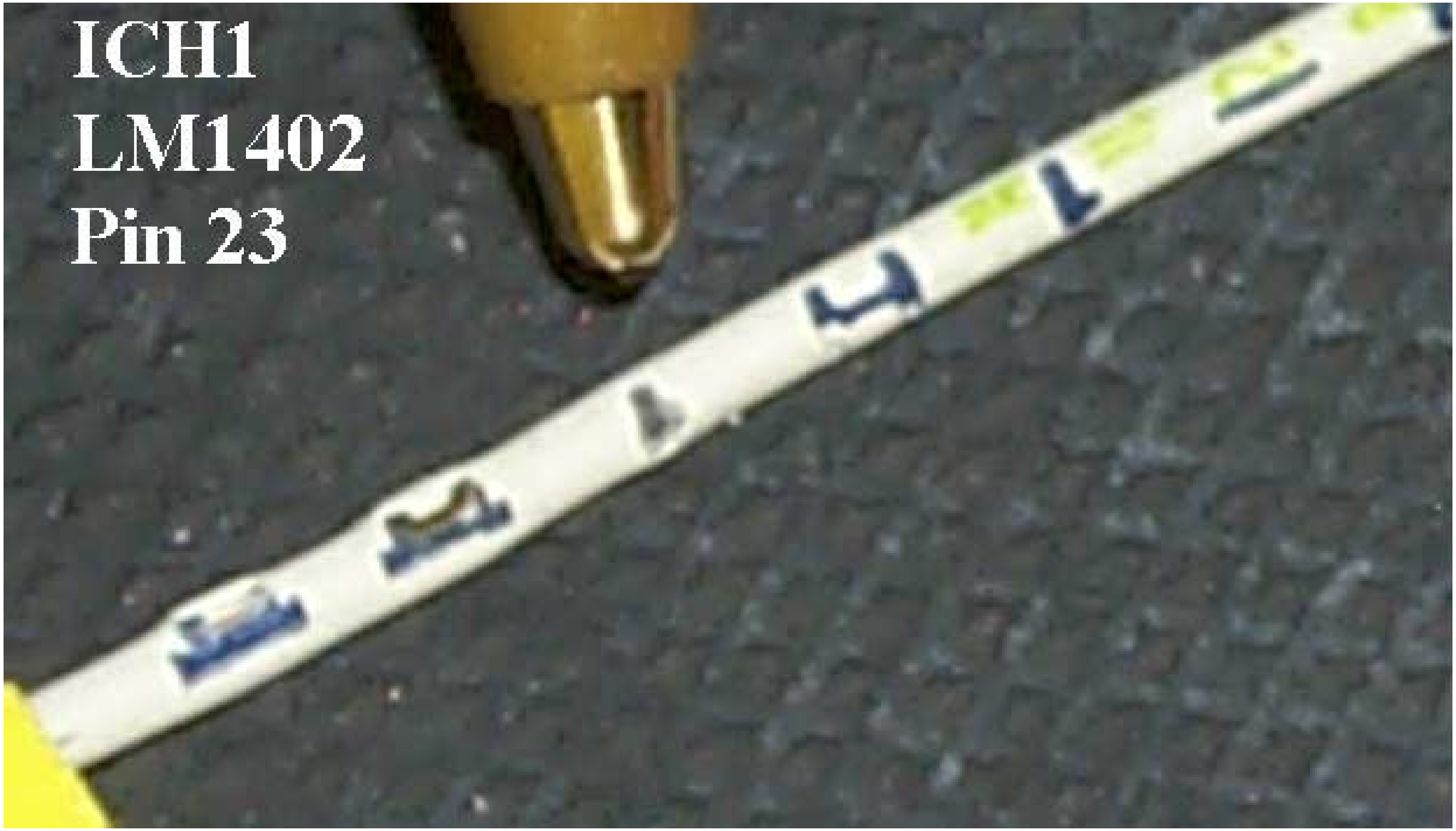
Burnt, Heat-Damaged Wire

Evidence of Arcing

Chaffing

Delamination

Breach at Hot Stamp



Data Summary

Wire Conditions	Findings			
	Significant Findings in All Zones	Significant Findings on Preselected	NDT Findings	Additional Lab Findings
Degraded Repair or Splice	2	0	≤ 7†	0
Heat Damage or Burnt Wire	15	7	2	+
Vibration Damage/Chafing	46	8	2+	+
Cracked Insulation	48	16	12+	++
Arcing	2	0	2	0
Delamination	1	0	1	0

† a non-environmentally sealed splice can only be considered degraded if was originally intended to be an environmentally sealed splice.

\+ some additional findings

++ numerous additional findings

Data Synthesis

Wire Conditions	Found By		Frequency			Potential Options for Prevention or Mitigation of Consequent Failure
	Visual – All Wire	On-board NDT	Unique	Infrequent	Common	
Degraded Repair or Splice	S	F		✓		Staggering of splices, design modification, re-fabrication with environmental splice, periodic rework.
Heat Damage or Burnt Wire	F	S			✓	Visual inspection, periodic rework, design modification, installation of heat or fire shielding.
Vibration Damage/Chafing	F	S			✓	Visual inspection, AFCB, ATE, design modification, periodic rework.
Cracked Insulation	O	F			✓	AFCB, DelTest, periodic rework, wire segregation or separation
Arcing	O	A		✓		AFCB, design modification, wire segregation or separation, periodic rework.
Delamination	O	F		✓		AFCB, design modification, wire segregation or separation

State of Wire in Aged Aircraft

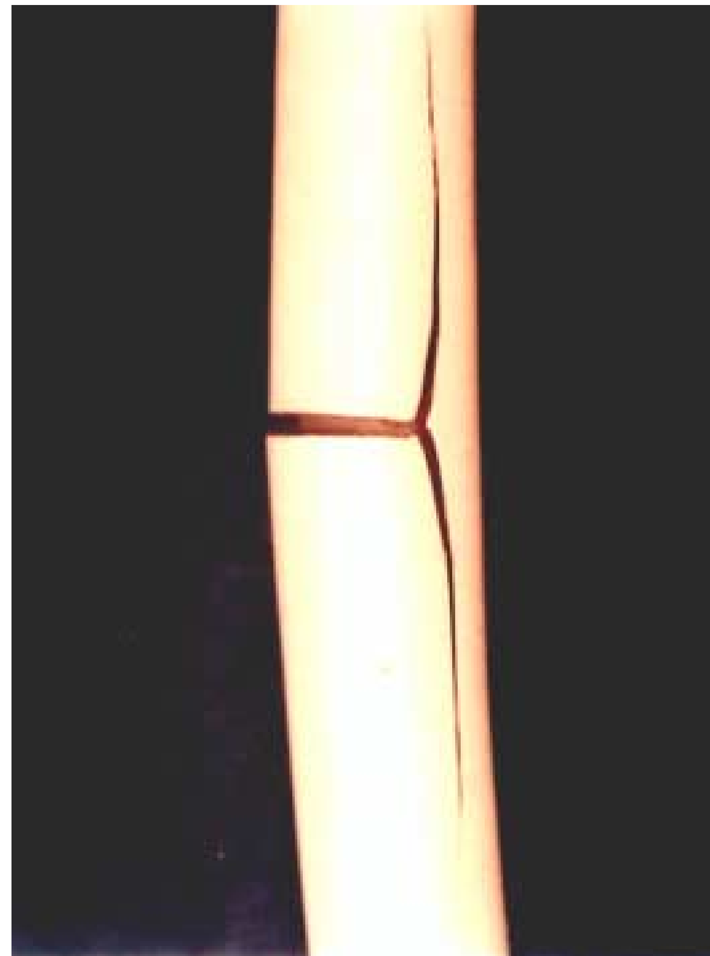
There were signs of characteristic degradation on most wire types:

- **Polyimide**: Instance of delamination were observed on the A300 and L1011.
- **PVC/Glass/Nylon**: Substantial degradation of wire on one the two DC-9 aircraft (cracking, thermal degradation).
- **Poly-X**: Characteristic radial cracking.

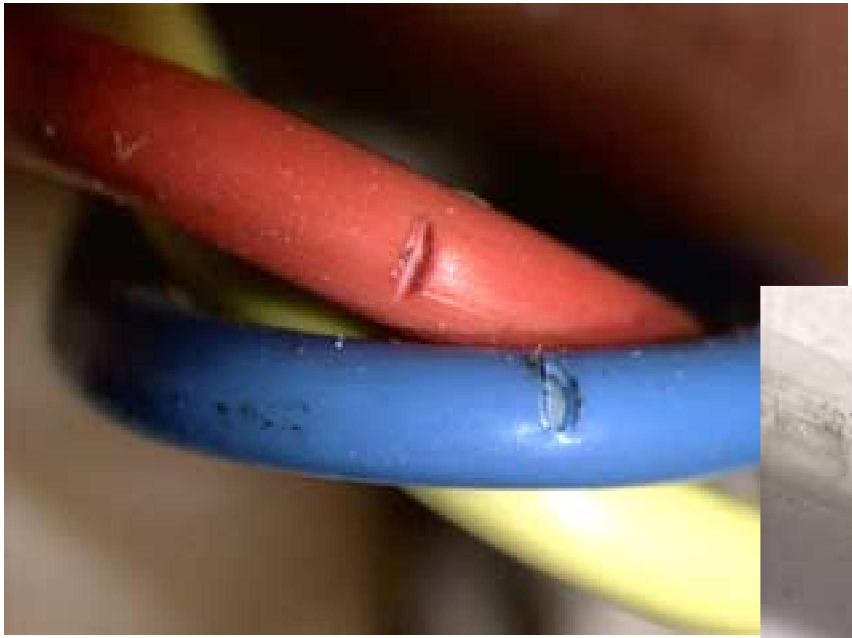
Polyimide

PVC/Glass/Nylon

Poly X



XL ETFE



Note: this characteristic damage in not aged-related (degradation).

State of Wire in Aged Aircraft

- **Mixed Wire Type**: At least one problem was observed in an improperly installed bundle. There was no physical evidence of chafing on properly configured bundles, but the data and analysis are insufficient to conclude.
- **Hot Stamp Markings**: Breaches were often co-located with hot stamp marks.
- **Cut-Off Wire**: Though not a wire degradation issues, this frequency of this finding is worth noting.
- **Flammability**: All wire types performed as expected – i.e. equivalent to new wire of the same type.

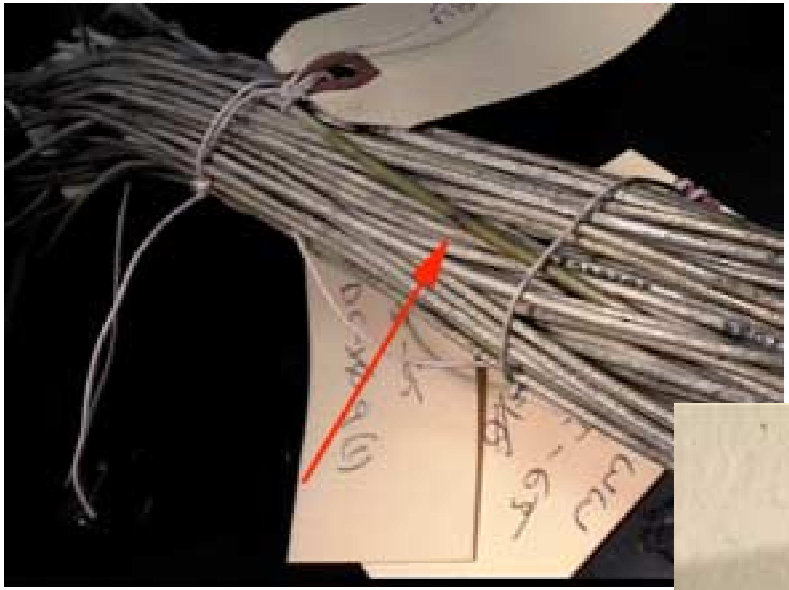
Adequacy of Visual Inspection

- Visual inspection is an effective tool in the management of wires subject to heat damage, burning, and chafing. In high-risk situations, visual inspection must be combined with other means of preventing or mitigating failure.
- Visual inspection is not adequate for the detection of degraded repair, cracking, arcing, or delamination. Where these conditions may occur, and where the consequence of wire failure is unacceptable, other means for prevention and mitigation must be used.
- Other means for prevention and mitigation of failure are identified in the reports conclusions.

Burnt or Heat Damaged Wire

Though the pictures show instances of burnt and heat damaged wire not visually detectable (because of spiral wrap in one case and the small size the damage in the other), this class of flaws is very often visually detectable.

Indirect Indicators



Obvious Discoloration of this single wire is associated with a flaw not visible to the naked eye.

Blue Water Contamination

The blue discoloration of the nylon and glass outer layers is exactly coincident with the yellowed (and presumably degraded) PVC insulating layer

Chaffing

This is an instance of generator feeder cables chafing against XL-ETFE power feeder cables. Though the chafed area is not visible the inappropriately routed and crossed wires are. The data indicates that chafing is often visually detectable.

Delamination

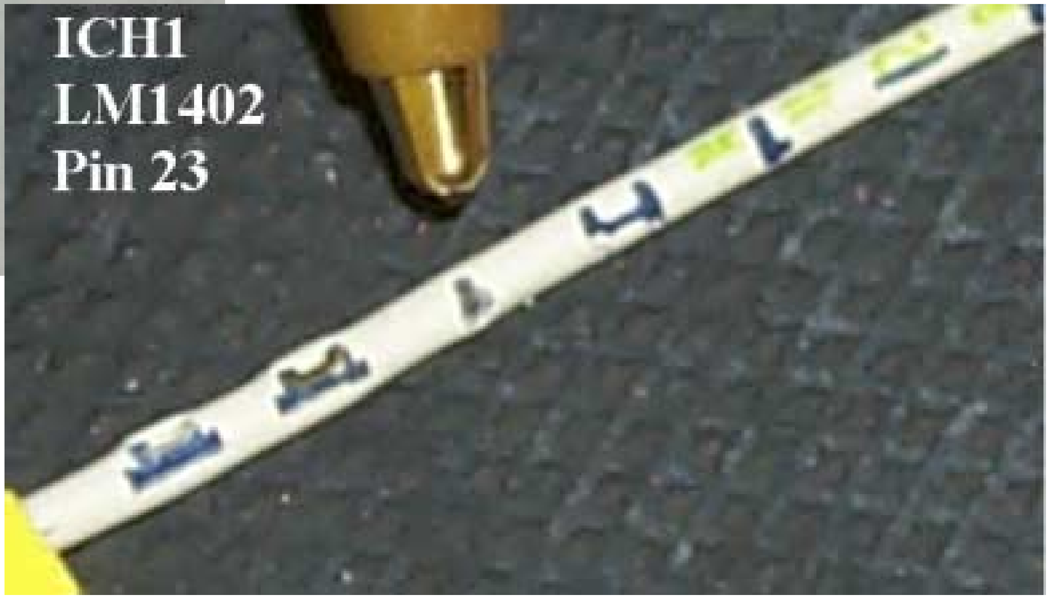
While intuitively it may seem that delamination is visually detectable, it can occur inside a bundle. This delamination was not detected visually.

Visually Detectable?

We cannot rely exclusively on visual inspection to detect cracked wire.

Imperceptible Flaws

This localized burning damage on an otherwise unremarkable wire is evidence of electrical arcing

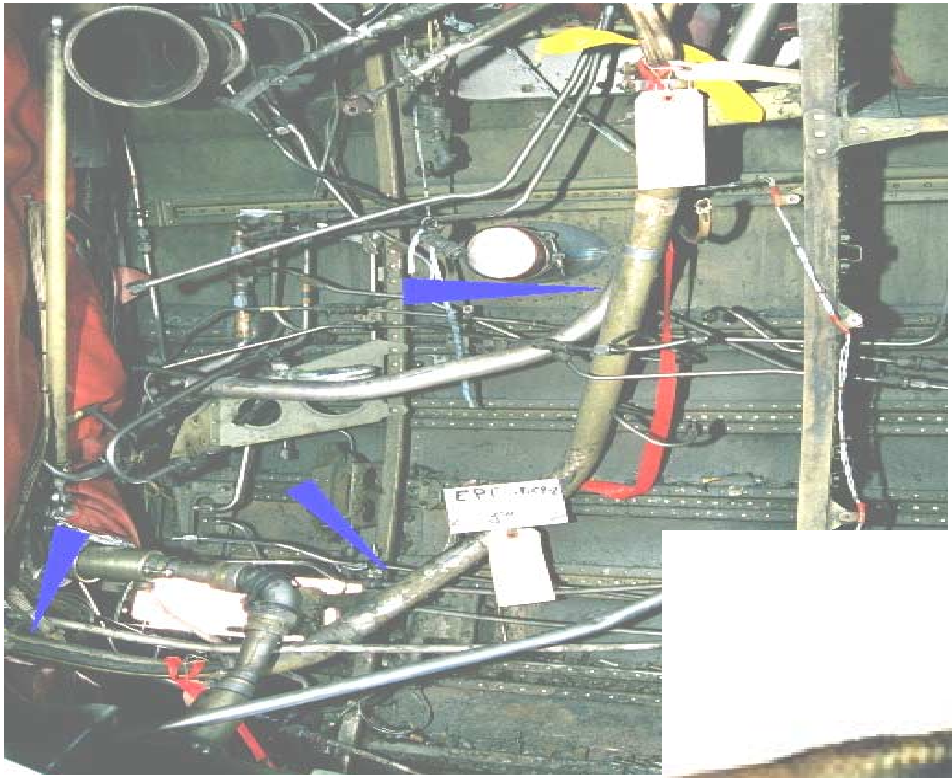


Insulation Breach at hotstamp

Hidden Deterioration

Though this PVC/Glass/Nylon wire has obviously darkened over time, the full extent of damage is not revealed until the nylon and glass layers are removed.

Inaccessible Flaws



The metal conduit at left was supposedly protecting the breached wire shown below.

Threat Assessment

- Flaws were categorized as unique, infrequent, or common. Each class handled separately.
- For all but unique flaws, the Working Group used a formal threat assessment procedure **for plausible, hypothetical situations of interest to ATSRAC**.
- In judging the threat, consideration was given to:
  - Aggravating or contributory factors
  - Wire insulation type
  - Estimated probability of existence
- In making recommendations consideration was given to:
  - Visual detectability
  - Efficacy of other inspection or testing

Generic Factors

Benign Environment: Low humidity, nonflammable environment. Few or no critical system wires in bundle. Uncontaminated and secured well.

Explosive Environment: An environment where there is a reasonable expectation of the presence of an explosive combination of gases during some phase of operation.

Flammable Materials: Surrounding materials that can sustain combustion. Includes the wire insulation itself (e.g. PVC but not polyimide.)

Other Critical Systems: The wire in question is bundled with other wires, at least one of which supplies current to a systems required for safe flight.

Moisture: Normal relative humidity in excess of 90% during some phase of flight (landing, takeoff, climb, cruise, decent, approach, landing), resulting in enhanced likelihood of shorting.

Vibration: Sufficient relative motion between wires or between wires and structure to cause or accentuate intermittent shorting.

Generic Factors (continued)

Contamination: Contamination as the result of normal operation or maintenance resulting in either enhanced flammability or likelihood of shorting.

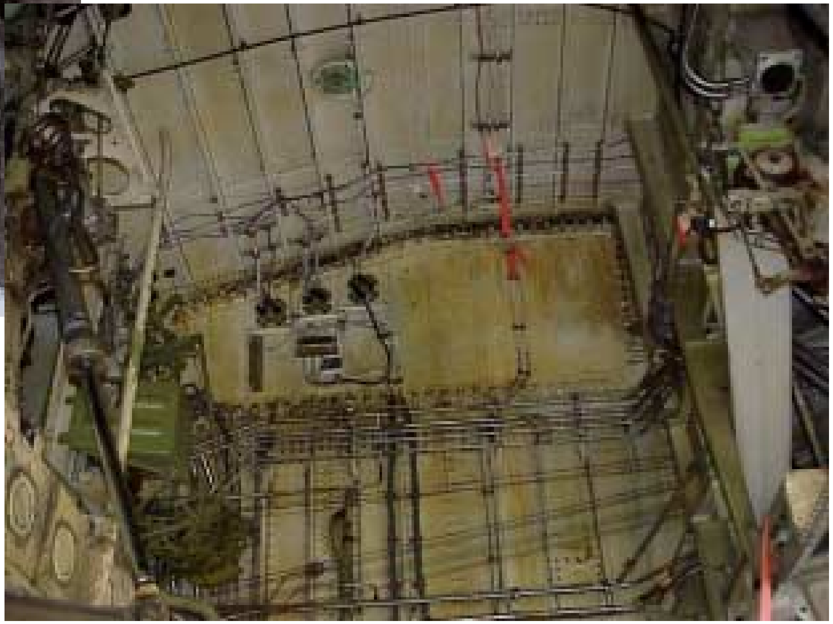
Cockpit or Electronics Compartment: High consequence failure locations within the aircraft.

Arc Tracking Potential: The presence arc-track-susceptible materials in the bundle in conjunction with those conditions which could precipitate sustained arcing

Potential for Excessive Resistance Heating: Wires with high current loads may fail as the result of excessive resistive heating at repair or splice locations. This failure can evolve into severely burnt, cracked, or melted insulation on the offending wire and its neighbors. With excessive heat and bare wire at these locations, the potential for fire is high.

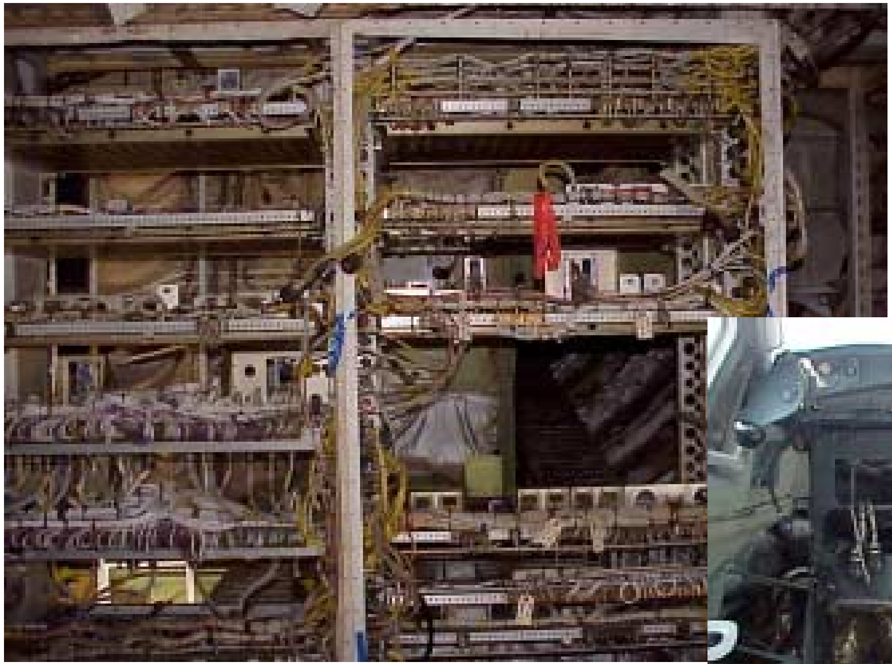
Contamination

Solid and fluid contamination can increase both the risk of electrical failure (by providing alternative conductive paths) and the potential for fire (by providing fuel).

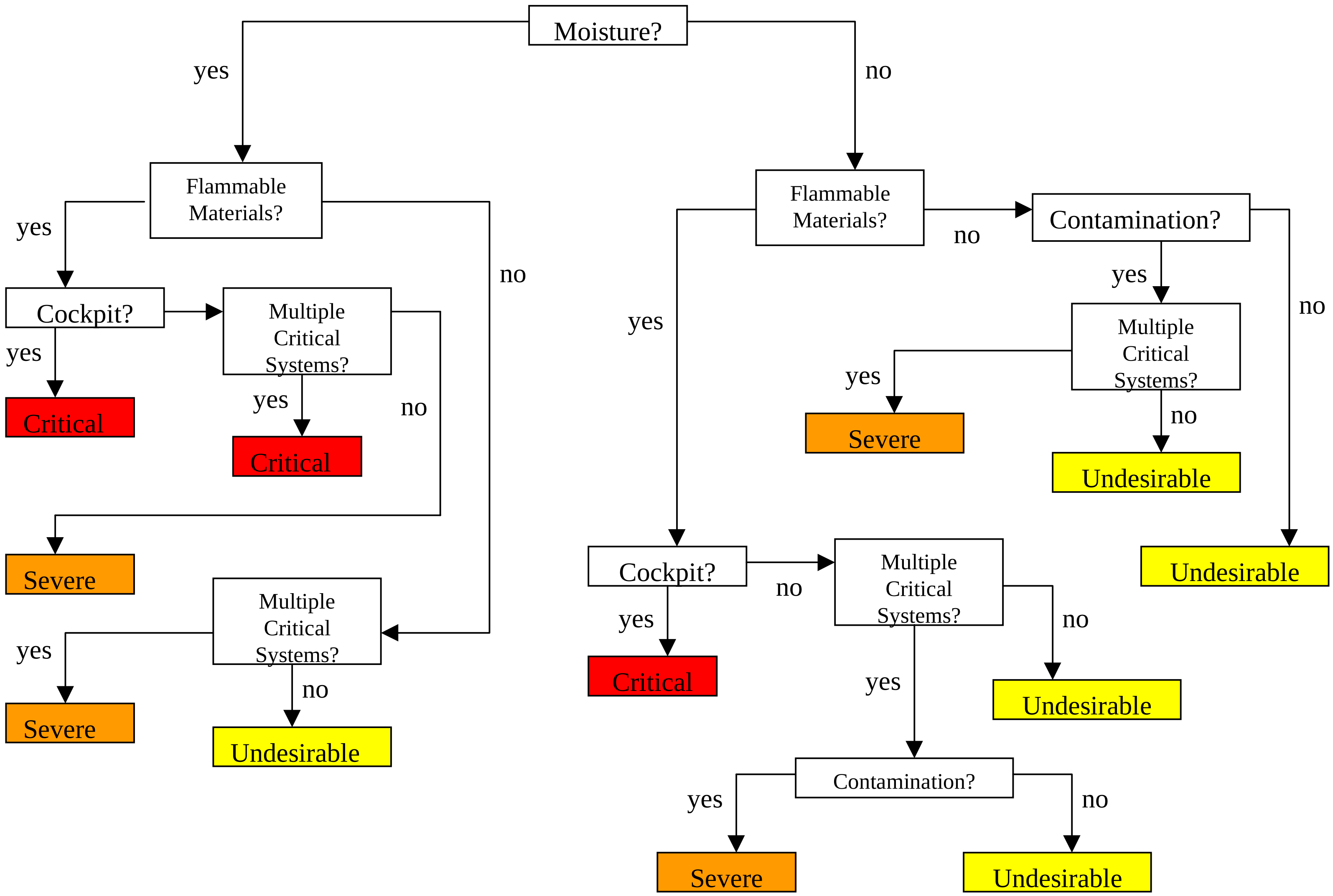


Electronics Bay and Cockpit

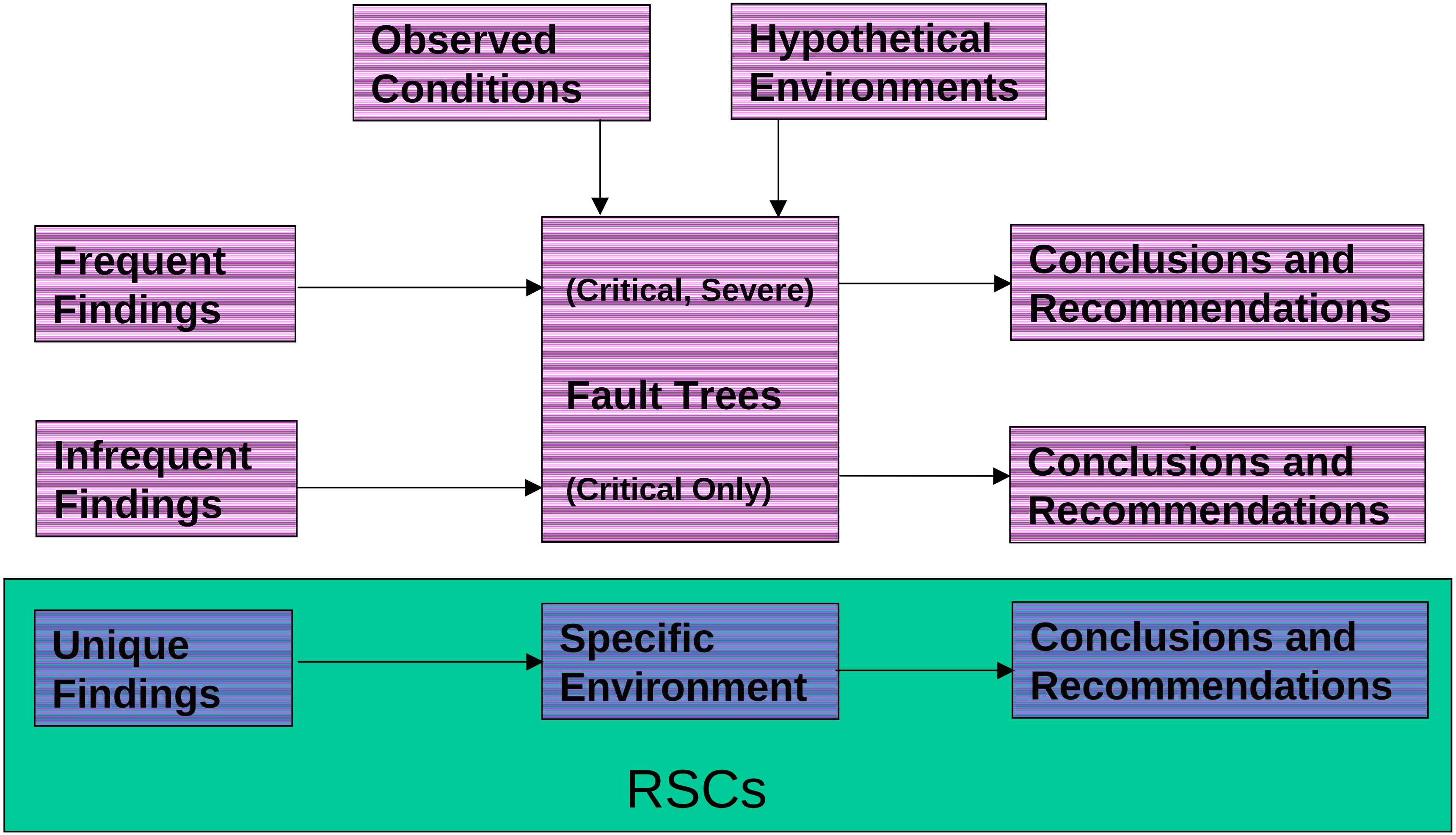
The abundance of wire in these zones as well as the importance of the systems they support demand that the cockpit and electronic bay receive special attention.



Delamination "Fault Tree"



Threat Assessment Summary



Recommendations Roadmap

Table 7-5-1: Degraded Splice

Situation	Recommendations
1. Any high current circuit with one of more of the conditions identified below.	This finding is relatively infrequent. Pre-emptive replacement of spl[illegible]ed wire with new wire or the rework of splices can minimize the potential for repairs or splices to degrade beyond acceptable limits. Any repair should be accomplished using OEM/FAA approved methods and materials appropriate for the environment (which may exceed the requirements of originally approved practice for aged aircraft). Periodic diagnostic testing (e.g. resistance evaluation, time domain reflectometry) can help to identify failing (high resistance) repairs and splices. Recommendations: Task Group 4: Update splicing practices as necessary. Consider procedure to tag locations of splices to aid in future visual inspections. Task Group 5: U[illegible]date training guidelines on a regular basis to correspond to ESPM updates. Emphasize the need to inspect spli[illegible] closely for obvious deterioration as well as proper materials and workmanship. Aircraft Manufacturer[illegible] Where appropriate utilize design practices which facilitate the repair of electrical interconnect systems wit[illegible]he need for splices. Develop splice vs. replacement of wire guidelines. Aircraft Operators: Review [illegible] and proficiency training practices for splice installation and inspection. Ensure full awareness of appr[illegible]terials and techniques. Other: The FAA should revise A[illegible]1B to stipulates that environmental splices are the preferred method of repairing wire in both SWAMP [illegible]AMP areas. Develop wiring configuration management software that will track the installatio[illegible] of splices. Develop best practices regarding the maximum number of splices permitted i[illegible]s of circuits based upon frequency and severity of potential splice failures.

Table 5-3 "Frequency" Category

Recommendations are consistent with the last column of Table 5-3

An generic observable condition

Recommendations are directed to specific organizations

Recommendations Roadmap

Fault Tree "Severity" Rating for the specific condition indicated

2b. Moisture, flammable materials, multiple critical systems	Given the specified conditions, the occurrence of this fault could lead to potentially critical consequences. Effective intervention can include reduction of moisture intrusion and minimization of flammable materials in the proximity of susceptible installations. Installation of heat shielding to protect susceptible installations can eliminate or mitigate heat damage. Because embrittled wires can fail collectively, proper separation of critical system wiring is essential. Additional Recommendations: <u>Task Group 3:</u> Investigate periodic, selective inspection and nondestructive testing of wire bundles supporting multiple flight critical systems. <u>Task Group 4:</u> Insure that drip guard installation and maintenance are appropriately specified. <u>Aircraft Manufacturers:</u> Review design practices regarding the use of drip guards for this specific situation. For this specific situation, investigate periodic, selective inspection and nondestructive testing of wiring. Develop updated wiring separation guidelines that consider loss of multiple critical functions from a common mode failure. <u>Aircraft Operators:</u> For this specific situation, investigate periodic, selective inspection and nondestructive testing of wiring. Investigate segregation and separation of wire installed after manufacture of the aircraft.

A specific observable condition from "Fault Trees". To be considered in conjunction with its more generic parent condition

Design and Modification

- Design considerations to re-emphasize fire and common mode/cause failure.
- Segregation of wire to reduce risk – consideration of multiple critical systems, fire potential, interaction with other systems.
- Design modifications to minimize moisture intrusion, contamination.
- Routing and separation decisions to consider wire type – (e.g. Polyimide-arcing, PVC-fire).

Enhanced SWPM

- Update repair practices – more stringent requirements for environmental splices.
- Specify application of diagnostic testing as added precaution in high risk applications, zones.
- Specify procedures to identify known catalytic agents and specify corrective action.

Enhanced Maintenance Practice

- Rework of suspect repairs and splices.
- Accelerated or prioritized removal of flammable materials from critical locations.
- Enhanced configuration control of wire systems.

On Condition Actions

- Perform rework in response to heat damage.
- Perform additional routine troubleshooting with diagnostic equipment in critical zones
- Perform invasive inspection in response to certain symptoms.

AFCI Preliminaries

Develop preliminary implementation plan:

- Who will be responsible within the organization?
- What operational procedures need to be developed?
- What maintenance procedures need to be developed?

R&D Recommendations

- The FAA should fully support its commitment to its wire degradation assessment project to begin this year.
  - As part of the degradation assessment project the FAA should analyze the effects of wire-to-wire chaffing.
  - Also as part of the degradation assessment project the FAA should analyze the effects of common contaminants on wire.
  - The degradation assessment project should be fully consistent with and build upon the work presented in the Intrusive Inspection Working Group Report.
- The FAA should aggressively pursue and promote arc-fault circuit breaker development.
- The FAA should aggressively pursue and promote the development of nondestructive test equipment for aircraft wiring.

R&D Recommendations

- The FAA should investigate the physical and functional integrity of any electrical interconnect system component whose failure could hazard the aircraft. This includes connectors, circuit breakers, relays, switches, shielding, grounds, and wire installation hardware.
- The FAA should determine the frequency and significance of non-environmental splices, and assess their potential impact on flight safety.
- The FAA should conduct research to assess the significance of unacceptably high resistance connections.

Comments

- The report is fully supported and endorsed by all participants in the Intrusive Inspection Working Group’s final meeting, December 12-14, 2000.
- One dissenting opinion remains.
- R&D Recommendations are currently being implemented by the FAA