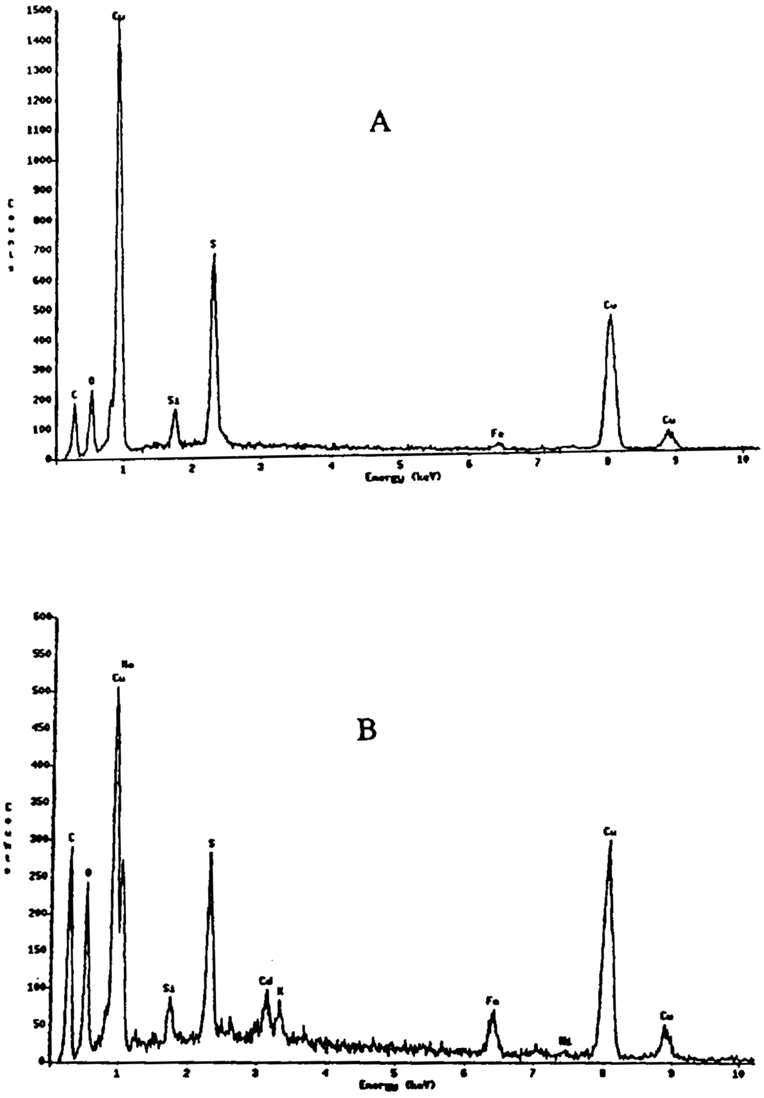
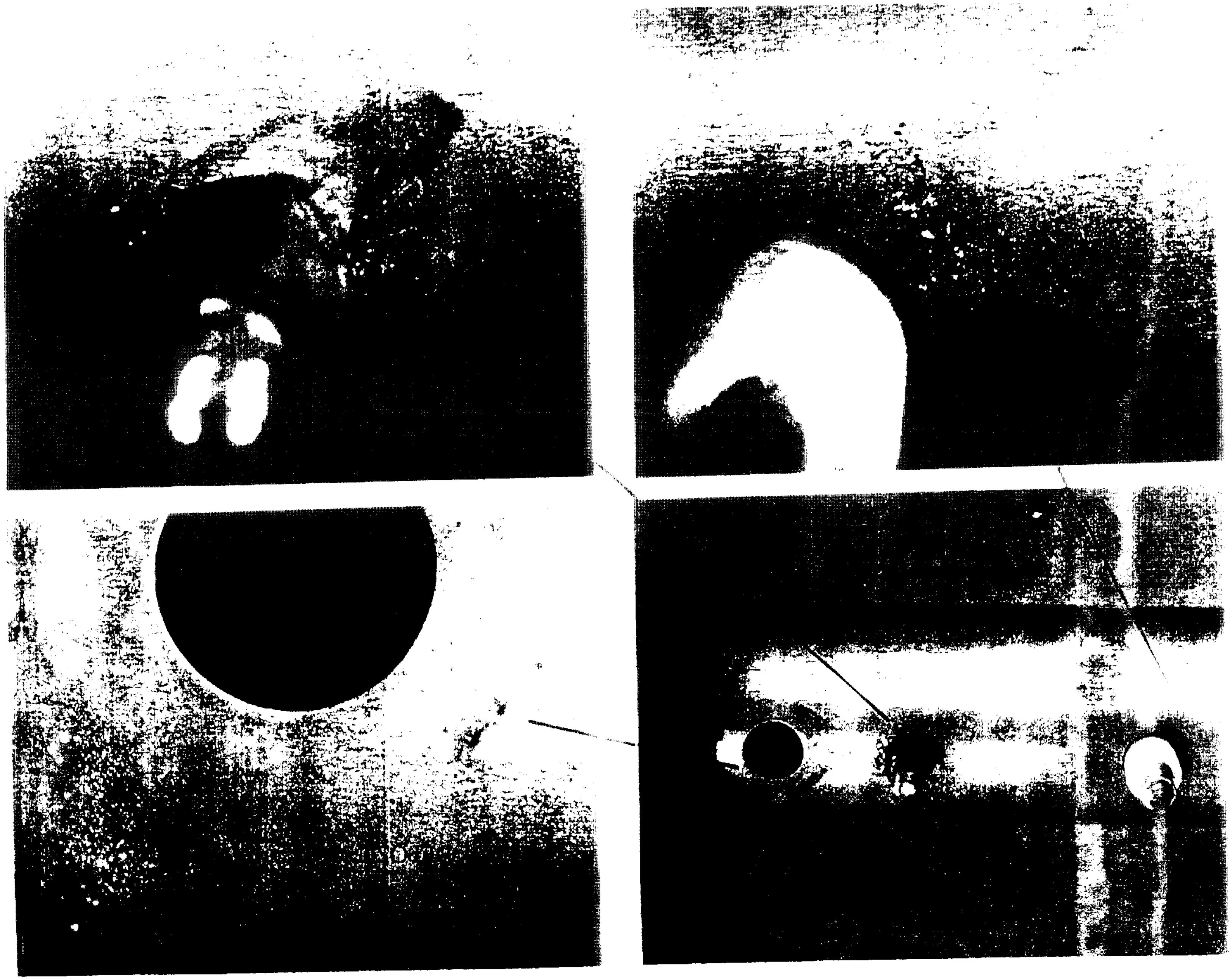


Figure 10. Electron microprobe elemental surveys of dark deposits sampled from the fuel quantity tank unit F44 Hi-Z terminal block (A) before and (B) after the month long sea water exposure.



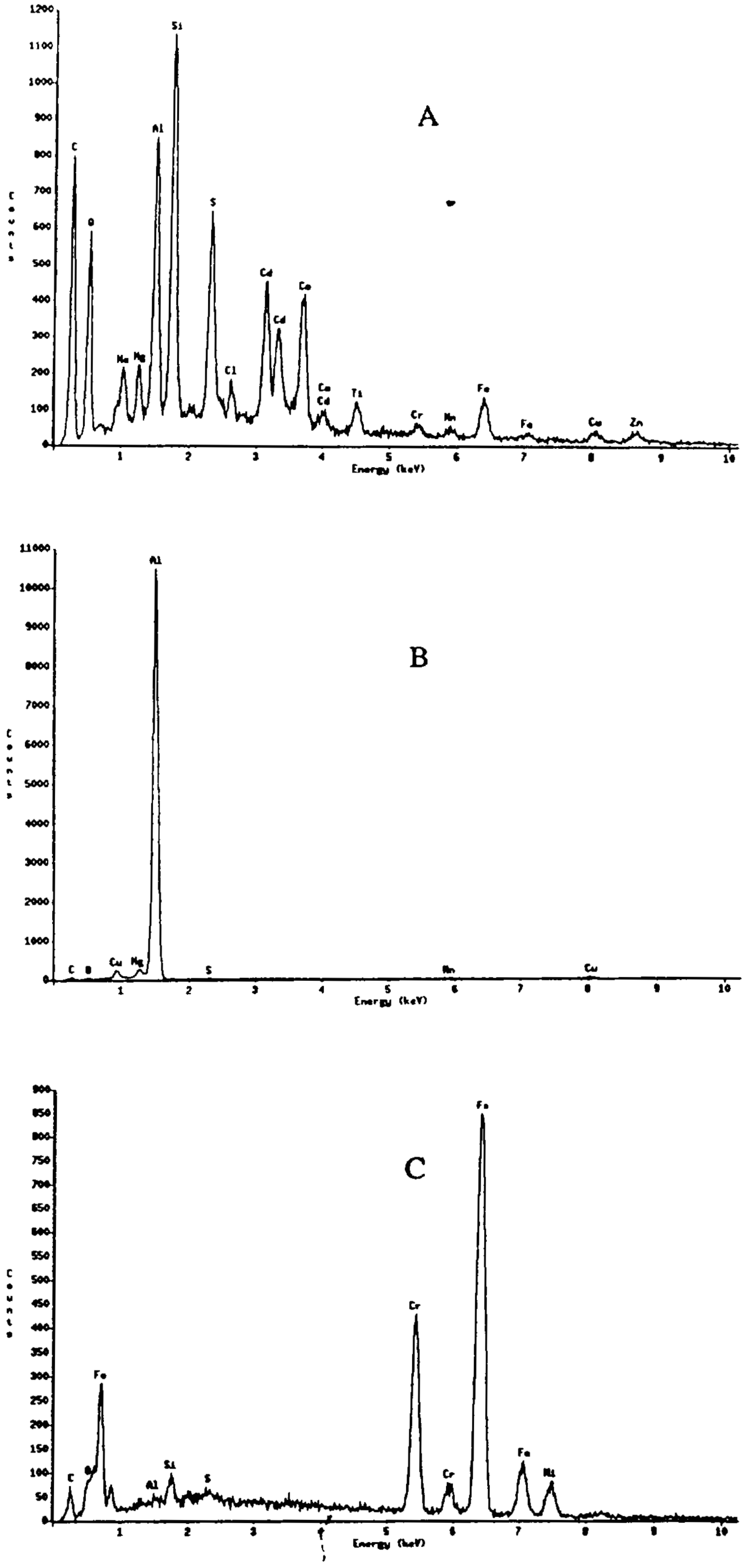


Figure 2. Electron microprobe elemental surveys of (A) the gray deposits indicated in Figure 1B, (B) an aluminum fragment and (C) a corrosion-resistant steel fragment from the surfaces shown in Figure 1.

NATIONAL TRANSPORTATION SAFETY BOARD
Office of Aviation Safety
Washington, D.C. 20594

February 1, 2000

SYSTEMS GROUP CHAIRMAN FACTUAL REPORT ADDENDUM FOR DEPOSITS ON FUEL TANK ELECTRICAL COMPONENTS

A. ACCIDENT: DCA96MA070

Location : East Moriches, New York

Date : July 17, 1996

Time : 2031 Eastern Daylight Time

Airplane : Boeing 747-131, N93119
Operated as Trans World Airlines (TWA) Flight 800

B. SYSTEMS SUB-GROUP

Chairman : Robert L. Swaim
National Transportation Safety Board (NTSB)
Washington, D.C.

Member : Chris Hartonas
Federal Aviation Administration (FAA)
Seattle, Washington

Member : Jon Regimbal
FAA
Seattle, Washington

Member : Richard Lidicker
Boeing Commercial Airplane Co.
Seattle, Washington

Member : Lou Taylor
Honeywell Commercial Aviation Systems,
Sensor Products Operation (CAS-SPO)
Minneapolis, Minnesota

Member : William Savage
Honeywell Commercial Aviation Systems,

Sensor & Guidance Products
Minneapolis, Minnesota

Member : Ken Craycraft
Trans World Airlines (TWA)
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Additional participants:

Dr. Merritt M. Birky
NTSB
Washington, D.C.

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Bill Wall
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David Johnson
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Dayton, Ohio

Dr. John Grant
University of Dayton Research Institute (UDRI) at AFRL
Dayton, Ohio

Mr. Robert Kauffman
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Stanley Blum
Crane Company, Hydro-Aire
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Paul Russ

Crane Company, Lear-Romec
Cleveland, Ohio

Dr. Michael McKubre
Stanford Research Institute International
Menlo Park, California

C. SUMMARY

On July 17, 1996, at 2031 EDT, a Boeing 747-131, N93119, crashed into the Atlantic Ocean, about 8 miles south of East Moriches, New York, after taking off from John F. Kennedy International Airport (JFK). All 230 people aboard were killed. The airplane was being operated as a 14 Code of Federal Regulations (CFR) Part 121 flight to Charles De Gaulle International Airport (CDG) at Paris, France, as Trans World Airlines (TWA) flight 800. Wreckage from the airplane was recovered from more than nine square miles of ocean. Reconstruction of portions of the wreckage found evidence of an explosion in the center wing fuel tank (CWT).

On April 4, 1997, the Systems Group found blackened deposits on fuel quantity indication system (FQIS) electrical connectors that came from fuel tanks of the accident airplane and other airplanes. An investigation into the deposits included laboratory research; a search for documents; and meetings with others who researched the subject for the FAA, the Air Force, manufacturers (of airplanes, FQIS, and pumps), and universities.

D. DETAILS OF THE INVESTIGATION
TABLE OF CONTENTS

TOWER AIR TERMINAL STRIP

A May 28, 1998, letter to FAA Inspector Charles Fowler from Mr. Paul Marks of Tower Air stated that on April 9, 1998, Tower Air personnel found deposit on a CWT (T347) terminal strip while performing maintenance on a Boeing 747. Maintenance personnel had been troubleshooting FQIS problems related to refueling included premature and delayed refueling shutoff, as well as problems with system wiring. The terminal strip was removed and given to FAA personnel on the scene, who provided it to the Safety Board.

The Safety Board tested portions of the terminal strip at different laboratories and the resulting reports are attached. Safety Board personnel first brought the terminal strip to the United States Air Force Research Laboratory (AFRL) Electronic Failure Analysis Laboratory[1] to test the electrical resistance and to document the deposits. The part was then carried the part to the Evans-East Laboratories in Plainsboro, New Jersey, on April 20, 1998, for testing of the chemical properties of the deposits in further depth. The part was carried back to AFRL, where Dr. John Grant of the University of Dayton Research Institute (UDRI) was provided with a section of the T347 terminal strip. The AFRL subsequently tested areas of the terminal strip to document how the deposits would react to electrical loads. A final portion of the terminal strip was used to attempt a breakdown test in the presence of flammable jet fuel vapors at the AFRL Electronic Failure Analysis Laboratory and the Fuels Branch Laboratory.

EVANS-EAST LABORATORY REPORTS

The attached laboratory reports that resulted from testing at Evans East were:

- Dated April 22, 1998, for examinations conducted with positive and negative time-of-flight secondary ion mass spectrometry (TOF-SIMS).
- Dated April 242, 1998, for examinations conducted with X-Ray Photoelectron Spectroscopy (XPS).

AIR FORCE RESEARCH LABORATORY REPORTS

The Safety Board sent numerous FQIS parts from the accident airplane and other airplanes to the AFRL Electronic Failure Analysis Laboratory. The parts included fuel quantity probes (tank units), CWT terminal strips (including the T347 part from Tower Air), and FQIS wiring. The laboratory submitted three[2] reports that were identified as:

- Report No. AFRL/MLSA 99-2, dated January 26, 1999.

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[1] Materials Integrity Branch of the Systems Support Division

[2] A previous AFRL report (WL/MLS 97-102) documented residues on FQIS components. A copy of the report was included in the Systems Group Chairman's Factual Report of November 17, 1997.

Report No. AFRL/MLSA 99-2 documented examination of FQIS parts removed from a retired 747, N134TW, that had entered service in 1970. Electrical resistance was measured between all combinations of the Hi-Z, Lo-Z, and Shield (ground) wire terminal posts. Appendix B to the report contained the results of XPS examinations performed at AFRL by Dr. John Grant of UDRI.

- Report No. AFRL/MLS 99-33, dated June 21, 1999.

Report No. AFRL/MLS 99-33 further documented FQIS components from N134TW (a retired TWA airplane) and included the examination of parts from other airplanes. Deposits were typically found on terminal block surfaces at locations where silver-plated copper wire was exposed to jet fuel and on wire insulation near exposed core conductors or shield braid. Electrical tests found resistance between terminals and direct probing of the deposits on the surface of various parts was conducted at closer distances to replicate the spacing between adjacent wires. Report No. AFRL/MLS 99-33 also described the T347 terminal strip that had been provided by Tower Air from a 747 CWT.

- Report No. AFRL/MLS 99-68, dated October 18, 1999.

Report No. AFRL/MLS 99-68 described how the thin-film sulfidation deposits break down under electrical loads and described development of a substitute deposit (vapor-deposited carbon on glass slides) used for repeatability of laboratory tests. Electrical break-down of the vapor-deposited carbon substitute deposits was used to repeatably ignite flammable (lighter fluid) vapors in an enclosed dish.

The Electronics Laboratory was not equipped to conduct testing with fuel vapors. Personnel from the Electronics Laboratory supplied seven vapor-deposited carbon samples to the Fuels Branch Laboratory for testing in fuel vapors. The Fuels Branch tests used a different test apparatus than had been used in the Electrical Laboratory and submitted a report dated January 6, 2000, that discussed the attempted ignition of fuel vapors.

INFORMATION FROM BOEING

The Safety Board requested that Boeing provide any documents pertaining to silver or copper sulfides on December 19, 1997. The Safety Board again asked for information about sulfidation on March 6, 1998, requesting information about fuel pump electrical motors that may have contained evidence of sulfidation and arcing damage. These requests resulted in a Boeing letter of April 23, 1998. The following documents were attached to the Boeing letter (and are attached to this report):

1. Boeing Materials Technology (BMT) Engineering Report MS21053, dated June 17, 1988, which described the examinations of 18 Hydro-Aire electrical fuel pump stators.

2. Boeing Analytical Engineering Report 2-5323-WP-91-97, dated March 20, 1991, described the "Analysis of Wing Tank Indicator Silvered Braid" from a B-757.

3. A Parker Bertea Aerospace Memorandum, dated August 18, 1992, documented the conditions of FQIS components removed from DC-10 airplanes.

4. Boeing Laboratory Report 9-5576-P+CA-025P, dated March 30, 1993, described examinations of electrical hardware from the fuel tanks of 747, 737, and DC-10 airplanes.

5. Boeing Laboratory Report 9-5576-P+CA-025P1, dated April 29, 1993, was the second report for an examination of electrical hardware from the fuel tanks of 747, 737, and DC-10 airplanes.

   Boeing conducted a literature search as part of Report 9-5576-P+CA-025P1 and attached were the following two reports:

   A. A report dated April 22, 1973, titled "Copper and Silver Corrosion by Aviation Turbine Fuels," written at the Indian Institute of Petroleum.

   B. The Journal of the Institute of Petroleum published a report dated September 1970, titled "Silver Corrosion by Aviation Turbine Fuel."

6. Boeing Analytical Engineering Report 9-5576-WP-97-272, dated August 5, 1997, (and discussions documented in the meeting of April 29, 1998) described electrical tests of FQIS parts that had sulfidation.[3]

Boeing submitted Equipment Quality Analysis Report (EQA) 7564R, dated April 28, 1999, to the Safety Board. The report includes numerous sections pertaining to Boeing inspections of two complete sets of Honeywell B-747-200 FQIS components and testing of selected components. Analytical Engineering Reports attached to EQA 7564R describe testing the FQIS parts electrically with a Vitrek Model 9441 Dielectric Analyzer and Andeen Hagerling Model 2500A Ultra-Precision Capacitance Bridge.[4] Attached to Report 7564R are other Analytical Engineering Reports that describe component examinations:

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[3] This report was also received attached to Equipment Quality Analysis Report 7564R, dated April 28, 1999.

[4] Examples are Analytical Engineering Reports 9-5576-WP-97-329, dated September 17, 1997, and 9-5576-WP-98-136, dated May 20, 1998.

Analytical Engineering Report 9-5576-WP-97-318, dated September 2, 1997, describing examination of a compensator.

Analytical Engineering Report 9-5576-WP-98-135, dated May 15, 1998, described testing of five parts "to visually determine the effectiveness of mechanically cleaning the surfaces and to quantify effects on electrical properties."

Analytical Engineering Report 9-5576-WP-98-136, dated May 20, 1998, noted that the Safety Board had requested input regarding further testing that could be performed.

On August 31, 1999, Boeing submitted EQA Report 7895R, dated June 7, 1999, containing the records of examining B-737 FQIS components.

MEETINGS

MEETING AT NTSB ON APRIL 29, 1998

The Systems Group met at Safety Board headquarters in Washington, DC, on April 29, 1998, to discuss progress in examinations of deposits found on fuel quantity indication system (FQIS) components. The group agreed that:

1. The deposit is a complex mixture with majority components of copper-sulfide and silver sulfide. The deposit was referred to as "sulfides" (or later as "sulfidation") in the plural tense, denoting that the term is a summary and not a precise definition.

2. The chemical characteristics were not sufficiently understood in the topics of deposit development, cleansing, or removal.

3. The accumulation of the deposit appeared to be time-dependent, rather than dependent upon flight time or another factor.

4. The deposit is extremely brittle and can be disturbed by removal of samples from fuel tanks.

5. Terminal strips found in fuel tanks have deposits that are generically similar to fuel probe and compensator terminal blocks, but allow increased samples for testing.

6. Electrical testing of the Tower Air T347 terminal strip at the Air Force Research Laboratory (AFRL) had found that the electrical resistance of the deposit varies with the test voltage applied. As a result, the group agreed that further testing

would require strict record keeping that includes applied voltage, test equipment type, and any other parameters.

7. Electrical testing of the same terminal strip found that thicker deposits had increased resistance. Resistance was between 10E4 to greater than 10E7 ohms in the laboratory tests that did not control operational altitude, humidity, and other atmospheric variables.

8. Boeing reported testing two shipsets of B-747 fuel probes and compensators that had been received. The Safety Board subsequently received further detail in Boeing report 7564R, dated April 28, 1999 (description attached).

9. During 1987-1988, eighteen Hydro-Aire fuel pump stators with arc-type damage had been submitted to the Boeing Equipment Quality Analysis (EQA) Laboratory. It was reported that the primary cause of the arcing was the cracking of the wire insulation which provided locations for arcing to adjacent metal components. In one pump, testing found that silver-sulfide deposits had been involved. (The complete report was discussed in a previous section as Report BMT MS21053.)

APRIL 20, 1999, MEETING AT AFRL

The Systems Group met at the AFRL with an FAA group that was organized to research sulfidation on April 20, 1999. The FAA Program Manager, Mr. William Emmerling, described the FAA research plan that had been funded as part of the Aircraft Catastrophic Failure Prevention Program. Mr. Emmerling introduced Dr. Michael McKubre as the FAA researcher into the subject of sulfidation. Mr. George Slenski presented the results of AFRL research conducted for the Safety Board investigation, which was subsequently described in AFRL reports (attached).

Mr. Robert Kauffman of UDRI described the prior research that he and others had conducted into sulfidation, oxidation, sulfide deposits, and other topics. Mr. Kauffman also showed the group numerous samples of sulfidation that he had created in his laboratory. Mr. Kauffman explained that some fuels have less sulfur content than others and that low-sulfur fuels created more deposits than fuels containing higher relative sulfur amounts. He presented a list of EXPECTED RESULTS FROM LOW SULFUR FUEL USAGE (attached).

Mr. Kauffman informed the group about the existence of National Aeronautics and Space Administration (NASA) Report TN-D-4327, dated November 20, 1967, and titled CHEMICALLY INDUCED IGNITION IN AIRCRAFT AND SPACECRAFT ELECTRICAL CIRCUITRY BY GLYCOL/WATER SOLUTIONS. (The report is attached.)

NOVEMBER 9, 1999, MEETING AT ARIZONA STATE UNIVERSITY

Mr. Kauffman had conducted testing since the meeting of April 20, 1999, and reported his results to a joint meeting of FAA/NTSB/industry personnel that was held at Arizona State University on November 9, 1999. Mr. Kauffman reported that substitution of jet fuel for the glycol[5] that was discussed in NASA Report TN-D-4327 resulted in black deposits on silver-plated wires and that flashes of light developed that were similar to what NASA had reported.

Dr. Robert Peck had an associate demonstrate a variation of this reaction with direct current to the meeting which subsequently ignited fuel vapors.

Dr. Michael McKubre reported that the formation of sulfur-containing conductive deposits from jet fuel on silver wire was possible with both AC and DC current. Dr. McKubre also provided a presentation on the electrochemical processes that had been identified or theorized for the FAA investigation.

MINIMIZING SULFIDATION

BFGOODRICH FQIS CHANGES TO MINIMIZE SULFIDE CREATION

The BFGoodrich representative to the meeting of November 9, 1999, related that the company improved the accuracy and reliability of military FQIS through a design changes that began in about 1993. The following were the changes to fuel tank wire termination methods:

1. Use of nickel-plated wire,
2. Use of fold-plated ring connector,
3. Sealant used in shrink tubes,
4. Separate inner and outer layers of shrink tube.

BFGoodrich also provided the Safety Board with sample assemblies and the following graphic (aircraft model identification deleted):

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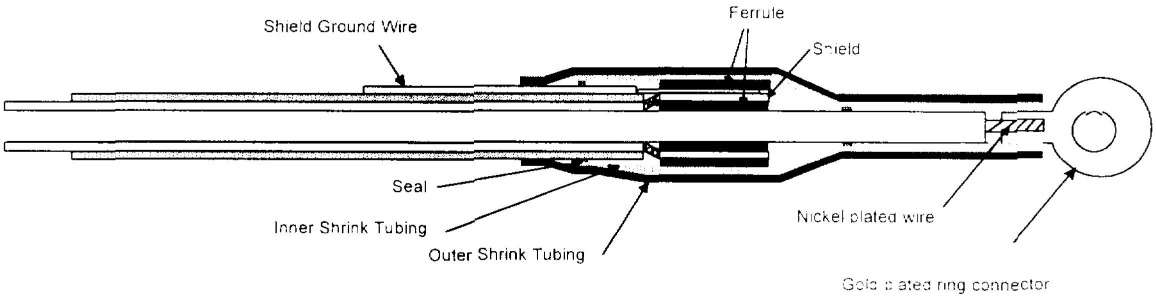
[5] Defined as ethylene glycol by the Webster's New World Dictionary, Third College Edition.



BFGoodrich Illustration of FQIS Ring Connector Attachment to Wire

The BFGoodrich representative stated that the improvement resulted in a large reduction in FQIS accuracy problems and that the inaccuracies had been based on leakage currents through the deposits. The BFGoodrich representative noted that approximately six years had elapsed since the change and that the time was nearly equal to the period that preceded the AFRL report.

REPLACEMENT OF WIRING IN FUEL TANKS

Boeing was asked about feasibility of replacing FQIS wiring in fuel tanks with nickel-plated wiring as is used on the Model 777 airplane. In a letter of December 7, 1999, Boeing wrote that "overall, the wholesale replacement of FQIS bundles in the tank is not recommended." The Boeing letter is attached.

On January 20, 2000, Boeing wrote that in addition to BFGoodrich, at least two other companies provide wire harness that have terminations that are resistant to sulfidation and the companies are Smiths Industries Aerospace - Civil Systems - UK, and Cinch Connector, Inc.; both of which supply fuel tank wire harnesses to Boeing.

Robert L. Swaim

Robert L. Swaim
TWA 800 Systems Group Chairman

2/2/00

NATIONAL TRANSPORTATION SAFETY BOARD

ATTACHMENTS TO THE SYSTEMS GROUP CHAIRMAN FACTUAL REPORT ADDENDUM FOR DEPOSITS ON FUEL TANK ELECTRICAL COMPONENTS

Ronald J. Hinderberger
Director

The Boeing Company
P.O. Box 3707 MC 67 [illegible]

[illegible]

BOEING

16 June 1999
B-H200-16710-ASI

Mr. R. Swaim, AS-40
National Transportation Safety Board
490 L'Enfant Plaza East, SW
Washington DC 20594

Subject: Terminal Strips, TWA 747-100, N93119 Accident off Long Island, NY - 17 July 1996

References: (a) B-H200-16701-ASI, Dated 28 May 1999
(b) Your email dated 15 June 1999

Dear Mr. Swaim:

The reference (a) letter forwarded seven terminal strips and provided total time and landings for the airplanes from which the terminal strips were removed. In your reference (b) message you requested a more detailed history of the terminal strips.

The terminal strips came from two different airplanes, two were from airplane line number 423 (delivered in Feb 1980) and the rest were from airplane line number 293 (delivered Sep 1976). At the time the terminal strips were removed from the airplane, the airline was asked for the history of the fuel quantity harness and probes.

One of the owners (LN 293) obtained the airplane 2 years ago and only searched records for the period of time of their ownership, as the rest of the records were in storage. The other owner (LN 423) had recently obtained the airplane with repair records going back for 5 years. As far as can be determined, the terminal strips had never been replaced on either airplane. These terminal strips are the terminal strips referred to in the EQA 7564R report.

If you have any questions, please do not hesitate to call.

Very truly yours,

Ronald J. Hinderberger
Director, Airplane Safety
Org. B-H200, M/S 67-PR
Telex 32-9430, STA DIR AS
Phone (425) 237-8525
Fax (425) 237-8188

CC Mr. A. Dickinson, IIC

Ronald J. Hinderberger
Director
Airplane Safety
Commercial Airplanes Group

The Boeing Company
P.O. Box 3707 MC 67-XK
Seattle, WA 98124-2207

7 December, 1999
B-H200-16839-ASI

Mr. R. Swaim, AS-40
National Transportation Safety Board
490 L'Enfant Plaza East, SW
Washington DC 20594

Subject: Nickel-Plated FQIS Wiring, TWA 747-100 N93119 Accident off Long Island, N.Y. – 17 July 1996

You questioned whether it is feasible to replace the Fuel Quantity Indication System (FQIS) wiring in fuel tanks with nickel-plated wiring as is used on the model 777 airplane.

In order to replace silver plated wiring with nickel-plated wiring in the tank, the entire harness would have to be removed and replaced. This is a difficult task on all of our airplanes. Every airplane requires a confined space entry in an area with fuel vapor, requiring maintenance personnel to wear the appropriate safety gear. In addition, working in confined spaces of fuel tanks carries the risk of damage to the surrounding fuel system equipment. Replacement of wire bundles in center fuel tanks is somewhat easier than in the main tanks, especially on the wide body airplanes, due to the large size of the tank. In our narrow body airplanes, even the center tanks are small and the wing tanks have very small areas for access to the wiring and probes.

Overall, the wholesale replacement of FQIS bundles in the tank is not recommended.

If you have any questions, please do not hesitate to call.

Very truly yours,

Ronald J. Hinderberger
Director, Airplane Safety
Org. B-H200, MC 67-PR
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Seattle WA 98124-2207

BOEING

23 April 1998
B-B600-16396-ASI

Mr. R. Swaim, AS-40
National Transportation Safety Board
490 L'Enfant Plaza East, SW
Washington DC 20594-2000

Subject: Copper/Silver Sulfides, TWA 747-100, N93119 Accident off Long Island, NY, 17 July 1996

References: (a) Your email dated 19 Dec 1997
(b) Your email dated 6 Mar 1998

Dear Mr. Swaim:

In your reference (a) email, you requested copies of reports on copper/silver sulfides found on fuel probes and other components. In reference (b) you requested copies of reports on fuel pumps that may have had evidence of arcing as a result of copper/silver sulfides.

Enclosed with this letter are copies of reports and other information we have been able to locate at Boeing. Following reports are enclosed:

1. Summary statement in response to reference (b)
2. Letter No. T-6757-1-T1541, Boeing to Hydro-Aire
3. Engineering Report No. MS21053, dated June 17, 1988
4. EQA Report No. 5892, dated April 15, 1991
5. Laboratory Report No. 9-5576-P+CA-025P, dated March 30, 1993
6. Laboratory Report No. 9-5576-P+CA-025P1, dated April 29, 1993
7. Report No. 9-5596-P+CA-212, dated Aug 15, 1994
8. Report No. 9-5576-P+CA-201, dated March 14, 1996
9. Paper on Copper and Silver Corrosion by Aviation Turbine Fuel, by Raghunath P. Tripathi et al Apr 22, 1973
10. Institute of Petroleum, Silver Corrosion by Aviation Turbine Fuel, by B. J. Budd and R. P. Sanger, Sep 1970
11. Report by Parker Hannifin Corporation, dated Sep 18, 1992
12. Analytical Engineering Report No. 9-5576-WP-97-272, dated Aug 5, 1997
13. Analytical Engineering Report No. 9-5576-WP-97-230, dated June 17, 1997

If you have any questions, please do not hesitate to call.

Very truly yours,

John W. Purvis
Director, Air Safety Investigation
Org. B-B600, M/S 67-PR
Telex 32-9430, STA DIR PURVIS
Phone (425) 237-8525
Fax (425) 237-8188

Enclosures: As noted

cc: Mr. A. Dickinson, IIC (w/o Enclosure)

BMT
BOEING MATERIALS TECHNOLOGY

Approved for outside distribution.

J. T. Rogers, Chief - 767/747
Structures Technology

Engineering Report No.: MS 21053

Date: June 17, 1988

Design Drawing
Part Name: Stator - Fuel Boost Pump

Part Number: Crane, Hydro-Aire
Div. No. 78-17515

ATA Index: 2822 **Responsible Design Group:** Fuel Systems

Customer: [redacted] **Model:** 747 **Registry No.:** See Table I

Line Position No.: N/A **Flight Hours:** N/A **No. of Landings:** N/A

Material: Various Stator Components (see text) **Material Specification:** Fuel boost pump specification - 60889004

References: (a) [redacted]
(b)
(c) BAC Analytical Engineering Report No. 2-3623-2-RF-087-366 (July 31, 1987).

Heat Treat: N/A

Finish: N/A

BACKGROUND

In November 1986, [redacted] advised Boeing of a problem with shorted fuel boost pump stators. Boeing performed an Equipment Quality Analysis (EQA) on returned [redacted] fuel boost pumps in December 1986. The malfunctions were reportedly due to electrical causes. Between January 1986 and June 1987 [redacted] recorded twenty-three fuel boost pump removals due to stator shorting. In January 1988 they reported an additional fifteen instances of fuel boost pump malfunctions due to shorted stators. Another EQA was performed in February of 1988 on two fuel boost pumps and four separate stators which had malfunctioned. The results of that analysis listed numerous stator defects including insufficient winding insulation, defective fuses, evidence of fabrication damage (fuses forced into the windings), and evidence of corrosion. The stators removed from these two pumps (listed as Nos. 8 and 9 in Table I) and the four separate stators were sent to BMT for metallurgical analysis along with twelve additional [redacted] stators of unknown history. In addition, BMT requested and received a new stator for analysis.

RESULTS

I. GENERAL DESCRIPTION OF FUEL BOOST PUMP AND COMPONENTS

A. BOOST PUMP

The main function of the fuel boost pumps is to supply fuel pressure to the engine driven fuel pumps. There are four boost pumps per wing (Fig. 1), two for each main fuel tank. Power for the pumps is 115 volts, 400 cycles, 3 phase alternating current. External resettable 10 amp circuit breakers are in series with each phase. The pump motor is cooled by forced circulation of fuel. Consequently, the fuel is in direct contact with the wire windings of the motor stator and armature.

B. STATOR

The stator component of the pump motor (e.g. Fig. 2) is composed of three sets of copper wire windings wound on a laminated steel core. Coils of wire from the three different phases are separated by insulating paper. Each set of windings has a non-resettable, in-series, thermal fuse soldered to the end of the winding. The other lead of the fuse is soldered to electrical leads covered with red, green, or black colored teflon insulation. (The fuses or windings will be referred to as belonging to either the red, green or black phases). Each fuse lead connection is wrapped with a thin plastic insulating film. The fuse and wrapped leads are encased in a fiberglass sheath or sometimes multiple sheaths and incorporated into the winding wrap at one end of the stator (e.g. Fig. 3). During fabrication, the ends of the stator are compressed (required to satisfy a dimensional envelope) which results in the fuse cases being pressed into the adjacent windings. A final step in stator fabrication is a vacuum impregnation with an epoxy varnish and an oven bake.

II. DESCRIPTION OF STATOR COMPONENTS

A. WINDING WIRE

The AWG 24 gauge wire (Class 220, Type M2 per MIL-W-583C) is composed of a copper conductor surrounded by multiple layers (eight were counted in several instances) of a polyimide film. Each layer is approximately .00013 inches thick. After the stator is vacuum impregnated with the epoxy varnish, a thin epoxy film of varying thickness (.00005 inches was measured in one case) covers the polyimide layers (in areas where the varnish had access). The insulating layers may be seen in Fig. 9.

B. FUSES

The thermal fuses are composed of a non-conductive thermal pellet material (p-terphenyl) compressing two spring loaded silver plated contacts together. These components are contained in a silver plated brass fuse case. One of the internal contacts makes electrical contact with the inside of the fuse case, resulting in an electrically hot case. A wire is brazed to the end of the fuse case providing one of the fuse leads. The other lead consists of a wire connected to the internal contact and isolated from the case by a ceramic insulator. The fuse model (No. 415) used in the stators activates at 420°F.

III. DESCRIPTION OF STATOR DAMAGE

A. GENERAL

The eighteen stators were examined and the findings recorded in Table I. There were rusted areas on almost all of the stator laminated steel cores. No significance was attached to this since No. 16 stator exhibited no rust, yet still malfunctioned. The electrical resistance of the individual phase windings was not recorded since in some cases windings that were obviously destroyed measured low resistance, indicating wires had fused together.

Sixteen of the 18 submitted stators exhibited extensive arc burned areas covered with a black sooty appearing deposit, (refer to Fig. 2). After removal of the insulation wrapping, the arc burned areas appeared as shown in Fig. 4 with numerous wires melted through and in some instances fused to adjacent wires. Eight of the eighteen stators had arc burned areas immediately beneath one of the thermal fuses (refer to Fig. 3). In all these latter cases, when the insulation and lead wires were removed a hole was found in the fuse case (see Fig. 10). In the remaining ten stators, five had arc burned areas on the end of the stator opposite the fuses while four had arc burned areas on the fuse end, but next to the core. One of these stators, No. 8 which exhibited only a minor arc burn on the stator end opposite the fuses (Fig. 5) passed the EQA electrical test inspection. The remaining stator (No. 18) exhibited no severe arc burns but had a fuse which lost electrical continuity with no evidence of arcing or burning. Examination of this fuse revealed extensive corrosion pitting had penetrated the fuse case (Fig. 6) exposing the thermal pellet material to fuel (fuel has been shown capable of dissolving the pellet material, reference (c)).

Stator No. 18 with the corroded fuse case and Stator No. 8 were considered the best examples to examine for incipient causes of the stator malfunctions. Any defects observed on the other severely burned stators may have been produced by higher current and overheating as a result of the original malfunction.

B. CRACKS IN WIRE INSULATION

Numerous circumferential cracks were observed in the copper wire insulation (Fig. 7) from all stators, including the new stator. These cracks were visible to the naked eye, and thus not in compliance with the wire specification requirements. The cracks were consistently observed only at the convex sides of bends. There was no correlation with severity of bend since some of the most severe cracking occurred on relatively gentle bends. Also, severity of cracking varied considerably from stator to stator.

Scanning electron microscopic (SEM) analysis indicated the cracking occurred in the polyimide layers. Fig. 8 (a and b) shows the underlying cracks are bridged by a surface film indicating the epoxy film to be intact. In Fig. 9, a wire with cracks in the insulation was severely bent to open the cracks up. This revealed the flat fracture surface of a prior crack in the polyimide layers with the plastically deformed end of the epoxy film stretched over the lip.

When a similar wire with cracks on the one side was squeezed into a zero bend radius in the opposite direction no cracks occurred in the polyimide or epoxy layers. This test was performed on wires from the new and used stators with the same result. This showed that the polyimide insulation is capable of extensive deformation without cracking in air at room temperature.

These observations and tests indicate that cracking occurs in the polyimide wire insulation during stator processing since they were always on the convex side of bends and were observed in a new stator. The conditions present during stator processing are unknown. Therefore, the cause of the cracking was not investigated further.

C. FUSES

A noted in Section IIIA, one of the most frequent locations for arcing (8 out of 18 stators) was immediately beneath one of the thermal fuses. In all such cases the fuses were severely damaged with large holes burned through the fuse cases. The burn holes did not occur in any one location on the fuse cases. As shown in Fig. 10, they occurred (A) on the thermal pellet end, (B) along the side of the whole case and (C) on the end opposite the thermal pellet. With two exceptions, all the damaged fuses had lost electrical continuity. In one of these exceptions (the other was unavailable for examination) the burn hole was located on the fuse case end opposite the thermal pellet. The case had melted and fused to an inner contact lead resulting in permanent continuity. All the unburned fuses still had electrical continuity except for the one corroded fuse from No. 18 stator (see IIIA).

An analysis of these same type of fuses (reported in reference (c)) indicated a poor braze joint connection at one end of the fuse might be a source of stator malfunction. This did not appear to be a common defect in these stators since in many cases even though the fuse case was severely damaged. The braze joints were intact with no evidence of damage.

To determine if the remaining fuses functioned normally a number of them were heated in an oven to temperatures between 400°F and 450°F. As shown in Table II, all of the nine fuses tested were activated in this temperature range indicating that over-temperature operation was not a contributing factor to the stator damage. As noted, two of the fuses had obviously leaked since the normally dry thermal pellet material was found to be wet and smelled strongly of fuel after cutting open the fuse cases. However, even these fuses activated properly.

In numerous cases, when undamaged fuses still encased in the sheaths were mechanically separated from the top of the copper windings, a powdery corrosion product was observed at cracks in the copper wire insulation (Fig. 11). In several cases, a trail of green corrosion products could be followed from these locations through the fiberglass sheath directly to corrosion pits on the fuse surface. An extreme case of this was already noted in Stator No. 18 where the pits penetrated the fuse case. This corrosion product was identified as a copper chloride compound, probably $Cu_2Cl(OH)_3$, by energy dispersive X-ray analysis and X-ray diffraction.

Clearly, in some cases, an electrolytic corrosion couple had formed between the silver plated brass fuse case and the copper wire. Examining the fuse cases closely, including one from the new stator, revealed that a high percentage of their surfaces were not coated with epoxy. During stator fabrication the epoxy had failed to consistently penetrate through the fiberglass sheath to the fuse case surface. Examination of the fiberglass sheaths revealed that occasionally the epoxy failed to bridge the gaps in the fiberglass cloth allowing fuel access through that barrier. The majority of the fuse cases had a black tarnish (Ag_2S) on the silver plating which outlined the weave of the fiberglass sheath, providing further evidence of fuse contact with fuel. When the fuse as well as the lead connections were wrapped with a plastic film, as was observed in several stators, the fuse cases were observed to be in excellent condition with no tarnish.

D. BURN SPOTS ON THE WIRES

As noted earlier, stator No. 18 was the only stator without an obvious arc burn spot (corrosion had penetrated the fuse case). Detailed examination revealed very small localized burn spots. There was a black sooty appearing deposit covering the wire in one case (Fig. 12) while in another there was no deposit present but the epoxy coating was discolored and slightly bubbled (Fig. 13). These burn spots, sometimes found on the other stators, always occurred at a crack in the wire insulation. Scraping the insulation from these locations revealed a slightly tarnished or oxidized copper surface. It appears likely the burn spots are the early stages of the more extensive arc burns observed in the other stators.

DISCUSSION

There were several contributing factors to the stator malfunctioning. However, the primary one was cracking in the wire insulation which provided locations for arcing to adjacent metal components including other wires. The observations of the electrolytic corrosion products between the wire and fuses attest to the presence of electrolyte and thus suitable conditions for arcing at all locations in the stator. A particularly vulnerable location for arcing was underneath the thermal fuses.

SUMMARY

1. Arc burn areas of varying degrees were observed in the copper windings of all 18 stators. The arc burns occurred at various locations on the stators, although in many cases under a thermal fuse.

2. Circumferential cracks were observed (visually) in the polyimide insulation on the copper wire in all of the stators (including the new one). These cracks were not in compliance with the wire specification (MIL-W-583C). Although cracking occurred during stator processing, the cause of the cracking could not be determined.

3. The cracks in the wire insulation were the primary cause of the arc burns and resulting stator malfunctioning.

4. Most of the fuse cases were tarnished and/or corrosion pitted although they still retained function. In the few instances where the fuses were wrapped in plastic film the cases exhibited no evidence of tarnish or corrosion pits. There is no requirement in the specifications for the method of fuse insulation.

ACKNOWLEDGEMENTS

Background information, problem identification, and helpful discussions: Rick Sparks.

Prepared by ____ for
D. N. Fager

HJO Approved by ____
E. W. Smith

TABLE I
BACKGROUND INFORMATION AND VISUAL OBSERVATIONS

Stator I.D.	a. Plane Registry No. b. Date removed from plane c. Stator Serial No. d. Date stamped on stator e. Revision	Fuse Condition	Winding Condition	Remarks
No. 1	a. N.A. b. N.A. c. N.A. d. N.A. e. Rev. E	Black fuse open, hole burned in fuse case; Other fuses-good	Large arc burn located under black fuse	
No. 2	a. [redacted] b. N.A. c. 06841663 d. N.A. e. Rev. F	Red fuse open, hole burned in case; Other fuses-good	Large arc burn region located under red fuse	
No. 3	a. N.A. b. N.A. c. N.A. d. June 7, 1984 e. Rev. F	Fuses good	Large arc burn region on fuse side of stator next to core; Windings shorted to core	
No. 4	a. [redacted] b. 1/19/88 c. 1183113 d. N/A e. Rev. E	Black fuse open, hole burned in fuse case; Other fuses-good	Large arc burn region located under black fuse	
No. 5	a. [redacted] b. 1988 c. 11841198 d. 3/17/86 e. Rev. F	Black fuse open, hole burned in fuse case; Other fuses good	Large arc burn region located under black fuse	

TABLE I (Continued)

Stator I.D.	a. Plane Registry No. b. Date removed from plane c. Stator Serial No. d. Date stamped on stator e. Revision	Fuse Condition	Winding Condition	Remarks
No. 6	a. [redacted] b. 1/24/88 c. 06841167 d. 4/20/84 e. Rev. F	Black fuse open, hole burned in fuse case; Other fuses good	Large arc burn region located under black fuse; Windings shorted to core	
No. 7	a. N/A b. N/A c. N/A d. 7/14/86 e. Rev F	Black fuse open, hole burned in fuse case; Other fuses good	Large arc burn region located under black fuse	
No. 8	a. N/A b. N/A c. 10841187 d. N/A e. Rev F	Fuses good (wrapped in plastic)	Small burned location on end opposite fuses	Reported to be a proper functioning stator, One of the stators fro the two pum sent to EQA with the warranty seals intact
No. 9	a. N/A b. N/A c. 09841176 d. N/A e. N/A	Green fuse open, hole burned in fuse case; Other fuses good	Large arc burn region located under green fuse	One of the stators fro the two pum sent to EQA with the warranty seals intact.

TABLE I (Continued)

Stator I.D.	a. Plane Registry No. b. Date removed from plane c. Stator Serial No. d. Date stamped on stator e. Revision	Fuse Condition	Winding Condition	Remarks
No. 10	a. [redacted] b. N/A c. 11841188 d. 6/7/84 e. Rev. F	Fuses good	Large arc burn region on fuse side of stator next to core; Windings shorted to core	
No. 11	a. [redacted] b. 1/15/88 c. 08841172 d. 9/2/84 e. Rev. F	Fuses good (wrapped in plastic)	Large arc burn region on opposite side of stator from fuses; Windings shorted to core	
No. 12	a. [redacted] b. 1/21/88 c. 05851224 d. 4/9/85 e. Rev. F	Fuses good	Large arc burn region on opposite side of stator from fuses	
No. 13	a. [redacted] b. 2/21/87 c. 04861304 d. N/A e. Rev F	Fuses good	Large arc burn region on fuse side of stator next to core; Windings shorted to core	
No. 14	a. [redacted] b. 3/1/88 c. 02800683 d. N.A. e. Rev E	Black fuse good, Other fuses N/A	Large arc burn region on opposite side of stator from fuses	

TABLE I (Continued)

Stator I.D.	a. Plane Registry No. b. Date removed from plane c. Stator Serial No. d. Date stamped on stator e. Revision	Fuse Condition	Winding Condition	Remarks
No. 15	a. N/A b. N/A c. N/A d. 2/28/87 e. Rev. F	Green fuse open, hole burned in fuse case; Other fuses good	Large arc burn region located under green fuse	
No. 16	a. [redacted] b. 1/18/88 c. 11790542 d. 3/29/86 e. Rev. F	Fuses good	Small arc burn region located on fuse side of stator next to core; Windings shorted to core	Very clean appearing stator (i.e no rust on core, windi relatively free of residue).
No. 17	a. [redacted] b. 12/30/87 c. 02811071 d. 6/6/85 e. Rev. F	Fuses good	Large arc burn region located on side of stator opposite fuses; Windings shorted to core	
No. 18	a. N/A b. N/A c. N/A d. N/A e. Rev. E	Black fuse open, corrosion hole through fuse case; Other fuses good	Windings appear to be good, no readily visible evidence of arcing	

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TABLE II

Fuse No.	Condition of Fuse Case	Electrical Resistance		Test Temp.	Condition of Thermal Material	Comments
		Initial	Final			
1	Black tarnish with corrosion pits through silver plate into brass	0	∞	400°F	wet	There was positive pressure in the fuse upon puncturing case after the test. Also a fuel smell was noted.
2	Black tarnish	0	∞	450°F	dry	
3	Bright, tarnish free	0	∞	450°F	dry	
4	Black tarnish	0	∞	450°F	dry	
5	Black tarnish with deep corrosion pits into brass	0	0	405°F	dry	
		0	∞	422°F		
6	Bright, tarnish free	0	0	405°F	dry	
		0	∞	422°F		
7	Black tarnish with deep corrosion pits into brass	0	0	405°F	wet	A fuel smell was noted upon puncturing the fuse case after the test.
		0	∞	422°F		
8	Mildly tarnished	0	0	405°F	dry	
		0	∞	422°F		
9	Mildly tarnished	0	0	405°F	dry	
		0	∞	422°F		

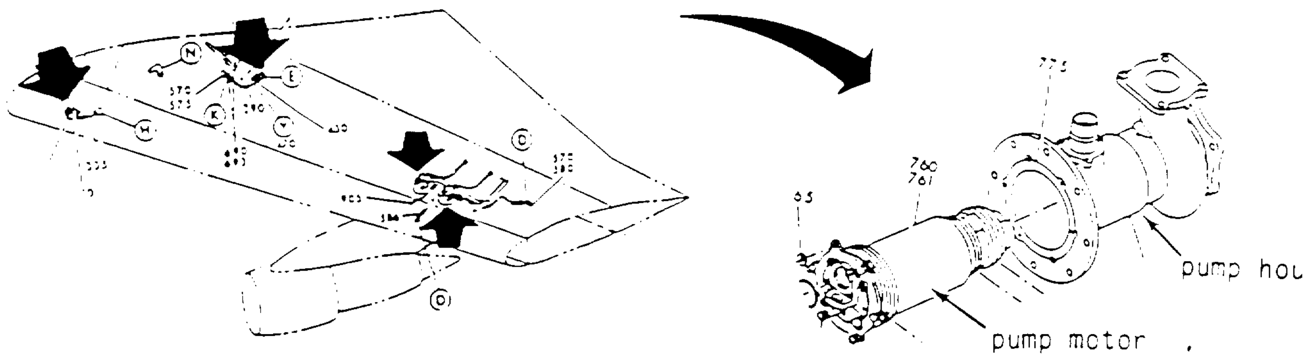


Fig. 1 Illustrations showing the locations of the fuel boost pump.

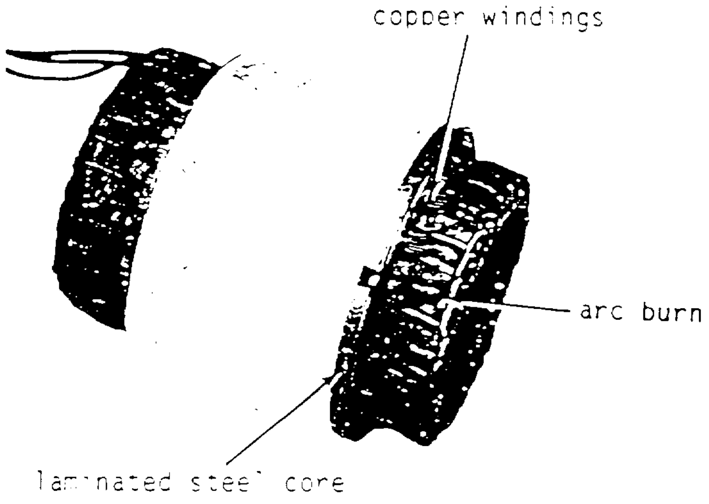


Fig. 2 Photograph of a stator component from a fuel boost pump (Mag. 0.75X).

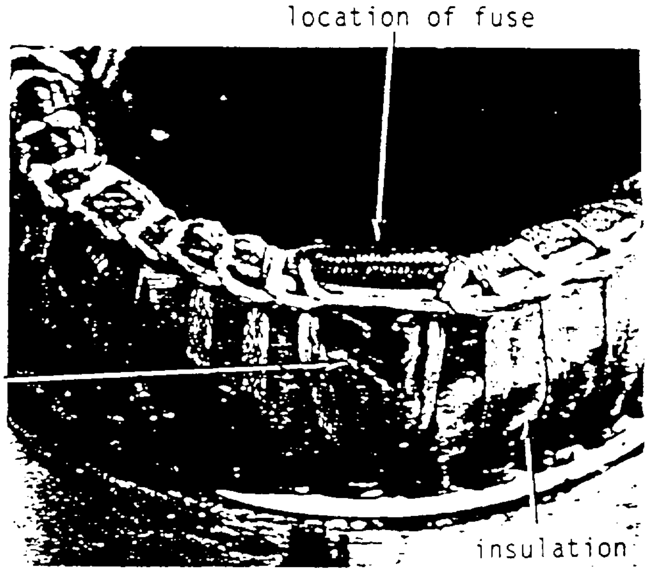
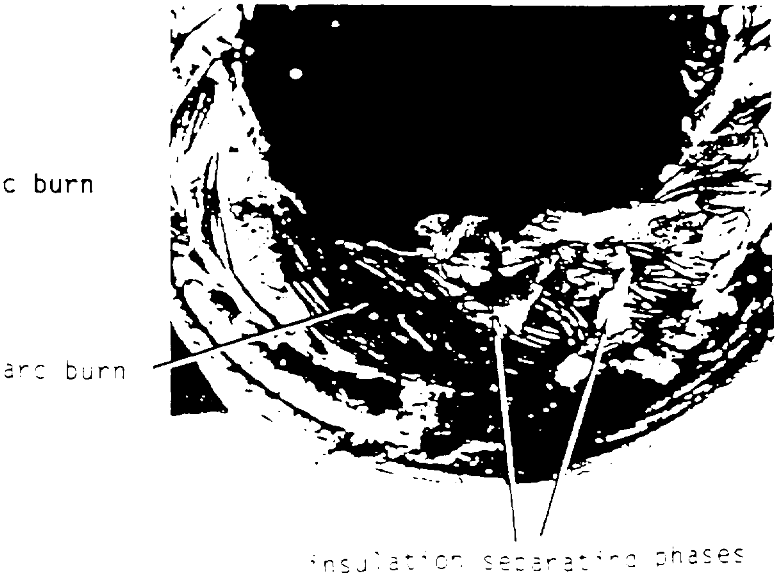


Fig. 3 Photograph showing the thermal fuse incorporated in the winding insulation wrap (Mag. 1.75X).

Fig. 4 Photograph showing a typical arc burn after removal of insulation layers (Mag. 1.6X).



ORIGINALS IN
CENTRAL FILE

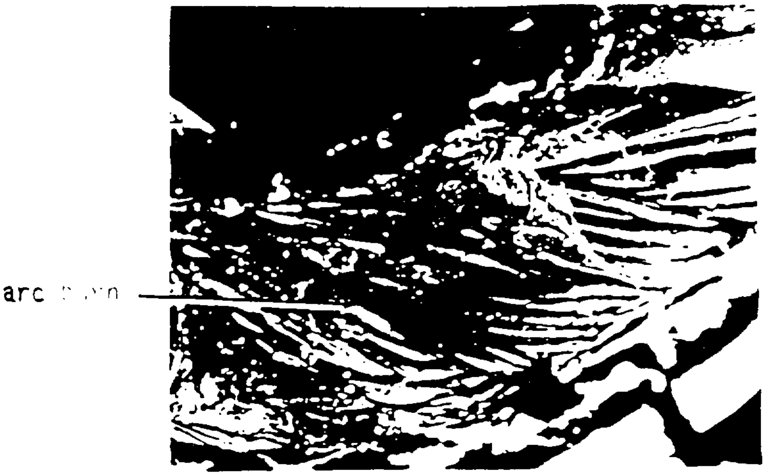


Fig. 5 Photograph of the smaller burn area located on Stator No. 8. This stator had passed the EPA electrical tests (Mag. 5X).

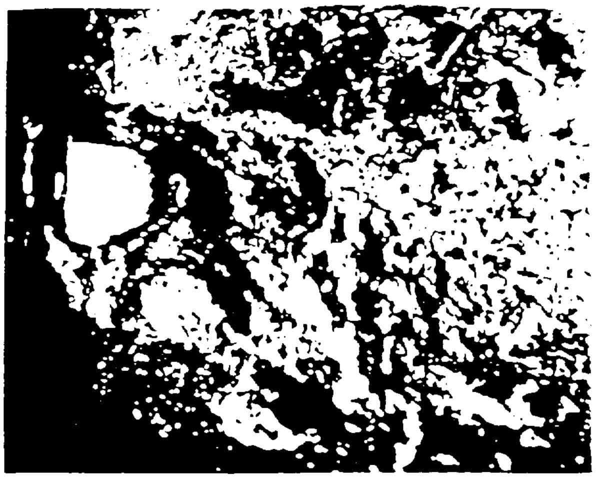


Fig. 6 Photograph of the fuse case fr Stator No. 18 showing the extensive corrosion pitting which penetrated the case (Mag. 21X).

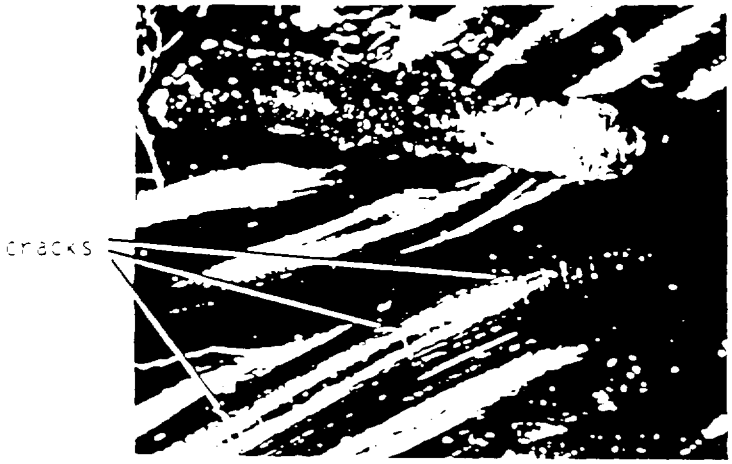


Fig. 7 Photograph showing typical circumferential cracks in the wire insulation (Mag. 16X).

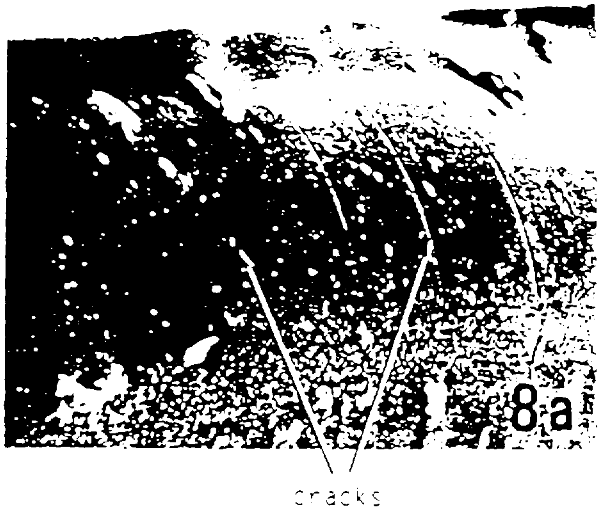


Fig. 8 SEM photomicrographs showing the underlying insulation cracks bridged by a surface film (Mag.(a) 190X, (b) 4000X).

ORIGINALS IN
CENTRAL FILE

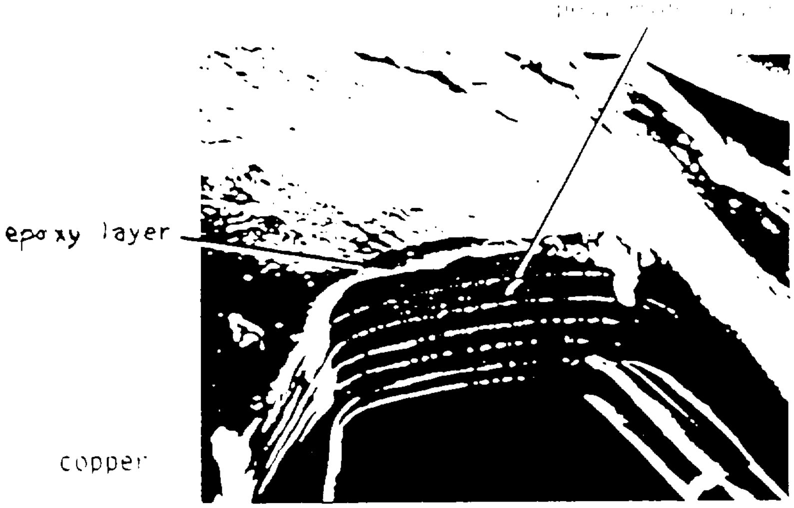


Fig. 9 SEM photomicrograph of the fractured wire insulating films after severe laboratory bending (Mag. 1000X).

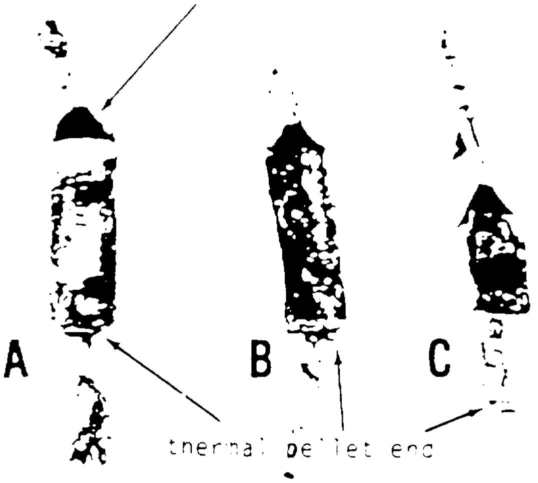


Fig. 10 Photograph of three arc burned fuses showing three different burn hole locations, A) thermal pellet end, B) al the whole length, and C) opposite the thermal pellet end (Mag. 2.5X).

Fig. 11 Photograph showing corrosion products at cracks in the wire insulation adjacent to a fuse (Mag. 16X).

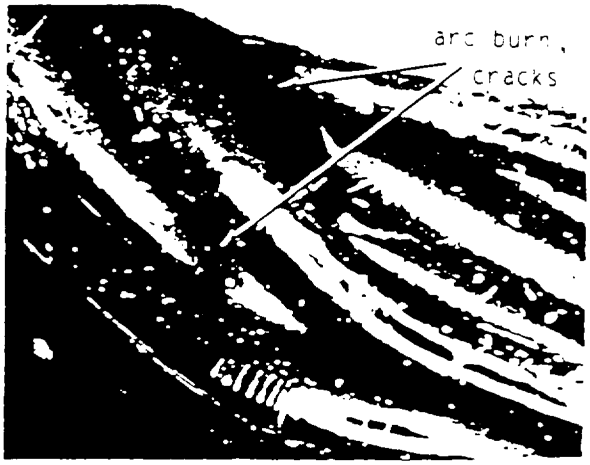


Fig. 12 Photograph showing burn spots at cracks in the wire insulation (Mag. 16X).

Fig. 13 Photograph showing a hot spot where the epoxy film was discolored and slightly bubbled (Mag. 32X).

ORIGINALS IN
CENTRAL FILE

ANALYTICAL ENGINEERING REPORT

TO: J. I. Murphy
237-7410

M/S 66-19
R-6711

NO.: 2-5323-WP-91-97

ITEM NO.: CHEM 8825

DATE: March 20, 1991

MODEL: EQA-757

GROUP INDEX: 2-5323 - Analytical Engineering, Chemical/Physical

SUBJECT: Analysis of Wing Tank Indicator Silvered Braid

BACKGROUND

A fuel quantity indicator from the right wing tank of an [redacted] had a long history of blanking after only 750 hours in service. The harness from this assembly which is submerged in fuel was removed. The silver coated copper wire of both the red and the black harness braids were observed to exhibit a black coating where they protrude from the terminal crimp connector, as shown in Figures 1 and 2. A request was received to identify both the black contaminant and the failure mode for the indicator blanking problem.

EXPERIMENTAL AND RESULTS

The extent of the black contamination was determined by disassembly of the terminal crimp connectors. A jeweler's saw was used to cut through the outer sleeve, which was then removed to expose the crimp connection. Figure 3 displays a photomicrograph of this crimp connection for the red terminal after prying the crimp apart enough to observe the silvered wires of the braid. Figure 4 shows the same region of the black coded braid after again using the jeweler's saw to remove half of the crimp connector. It is readily observed from these figures that the black contaminant has migrated up into the crimp connector even after only 750 hours in service.

The black coating on the silvered wires was identified by electron microprobe spectroscopy to be composed of silver, copper and sulfur, as shown for both the red and the black terminals in Figures 5 and 6. Spectra of these contaminants were also acquired using an infrared microscope, and are presented in Figures 7 and 8. From the bands at 1375, 1460 and near 2900 wavenumbers, these spectra show that a hydrocarbon such as jet fuel remains adsorbed to both braids. In addition, the other bands in the spectra between 1100 and 1200 wavenumbers, more prevalent on the red terminal, are due to the presence of sulfate. Both silver and copper sulfate are white and therefore do not account for the color of the contaminant. However, silver and copper sulfides are black, and do not give rise to infrared absorptions in the region detected by the infrared microscope. Thus the infrared spectra shown are consistent with the presence of silver and copper sulfides, some of which has been oxidized to sulfate especially on the red braid.

DISCUSSION AND CONCLUSIONS

Both silver and copper sulfides and sulfates are highly electrically insulating. Although the black contamination does not appear visually to have fully penetrated the crimp connection, the failure of these harnesses indicates that the contamination has disrupted electrical continuity even after a short service lifetime. The source of the sulfur in the contaminant is most likely jet fuel. Because of its susceptibility to sulfidation, elemental silver should never be placed in contact with sulfur containing liquids. The sulfidation of the silver braid due to contact with jet fuel will continue to worsen with time, probably leading to more frequent blanking. A solution to this problem is to prevent the jet fuel from reaching the silver. At the terminal of the braid, this can be achieved by solder dipping of the crimp connector. Typical lead/tin solder alloys are not susceptible to sulfidation.

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M/S 73-09, 237-7174

Approved by:
W. L. Plagemann, 2-5323
M/S 73-09, 234-3025

Photomicroscopy: J. A. Brewer, 2-5323, 237-1750
EDX Analyses: E. A. Miller, 2-6833, 773-5773

ATTACHMENT 8

THE BOEING COMPANY
PARTICLE AND CONTAMINATION ANALYSIS LABORATORY
IMAGE ANALYSIS LABORATORY

LABORATORY REPORT

Report #: 9-5576-P+CA-025P
Date: March 30, 1993

To: Don Fitzwater
Orgn:
M/S:
Phone:

Subject: Preliminary Report on Electrical Connector and Accessory Hardware Testing
Source: 747, 737, and DC-10 Materials
References

INTRODUCTION:

This is a preliminary report on the study of corrosion on electrical hardware from fuel tanks of 747, 737, and DC-10 aircraft operated by [redacted]. Additional reports will be issued as the study continues.

Multiple examples of electrical hardware and connectors were receive for an evaluation of corroded wiring and terminals. The samples were from 747, 737 and DC-10 aircraft. Additional materials will be evaluated as a continuation of this study and will include testing to evaluate the resistance to corrosion on exposure to commercial jet fuel for materials not previously exposed on aircraft.

One question to be resolved by this investigation was to determine the relative susceptibility of silver or nickel plated copper wire to corrosion in fuel tank environments and the mechanism for that corrosion. A second question was the reliability of connectors attached to multistrand copper wiring that has been nickel or silver plated. This report presents preliminary findings on both of these questions.

RESULTS:

Photographs 1, 2, 3, 4, 5, 6, 7,and 8 show the samples received to date. All of the silver plated copper wire exposed to fuel exhibited corrosion (Photographs 9, 10, and 11). The nickle plated wire showed no corrosion. The relative exposure time of these samples in not known so care must be taken in interpreting these preliminary results. The results to date do indicate that the silver plated copper wire exposed to fuel does corrode over time. The nickel plated copper wire may corrode but the samples provided to date do not exhibit the effects of even the earliest stages of corrosion.

The corrosion on the silver plated copper wire contained reduced sulfur species. Tests of the dark discoloration on the Teflon wrap insulation was also positive for reduced sulfur. The brown shrink wrap over the Teflon exhibited a very strong reduced sulfur response. Micro-Fourier infrared spectroscopy indicated no hydrocarbon in these deposits after cleaning. This indicates that the deposits are sulfides. The black film seen on the corroded wire is easily reduced to metallic silver by heating over an alcohol flame. This is also consistent with sulfides of silver. Reduced sulfur does play a significant role in the corrosion of the silver.

An examination of the crimped and soldered terminals on the nickel plated copper wire from the 737 aircraft appeared to be acceptable (Photograph 12, 13, and 14). The wiring formed a good compression joint with the connector and the solder formed a tight seal at the open end of the connector (Photograph 15). The solder did not wet the nickel plate as well as it did the tin plate on the connector and a void can be seen down the center of the wire bundle beneath the terminal solder cap. Additional samples will have to be examined but preliminary results indicate that nickel plated copper wire would be acceptable in this application.

CONCLUSION:

Preliminary results indicate corrosion is degrading the silver plated copper wire exposed to fuel. The nickel plated copper wire does not exhibit this corrosion but may not have been exposed as long as the silver plated copper wire may have been. The connector joint with the nickel plated copper wire looks acceptable. The investigation is continuing to evaluate the mechanism responsible for the corrosion of the silver plated copper wire and to evaluate the nickel plated wire as an acceptable replacement if it is demonstrated to be less susceptible to corrosion. Reduced sulfur species in the fuel are a likely corrosion initiator.

Prepared By:________________ Approved By:________________ Orgn: 9-5576
E. R. Crutcher For W. L. Plagemann

ATTACHMENT C

THE BOEING COMPANY
PARTICLE AND CONTAMINATION ANALYSIS LABORATORY
IMAGE ANALYSIS LABORATORY

LABORATORY REPORT

Report #: 9-5576-P+CA-025P1
Date: April 29, 1993

To: Don Fitzwater
Orgn:
M/S: 02-AK
Phone: 294-1857 or 773-7297

Subject: Test Plan for Evaluating Electrical Connector and Accessory Hardware
Source: Fuel Tank Wiring and Connector Materials
References: Report 9-5576-P+CA-025P

INTRODUCTION:

This is the second preliminary report on the study of corrosion on electrical hardware from fuel tanks of 747, 737, and DC-10 aircraft operated by [redacted] Additional reports will be issued as the study continues.

Many of the supplied samples from various aircraft have been studied in detail to characterize the corrosion seen on the silver plated copper wire. A literature search has also been conducted. One of the more interesting papers found in this search is included with this report. It presents the results of a series of experiments performed to characterize the relative fuel stability of silver and copper in aircraft fuel systems. Their study was conducted in response to the grounding of an entire fleet of aircraft in which silver had been used on the fuel pump slipper pads. We propose to design our performance test of wiring components in fuel based on some of their discoveries. This report presents additional findings on wiring removed from aircraft fuel tanks and outlines the test procedure we intend to use for the evaluation of new wiring configurations.

RESULTS:

Earlier (see referenced report) the corrosion on the silver plated copper wire was found to be the result of sulfidation, corrosion by the presence of reduced sulfur species. The two most active forms of sulfur in fuel are hydrogen sulfide from biological activity and elemental sulfur in solution from the crude oil precursor or as a result of fuel "sweetening" processes. Examination of cross-sectioned connectors (Photographs 1 thru 6) confirmed the role of sulfur in the corrosion process (Photographs 7 thru 9). Photographs 7 and 8 illustrate the corrosion process seen in one of the DC10 connectors (seen in Photograph 4, left side). It is typical of that seen in all of the silver coated copper wire connectors. The silver has been entirely converted to black silver sulfide (gray halo) and the copper wire itself has become severely pitted and in some cases is completely corroded away. Photograph 9 shows the corrosion of brass beginning in the same connector.This corrosion took place along a small section of the brass only where it contacted the Teflon insulation near where the wire exited the connector at the end without shielding. The brass adjacent to the corroded silver and copper of the shield wire exhibited no corrosion (Photograph 8). Corrosion of silver and copper in aircraft fuel systems as a result of exposure to sulfur is a well documented problem (see papers attached). In the case of silver coated copper wire in the fuel system failure is most often due to corrosion based on unpublished customer claims. This claim would not seem unreasonable based on our examination of the wiring from fuel systems and the literature on corrosion of copper and silver in fuel systems. Over time spans of many years it would be unusual if the wiring did not fail as a result of corrosion.

The development of an experiment to evaluate the relative age stability or resistance to corrosion of different combinations of metals in wiring assemblies has progressed rapidly. Initially some of the older sections of wiring that didn't exhibit corrosion were placed in clean fuel from Boeing Field. No degradation was evident over two weeks exposure. This was the expected result based on the non-corrosive requirements of commercial jet fuel. We had performed this initial test in clear glass bottles which compromised the results due to the ease with which corrosion inhibiting peroxides are created in fuels by exposure to light. This fact was discovered in the subsequent literature review. The design of the experiment we are now proposing includes the use of dark containers, elevated temperatures (40 C), copper sheet, silver sheet, a synthetic fuel of iso-octane and toluene, and an elemental sulfur challenge. We propose to place each component to be evaluated in a test tank with a small strip of copper (per ASTM D 130), a small strip of silver (per British standard IP 227), and sufficient fuel to meet the volume to surface area requirements of the standard methods. A budget for materials will be required to implement the test (see attached list of supplies and equipment).

CONCLUSION:

Elemental sulfur in solution and hydrogen sulfide in the fuel are the most likely causes for the corrosion of the wiring in the fuel system. Elemental sulfur is a natural impurity in fuel and can be introduced during the normal fuel production processes. Hydrogen sulfide is often produced in fuel as a result of biological activity in storage tank water bottoms. Commercial aircraft can be expected to encounter these problems at various times over the life of the aircraft. To evaluate the performance over time of different wiring materials an experiment has been devised based on both American and British standards to track the rate of corrosion of these materials in a synthetic fuel with a predetermined corrosion challenge. This experiment will qualitatively compare the corrosion resistance of these materials to one another and to pure copper and pure silver. A list of supplies needed to perform this experiment is attached.

Prepared By:______________ E. R. Crutcher Approved By:______________ For W. L. Plagemann Orgn: 9-5576

ATTACHMENT F

Copper and Silver Corrosion by Aviation Turbine Fuels

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Indian Institute of Petroleum, Dehradun (U. P.), India

The corrosion in the fuel system of aeroengines has been invariably attributed to some undesirable sulfur compounds present in aviation turbine fuels (ATF's). The corrosiveness of the fuel is measured by a combination of copper strip and silver strip corrosion tests. The present paper relates various aspects of corrosiveness of different types of sulfur compounds in ATF's toward copper and silver. The corrosive action of elemental sulfur in the presence of naturally occurring sulfur compounds and organic peroxides has been fully discussed on the basis of experimental data. Of the various types of sulfur compounds likely to be present in ATF's, only hydrogen sulfide and elemental sulfur were found to be corrosive to copper and silver at very low dosages. Naturally occurring sulfur compounds and peroxides were observed to inhibit the corrosive action of elemental sulfur to some extent. Silver is more susceptible to corrosion than copper.

1. Introduction

The problem of corrosion of metals in aeroengine fuel systems by Aviation Turbine Fuels (ATF's) arises mainly from the chemical composition of the fuel and the environmental conditions during storage, distribution, and use of the product. The chemical constituents responsible for corrosion either originate from the source crude and the subsequent refining processes used or arise through bacterial contamination of the fuel depending on conditions of storage and subsequent handling facilities.

The corrosion by ATF's has been attributed to the presence of sulfur compounds (Bentur, *et al.*, 1962, 1964). These may be inherently present in the fuel or may sometimes get introduced during sweetening treatments such as in "Doctor" and "Bender" processes which use elemental sulfur for removal of mercaptans. Besides, certain microorganisms, *viz.*, the sulfate-reducing bacteria (Wachs, *et al.*, 1964) can give rise to corrosive hydrogen sulfide if the fuel is stored over stagnant water bottoms containing inorganic sulfates. More recently fuel-soluble chlorides (Love, *et al.*, 1967) associated with "hypochlorite and copper chloride sweetening processes" have also been reported to cause sticking and corrosion problems in aircraft fuel pumps.

In a majority of the cases, however, the corrosiveness of the ATF's has been traced to undesirable sulfur compounds. Owing to a number of copper and brass parts used in the aeroengine fuel system, the corrosiveness of ATF's is determined by the well-known ASTM D 130 (1956, 1968) copper strip corrosion test, which is based on discoloration of standard copper strip immersed in the fuel at 100° for 2 hr. However, later when some of the aircraft fuel pumps used silver-plated slipper pads on account of their satisfactory bearing properties (Thompson, *et al.*, 1964), it was observed that the existing copper strip corrosion test was not adequate to ensure noncorrosivity of the fuel to these silver surfaces and need was felt to incorporate a silver strip corrosion test (Thompson, *et al.*, 1964; Budd and Sanger, 1970) in the ATF's specifications. During August 1965 similar cases of corrosion of silver-plated slipper pads of Caravelle aircraft fuel pumps occurred in India also (Krishna, *et al.*, 1967), leading to grounding of the entire fleet. The fuel in question passed the existing copper strip corrosion test and still caused the corrosion of silver-plated components.

In the light of these observations, systematic studies on the causes and mode of corrosion of copper and silver surfaces were considered. The object of the present investigation was to study the types of sulfur compounds that can cause corrosion and the maximum ratios of these compounds which can be tolerated without causing corrosion to either copper or silver strips under standard conditions of the tests. The variations in composition of sulfur compounds and the inhibiting effect of organic peroxides (Bentur, *et al.*, 1962, 1964) toward corrosion by elemental sulfur have also been investigated. Three commercial ATF's and one sulfur-free ATF were chosen. Varying amounts of hydrogen sulfide, elemental sulfur, mercaptans, monosulfides, disulfides, and thiophene were added individually or in admixture with elemental sulfur, and the corrosiveness of the resulting ATF's toward copper and silver strips was examined. The effect of peroxides was studied by exposing the ATF's to sunlight and subsequently examining the exposed samples for their corrosivity.

2. Experimental Section

2.1. **Materials.** 2.1.1. **Bulk ATF Stocks.** For these investigations the following four bulk ATF stocks were used: (i) ATF-A, which was obtained from Air Service Station A; (ii) ATF-B, which was obtained from another Air Service Station B; (iii) ATF-C, which is a mixture of various commercially acceptable ATF's; (iv) ATF-D, which is a low sulfur level ATF (140–240° true boiling point cut) and was prepared by catalytic hydrosulfurization using Co–Mo catalyst over alumina support, the total sulfur content being brought down to 0.4 ppm from an initial value of 24 ppm.

All these stocks were examined as such as per DERD 2494 (Issue-4) specifications for aviation turbine fuels of the kerosine type. The stocks were found to conform to all the required specifications. In addition, the concentrations of total sulfur, hydrogen sulfide, mercaptans, and elemental sulfur initially present in each of these samples were also determined.

2.1.2. **Individual Sulfur Compounds Used.** Compounds of this type are (i) hydrogen sulfide (freshly prepared in this laboratory), (ii) elemental sulfur (precipitated sulfur of high purity), (iii) mercaptans (tertiary butyl and phenyl mercaptans from Phillips Petroleum Co.), (iv) sulfide and disulfide (Phenyl ethyl sulfide and di-*tert*-butyl disulfide from Phillips Petroleum Co.), and (v) thiophene (high-purity product from S. Merck, A. G.).

Table I. Sulfur Compounds Initially Present in the ATF Stocks

Characteristics	ATF-A	ATF-B	ATF-C	ATF-D
otal sulfur, wt %	0.082	0.078	0.078	0.00004
Hydrogen sulfide, ppm (w/w)	Nil	Nil	Nil	Nil
Mercaptan sulfur, ppm (w/w)	3	4	3	Nil
Elemental sulfur, ppm (w/w)	10	6	6	Nil
Peroxide value, mequiv of oxygen/kg	0.32	0.24	0.22	0.13
Classification of copper strip corrosion test, 2 hr at 100° (bomb)	<1a	<1a	<1a	<1a
Classification of silver strip corrosion test, 16 hr at 45°	0	0	0	0

2.2. Preparation of Blends. Samples of ATF's containing varying amounts of different types of sulfur compounds were prepared by proper dilution of concentrated solutions which were made by very accurate weighings. Synthetic mixtures ontaining elemental sulfur and other types of sulfur compounds were also prepared by suitable dilution. The hydrogen sulfide concentration in prepared samples was measured by the potentiometric method.

All the blends were stored in dark bottles in order to avoid peroxide formation on exposure to sunlight. The "exposed" samples for determining the effect of peroxides were prepared by exposing the ATF's to sunlight in transparent glass bottles for 0.5 hr.

2.3 Test Procedures. The following analytical procedures were adopted for testing the corrosive properties and determining the concentration of different sulfur compounds: (i) copper strip corrosion, ASTM D 130-68/IP 154-64 (1968); (ii) silver strip corrosion, IP 227-68 (1968), based on the method proposed by Thompson, *et al.* (1964); (iii) total sulfur (50-300 ppm), IP 107/65 (1968); (iv) total sulfur (0-200 ppm), UOP 357-64 (1968); (v) hydrogen sulfide and mercaptans, UOP 163-67 (1968); (vi) Doctor test, IP 30/56 (1968); (vii) elemental sulfur, colorimetrically (Bartlett and Skoog, 1954); (viii) peroxide content, ASTM D 1832-65 (1968).

3. Results and Discussion

3.1. Corrosion Studies with Individual Sulfur Compounds. The concentrations of the different sulfur compounds initially present in the three commercial ATF stocks (A, B, C), as well as sulfur-free ATF-D prepared in this laboratory, are given in Table I. The total sulfur in the case of three commercial ATF's is low, it being in traces in the ydrosulfurized stock ATF-D. Hydrogen sulfide is absent in all the four stocks. Though 3-4 ppm of naturally occurring mercaptans and 6-10 ppm of elemental sulfur are present in the three commerical ATF stocks, they do not show any corrosivity both in the copper and in the silver strip tests.

As per British DERD 2494 (Issue-4) and Indian Standards 1571-68 specifications, ATF's with a copper strip corrosion rating of 1b max ("slight tarnish") and silver strip corrosion rating of 1 max ("slight tarnish") are acceptable for commercial use in aircrafts. Beyond the "slight tarnish" rating the fuels are known to cause corrosion to copper and silver parts in actual service. The rating systems of the two methods are described in Table II for easy interpretation of the results.

Table II. Description of Copper and Silver Strip Corrosion Ratings

Classification	Designation	Description
		Copper Strip
1a	Slight tarnish	Light orange, almost the same as a freshly polished strip
1b		Dark orange
2a	Moderate tarnish	Claret red
2b		Lavender
2c		Multicolored with lavender-blue or silver or both, overlaid on claret red
2d		Silvery
2e		Brassy or gold
3a	Dark tarnish	Magneta overcast on brassy strip
3b		Multicolored with red and green showing (peacock) but no gray
4a	Corrosion	Transparent black, dry gray or brown with peacock green barely showing
4b		Graphite or lusterless black
4c		Glossy or jet black
		Silver Strip
0	No tarnish	Same as freshly polished strip, except possibly for some very slight loss of luster
1	Slight tarnish	Faint brown or white discoloration of strip
2	Moderate tarnish	Surface of strip showing various shades of blue and mauve
3	Slight blackening	Patches of black on surface or uniform thin film of black deposit
4	Blackening	Uniform heavy blackening with or without scale

3.1.1. Corrosion Studies with Hydrogen Sulfide and Elemental Sulfur. The data on corrosiveness of the four different ATF stocks with varying dosages of added hydrogen sulfide and elemental sulfur individually are reported in Table III. The results show that hydrogen sulfide is corrosive to copper as well as silver even at levels of 1 ppm in all four fuels studied here. Also at a particular level of added hydrogen sulfide, the corrosiveness of the four fuels is almost identical in both the cases irrespective of the total sulfur present or the type of fuel. In the presence of hydrogen sulfide, the fuels therefore do not appear to differ in their ability to cause corrosion to copper and to silver strips.

The data on the corrosiveness of the ATF's in the presence of added elemental sulfur indicate that the fuels differ in their ability to cause corrosion to copper as well as silver strips. ATF-A having originally 0.082% total sulfur and 10 ppm of elemental sulfur causes corrosion of the silver strip (rating 2) on addition of 2.5 ppm of elemental sulfur, whereas

Table III. Effect of Hydrogen Sulfide and Elemental Sulfur

Fuel	Hydrogen sulfide added, ppm											
	1.0		2.0		3.0		5.0		10.0		20.0	
	Cu•	Ag•	Cu	Ag	Cu	Ag	Cu	Ag	Cu	Ag	Cu	Ag
ATF-A	2c	2	2c	2	2d	2	3a	3	4a	3	4b	4
ATF-B	2c	2	2c	2	2c	2	3a	3	3b	3	4a	4
ATF-C	2c	2	2c	2	2d	2	3a	3	3c	3	4a	4
ATF-D	2b	2	2c	2	2c	2-3	3a	3	3b	3-4	4a	4

Fuel	Elemental sulfur added, ppm											
	0.5		1.0		2.5		5.0		10.0		15.0	
	Cu	Ag	Cu	Ag	Cu	Ag	Cu	Ag	Cu	Ag	Cu	Ag
ATF-A	<1a	0	<1a	0	1a	1-2	2b	2	2d	3	3b	3-4
ATF-B	<1a	0	<1a	0	1a	1	<1b	2	3a	3	3b	3
ATF-C	<1a	0	<1a	0	<1a	0	1a	1-2	2b	3	2d	3
ATF-D	<1a	0	1a	1-2	2a	3	2c	3	3a	3-4	4a	4

• Cu and Ag signify the copper and silver strip tests, respectively, in this and other tables.

Table IV. Effect of Mercaptan, Monosulfide, Disulfide, and Thiophene Type Sulfur

Fuel	Mercaptan sulfur added, ppm									
	20		50		100		200		350	
	Cu	Ag	Cu	Ag	Cu	Ag	Cu	Ag	Cu	Ag
ATF-A + *tert*-butyl mercaptan	<1a	0	<1a	0	<1a	0	<1a	0	<1a	0
ATF-A + phenyl mercaptan	1a	0	1a	0	1a	0	1a	0		
ATF-D + *tert*-butyl mercaptan	<1a	0	<1a	0	<1a	0	<1a	0	<1a	0
ATF-D + phenyl mercaptan	<1a	0	<1a	0	<1a	0	<1a	0	<1a	0

Fuel	Monosulfide sulfur or disulfide sulfur added, ppm					
	250		500		1000	
	Cu	Ag	Cu	Ag	Cu	Ag
ATF-A + phenyl ethyl sulfide	1a	0	1a	0	1a	0
ATF-B + phenyl ethyl sulfide	1a	0	1a	0	1a	0
ATF-D + phenyl ethyl sulfide	1a	0	1a	0	1a	0
ATF-A + di-*tert*-butyl disulfide	1a	0	1a	0	1a	0
ATF-B + di-*tert*-butyl disulfide	1a	0	1a	0	1a	0
ATF-D + di-*tert*-butyl disulfide	1a	0	1a	0	1a	0

Fuel	Thiophenic sulfur added, ppm							
	50		100		200		350	
	Cu	Ag	Cu	Ag	Cu	Ag	Cu	Ag
ATF-A + thiophene	1a	0	1a	1	1a	1	1a	1
ATF-D + thiophene	1a	0	1a	0	1a	0	1a	0

the fuel passes the copper strip corrosion test (rating 1a) at the same level of added elemental sulfur. ATF-B and ATF-C, both having the same total sulfur and elemental sulfur content originally also differ in their corrosiveness to the silver strip, particularly on the addition of 2.5 ppm of elemental sulfur. Both of these samples, however, fail in the silver strip corrosion test (rating 2) with a copper strip rating (1b) still within specifications on the addition of 5.0 ppm of elemental sulfur. In case of ATF-D originally containing 0.4 ppm of total sulfur and no elemental sulfur, the corrosion of the silver strip (rating 2) takes place even on the addition of 1 ppm of elemental sulfur. Also for ATF-D, the corrosion ratings of copper and silver strips are comparatively higher than those of other fuels at all levels of added elemental sulfur, indicating that a sulfur-free ATF is more susceptible to the corrosive action of elemental sulfur than the normal commercial ATF's.

It is thus clearly observed that the corrosion by elemental sulfur differs from fuel to fuel depending upon the total sulfur content and the types of other sulfur compounds present in it. The commercial stock ATF-A fails the silver strip test (rating 1-2) at 12.5-ppm concentration (10 ppm originally present + 2.5 ppm added) of elemental sulfur, whereas sulfur-free ATF-D fails the same test (rating 1-2) at the 1-ppm level. At these levels of elemental sulfur, however, both fuels pass the copper strip corrosion test (rating 1a), clearly indicating the inadequacy of this test to ensure noncorrosivity of the fuels toward silver surfaces. The data also indicate that hydrogen sulfide is more corrosive than elemental sulfur toward copper as well as silver strips.

3.1.2. Corrosion Studies with Mercaptans, Mono- and Disulfide, and Thiophenes. The data on corrosiveness of different types of sulfur compounds commonly encountered in ATF's are given in Table IV. The data indicate that mercaptans, mono- and disulfides, and thiophenic type of sulfur are not corrosive toward copper and silver strips under the conditions of test even at very high concentrations. Such concentrations are not likely to be encountered in refined commercial fuels. For mercaptans such high concentrations

Table V. Effect of Elemental Sulfur along with Mercaptan, Sulfide, Disulfide, and Thiophene Type Sulfur

Fuel	Elemental sulfur added, ppm					
	2.5		5.0		10.0	
	Cu	Ag	Cu	Ag	Cu	Ag
ATF-A	1a	1-2	2b	2	2d	3
ATF-D	2a	3	2c	3	3a	3-4
Effect of Mercaptan Type Sulfur[a]						
ATF-A + 50 ppm of mercaptan sulfur[a]	<1a	0	<1a	0	1a	2
ATF-A + 50 ppm of mercaptan sulfur[b]	1a	0	1a	0	1b	1
ATF-D + 50 ppm of mercaptan sulfur[a]	1a	0	1a	0	1b	1
ATF-D + 50 ppm of mercaptan sulfur[b]	1a	0	1a	0	1b	0
Effect of Sulfide and Disulfide Type Sulfur[c]						
ATF-A + 100 ppm of monosulfide sulfur	<1a	1	<1a	1-2	1b	2
ATF-D + 100 ppm of monosulfide sulfur	<1a	0	1	0	1b	1-2
ATF-A + 250 ppm of disulfide sulfur	<1a	1	1a	2	2a	2
ATF-D + 250 ppm of disulfide sulfur	<1a	0	1b	0	2b	2
Effect of Thiophenic Type Sulfur[d]						
ATF-A + 100 ppm of thiophenic sulfur	<1a	1-2	1a	2	2a	3
ATF-D + 100 ppm of thiophenic sulfur	<1a	2	<1a	3	2d	3-4

[a] *tert*-Butyl mercaptan. [b] Phenyl mercaptan. [c] Phenyl ethyl sulfide and di-*tert*-butyl disulfide. [d] Thiophene.

are not permitted because these are known to be reactive with certain elastomers and also they impart obnoxious odor to the fuel. The data, however, run contrary to the observations of Bentur, *et al.* (1962) that tertiary mercaptans and disulfides can also be corrosive.

3.2. Combined Corrosive Action of Elemental Sulfur and Other Sulfur Compounds. Since the three commercial ATF's showed nearly identical behavior on addition of various sulfur compounds, only one of these, *viz.*, ATF-A, was taken for further work, besides the sulfur-free ATF-D. These two stocks were taken to study the combined modifying action of added elemental sulfur and other types of sulfur compounds toward copper and silver strips under standard conditions of the two tests. The data on the combined effect of elemental sulfur with mercaptan, mono- and disulfide, and thiophenic type sulfur are reported in Table V.

The data show that mercaptans have a tendency to inhibit the corrosiveness of elemental sulfur to a certain extent. The AFT-A containing 50 ppm of mercaptan sulfur shows no tarnishing of copper (rating 1a) or silver strips (rating 0) on the addition of 5 ppm of elemental sulfur. In the absence of added mercaptans, the same fuel had shown good corrosivity toward the silver strip (rating 1-2) even on the addition of 2.5 ppm of elemental sulfur. The influence of mercaptans in counteracting the effect of elemental sulfur is more pronounced in the case of sulfur-free ATF-D. In this case of contaminating the fuel with 50 ppm of mercaptan sulfur (as phenyl mercaptan), even a 10-ppm added dosage of elemental sulfur shows very little corrosivity of the fuel toward copper (rating 1b) and silver strips (rating 0). The silver strip is observed to be more sensitive to the action of elemental sulfur than the copper strip.

The monosulfide and disulfide types of sulfur were also observed to modify the action of elemental sulfur. ATF-A contaminated with 5 ppm of elemental sulfur and 100 ppm of monosulfide sulfur gives a lower rating of corrosion of copper and silver strips than in the absence of any monosulfide sulfur. At the same time, this fuel causes corrosion of the silver strip (rating 2) but passes the copper strip corrosion test (rating 1b). In case of ATF-D also, there has been a considerable reduction in the corrosive action of elemental sulfur in the presence of 100 ppm of added monosulfide type sulfur. At this level of monosulfide sulfur, the corrosion of the silver strip (rating 1-2) takes place only on the addition of 10 ppm of elemental sulfur. Without addition of monosulfide in this fuel, even 2.5 ppm of added elemental sulfur caused corrosion of both copper as well silver surfaces. The disulfides also antagonize the action of elemental sulfur to the same extent as monosulfide sulfur. At the same level of added elemental sulfur the antagonistic action of mono- and disulfides has been more pronounced in the case of sulfur-free ATF-D than the commercial ATF-A.

The data on thiophenic type sulfur (Table V) also indicate its antagonistic action on the corrosive effect of elemental sulfur. The inhibitive effect is more pronounced on the corrosivity toward the copper strip than toward the silver strip. For the same added amount of added elemental and thiophenic sulfur, the sulfur-free ATF-D gives a higher corrosion rating for the silver strip than for the ATF-A sample. The ATF-D, contaminated with 100 ppm of thiophenic sulfur and 2.5 ppm of elemental sulfur, causes corrosion of the silver strip (rating 2) and still passes the copper strip corrosion test (rating 1a) indicating that the latter test alone might not be adequate to detect corrosion of silver surfaces of aircraft fuel pumps.

It is evident from these results (Table V), that all normal commercial fuels containing more than 20 ppm of elemental sulfur would be rendered corrosive toward copper and silver strips even in the presence of maximum permissible amounts

Table VI. Effect of Peroxides on the Corrosivity of Elemental Sulfur

Fuel	Elemental sulfur added, ppm											
	1.0			2.5			5.0			10.0		
	Cu	Ag	Peroxide*	Cu	Ag	Peroxide*	Cu	Ag	Peroxide*	Cu	Ag	Peroxide*
ATF-A (unexposed)	<1a	0	0.32	1a	1-2	0.32	2b	2	0.32	2d	3	0.32
ATF-A (exposed)	<1a	0	0.40	1a	1	0.42	2a	2	0.46	2d	3	0.44
ATF-D (unexposed)	<1a	1-2	0.13	2a	3	0.13	2c	3	0.13	3a	3-4	0.13
ATF-D (exposed)	<1a	0	0.25	<1a	0	0.30	1a	0	0.40	1b	1	0.40

* Peroxide value is expressed here in milliequivalents of oxygen per kilogram of sample.

of mercaptans, sulfides, or disulfides. In other words some commercial fuels can tolerate up to 20 ppm of elemental sulfur depending upon the total sulfur content of the fuel and other types of sulfur compounds present.

Apart from the type of sulfur compounds studied here, a certain amount of sulfur is present as nonreactive "residual sulfur." Very little information is available regarding its role in inhibiting corrosion.

3.3. Corrosion Studies with Elemental Sulfur in the Presence of Peroxides. It has already been reported that the presence of peroxides reduces the corrosivity of aviation gasoline (Bentur, *et al.*, 1962, 1964). Some of these peroxides are formed by ambient-temperature oxidation on exposure of the fuel to sunlight.

In order to determine the inhibiting effect of these peroxides on ATF's experiments were conducted on ATF-A and ATF-D. The two samples containing varying amounts of elemental sulfur were exposed to direct sunlight; the peroxides so generated were determined quantitatively and the fuels were examined for corrosivity toward copper and silver strips. The data reported in Table VI show that in case of ATF-A, the generated peroxides did not have a marked influence in inhibiting the corrosive effect of elemental sulfur, as the unexposed sample originally contained a fair ratio of peroxides. In case of ATF-D, there has been a considerable reduction in the corrosiveness of the fuel toward both copper and silver strips. This fuel even with 10 ppm of elemental sulfur on exposure to sunlight is rendered completely noncorrosive, whereas the unexposed fuel with the same amount of elemental sulfur causes sufficient corrosion of both copper as well silver strips.

The behavior of ATF-A, however, shows that there is a limit of peroxide formation in a fuel under a given set of conditions and the peroxides so formed can inhibit the corrosive action of elemental sulfur up to a certain level depending upon the type of fuel.

4. Conclusions

The data presented in this paper indicate that hydrogen sulfide is corrosive to copper as well as silver strips even at the 1-ppm level in all ATF's. The corrosive level of elemental sulfur differs from fuel to fuel; it may vary from 1 to 20 ppm depending upon the total sulfur content and types of other sulfur compounds present in the ATF.

Mercaptan, mono- and disulfide, and thiophenic sulfurs are noncorrosive to copper and silver at all concentrations under the conditions of the two tests. They, in fact, tend to inhibit the corrosive action of elemental sulfur up to a certain extent. The peroxides have also been observed to inhibit the corrosiveness of the fuels up to a certain level of elemental sulfur.

At the same level of total sulfur the fuels differ in their ability to cause corrosion to copper and silver strips. Fuels which pass the copper strip corrosion test can still cause corrosion of silver surfaces, though no case of the reverse type was noticed.

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ATTACHMENT 9

THE INSTITUTE OF PETROLEUM

Silver Corrosion by Aviation Turbine Fuel

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SUMMARY

Six years ago a laboratory silver corrosion test was developed and incorporated in aviation turbine fuel specifications as a control against corrosion of silver-coated components in fuel pumps.

The reactivity of hydrogen sulphide and elemental sulphur to silver has been established under these test conditions.

A new test has been developed which requires a smaller sample size and shorter test duration than those of the current IP 227/68T but is of similar severity. This test has been adopted by the IP for inclusion in the 1971 standards.

INTRODUCTION

In order to provide satisfactory rubbing surfaces within the variable displacement, piston-type high-pressure fuel pumps used in the majority of British aircraft engines, the manufacturers have found it necessary to coat the surfaces of the "slipper pads" with silver. Although pumps using other materials have been developed for current and future applications, it is expected that the silver-plated units will continue in service for some years.

Premature pump wear, leading in some cases to rapid failure, has been attributed to sulphiding of the silver surfaces.[1] Because of such occurrences, a simple test procedure for detecting corrosivity of fuels towards silver was developed by Shell Research Ltd. The conditions of this test were verified in a rig using a Lucas Model B pump from a Rolls-Royce Dart engine. The background and details of this work were presented by Thompson, Hills, Brown, and Lewis.[2]

As other specification tests, including the ASTM D 130/IP 64 copper corrosion test, were not able to predict silver corrosion problems, the Shell CL 1 silver corrosion test was introduced as a requirement in the British Government specification D Eng RD 2494 in 1966.

With some slight modifications the test became an IP standard in 1968.[3] Essentially a 3 inch silver strip is immersed in one l of fuel at 45° C for 16 hr. The strip is rated numerically 0–4 depending upon the final colour produced. The D Eng RD 2494 specification maximum is 1.

This paper deals with an investigation into some reactions between silver and sulphur compounds in fuel and also the development of a quicker test method.

REACTIVITY OF SULPHUR COMPOUNDS TO SILVER

To eliminate interference from traces of corrosion-inhibiting compounds occurring naturally in turbine fuels, our investigations were conducted in a model fuel consisting of 15 per cent vol toluene and 85 per cent vol iso-octane.

Reaction between Inhibitors

Mercaptans, disulphides, and peroxides can be found in aviation fuels. These compounds can inhibit the effect of reactive sulphur on silver, as shown in Table I. As the

TABLE I

Corrosion Properties of Sulphur in Presence of Other Compounds

(All blends contain 1 ppm elemental sulphur)

Additive	Copper corrosion (ASTM D 130/ IP 64)	Silver corrosion IP 227/68T
None	2c	3–4
Mercaptan (10 mg/l S)		
n-Hexyl	1a	2
t-Hexyl	1a	2–3
t-Octyl	1b	1
Sulphides (1000 mg/l S)		
Di-n-butyl . . .	1a	3
Diphenyl . . .	1b	2–3
Sulphides (30 mg/l S)		
Di-n-butyl . . .	2a	3
Diphenyl . . .	2b	2–3
Disulphides (1000 mg/l S)		
Di-t-hexyl . . .	1b	4
Diphenyl . . .	1a	1
Disulphides (30 mg/l S)		
Di-t-hexyl . . .	2c	4
Diphenyl . . .	1b	1
Hydroperoxide (5 m.equiv/l)		
t-butyl	1a	0

mechanism of inhibition varies from one type of compound to another, it is possible for one inhibitor to nullify the effect of another. In such instances it is possible that two sulphur-containing fuels, naturally inhibited and each separately non-corrosive towards silver, could, when mixed, give a corrosive fuel.

This possibility was confirmed using fuels containing sulphur inhibited by either ditertiary butyl peroxide or tertiary octyl mercaptan, as shown in Table II.

TABLE II

Interaction of Compounds

Additives and sulphur	Silver corrosion IP 227/68
Sulphur (0·5 mg/l) and *t*-octyl mercaptan (10 mg/l S) . .	0
Di-*t*-butyl peroxide (1 meq/l) .	0
50/50 mixture of above fuels .	2

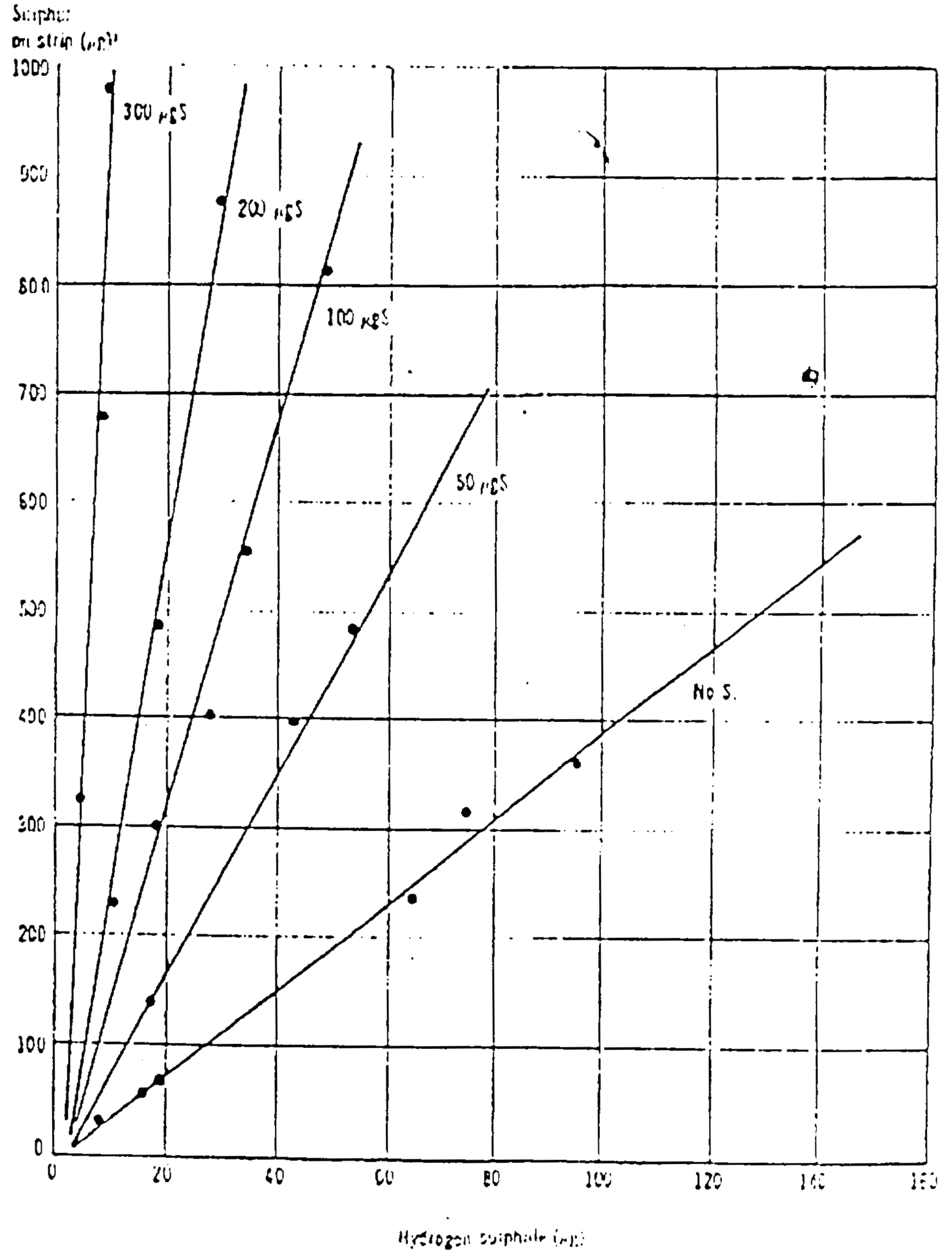

Fig. 1. Corrosion by hydrogen sulphide and elemental sulphur.

Reaction between Sulphur and Hydrogen Sulphide

The synergistic effect of hydrogen sulphide and elemental sulphur in turbine fuel on silver corrosion has been demonstrated by various workers.[4] Thus the possibility arises of a corrosive fuel being produced from the mixing of two non-corrosive fuels, one containing elemental sulphur and the other containing hydrogen sulphide, both below the concentration which causes corrosion. In addition, there is the possibility of a fuel deteriorating during transit or storage because of the oxidation of some hydrogen sulphide to sulphur. Our work shows that such reactions are possible.

Silver Sulphide Formation

By comparing the initial hydrogen sulphide and elemental sulphur concentrations with the sulphur deposited on a silver strip (IP 227/65T conditions, but using a stoppered and cleaned flask) the following observations were made:

1. With hydrogen sulphide there is a linear relationship between the initial hydrogen sulphide concentration and the square of the sulphur deposited on the silver strip.

2. With hydrogen sulphide and elemental sulphur this linear relationship still holds, but the slope of

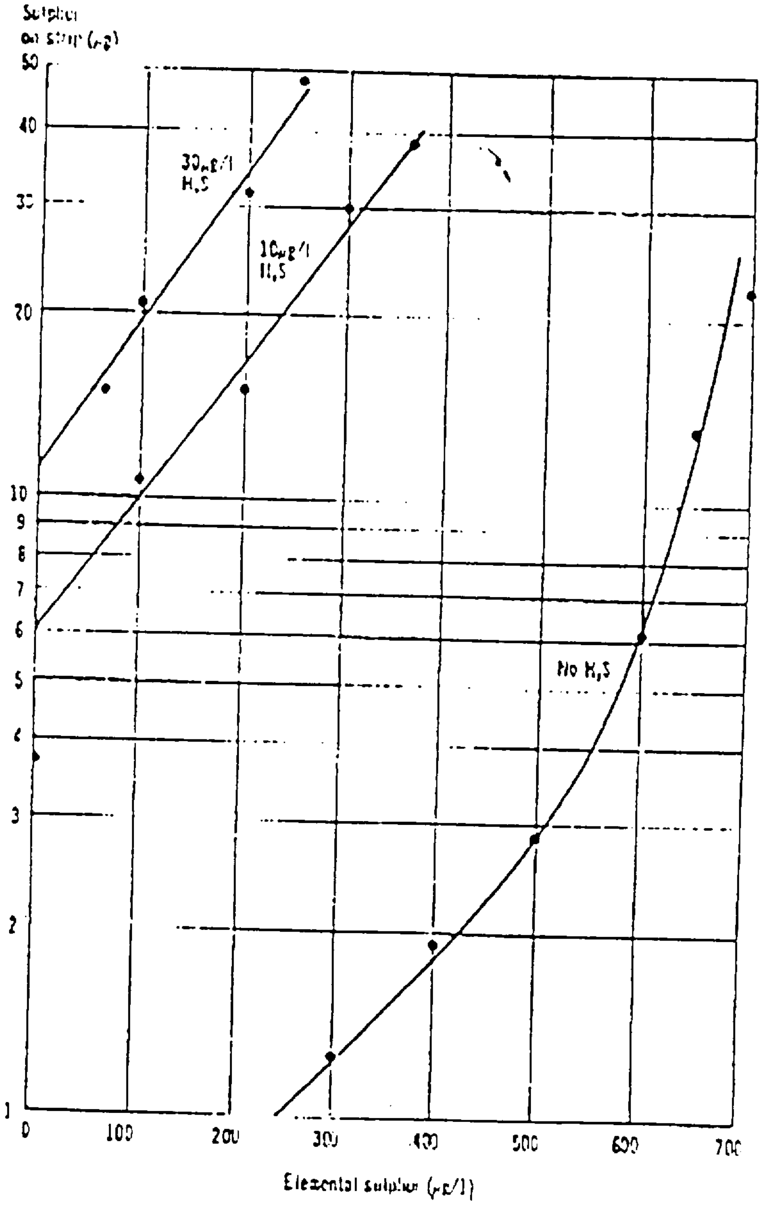

FIG. 2. Corrosion by elemental sulphur and hydrogen sulphide.

the curve increases with elemental sulphur content (Fig. 1).

3. Synergism occurs between hydrogen sulphide and elemental sulphur, as may be seen in Table III and also Fig 2.

TABLE III

Corrosion by Hydrogen Sulphide and Elemental Sulphur

Sulphur (μg/l)	Hydrogen sulphide (μg/l)	Sulphur on strip (μg)	Strip rating (IP 227/68T)
200	0	0	0
300	0	1·5	1
0	10	6	0/1
200	10	17	1/2
300	10	28	3

4. With elemental sulphur, in the absence of hydrogen sulphide, no corrosion occurs for sulphur contents below 200 μg/l; there is a gradual increase in reaction between 300 and 500 μg/l, then above 500 μg/l there is a rapid increase in the extent of corrosion during the test period (Fig 2).

5. With the model fuel system, the approximate amount of hydrogen sulphide or elemental sulphur required to give a 1 or 2 strip rating is as follows:

Rating	1	2
Elemental sulphur (μg/l)	300 (1·5/2)	500 (2·5/3)
Hydrogen sulphide (μg/l)	8 (5)	80 (20)

The values in brackets are the amounts of sulphur found on the strip in μg.

The amount of silver sulphide formed at a particular strip rating is considerably higher for hydrogen sulphide.

Coloration of the Strip

Our results show that different sulphide compounds produce different strip colours, hydrogen sulphide giving brown followed by purple, whilst elemental sulphur gives brown followed by green, blue-green, and black. The classification given in method IP 227/68T was intended as a reporting guide and, in any case, any further staining past the initial brown stage represents an unacceptable fuel. Therefore, it is not necessary to consider colour standards for colours other than brown. The colour standard used for "Thermal Stability of Aviation Turbine Fuel" (ASTM D 1660–IP 197) is satisfactory for differentiating between the brown colorations and has been incorporated in the latest method.

Changes during Storage

Samples of odourless kerosine were flushed with either air or nitrogen and approx. 14 μg/l of hydrogen sulphide added to each. Ten l of each sample were stored in metal containers, one-l portions being taken at intervals up to 28 days for hydrogen sulphide and silver corrosion determinations.

The results, shown in Figs 3 and 4, indicate that with the air-flushed sample there was an increase in silver corrosivity, even though the content of hydrogen sulphide decreased. With the nitrogen-flushed fuel, the silver corrosivity decreased, as did the hydrogen sulphide content. It is assumed that with the air-flushed fuel, some hydrogen sulphide was oxidized to sulphur, and thereby causing the synergistic corrosive action referred to earlier.

IMPROVEMENTS IN TEST METHOD

Loss of Hydrogen Sulphide

In our earlier work it was found that the amount of hydrogen sulphide required in a model fuel of 15 per cent vol toluene, 85 per cent vol *iso*-octane to cause

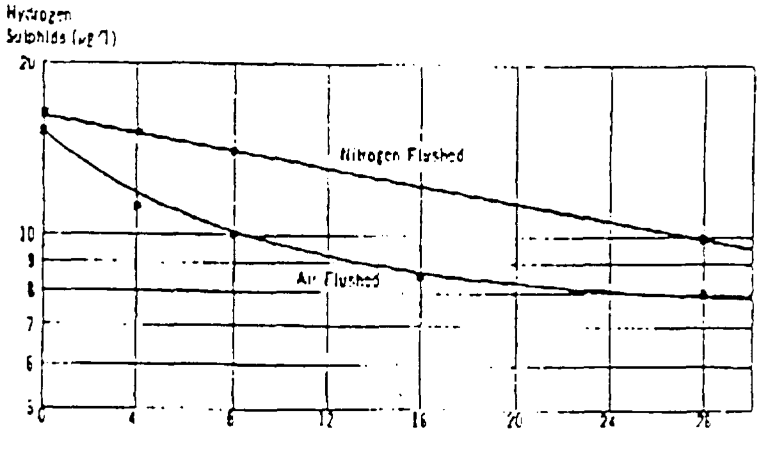

Fig 3. Storage test—reduction of hydrogen sulphide concentration with time.

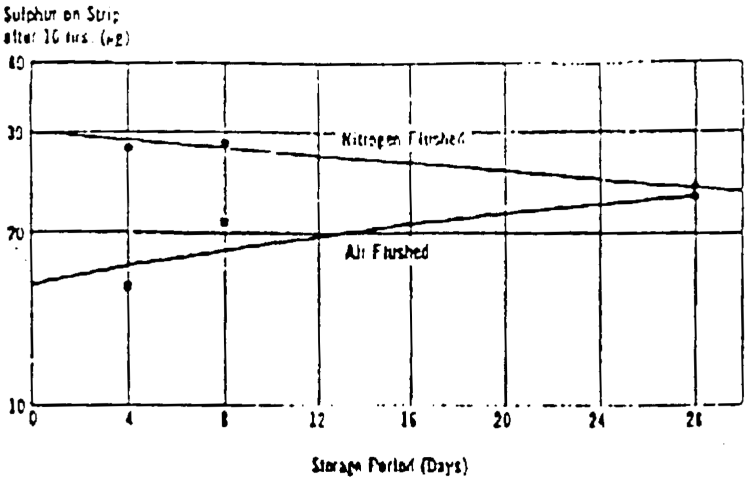

FIG 4. Storage test—silver strip corrosion after storage.

corrosion varied considerably from one occasion to another. Therefore, before the work described above was undertaken, the repeatability of IP 227/68T was improved considerably by slight modifications.

In an attempt to obtain a correlation between hydrogen sulphide concentration and silver corrosion (the test was carried out at 45° C for a 16-hr period using silver strips with a surface area of 23 cm^2 with one l of fuel) the results given in Table IV were obtained.

TABLE IV

Corrosion of Silver by Hydrogen Sulphide

Hydrogen sulphide (μg/l)		Sulphur on strip (μg)	Hydrogen sulphide loss (μg)	Strip rating*
Initial	Final			
18	2	5	11	1
24	3	6	15	1
62	12	7	43	1
64	21	10	33	1
85	10	6	69	2

* For strip rating system, see Appendix.

When the sum of the amount of sulphur deposited on the strip and the final hydrogen sulphide concentration is compared with the initial hydrogen sulphide concentration, it is apparent that there is an appreciable loss of hydrogen sulphide during the test.

Loss from Solution

One-l samples of hydrogen sulphide-containing model fuel were stored at 45 °C for 16 hr in the normal test apparatus but without the silver strip; some flasks were sealed with either corks or corks covered with aluminium foil.

The results shown in Table V indicate that an appreciable percentage of the hydrogen sulphide is lost during the normal test procedure. This loss can be considerably reduced by sealing the flask. Thus, in the silver corrosion test, a significant improvement should be obtained by replacing the condenser, which allowed the sample to be exposed to the atmosphere, by a stopper.

It also became apparent at this stage that, unless adequate precautions were taken, a loss of hydrogen sulphide could occur during transfer of the sample from one flask to another before starting the actual test.

Loss due to Oxidation

The effect of dissolved oxygen on the hydrogen sulphide concentration was briefly examined. The solvent was flushed for 2 hr with air or nitrogen prior to the addition of the hydrogen sulphide. One-l samples were then stored at 45° C for 16 hr in a flask stoppered with a cork covered with aluminium foil. The initial and final hydrogen sulphide concentrations are given in Table VI.

TABLE V

Loss of Hydrogen Sulphide with Stoppered and Unstoppered Flasks

Stoppering of flask	None as in IP 227/68T	Cork	Cork covered with aluminium foil
Initial hydrogen sulphide (μg/l)	71, 53, 24, 39	56, 60, 20	60, 34, 34, 27, 17, 15
Final hydrogen sulphide (μg/l)	19, 9, 3, 9	27, 36, 16	42, 27, 29, 21, 17, 13
Loss (%)	74, 83, 88, 77	52, 40, 20	30, 20, 15, 22, 0, 13
Average loss (%)	80	37	17

TABLE VI

Effect of Dissolved Oxygen on Hydrogen Sulphide Concentration

Flushing gas	Nitrogen	Air	Oxygen
Hydrogen sulphide (μg/l)			
Initial . .	28	34	34
Final . . .	22	28	29
Loss % . .	21	18	15

The results indicate that there is no significant loss of hydrogen sulphide due to oxidation during the test period.

Loss due to Adsorption

Koninklijke/Shell Laboratorium, Amsterdam, showed that results can be affected by adsorption of hydrogen sulphide on the sample containers. Natural or synthetic rubber seals must be avoided. Adsorption of hydrogen sulphide also occurs on the walls of glass containers. This effect was only small during the relative short duration of the test, but could become significant for the longer periods involved during transportation of the sample. The adsorption of hydrogen sulphide could be significantly reduced by prior acid cleaning of the containers.

DEVELOPMENT OF RAPID TEST

Since the deletion of potential gum from the D Eng RD 2494 specification, the silver corrosion test is the only requirement which cannot be completed during a working day. The Ministry of Technology and also the petroleum companies were, therefore, interested in reducing the test duration to 6 hr or less and also, if possible, reducing the sample size. The IP Stability of Light Distillates Panel (ST-B-8) acted as the co-ordinating body in this work.

Reduction of Sample Size

For convenience of handling it was considered desirable to reduce the sample size as much as practically possible from the present test requirement of one l.

Various sample sizes of prepared corrosive avtur were tested for silver strip corrosion by IP 227/68T (16 hr at 45° C). The results are given in Table VII.

TABLE VII

Effect of Reduction in Sample Size on Silver Corrosion

Sample	Avtur + 2 mg/l elemental sulphur		
Sample size (ml)	500,	250,	100
Visual rating	1+	1	1−
	——decreasing brown coloration——		

The corrosion gradient obtained suggested that uniform results would be obtained if the silver strip size was reduced proportionately with the sample size, and this was confirmed experimentally (see Table VIII). As identical results were obtained, it was considered that the sample size could be reduced to 250 ml, provided the silver strip was reduced accordingly.

TABLE VIII

Effect of a Reduction in Strip Size with Sample Size

Sample	Avtur + 2 mg/l elemental sulphur		Avtur + 4 mg/l elemental sulphur		
Sample size (ml)	500	250	1000	500	250
Strip size	½	¼	Normal	½	¼
Rating	1	1	2	2	2

Reduction of Test Duration

Effect of heating rate

The time taken for a fuel to reach the test temperature of 45° C in (*a*) the usual incubator, and (*b*) in a water bath, was found to be:

Incubator	300 minutes
Water bath	20 minutes

Using one-l samples in conical flasks it was found that the test period could be considerably reduced by using a water bath. The results given in Table IX indicate that a test period of 5 hr is adequate.

As 45° C is not a common test temperature, it was decided to raise the temperature slightly to 50 ± 1° C to permit the use of a viscosity or copper strip bath.

TABLE IX

Comparison of a 5- and 16-hr Corrosion Test

Sample	Model fuel + 1 mg/l elemental sulphur		Naturally corrosive fuel	
Heating method	Incubator	Water-bath	Incubator	Water-bath
Test period (hr)	16	5	16	5
Rating	3	3	4	4

Reduced sample size with reduced test duration

A test tube was found more convenient than a conical flask for 250 ml samples, particularly when using a viscometer bath. To reduce the effect of light on corrosion, amber-glass tubes of 300-ml capacity were used. It was found, however, that the extent of corrosion occurring with the small-scale test at 50° C was often less than that occurring in the normal procedure using an incubator at 45° C. This was attributed to a lack of convection currents in the sample after reaching the test temperature, thus limiting the amount of corrosive sulphur reaching the strip. A means of stirring was, therefore, investigated.

Mechanical stirring was tried and was found to increase the corrosion rate, but was rejected as it was too cumbersome. The use of a cold-finger condenser immersed in the fuel with the silver strip suspended from the lower end proved very satisfactory.

To ensure that the condenser did not adversely affect the test temperature, temperature measurements were made by means of a thermocouple immersed in the fuel at the point where the silver strip is normally suspended during test. The results given in Table X show that the use of the condenser did not significantly affect the test temperature.

A flow rate of 10 ml/minute was adopted for future work. Comparison of the small-scale test with and without the use of the condenser and with the normal 16 hr test is shown in Table XI.

A further series of tests was carried out using the model fuel containing 2 mg/l of elemental sulphur and the silver strips rated after one, 2, 3, 4, and 5 hr. The results are given in Table XII, and from these it is seen that after 3 hr the corrosion on the strip was similar to that in the normal test after 16 hr. It was, therefore, decided that an acceptable test period would be 4 hr with this test.

Tests were carried out in comparison with the current IP 227/68T using Avtur and model fuel contaminated with hydrogen sulphide. Table XIII indicates that very good correlation was achieved. The modified test was, therefore, put forward to the IP as a suitable shortened version of the standard test.

TABLE X

Effect of Condenser Flow Rate on Temperature

(Bath temperature 50° C)

Condenser flow rate (ml/minute)	Temperature of cooling water (°C)	Temperature (°C) of fuel at the test piece
90	15	46·4
30	15	47·2
10	15	48·6
10	4	48·6
10	30	49·3

TABLE XI

Comparison of Various Procedures

Model fuel containing elemental sulphur (mg/l)	2	3	4
IP 227/68T (16 hr in incubator at 45° C) . .	3−	3	3+
Small-scale static test (5 hr at 50° C) . . .	<3−	3−	3
Small-scale with condenser (5 hr at 50° C) . .	3−	3	3+

TABLE XII

Effect of Test Duration

Time (hr)	Appearance of strip	Rating
1	Faint black patches	<3−
2	Deeper black patches	3−
3	Uniform light blackening	3
4	Uniform light blackening	3
5	Uniform light blackening	3

TABLE XIII

Comparison with Fuels Containing Hydrogen Sulphide

Fuel	Concentrations of hydrogen sulphide (μg/l)	IP 227/68T (16 hr)	Proposed method (4 hr)
Model fuel .	50	1	1
	100	1+	1+
	200	2	2
Avtur . .	50	1+, 1	1, 1
	100	2, 2−	2−, 1+
	200	2+, 2	2−, 2

Evaluation of Test by Other Laboratories

In order to permit the use of a standard 8-oz bottle for the despatch of samples, it was decided to modify the test further to 200 ml sample size and one-fifth length (14–16 mm) silver strip. The apparatus was supplied to various laboratories with the request that synthetic or naturally corrosive fuels be examined by the proposed test in comparison with IP 227/68T.

The results obtained by BP, Chemical Inspectorate, (Harefield), Lucas, and Shell Oil (U.S.A.) are given in Table XIV. In addition, it was stated by Mobil that they examined fuels containing added elemental sulphur and had obtained similar results by both methods. Also three Shell U.K. refineries carried out comparative tests on their normal avtur productions. Some 30 fuels were examined, and with one exception both procedures gave zero ratings. The exception gave a zero rating by the proposed method and a 95 per cent zero/5 per cent one rating IP 227/68T.

It was generally considered that the short test was slightly less severe than the current IP 227/68T and that operators would prefer the use of one-quarter scale rather than one-fifth scale test. It was decided that the quarter-scale test should be used in any future work.

IP CORRELATION PROGRAMME ON REVISED METHOD

Programme

The preliminary results obtained with the shortened test by the various laboratories were considered to be sufficiently encouraging for the panel to proceed with a

TABLE XIV

Comparison of Proposed Test with IP 227/68T

Laboratory	Base fuel	Added corrosive sulphur: Hydrogen sulphide (mg/l)	Added corrosive sulphur: Elemental sulphur (mg/l)	Test: Proposed	Test: IP 227/68T
BP	Copper-sweetened Avtur	—	2	0	0/1
	Copper-sweetened Avtur	—	9	1	1
	Hydrotreated Avtur	..	2	1	3
	Hydrotreated Avtur	—	3	3	3
	Avtur with	—	2	1	2
	"natural mercaptans"	—	3	2	3−
	Avtur	0·1	–	1	1/2−
	Avtur	0·4	..	1	1
Chemical Inspectorate, Harefield	Avtur	—	3	3	3
		—	2	2	2
		—	1	1	1
		1	–	2	2
		0·5	–	2	2
Lucas	Avtur	5	–	2+	2+
		5	–	2−	2
		5	–	2	2+
		2	–	2·1	2+
		2	–	2+	2
		1	–	2	2−
		1	–	2	2−
Shell Oil—Houston refinery	Denormalized kerosine*				
	19.5.69	Trace	Trace	4	4
	9.7.69	Nil	Nil	2	2
	14.7.69	,,	,,	2	3
	15.7.69	,,	,,	2	2
	21.7.69	,,	,,	0	0
	28.7.69	,,	,,	2	2
	5.8.69	,,	,,	2	2
	11.8.69	,,	,,	2	2
	18.8.69	,,	,,	2	2
	25.8.69	,,	,,	2	2
	29.8.69	,,	,,	1	1

* This is hydrotreated material and was chosen because of its natural corrosive characteristics.

correlation programme. Nine laboratories took part and examined five different samples as follows:

Sample	Description
A and B	Commercial hydrotreated fuel to which a small proportion of unstripped kerosine containing hydrogen sulphide had been added.
C	Commercial acid-treated kerosine.
D	Wet-treated kerosine with added untreated kerosine which contained hydrogen sulphide and a high concentration of mercaptans.
E	Hydrotreated kerosine with added elemental sulphur and mercaptans.

Each laboratory carried out duplicate tests by IP 227/68T and by the proposed test of 4 hr duration. Some laboratories also extended and proposed test to 6 hr.

Results

The results are given in Table XV.

Perfect agreement was obtained by the two tests and between laboratories on samples A and B. The agreement obtained on sample C was also very good, most results being a zero rating with three laboratories reporting a 1 strip by IP 227/68T. In each case the 1 ratings were due to faint discoloration at the edges of the strips, so the differences between the tests were marginal. With the exception of one rogue result, good agreement was also obtained on sample E; if anything, the proposed test rated the fuels slightly more severely than the IP 227/68T test.

The main differences between methods occurred with sample D. In nearly every case the proposed test gave the fuels a 1 rating, whereas the IP 227/68T test gave a 2 rating. The sample was intended to represent a commercial fuel which had become contaminated with untreated fuel. The sample failed the D Eng RD 2494 specification on mercaptan content. The sample was apparently somewhat unstable and became more reactive on prolonged heating, thus giving more deposits in the longer test. It could even be argued that the proposed short test is more representative of the actual residence time of the fuel at elevated temperatures in the aircraft pump. However, the pump and engine manufacturers required that the proposed test should be no less severe

TABLE XV

Results of IP Correlation Programme

Sample	A			B			C			D			E		
Method*	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Esso, Abingdon	3		3	2		2	0		0	1		2	2		2
				2		2	0		0	1		2	2		2
BP, Sunbury	3	3	3	2	2	2	0	0	0	1	1	2	3	3	2
	3	3	3	2	2	2	0	0	0	1	1	2	3	3	2
Chemical Inspectorate, Harefield	3	3	3	2	2	2	0	0	1	1	2	2	3	3	2
	3	3	3	2	2	2	0	0	1	1	2	2	3	3	2
Shell, Shell Haven refinery	3	3	3	2	2	2	0	0	0	1	2	2	2	2	2
	3	3	3	2	2	2	0	0	0	1	2	2	2	2	2
Mobil, Coryton refinery	3	3	3	2	2	2	0	0	1	No results					
	3	3	3	2	2	2	0	0	1						
Mobil, Technical Service Laboratory	3	3	3	2	2	2	0	0	1	2	2	2	3	3	3
	3	4	3	2	2	2	0	0	1	2	2	2	3	3	3
Lucas, Birmingham	3		3	2		2	0		0	1		2	2		2
	3		3	2		2	0		0	1		2	2		2
Texaco, King's Langley	3	3	3	2	2	2	0	0	0	2	2	2	0	0	3
	3	3	3	2	2	2	0	0	0	2	2	2	0	0	0
Shell, Egham	3		3	2		2	0		0	1		2	2/3		2
	3		3	2		2	0		0	1		2	2/3		2

* Methods:
1. Proposed test (4 hr)
2. Proposed test (6 hr)
3. IP 227/68T.

than the current standard test. The panel, therefore, agreed to modify the wording of the 2 rating in the proposed method in order to make the results on sample D by the two methods comparable.

The differences in ratings on sample D by the two methods was small. The colorations of the strips obtained by the proposed test were generally an overall straw or brown stain, whereas the strips obtained by IP 227/68T had, in addition to the brown, an overlay of "peacock" colorations. It was apparent that the strip classifications in the current method were inadequate to cover the appearance of the strips obtained by the proposed test. The 1 classification covers faint brown colorations but no mention is made at all of overall medium or dark brown colorations. The classification table was, therefore, revised, the description of the No. 1 strip being left essentially unaltered and that of the No. 2 strips being re-written to cover overall brown stains, in addition to peacock colorations.

The revised classifications more closely interpret the intentions of the D Eng RD 2494 specification. This specification allows a 1 classification with the intention that fuels giving a faint tarnish do not fail. It was never the intention to allow a pass with fuels which show heavy brown colorations.

The revised results were submitted to the IP Precision Evaluation Panel. The results were not amenable to the normal statistical procedures, as broad classifications rather than discrete numerical values were involved. It was concluded that within the 95 per cent probability duplicate results by the same operator should agree and that results submitted by two laboratories should be considered suspect only if they differed by more than one rating. It was also concluded that, with the revised classification, the current and proposed methods should rate the fuels with the same severity.

CONCLUSIONS

The reactivity of hydrogen sulphide and elemental sulphur to silver has been established. A synergistic effect between hydrogen sulphide and elemental sulphur has been found. Under certain circumstances, mercaptans, disulphides, and peroxides can inhibit corrosivity. However, mixtures of these components can nullify their inhibitory effect.

A new test has been developed requiring a smaller sample and shorter test duration than those in the IP 227/68T test. The new test has been shown to have a similar severity to the current test. This test has been approved by the Ministry of Technology as a specification test and has been adopted by the IP; it will be published in the Standards in 1971.

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Appendix

SILVER CORROSION BY AVIATION TURBINE FUELS

IP 227/71

1. SCOPE

1.1 This method describes a procedure for the detection of the corrosiveness to silver of aviation turbine fuels.

2. OUTLINE OF METHOD

2.1. A polished silver strip is completely immersed in 250 ml of fuel at 50 ± 1°C for a period of 4 hr, or any longer period which may be specified. At the end of this period, the silver strip is removed from the sample, washed, and evaluated for corrosion.

3. APPARATUS

3.1. *Test Apparatus*, see Fig 1, comprising:

3.1.1. *Test Tube*—250-ml capacity, made of heat-resistant amberglass and fitted with a B.45 ground glass socket.

NOTE 1: Clear glass test tubes may be used provided light is excluded from the sample.

3.1.2. *Cold-finger Condenser*—fitted through a B.45 stopper such that an 85-mm length of the condenser is immersed in the fuel. The condenser should be fitted with a glass hook from which the silver strip can be suspended.

NOTE 2: If more than one apparatus is in use, the condensers should be connected in parallel so that each condenser has a similar efficiency. It may be necessary to control the inlet water temperature to 20 ± 5°C.

3.1.3. *Glass Cradle*—for suspension of the silver strip in the fuel such that the top of the strip is 25 to 30 mm below the bottom of the condenser.

3.2. *Water Bath*—capable of maintaining the tube and its contents at a temperature of 50 ± 1°C. The bath should be fitted with a lid having holes to accommodate the test tubes.

3.3. *Strip Vice*—for holding the silver strip firmly without marring the edges. The type specified in ASTM D130–IP 154 is suitable.

3.4. *Thermometer*—any thermometer capable of indicating the temperature of the bath within the limits stated in para 3.2.

4. MATERIALS

4.1. *Iso-octane*—conforming to the specification for ASTM knock test grade iso-octane.

4.2. *Silver Strip*—assaying at 99·9% Ag and having the dimensions of length 17 to 19 mm, width 12·5 to 12·7 mm, and thickness 1·5 to 3·0 mm.

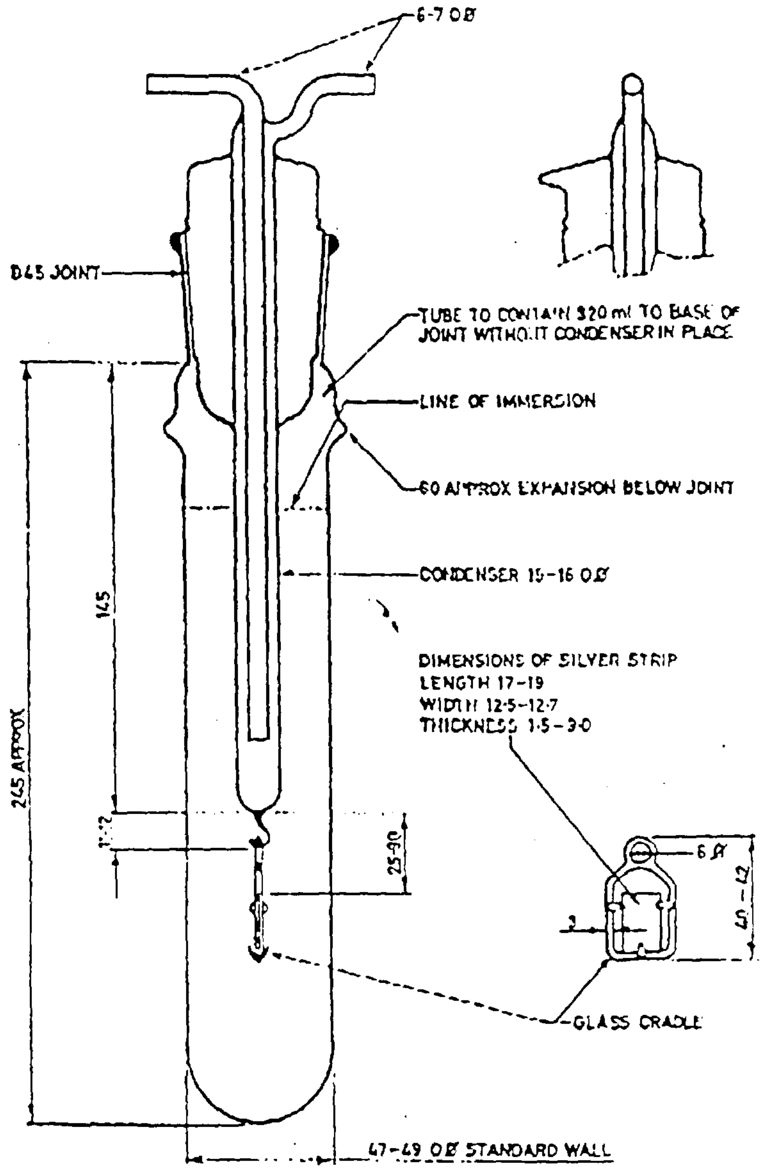
4.3. *Polishing Materials*—silicon carbide or alumina grit paper of varying degrees of fineness including 240 grit silicon carbide paper or No. 00 emery cloth or equivalent; also a supply of 150 mesh silicon carbide grain and pharmaceutical grade absorbent cotton wool.

5. PREPARATION OF STRIPS

5.1. *Surface Preparation*. Remove all surface blemishes from all six sides of the strip with silicon carbide or alumina grit paper to accomplish the desired results. Finish with 240 grit silicon carbide paper or No. 00 emery cloth, or its equivalent, removing all marks that may have been made by other grades of paper used previously. Immerse the strip in the iso-octane, from which it may be withdrawn when proceeding to the final polishing step.

NOTE 3: As a practical manual procedure for surface preparation, place a sheet of the abrasive paper on a flat surface, moisten it with the iso-octane, and rub the strip against the paper with a rotary motion, protecting the strip from contact with the fingers with an ashless filter-paper. Alternatively, the strip may be prepared mechanically, using appropriate grades of dry paper or cloth.

5.2. *Final Polishing*. Remove a strip from the iso-octane. Holding it in the fingers protected with ashless filter-paper, polish first the ends and then the sides with the 150-mesh silicon carbide grains picked up from a clean glass plate with a pad of cotton wool moistened with a drop of the iso-octane. Wipe vigorously with fresh pads of absorbent cotton and subsequently handle only with stainless steel forceps; *do not touch with the fingers*. Clamp in the vice and polish the main



DIMENSIONS IN MILLIMETRES

Fig 1. Test apparatus.

surfaces with the silicon carbide grains on absorbent cotton. Rub in the direction of the long axis of the strip, carrying the stroke beyond the end of the strip before reversing the direction. Clean all metal dust from the strip by rubbing vigorously with clean pads of absorbent cotton until a fresh pad remains unsoiled. Immerse the strip in the sample within 1 min of completing the final polishing.

Note 4: It is important to polish the whole surface of the strip uniformly to obtain a uniformly stained strip. If the edges show wear (elliptical surface) they will be likely to show more corrosion than the centre. The use of a vice facilitates uniform polishing.

6. SAMPLE

6.1. It is particularly important that care should be taken during sampling and subsequent handling to eliminate aeration of the samples and to protect them from exposure to direct or even diffused daylight. Samples of 250 ml minimum size should be collected in containers which will not affect the corrosive properties of the fuels. Clean dark-brown bottles are preferred. Fill the container to leave not more than 5% ullage and close it immediately after taking the sample. Store the sample in a cool place, preferably below 4°C. Test the sample as soon as possible after receipt and immediately after opening the container.

NOTE 5: Experience has shown that tinplate containers are particularly bad in this respect.

6.2. If suspended water (haze) is observed in the sample (Note 6), filter through a medium rapid quantitative filter paper (e.g. Whatman No. 1 or No. 4), into the clean, dry test tube. Carry out this operation in a darkened room or under a light protected shield.

NOTE 6: Contact of the silver strip with water before, during, or after the completion of the test run, will cause staining, making it difficult to evaluate the strips.

7. PROCEDURE

7.1. Pour 250 ml of the sample into the clean test tube. Suspend a freshly polished strip from the hook on the condenser by means of the glass cradle. Carefully lower the strip and condenser into the sample.

7.2. Place the tube in the water-bath and maintain the temperature at 50 ± 1°C for 4 hr or for any longer period which may be specified. During the test period, run water through the condenser at a rate of 10 ml/min to induce thermal stirring [Note 2]. At the end of the test period remove the silver strip from the tube and immerse it in the iso-octane. Withdraw the strip immediately, dry it with quantitative filter paper (by blotting not wiping), and inspect it for evidence of corrosion.

8. INTERPRETATION

8.1. Interpret the corrosiveness of the sample according to the appearance of the test strip by means of the classification given in Table I.

TABLE I

Silver Strip Classification

Classification	Designation	Description
0	No tarnish	The same as freshly polished strip, except possibly for some very slight loss of lustre
1	Slight tarnish	Faint brown or white discoloration of strip [Note 7]
2	Moderate tarnish	Peacock colours such as blue or mauve or medium/dark straw or brown coloration [Note 7]
3	Slight blackening	Patches of black on surface or uniform thin film of black deposit
4	Blackening	Uniform heavy blackening with or without scaling

NOTE 7: The ASTM Colour Standard for the Thermal Stability of Turbine Fuel (ASTM D1660 IP 197) should be used to differentiate between the brown colorations mentioned in classifications 1 and 2. Any brown coloration less than ASTM No. 4 should be rated classification I.

9. REPORT

9.1. Report the result as Silver Corrosion, IP 227/71, followed by the pertinent classification number from Table I and the duration of the test.

10. PRECISION

10.1. The following criteria should be noted for judging the acceptability of results (95% probability) [Note 8].

10.1.1. *Repeatability.*—Duplicate results by the same operator should be considered suspect if the ratings differ.

10.1.2. *Reproducibility.*—The results submitted by each of two laboratories should not be considered suspect unless the two ratings differ by more than one.

NOTE 8: These precision values have been obtained by statistical examination of inter-laboratory test results and were first published in 1971. This programme also showed that this method rates fuels with a similar severity to the former method, IP 227/65 T.

ATTACHMENT H

Parker

Parker Hannifin Corporation
Gull Electronic Systems Division
70 Corporate Drive
P.O. Box 9400
Smithtown, NY 11787 USA
Phone (516) 231-3737

September 18, 1992

[redacted]

Attention: [redacted]

Dear Dave:

The attached report was based on several major airlines reporting DC-10 isolated fuel quantity anomalies in flight which could not be duplicated on the ground.

Sample wiring was furnished by Robert Schwarz, Aircraft Systems Engineer, at Federal Express.

This report is forwarded to you for your general information. If you have any further questions, please contact Parker/GESD Customer Service Engineering.

Very truly your,

John Dungee

John Dungee
Customer Service Engineer
Customer Service Engineering

JD:pd

Enclosure

→ DFLU

Parker

MEMORANDUM

Parker Bertea Aerospace
Parker Hannifin Corporation
18321 Jamboree Road
P.O. Box C-19510
Irvine, CA 92713 USA
Phone (714) 833-3000

TO: J. Dungee, Gull ESD
FROM: R. Cashman
DATE: August 18, 1992
SUBJECT: LR 64246

PROBLEM

Seven connectors were removed from a DC-10 fuel tank after ten years of exposure to fuel. The connectors were coated with a black/green-black deposit which was particularly thick on the ferrule of the terminal connectors. Figure 1, Figure 2, and Figure 3 illustrate the typical appearance of this deposit. One triax connector, three shielded terminal connectors, and three non-shielded terminal connectors were submitted for analysis.

ANALYSIS

A. Electrical Resistance

The electrical resistance between different connector components was measured using a one ampere source. All measurements were at 70F. Table I summarizes the results:

Table I: Resistance of connector components

Measurement between parts (in milli-ohms)	#1 no shield	#2 shield	#3 no shield	#4 shield	#5 no shield	#6 shield
ferrule-center cond.	inf	inf	inf	inf	inf	inf
ferrule-terminal lug	inf	inf	inf	----	inf	inf
lug-center conductor	0.2	0.1	0.25	----	200	90
ferrule to shield	------	0.06	------	0.65	------	0.26
shield to center cond.	------	inf	------	inf	------	inf
ferrule-ferrule	500	30	200*	0.07	.015	.011

* Resistance was measured through two layers of 0.010" thick deposit

The electrical resistance of the triax connector was measured. The results are listed in Table II.

Table II. Resistance of elements in triax connector

component-component	resistance in milli-ohms
center conductor - center wire	0.00
center conductor to shield	infinite
shield to outer shell	infinite
wire shield -conductor shield	.072

B. Properties of the coating

The black/green black deposit was analyzed using Energy Dispersive Spectroscopy (EDS). The general element composition is illustrated in Figure 4. The compounds present in the deposit are copper (II) sulfide, copper (II) oxide and free copper metal. The black deposit, which was present on the lug, on the ferrule, and on the solder joint, was predominantly copper sulfide. Sulfides are present in jet fuel.

In a cross section through the ferrule of connector # 5, considerable corrosion of the base metal was noted. The deposit in this area contained both free copper metal and considerably more copper oxide than was present in other areas of the deposit.

DISCUSSION

No problem was found with the conductance through the solder joint at the lug end. This was true even though considerable deposit was present on the joint. Also, no problem was found with the shield of the shielded connectors (Table I).

The electrical properties of the deposit were variable as would be expected from the varied composition and thickness of the coating. The general electrical resistance on the copper sulfide deposit on the ferrule was roughly 80 times the resistance of copper. However, very high resistance was obtained on the tin plated lugs where there was no copper in direct contact with the copper sulfide deposit.

The corrosion of the ferrule is important because of the increased resistance of copper oxide and because the uneven surface produced reduces the contact force on the ferrule.

Robert Cashman
Senior Engineer
Materials & Processes

ATTACHMENT I

ANALYTICAL ENGINEERING REPORT

TO:	T. M. Mitchell 49-57	NO.:	9-5576-WP-97-272
CC:		ITEM NO.:	Chem 6007
		DATE:	August 5, 1997
		MODEL:	747

GROUP INDEX: 9-5576 - Analytical Engineering, Chemical/Physical

SUBJECT: Analysis of Fuel Quantity Tank Units for Copper Sulfide

BACKGROUND

Four fuel quantity tank units from 747 aircraft were submitted for analysis for copper-sulfur compounds. The parts had been labeled F40, F41, F42 and F44, respectively. The part number, serial number and manufacture date of each are listed in Table 1. Prior to this analysis, the four units had been subjected to electrical testing involving the application of high potential, and the possibility existed that they had sustained arc damage. Copper-sulfur compounds were of interest as a means by which a conductive path to ground might form in service.

CONCLUSIONS

Dark deposits on the terminal blocks from all four fuel quantity tank units have been identified as copper-sulfur compounds. The data are indicative primarily of reduced sulfur (copper sulfide), and not of sulfur in a higher oxidation state (sulfate or thiosulfate). The terminal blocks themselves were found to consist of 300-series corrosion-resistant steel which appeared to have been plated with copper, at least in some locations. Metallurgical evaluation of a cross-sectioned block is recommended if any question exists as to their composition. Black silver sulfide was identified on the Hi-Z terminal block hold-down nut from F44, the only nut from which dark deposits were sampled. Silver sulfide and copper sulfide tarnish can be expected to form on copper and silver surfaces in the presence of elemental sulfur or mercaptans.

Electrical arc damage was present on three of the fuel quantity tank units (F40, F42 and F44). In two units, arcing took place at the outer edge of the copper shield. In the third instance (F42), the arcing occurred between the shield and the lip of the opening in the outer (Lo-Z) aluminum tube. The arc damage spots in F42 were too small to observe without magnification. Electron microscopic analysis of the micro-arc sites is recommended as a means of characterizing the signature of arcing accompanied by minimal damage.

Additional analysis of the shields from F40 and F41 is recommended as well. The shield from F40 appeared to have experienced some corrosion, giving it a slightly red color. The laminated copper in the shield from F41 was nearly uniformly blackened. Analysis to determine composition of the black substance (copper oxide or copper sulfide) is recommended.

EXPERIMENTATION AND RESULTS

The fuel quantity tank units were disassembled and inspected for arc damage. Samplings from the terminal blocks were analyzed by infrared microspectroscopy and electron microprobe.

Disassembly and Inspection. The four probes are shown as received in Figure 1, and the terminal assembly of F40 is shown at higher magnification in Figure 2 for illustration. Arc damage, shown in Figures 3 and 4, was present at the edge of the copper shield that is indicated in Figure 2. The copper shield within the plastic laminate appeared to be slightly reddened in color, and what appears to be corrosion was present at one corner (Figure 5). Analysis of the corrosion product, the arc site and the shield surface is recommended. Dark deposits were present on the terminal assemblies, but to a greater degree on the Lo-Z terminal (Figure 6).

No arc damage was found on F41, but the copper shield was nearly uniformly blackened (Figure 7). Analysis to determine the identity of the black substance is recommended. Dark deposits were present on the surfaces of the terminal blocks. In this instance, the Hi-Z block had been more severely affected (Figure 8).

Micro-arc damage was present on F42 right at the edge of the opening in the outer Lo-Z aluminum tube (Figures 9 and 10). Electron microscopy of the arc-sites on the tube might be useful in characterizing arcing where minimal damage has been incurred. Heavy accumulations of dark deposits were present particularly on the Hi-Z terminal block from this unit (Figure 11).

Arc damage to F44 occurred along the same edge as in F40, but somewhat closer to the opening in the Lo-Z outer tube (Figures 12 and 13). Dark deposits were present on both terminal blocks, one of which is shown in Figure 14.

Analysis of the Dark Deposits. An infrared spectrum representative of the dark deposits from the terminal blocks is presented in Figure 15 along with a reference spectrum of copper sulfide (cuprous sulfide, Cu_2S). Condensed phase hydroxyl absorbs near 3400 wavenumbers, indicating the presence of some water of hydration or hydroxyl functional groups. The absorption near 1100 wavenumbers in both spectra in Figure 15 could be due to a sulfate impurity, but silicates also absorb near 1100 wavenumbers. Representative electron microprobe elemental surveys of the dark deposits, presented in Figure 16, provide clear indication that the deposits consist of copper-sulfur compounds and most likely of copper sulfide.

Varying concentrations of silicon and low concentrations of chromium, manganese and iron were also detected (16B). Essentially only silicon was detectable in the filaments observed on the terminal blocks (Figure 17A), shown in Figure 6, perhaps accounting for the silicon signal in the deposits. The blocks themselves were identified as a 300-series corrosion-resistant steel alloy which appeared to be plated with copper, at least in some locations. Metallurgical analysis is recommended to confirm composition if it is in question. Black deposits lifted from a hold-down nut on the F44 Hi-Z terminal block were identified as silver sulfide (Figure 17B).

The above results confirm that copper sulfide deposits formed on the fuel quantity tank units terminal blocks in service.

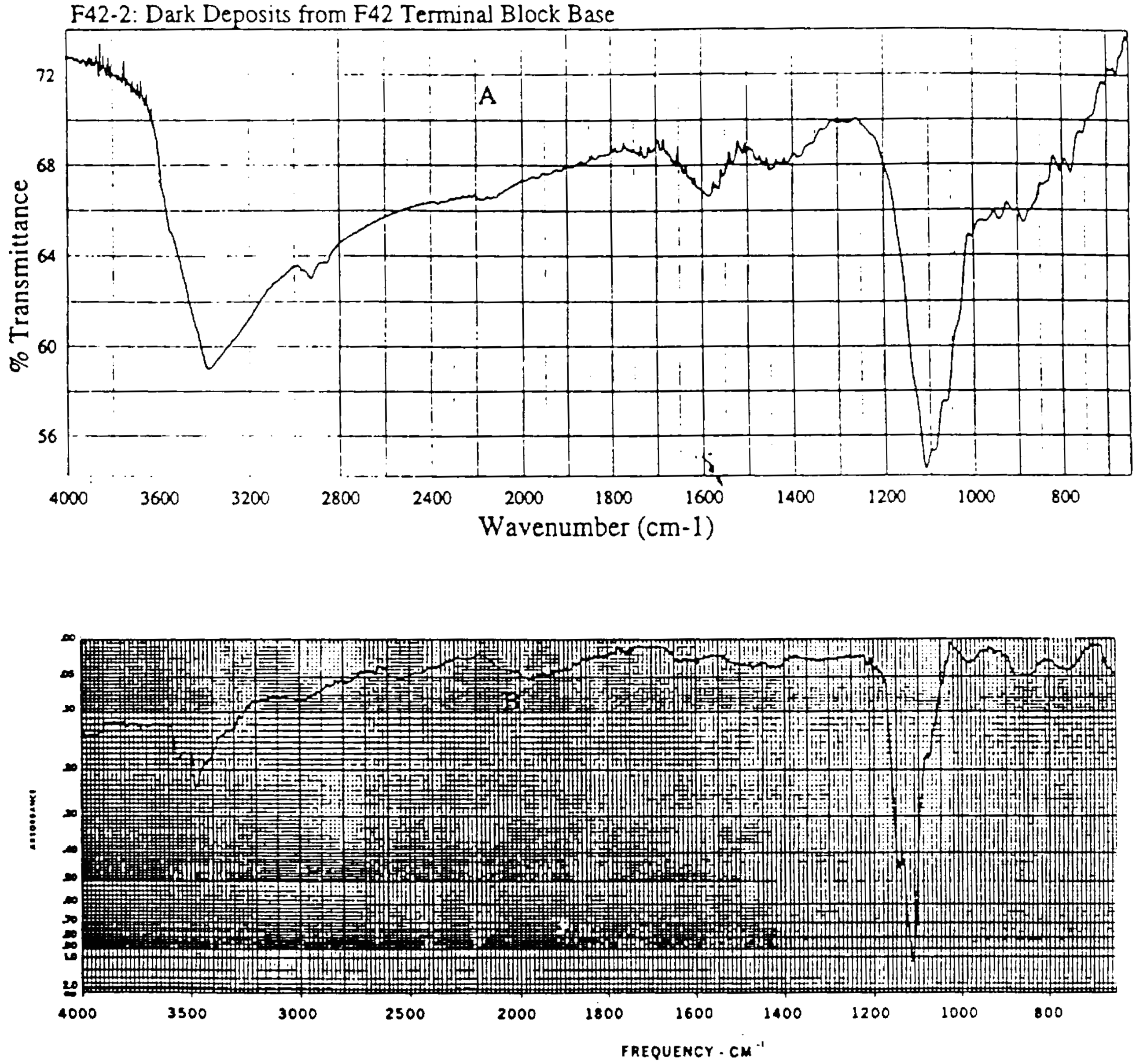
Prepared by D Bruce Skoropinski
D. B. Skoropinski
M/S 73-09, 234-2666

Approved by
W. L. Plagemann
M/S 73-09, 234-3025

Electron Microprobe: J. C. Wessel
Photography: J. A. Brewer

Table 1. Part Data and Observations for the Four Fuel Quantity Tank Units

Label	MFR P/N	S/N	MF Date	Observations
F40	FG420A12	W-66	Nov 1973	Arc Damage, Shield Corrosion, Dark Blocks
F41	FG420A13	W-29	Apr 1973	No Arcing; Copper Shield Black; Dark Blocks
F42	FG420A15	W-25	Oct 1973	Arc Damage, Terminal Blocks Darkened
F44	FG420A13	W-23	Mar 1973	Arc Damage, Terminal Blocks Darkened



F42-2: Dark Deposits from F42 Terminal Block Base

Figure 15. (A) An infrared spectrum of dark deposits on a terminal block from fuel quantity tank unit F42. (B) An infrared reference spectrum of cuprous sulfide, Cu_2S (© 1967, Sadtler Research Laboratories).

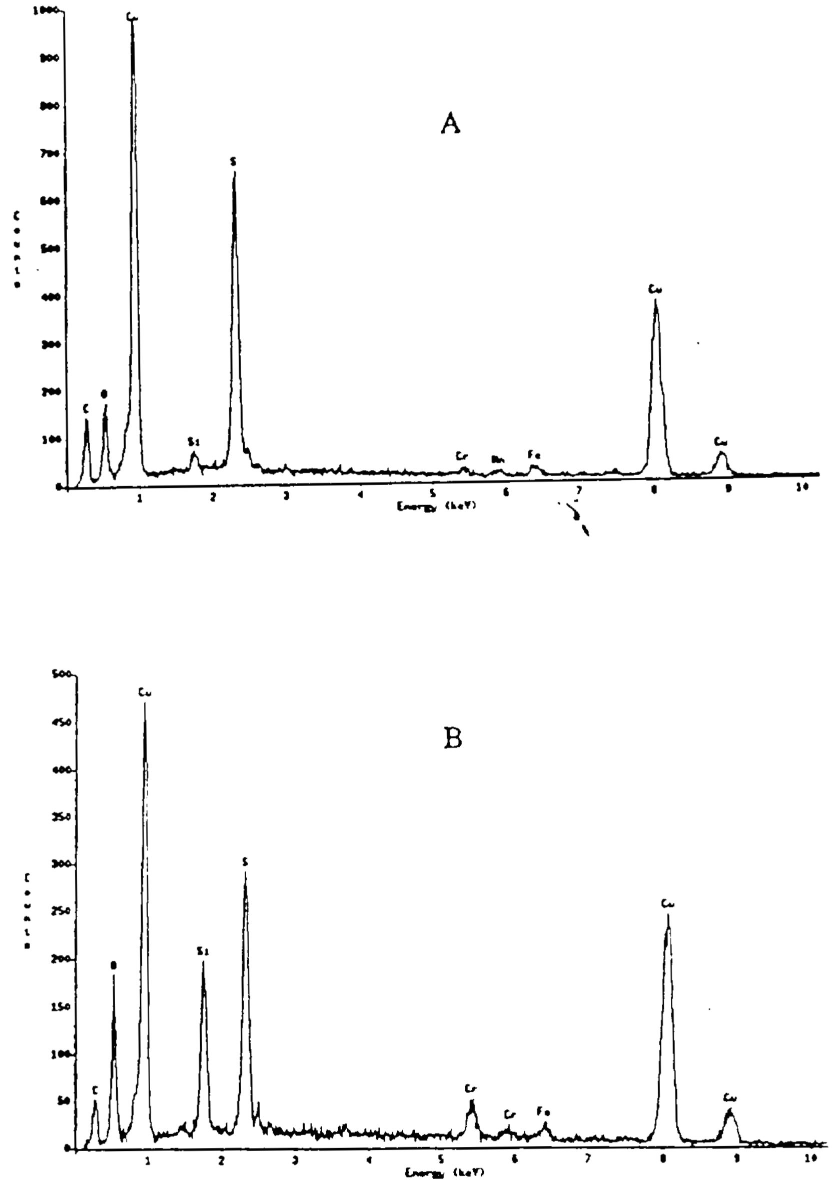


Figure 16. Electron microprobe elemental surveys of (A) dark deposits from the Hi-Z terminal block of F41 and (B) dark deposits from the Hi-Z terminal block of F42.

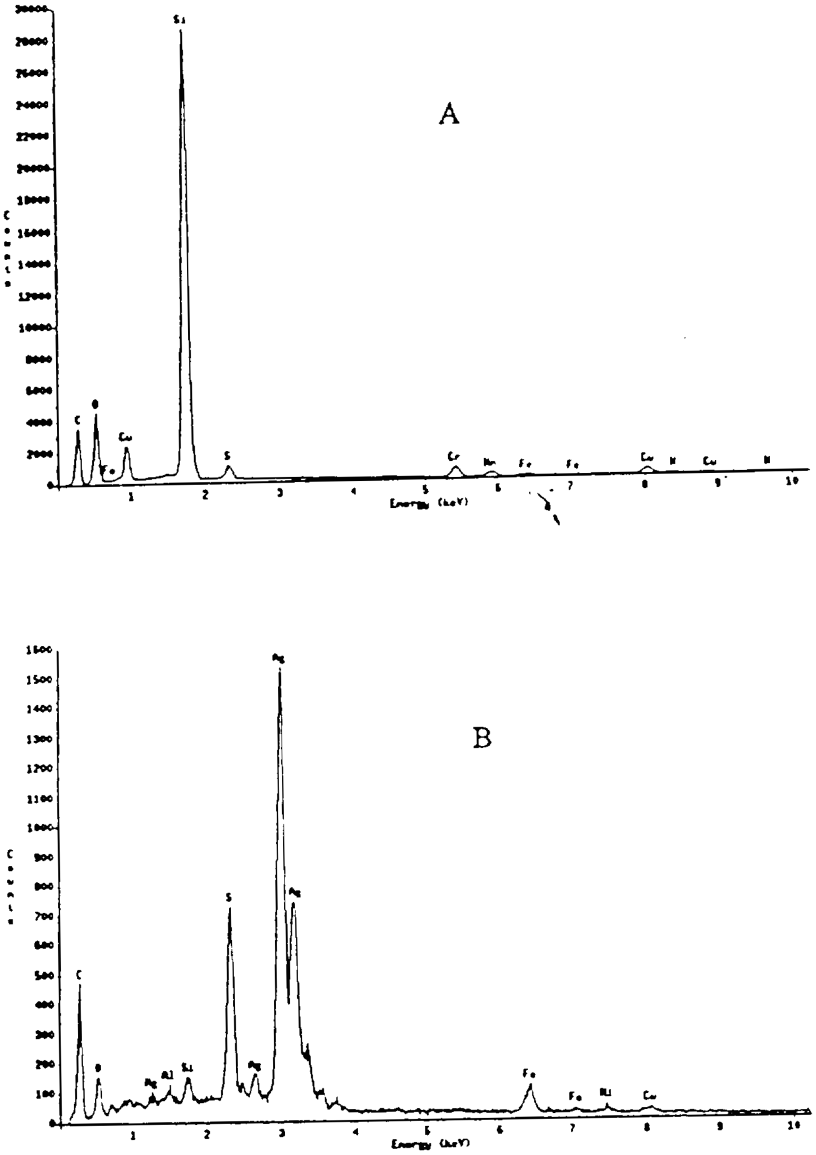


Figure 17. Electron microprobe elemental surveys of (A) filaments from the Lo-Z terminal block of F40 and (B) dark deposits from the Hi-Z terminal block hold-down nut of F44.

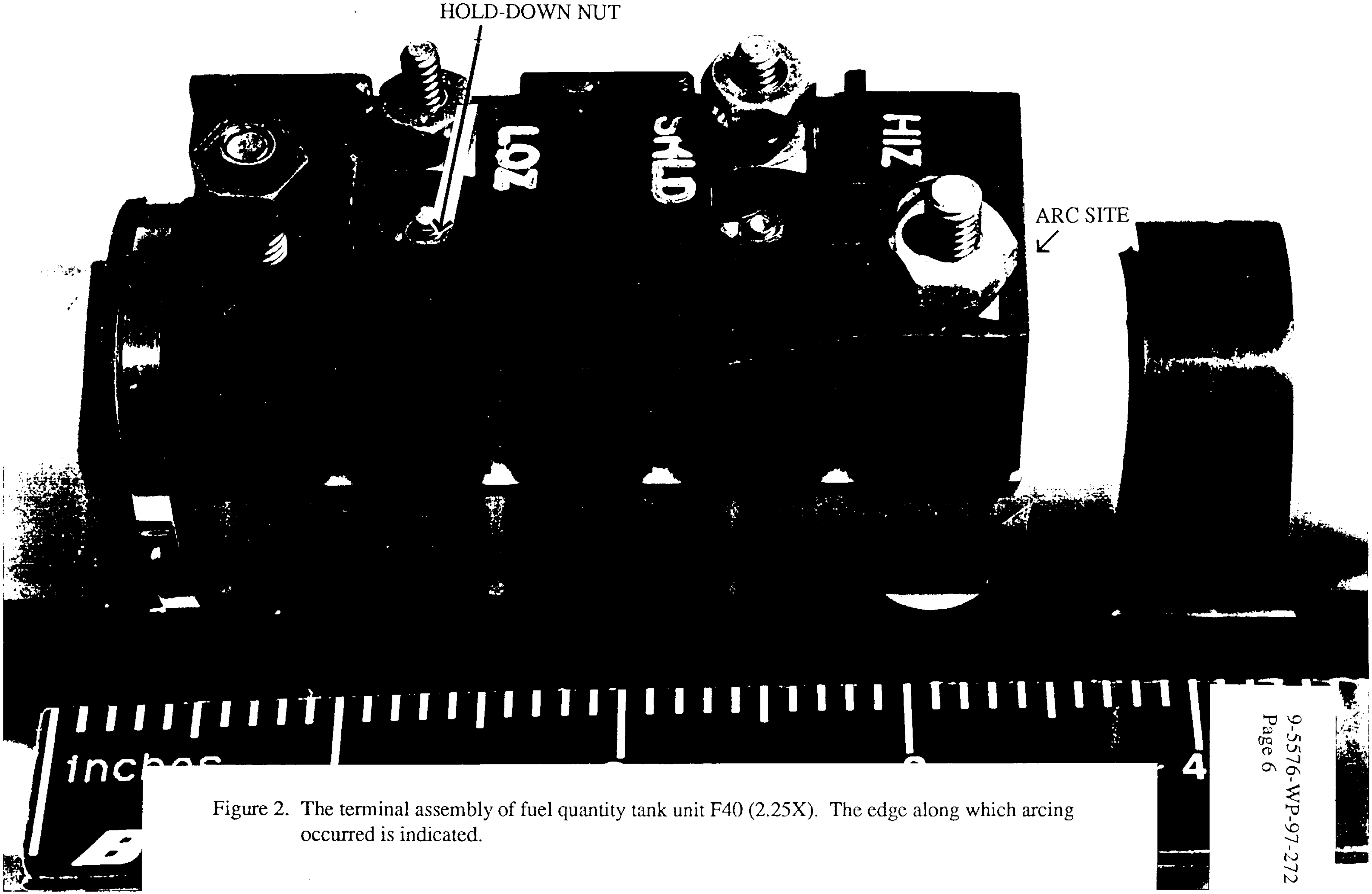


Figure 2. The terminal assembly of fuel quantity tank unit F40 (2.25X). The edge along which arcing occurred is indicated.

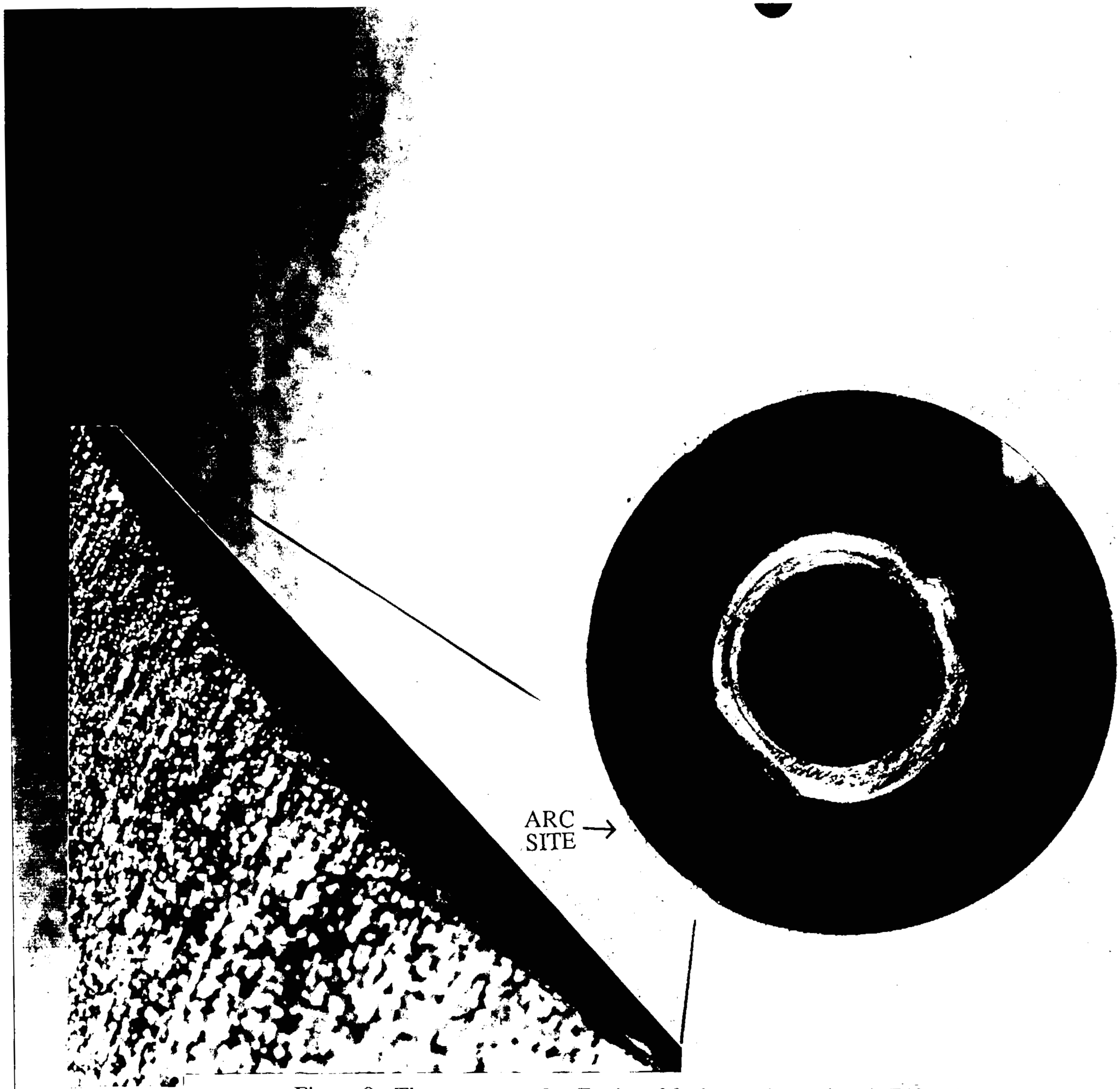


Figure 9. The outermost Lo-Z tube of fuel quantity tank unit F42, with the arc site at the lip of the opening indicated (12.2X). The arc site is shown in the inset at 90X.

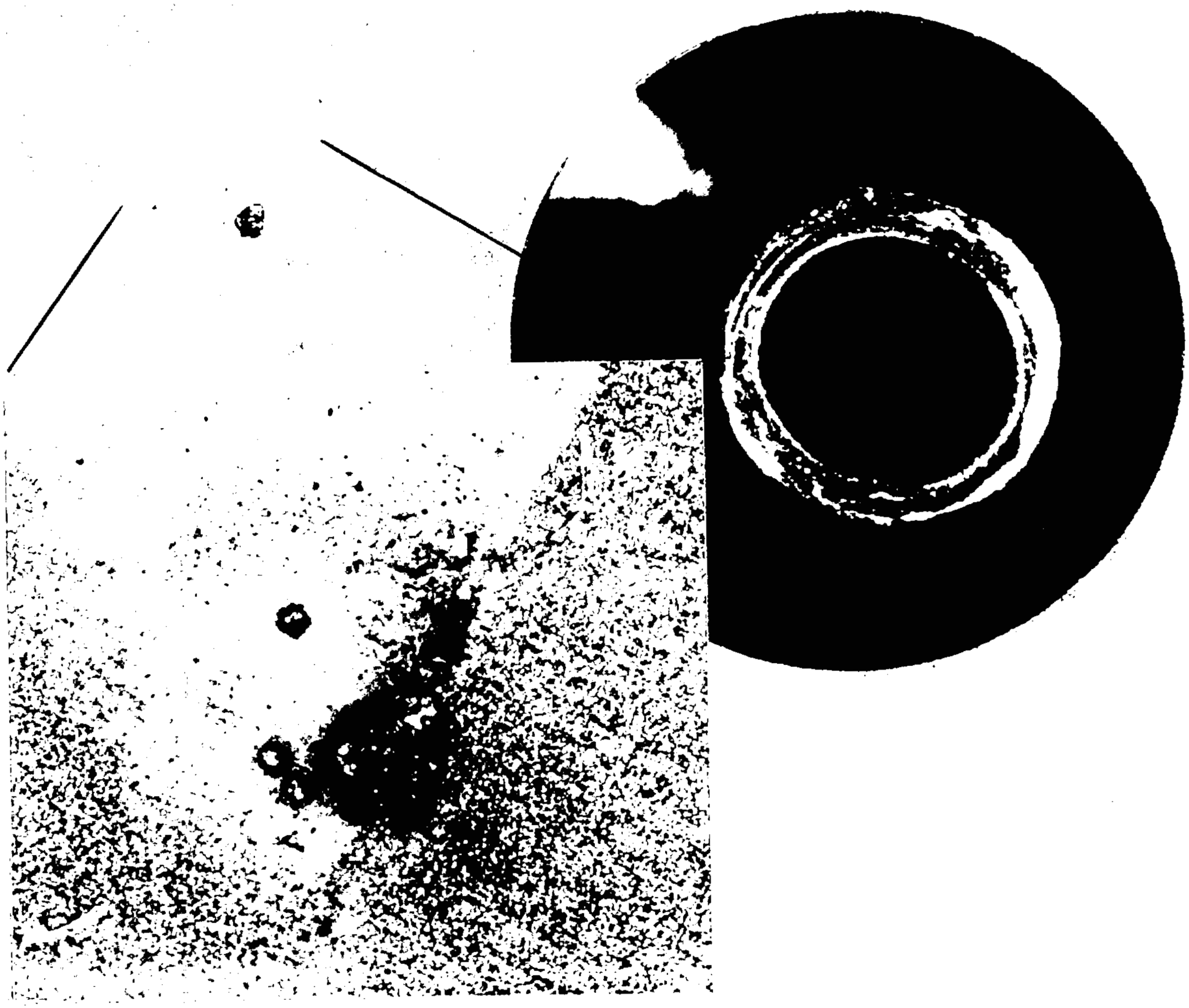


Figure 12. Arc damage to the outer Lo-Z aluminum tube of fuel quantity tank unit F44 (12X; inset, 49X).

ANALYTICAL ENGINEERING REPORT

TO: J.I. Murphy	M.S. 96-03	**NO.:**	9-5576-WP-98-250
CC:		**ITEM NO.:**	Chem 7148
		DATE:	October 2, 1998
		MODEL:	747

GROUP INDEX: 9-5576 - Analytical Engineering, Chemical/Physical

SUBJECT: Analysis of Fuel Quantity Indicating System (FQIS) Components

REFERENCE: Analytical Engineering Report 9-5576-WP-98-136, Sulfide Deposits – Recommendations for Testing, May 20, 1998, D.B. Skoropinski.

Components from several different Fuel Quantity Indicating System (FQIS) tank units and one compensator were submitted for identification of contaminants/deposits as well as material identification. The parts, labeled F10 (shown in Figure 1), F11, F30 and F48, were removed from Corsair 747 airplane RG124. The part number, serial number and manufacture date of each are listed in Table 1. Prior to this analysis, the four units had been subjected to electrical testing involving the application of high potential voltage, and the possibility existed that they had sustained arc damage.

CONCLUSIONS

The majority of the deposits identified on the FQIS components were identified as copper/sulfur compounds specifically copper sulfide and/or copper sulfate. These compounds are corrosion products that form when copper is exposed to sulfur. The primary source of sulfur in the fuel system is the fuel itself. Testing of copper sulfur compounds has indicated that copper (I) sulfide (Cu_2S) is not a conductive material, but that copper (II) sulfide (CuS) conducts quite well (reference). Thus, the presence of these deposits could, over time, provide a conductive path on the FQIS components. In addition, cadmium and silver compounds with sulfur were identified.

Exposure of the copper layer in the laminated copper shields was found to have occurred by a variety of mechanisms. For example, one shield had a hole in the polymer layer. In other places, the presence of copper/sulfur compounds suggests that the copper layer became exposed, perhaps through flow of the polymer with time under load. Finally, solder spatter on the surface of the shield was observed to penetrate the polymer layer. Exposure of the copper layer is of interest because it could provide a conductive path.

EXPERIMENTATION AND RESULTS

Identification of Materials. The materials from selected FQIS units were analyzed using infrared microspectroscopy (IR) and electron microprobe elemental analysis for the purpose of identification. Summarized results of these analyses are presented in Table 2. Supporting data is available on file.

Identification of Deposits. Representative deposits on the surface of the terminal block are shown in Figures 2 and 3. Deposits on the terminal studs can be seen in Figures 4 and 5. Samplings of deposits/contaminants from the FQIS units were analyzed using infrared microspectroscopy (IR) and electron microprobe elemental analysis. Summarized results of these analyses are presented in Table 3. Supporting data is available on file. The majority of the deposits identified are copper/sulfur compounds, specifically copper sulfide and/or copper sulfate. Determination of the form of copper sulfur compounds present (i.e.: copper (I) sulfide, Cu_2S; copper (II) sulfide, CuS; copper (I) sulfate, Cu_2SO_4; or copper (II) sulfate, $CuSO_4$) was not possible due to insufficient quantity of deposits to perform X-ray diffraction. These compounds are corrosion products that form when copper is exposed to sulfur. The primary source of sulfur in the fuel system is the fuel itself. In addition, cadmium and silver compounds with sulfur were also present.

Laminated Copper Shields. Several unique features were noted on the laminated copper shields. For example, several of the laminated copper shields were observed to have a mark on one side which appears to be a fingerprint apparently introduced during manufacturing (see Figure 6, for example). Dark deposits within the polymer layers are shown in Figure 7. A hole in the polymer laminate with exposed copper is shown in Figure 8. Evidence of holes in the polymer layers is of interest because they could provide a conductive path in service where the copper shield is exposed. Dark deposits were observed on several shields (see Figures 9 through 12). Dark deposits on the F30 shield around the center hole, shown in Figure 12, were identified as copper/sulfur compounds most likely copper sulfide and/or sulfate. The deposits shown in Figure 12 are consistent with exposure of the copper and subsequent corrosion.

Solder spatter, similar to that shown in Figure 13, was observed on multiple shields. The spattering presumably occurred during soldering of the shield to the screw. Although many of the solder spatter balls did not penetrate the polymer insulation layer, there was evidence that some solder balls had penetrated allowing exposure and subsequent corrosion of the copper shield. Penetration of the polymer layer is significant since exposure of the copper shield could provide a conductive path in service. The dark deposits on the surface of the collection of solder balls, shown in Figure 11, were identified as copper/sulfur compounds. The melting point of the fluorinated ethylene propylene polymer layer is approximately 545 °F, higher than the melting point of the solder (338 °F). Therefore, it is hypothesized that the penetration of the FEP layer occurred as a result of mechanical penetration over time rather than melting the polymer on initial contact.

Prepared by Catherine A. Barron
C.A. Barron
M/S 73-09, 237-8073

Approved by
W. L. Plagemann
M/S 73-09, 234-3025

Photography by J. Brewer.
Electron microprobe elemental analysis by J. Wessel.

Table 1. Part Data for the Four Fuel Quantity Indicating Components.

Installation Position	Type	Boeing P/N	Honeywell P/N	Serial Number	Manufacture Date
F10	Compensator	60B92010-41	F G420A41	V-2	January 1974
F11	Tank Unit	60B92010-38	F G420A38	U-7	January 1975
F30	Tank Unit	60B92010-21	F G420A21	V-75	December 1974
F48	Tank Unit	60B92010-26	F G420A26	W-60	October 1973

Table 2. Material Identification.

Component	Material
Terminal Block	Filled unsaturated polyester
Polymer layer on laminated copper shield	Fluorinated ethylene propylene (FEP)
Insulation Strip	Polytetrafluoroethylene (Teflon®)
Washer #1	2024 Aluminum
Washer #2	Carbon steel with cadmium plating
Smaller nut	A286 with silver plating
Larger nut	A286 with silver plating
Terminal Studs	303 corrosion resistant steel (CRES) and 304 corrosion resistant steel (CRES) brazed together with copper

Table 3. Results of Deposits/Contaminants Analysis.

Tank Unit	Component	Photograph	Elements Detected and Most Likely Identification
F10	Terminal block – top surface	Figure 2	Yellowed areas contain copper and sulfur Unstained areas contain only sulfur, no copper
F11	Terminal block – base	Figure 3	Copper/sulfur compounds Cadmium/sulfur compound(s)
F11	HiZ terminal stud	Figure 4	Dark deposit: copper/sulfur compounds Gray deposits: Copper/chromium/sulfur
F11	LoZ terminal stud	Figure 5	Green deposits: Chromium/carbon/oxygen, most likely chromium (III) sesquioxide (Cr_2O_3) Mustard-colored deposits: cadmium sulfide (CdS)
F30	HiZ terminal stud		Dark deposits: copper/sulfur compounds
F30	LoZ terminal stud		Green deposits: chromium, oxygen; most likely chromium (III) sesquioxide (Cr_2O_3)
F30	Insulation strip		Brown deposits: copper/sulfur compounds
F30	Laminated copper shield	Figure 13	Solder spatter: 60/40 tin/lead solder
F30	Laminated copper shield	Figure 10 and 11	Dark deposits on solder spatter: copper/sulfur compounds
F30	Laminated copper shield	Figure 13	Dark deposit next to solder spatter: Copper/sulfur compounds
F30	Nut		Black deposits: silver/sulfur compounds; most likely sulfides and/or sulfates.

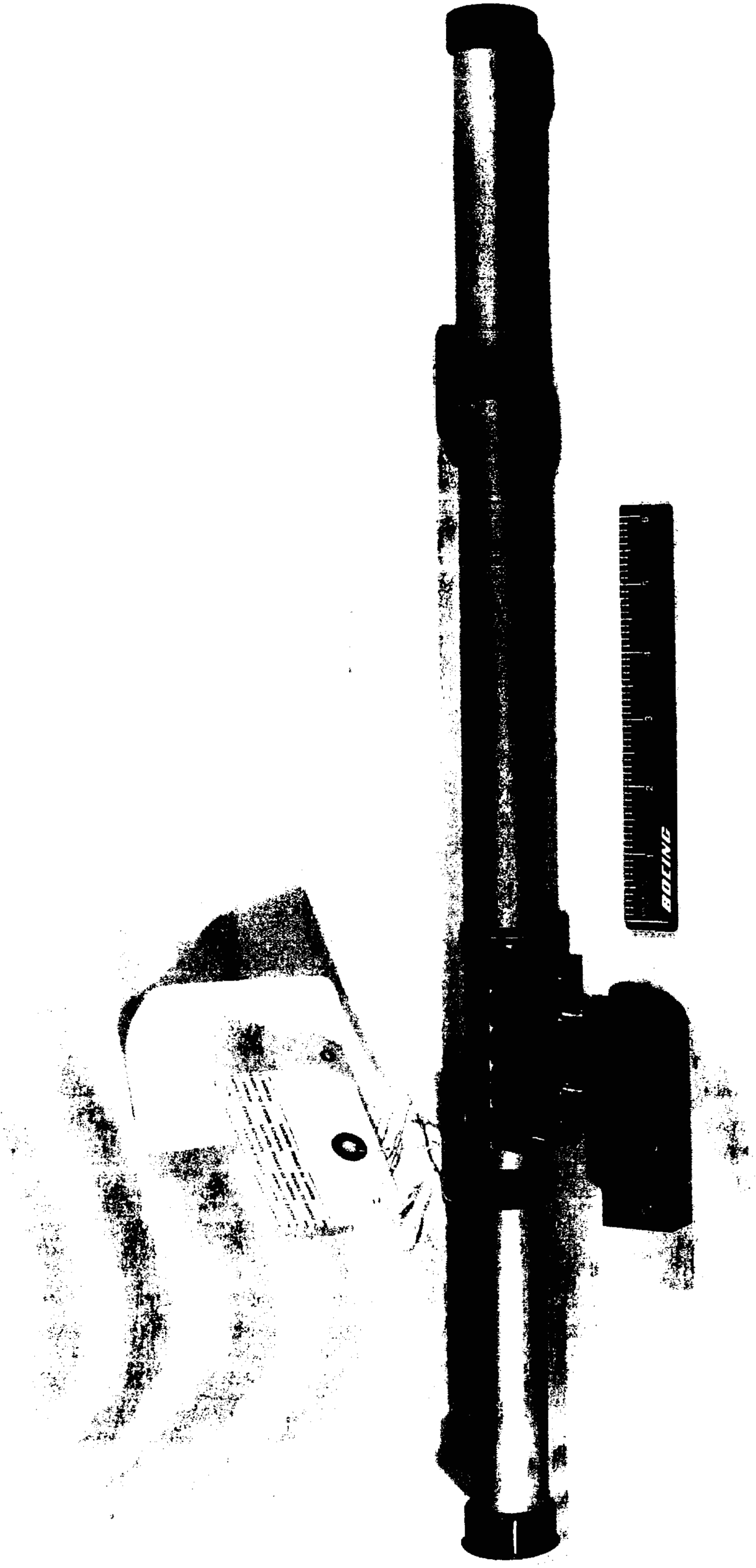


Figure 1. F10 Fuel Quantity Indicating System (FQIS) Compensator.

Figure 2. Deposits on surface of F11 terminal block between LoZ and shield (approximately 6.6X).

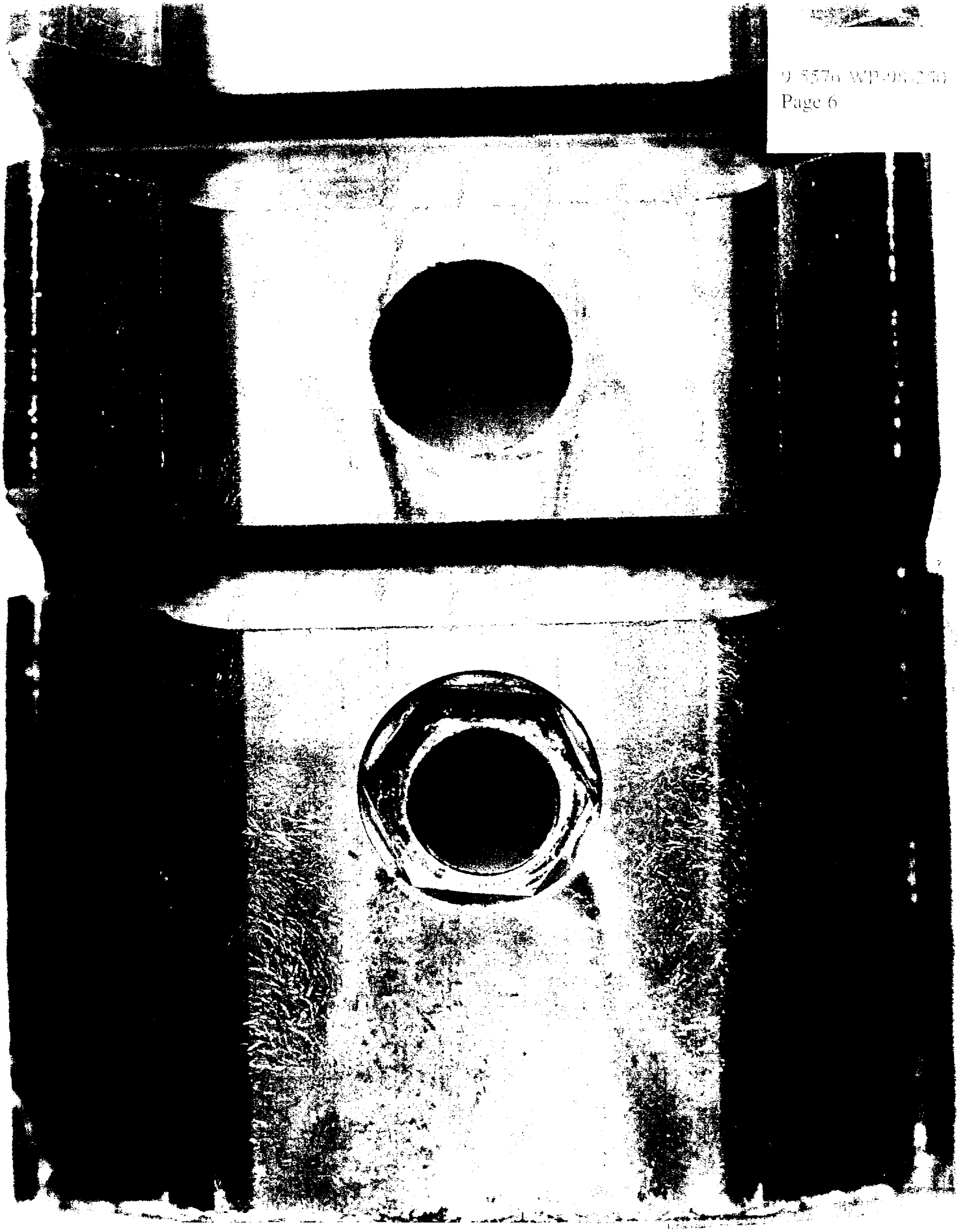


Figure 3. Deposits on underside of F11 terminal block (approximately 6.6X).

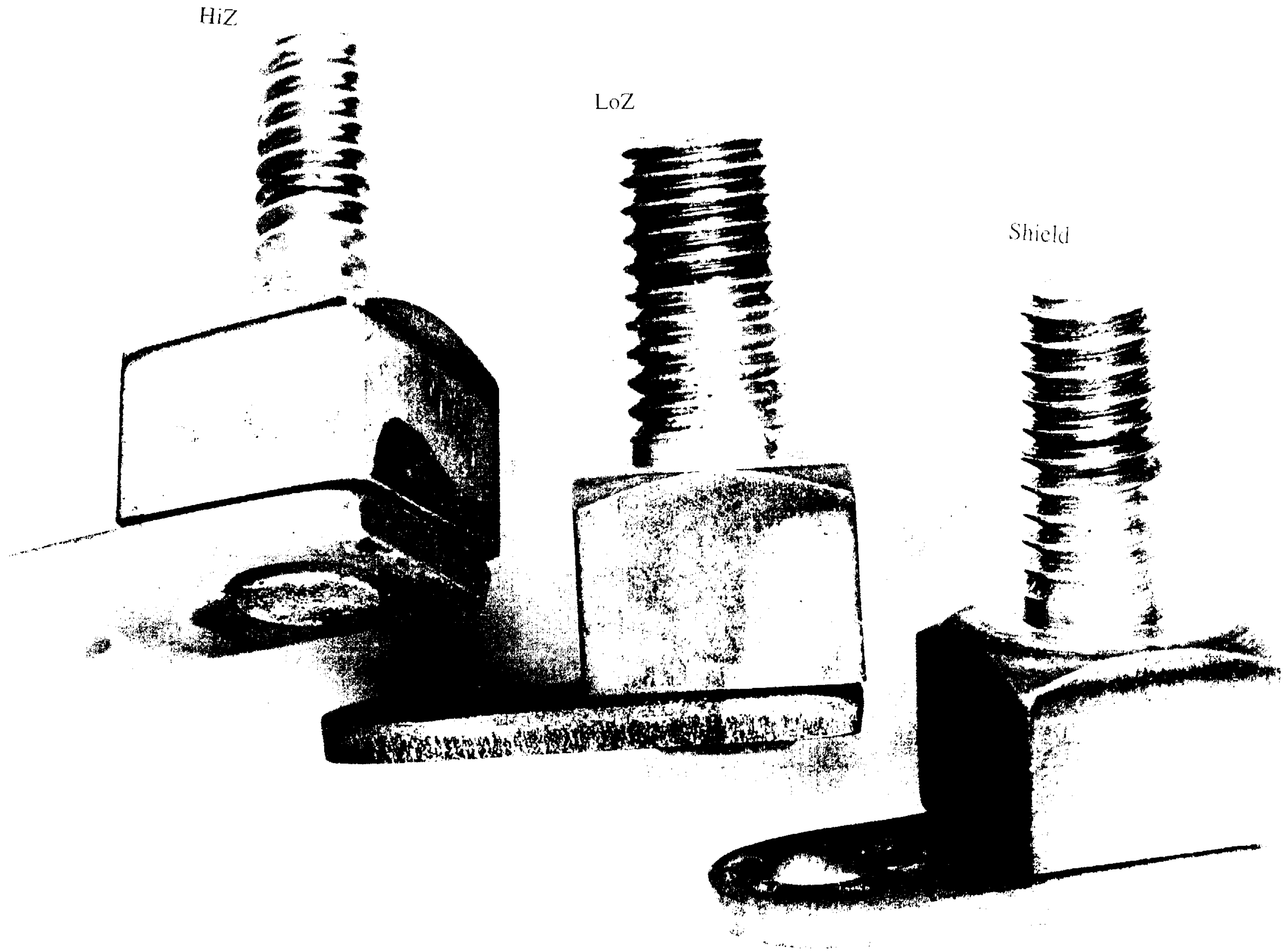


Figure 4. Dark deposits on F11 terminal studs (approximately 6.4X).

Figure 5. Green and orange deposits on the bottom of the F11 LoZ terminal stud (approximately 17.2X).

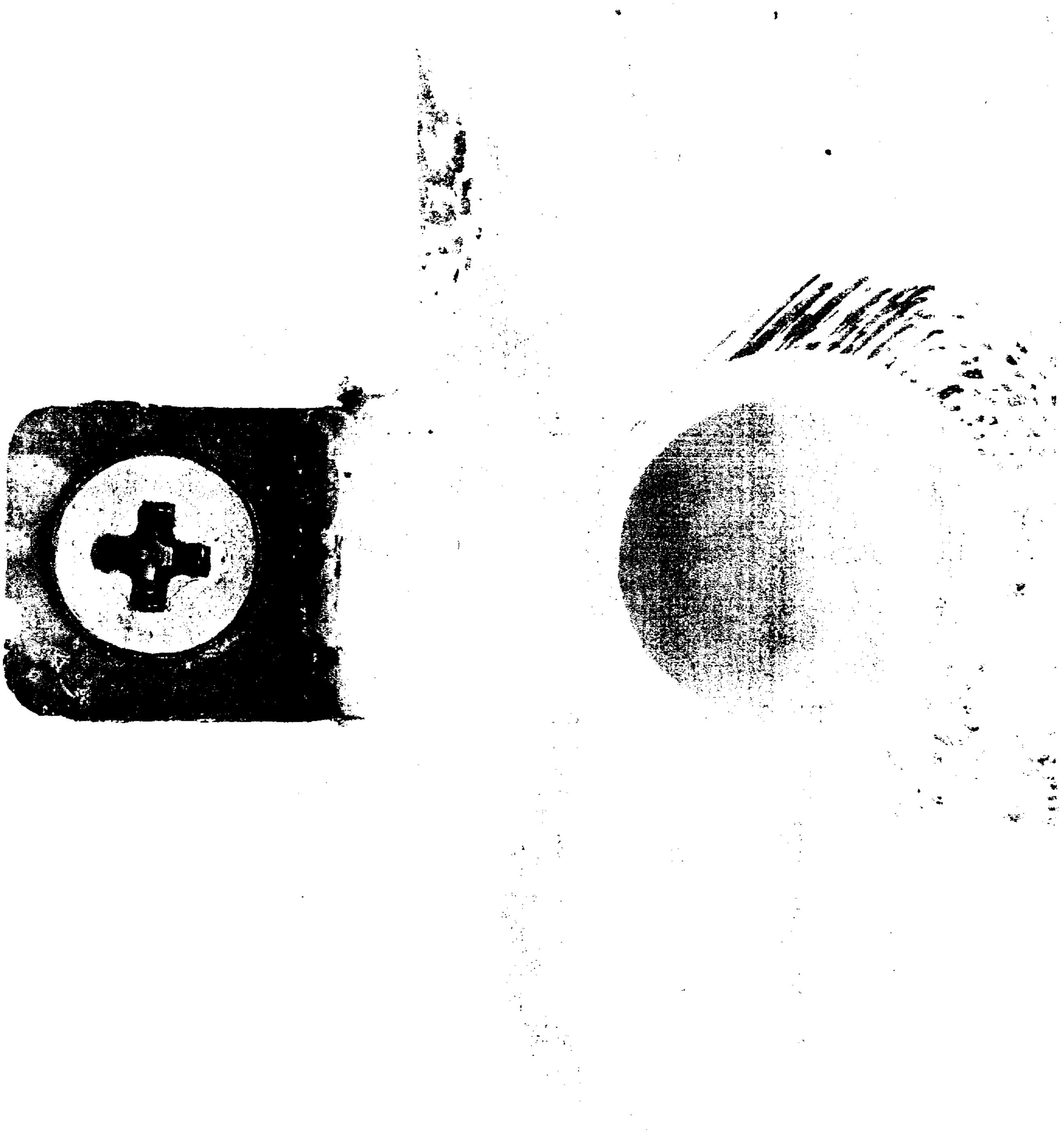


Figure 6. F11 laminated copper shield, bottom side (approximately 6.9X).

Figure 7. F11 laminated copper shield, top side (approximately 6.9X).

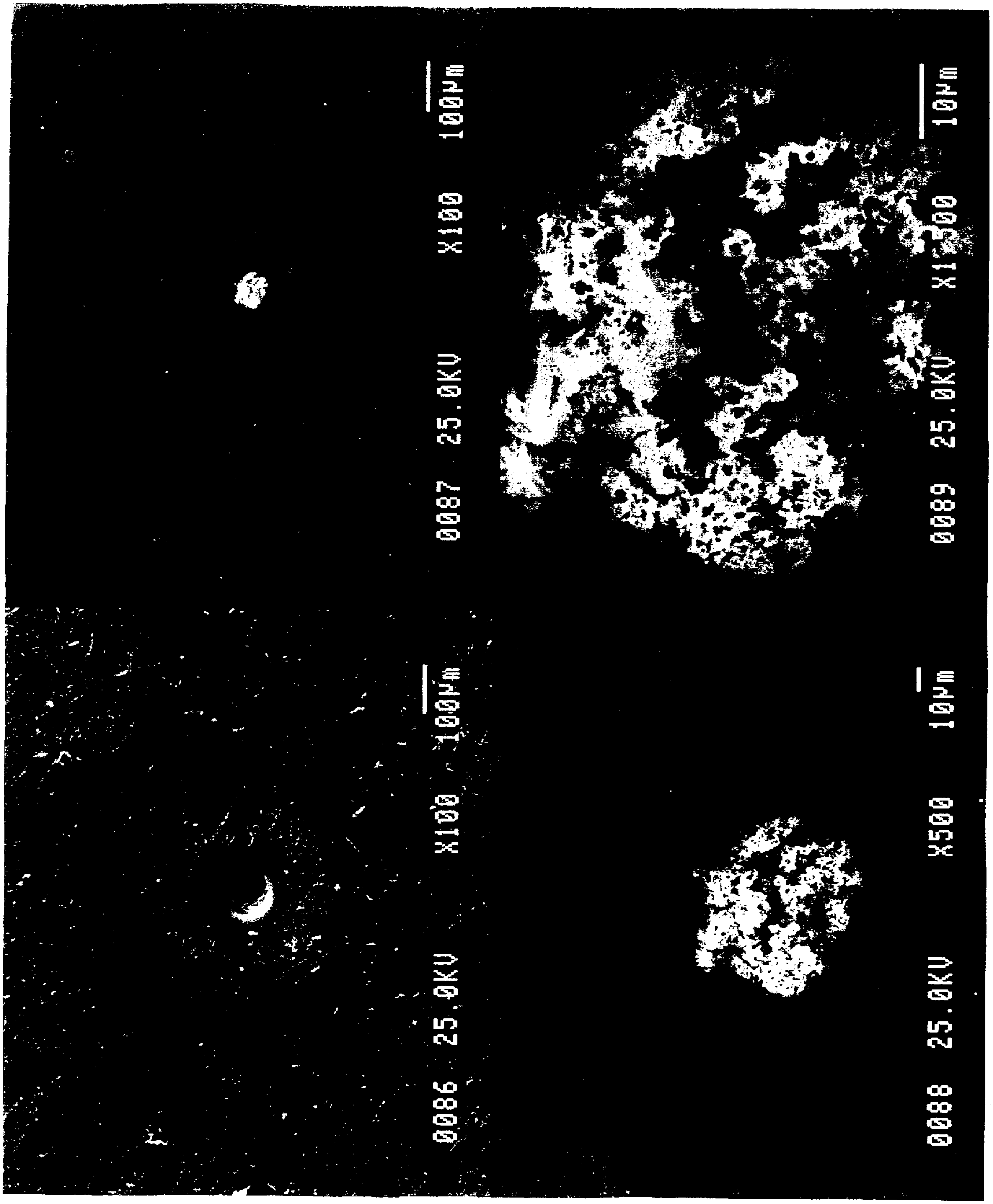


Figure 8. Electron micrographs of hole in F11 laminated copper shield.

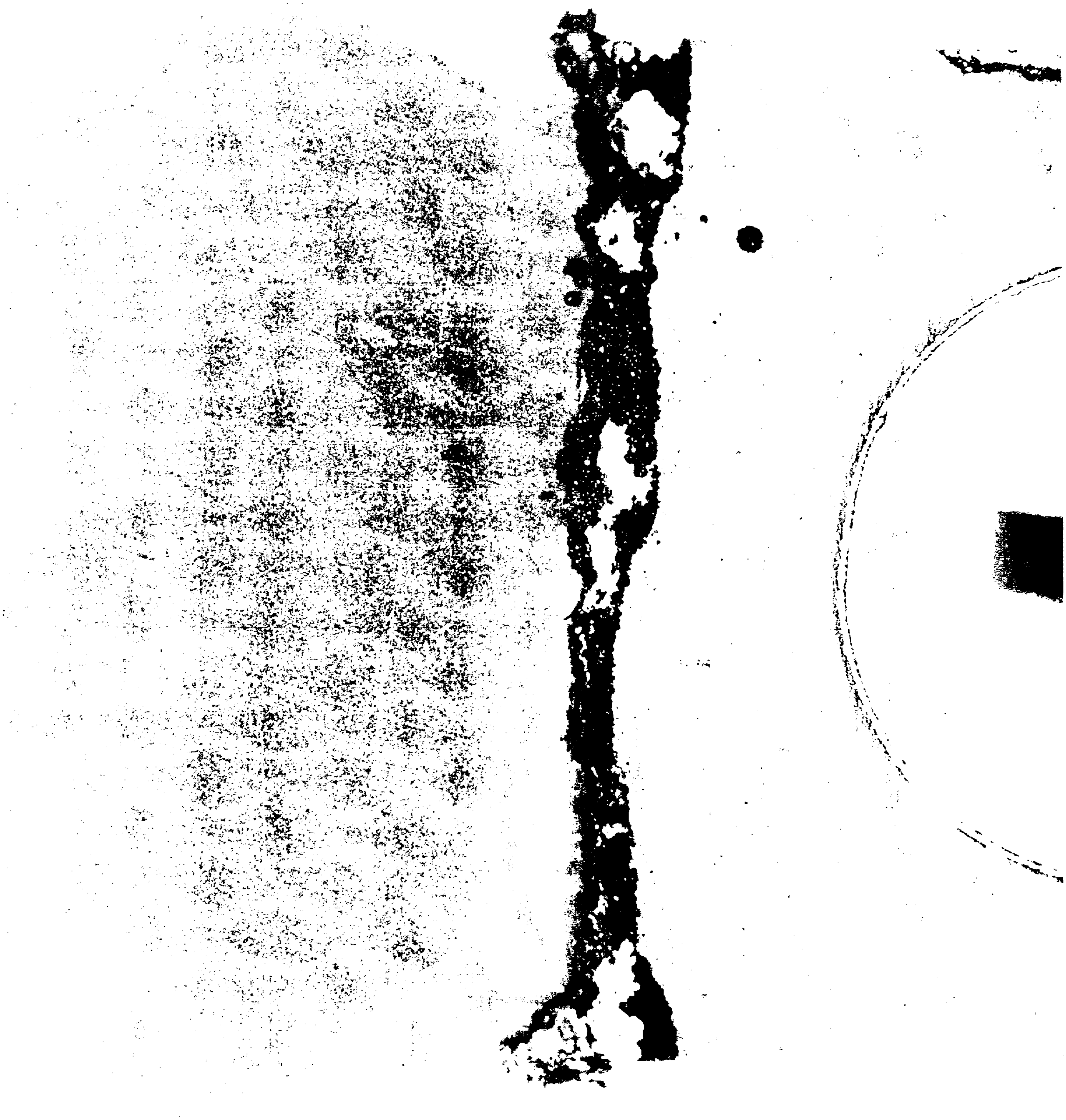


Figure 9. F48 laminated copper shield, bottom side (approximately 24.5X).

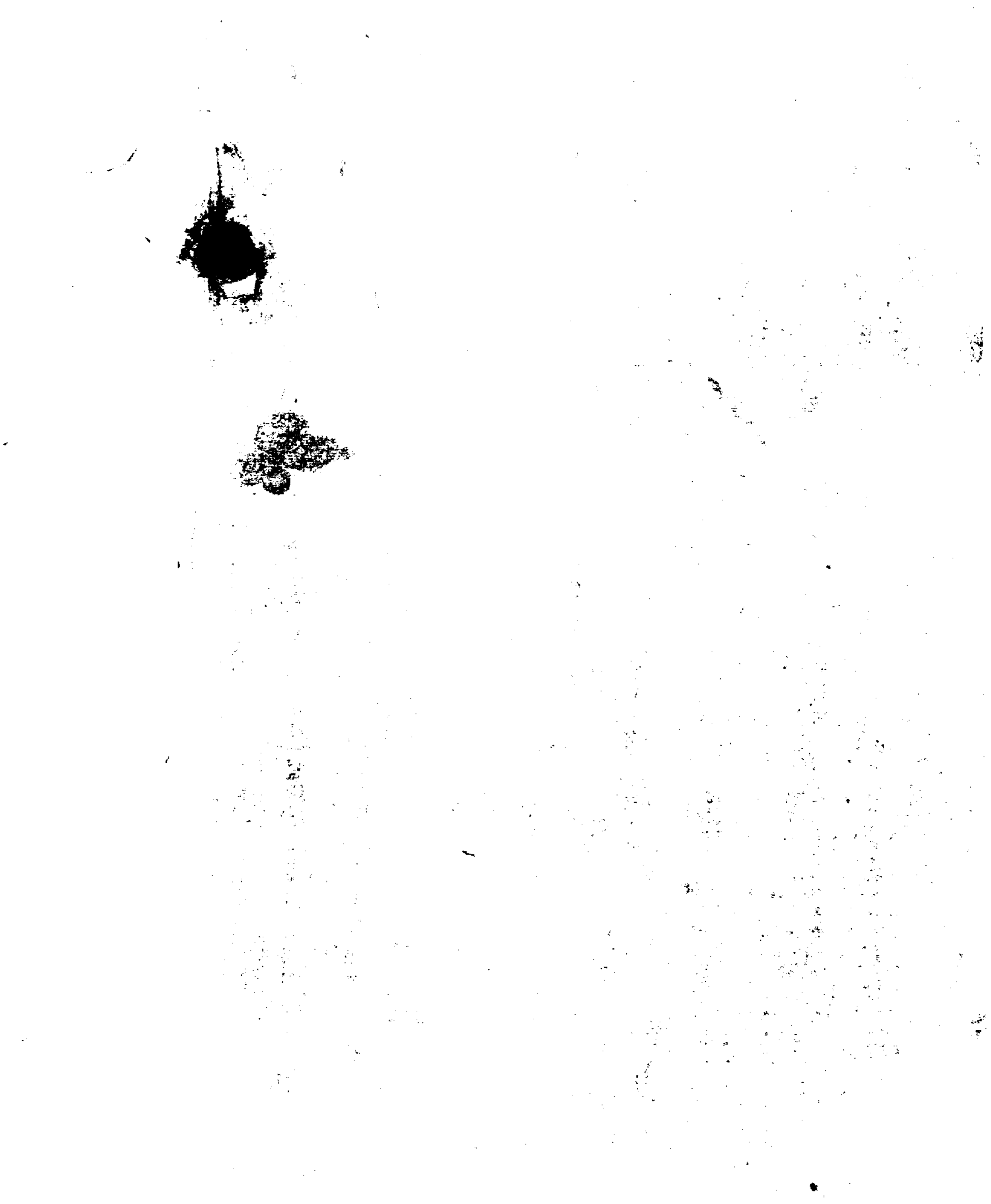


Figure 10. F48 laminated copper shield, top side (approximately 24.5X).

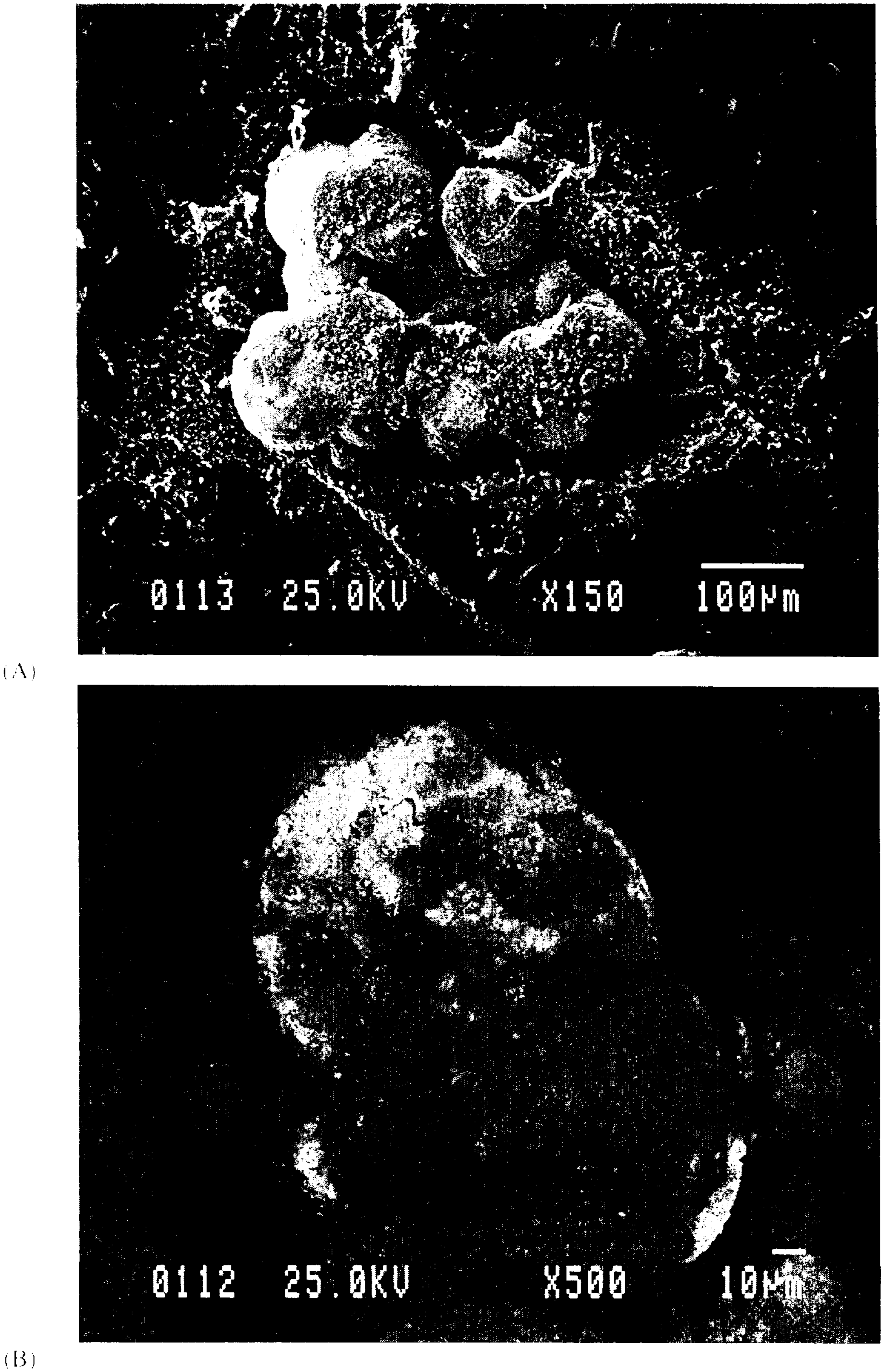


Figure 11. Electron micrographs of solder spatter on F48 laminated copper shield.

Figure 12. F30 laminated copper shield, top side (approximately 24.5X).

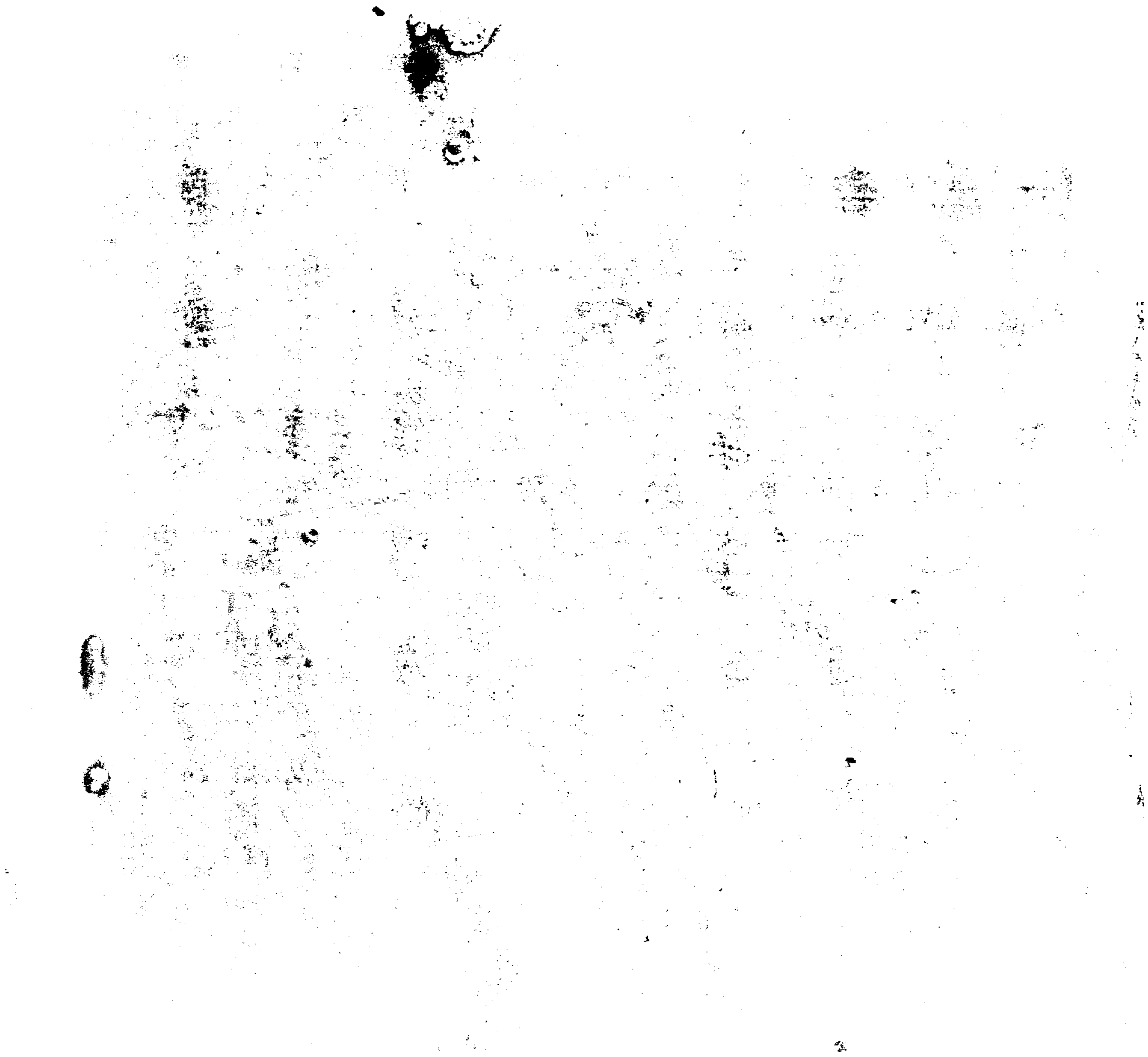


Figure 13. Solder spatter on surface of F30 laminated copper shield, bottom side (approximately 24.5X).

Ronald J. Hinderberger
Director
Airplane Safety
Commercial Airplanes Group

The Boeing Company
P.O. Box 3707 MC 67-XK
Seattle, WA 98124-2207

31 August 1999
B-H200-16754 -ASI

Mr. R. Swaim, AS-40
National Transportation Safety Board
490 L'Enfant Plaza East, S.W.
Washington DC 20594

Subject: 737 FQIS Tank Units Examination, TWA 747-100 N93119
Accident off Long Island, NY - 17 July 1996

Reference: B-H200-16677-ASI, dated 29 April 1999

Dear Mr. Swaim:

Enclosed with the referenced letter we have provided a laboratory report of the examination of Fuel Quantity Indication System (FQIS) components from two in-service 747 airplanes. We have recently completed similar laboratory examinations on 737 components in conjunction with the evaluation of the effects of aging on FQIS components. A copy of this 737 report is enclosed for your information.

If you have any questions, please do not hesitate to call.

Very truly yours,

for

Ronald J. Hinderberger
Director, Airplane Safety
Org. B-H200, M/S 67-PR
Telex 32-9430, STA DIR AS
Phone (425) 237-8525
Fax (425) 237-8188

Enclosure: EQA Report 7895R, dated June 7, 1999

CC Mr. A. Dickinson, IIC

EQUIPMENT QUALITY ANALYSIS REPORT

BOEING COMMERCIAL AIRPLANES
Renton, WA

TO:	Jerry Hulm	04-JU	**EQA NUMBER**:	7895R
CC:	R. Breuhaus	67-PR	**DATE**:	June 7, 1999
	T. Dunnigan	04-JU		
	R. Graham	70-09	**CUSTOMER**:	Boeing
	J. Everett Groat	04-JU		
	F.A. Jaques	70-09	**MODELS**:	737-200, 300
	Richard Lidicker	04-JU		
	K.K. Longwell	04-JU	**LINE NUMBERS**:	527, 640, 1221
	M. Penty	70-09		
	N. Tavernarakis	04-JU		

SUBJECT: *Examination of In-Service FQIS Tank Units and Compensators Removed from Three 737 Airplanes.*

IDENTIFICATION:

Part name	Tank Units & Compensators
Part numbers	10-61219-XXX*
Supplier	Simmonds Precision Products
Supplier part number	391041-XXX* & 391046-XXX*

* detailed parts lists are enclosed in the separate tables.

REFERENCE:

(a) Specification Control Drawing (SCD) 10-61219, Indicating System, Fuel Quantity.
(b) Specification Control Drawing (SCD) 10-60875, Cable Assembly, Fuel Tank.
(c) Specification Control Drawing (SCD) 10-60479, Connecting Components, Fuel and Oil Quantity Systems.
(d) Specification Control Drawing (SCD) 10-61827, Fuel Gauge Wire Bundle Assembly.

BACKGROUND:

Tank units, compensators and wiring were removed from the center and numbers one and two main tanks and submitted for analysis, in conjunction with the evaluation of the effects of aging on Fuel Quantity Indication System (FQIS) components. The tank units and compensators are the capacitance type where the dielectric difference between the air (1) and fuel (~2.188) is used to measure the height of the fuel. They were removed from two 737-200 and one 737-300 airplanes, from separate customers. These airplanes had accumulated totals of 53,109 hours/44,367 cycles; 60,773 hours/67,895 cycles; and 37,200 hours/26,231 cycles.

The tank units were visually/microscopically examined and subjected to various electrical tests. All testing was performed in ambient conditions of 70 degrees F. at sea level. Testing was performed after all of the removed components had been allowed to dry. Dielectric and insulation resistance testing was conducted through the cut ends of the wires attached to the component terminals. The tank units and compensators were submitted with approximately 12 to 18 inches of wire length still attached to the terminals in order to maintain the installation integrity of the wire/terminal junctions. The test data requires cautious interpretation as the test voltage requirements for the wire and components are different per the two, reference (a) and (c) specification control drawings. Due to the different test voltage requirements, some exceptions had to be made in order to make some comparative determination of the condition of the wires and components. Unfortunately, some of these test voltages exceeded the wire rating. The observations and results were documented.

SUMMARY:

The results of the examination and testing found that the tank units and compensators were in relatively good condition, especially considering their age and lengths of time in service. However, copper and silver sulfide/sulfate corrosion/contamination was evident. The amounts of visible fuel/corrosion staining varied, depending upon the number of hours that the components had accumulated and upon other variables (e.g. cleaning/overhaul, maintenance, etc.). Concentrations of conductive corrosion products were observed on the terminal ends, wire insulation, heat shrink and probe bodies. Analysis has disclosed that the contaminants, in evidence on both the components and the wire harnesses removed from inside the fuel tanks, are primarily copper/sulfur compounds, specifically copper sulfide and/or copper sulfate. These compounds are corrosion products that form when copper is exposed to sulfur. The primary source for the sulfur is the fuel, itself. Sulfur is present in fuel in several different forms, including free sulfur, mercaptan sulfur, sulfides, disulfides, thiophenes, sulfates, organic sulfate acids, sulfones and sulfoxides. The reaction mechanisms between the various forms of sulfur and available copper, as well as controlling variables (e.g. temperature, moisture availability, oxygen availability, pH, pressure, etc.) are unknown. Testing of reagents has confirmed that copper (I) sulfide (Cu_2S) is not a conductive material but that copper (II) sulfide (CuS) conducts well. See enclosed Conductivity Table. Although the contamination can reduce insulation resistance and dielectric strength, the contamination is yet to be fully characterized or understood.

It is difficult to draw conclusions regarding contamination buildup as only a result of age. There are many factors that can either exacerbate or retard the contamination buildup. Any attempt to correlate the units, which provided anomalous electrical test results, to installation locations needs to be interpreted cautiously for a variety of reasons. Very few, if any, installations are intact from the "as delivered" condition (although some may be). Individual components or wire harnesses have been changed for a variety of reasons. In some cases, maintenance or other reasons may have dictated changing out equipment (e.g. overhaul, compliance to checks, etc.). The fuel used over the years and any additives, etc. also plays a part in the reaction and eventual formation rate of copper/silver sulfur/sulfide corrosion products. Temperature exposure, moisture content, biological influences and pressure altitude are all likely contributors to the formation of corrosion products as well. So many variables contribute to variation in the individual airplanes examined that no clear associations of maintenance practices, installation location or other major factors could be identified, at this time, as being the "most significant variable" that may accelerate the formation of contamination and eventual corrosion products. Copper and silver exposed to fuel over time will result in corrosion products.

Two distinctly different style wire harnesses were attached to the probes. Some tank units and compensators were submitted with old wire harnesses (brown) and the newer harness (green). The newer green harnesses are made of nickel coated copper wire; the older brown harnesses were made of silver coated copper wire. Some of the newer nickel harnesses' terminal ends were crimped and soldered with no bare copper conductors visible. The soldering process had effectively covered the bare, cut ends of the wire strands and prevented the copper from easily reacting with sulfur (from fuel and polysulfide sealant) thereby reducing the resulting corrosion products on the new style harness. Most of the older silver wire harnesses' terminal ends were only crimped, not soldered, exposing the bare ends of the copper wire to the sulfur in the fuel. Chemical reaction of the fuel with the silver of the eyelet terminal end and the copper of the exposed conductor wire strands (at the crimp) had resulted in the formation of corrosion products which (in some cases) had coated the crimp junction and had migrated along the length of the wires and onto the probe body as well. This accumulation of corrosion products resulted in a number of tank units/compensators having lower insulation resistance and dielectric strength properties when compared to new parts acceptance standards. One older silver harness was found to have terminal ends that had been crimped and soldered; these had been reworked and the tank units and compensators had been overhauled. This overhaul process had effectively reduced the corrosion.

The examination of the components and harnesses has found that it is typical to find wiring harnesses and tank units or compensators that have been replaced over time in-service. Of the three airplanes examined, only line number 1221 is believed to have had all original equipment (and this is not known for certain). Although this airplane had the newer style nickel harnesses, the terminal ends were only crimped and not soldered. There was an interim period of time where several new style harness configurations were manufactured. Some were made using the older style, square, silver coated terminal ends and some with the newer round, nickel coated terminal ends. Some of these interim harnesses were made with only crimped terminal ends prior to being both crimped and soldered. Soldering initiated in production with line number 1576. Although this condition exposed the copper wire ends to fuel, the electrical tests noted no adverse condition with the wire harness/terminal junctions (L/N 1221).

An inspection of all of the associated FQIS tank wiring submitted noted a location at tank unit F5 (R/H), of line number 640, where the braided shielding and the wire insulation for the LoZ (red) had been chafed at one location. The LoZ conductor was not exposed. The wire had been looped in a tight circle through a clamp (approximately 3-4 loops) adjacent to that location. It is not known why the wire had been looped several times through the clamp. What caused the wear is also unknown. A second wire was found with the shield wire insulation and shield braid chafed through at position F8 (R/H). This location also occurred at a series of looped wires attached to and adjacent to F8. Any positive identification, of the locations where chafing occurred (between the wires and some place in the installation), was not established due to the fact that the units had been removed from the installation and submitted for examination. The two preceding locations were the only two locations where any wire chafing or wear was noted. The wire harness lengths (attached to the connectors) were free of any wear or chafing. An examination of tank unit F18 L/H, noted a location where the anodize coating of the outer tube had been worn through. **See photograph 1**. A corresponding location of superficial wear of the outer protective sheath was found on the wires attached to F18.

Photograph 1. F18 L/H Chafing wear. Corresponding wire, protective braid was only superficially chafed

All electrical tests of the tank units and compensators were conducted through the cut ends of the remaining, attached wire segments. A Vitrek, model 944i dielectric analyzer was used to test the subject units for dielectric withstanding voltage/current values and insulation resistance values below 10 gigohms. A Guideline Instruments, model 6500A digital teraohmeter was used to verify resistances in excess of 10 gigohms. The specification control drawing (SCD) 10-61219 was used as the reference for comparative acceptance testing. Although the reference (a) document requires a test voltage of 3000 VDC, only 1500VAC was used initially. When interpreting the test results, it should be taken into consideration that the SCD testing is typically performed on the tank unit or compensator by itself and not through the associated wiring. The wiring has a different test voltage rating. Per the reference (c), test voltage for the wire is rated at 1000VAC. Testing was halted automatically when the resistance dropped below the low preset threshold of one megohm on the tester (SCD requirement [for tank unit/compensators] is 1-11 megohm depending upon the specific dash number of the part). All of the tank units and compensators, themselves, were found to be functionally acceptable. After the initial testing at 1500 VAC, one ship set (only line number 527) was subsequently subjected to 3000 VDC through the wires attached. This test condition exceeds the wire rating of 1000 VAC. The one dielectric breakdown of the F18, R/H wire, occurred between the coax and shield at 2758 VDC. This dielectric breakdown of the wiring occurred at a voltage well above the rating of the wire and may in fact, have occurred as a result of over-stress of the wire by the test itself. The breakdown occurred between one strand of the shield wire which had been entrapped between the heat shrink sleeve and the insulation of the coax conductor, during an isolated manufacturing flaw. However, it should be noted that initial testing of this wire/tank unit, at 1500 VAC (still above the 1000 VAC requirement), noted no discrepancies at all.

EXAMINATION RESULTS:

Line Number 527:

A total of 22 tank units and 2 compensators (24 total) were received for test and analysis from line number 527. They had been removed from the numbers 1 and 2 main tanks. No FQIS parts were received from the center tank installation. This airplane (737-200) had accumulated 53,109 hours and 44,367 cycles. It had been delivered in August of 1978. It had been in service for 21 years. An identification table, detailing part numbers, dates of manufacturing and serial numbers, is enclosed as Table I, section A.

Examination revealed that the majority of the components removed from the L/H main tank may have been original installation with the exception of one newer unit. The wiring harness from the L/H installation was newer and not original equipment. The examination of the components removed from the R/H main tank revealed a mix of dates including 7 units that were significantly older than the delivery date of the airplane. The wire harnesses and respective connectors were not received for analysis. Only the sections of the harnesses that remained attached to the submitted tank units and compensators were examined. Although some of the older units exhibited some staining on the outer tube body (in comparison to the other units examined), all of the units were in relatively good condition. Detailed examination observations are documented in Table I, Section B.

The majority of tank units/compensator removed from the R/H (#2) main tank were manufactured in the 1960s. The majority of tank units/compensator removed from the L/H (#1) main tank had been manufactured in the 1970s. The wire harness segments, attached to the tank units/compensator, from the R/H main tank, were an older style, silver harness; the sheathing was brown in color and the wire was a silver plated type. In contrast, the wire segments from the L/H main tank probes were of a newer style with green sheathing and nickel plated wire. There were no part numbers or wire identification on the remaining wire segments (attached to the tank units and compensators) to positively identify the wires, wire harnesses or dates of manufacture.

The manufacturing dates of the tank units and compensator in the #1 L/H tank were as follows:

1976 - qty. 10
1977 - qty. 1

1980 - qty. 1

The manufacturing dates of the tank units and compensator in the #2 R/H tank were as follows:

1967 - qty. 2
1968 - qty. 5
1976 - qty. 2
1978 - qty. 1
1988 - qty. 1
1991 - qty. 1

(The airplane was delivered on August 4, 1978).

An examination of all units noted that the older tank units/compensator, from the #2 R/H main tank, were reasonably clean and free of stains on the outside of the tubes. All of the units that were manufactured prior to 1978 are not likely to be original equipment since the airplane was delivered in 1978. In comparison, however, the newer tank units/compensator from the #1 L/H main tank were stained and dirtier.

All wire harness segments (both older [silver] and newer [nickel]) attached to tank probes had eyelet terminal ends that had been both crimped and soldered. There were two styles of eyelet terminal ends that corresponded to the old [silver] or new [nickel] harnesses respectively. The older, silver wire had rectangular, silver plated eyelet terminals and the new nickel wire had round, nickel-plated eyelet terminals. The terminal ends of the nickel wire harnesses were relatively free of staining or discoloration from corrosion products. Some dark contamination was observed on the silver wire harnesses between the terminal end and heat shrink, covering the shield termination. It appeared that the older silver harness terminations had been reworked. The older silver, square terminal ends were not soldered until mid 1988 and this airplane had been delivered prior to that.

Most of the tank units and compensators had some varying amount of green primer (from fuel tank) that had splashed onto the exterior probe body (at the bottom of the units).

The R/H, F2 compensator, R/H, F18 tank unit, and L/H, F10 tank unit were observed to have cracked coax insulator blocks. This condition did not affect their dielectric or insulation resistance values negatively.

<u>Line Number 640:</u>

A total of 24 tank units and 3 compensators (27 total) and their respective wire harnesses were received for test and analysis from line number 640. They had been removed from the center and numbers 1 and 2 main tanks. This airplane (737-200) had accumulated 60,773 hours and 67,895 cycles. It had been delivered in March of 1980. It had been in service for

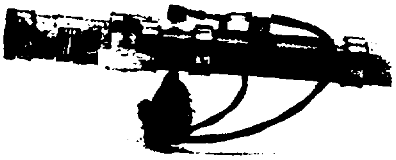
19 years. An identification table, detailing part numbers, dates of manufacturing and serial numbers, is enclosed as Table II, section A.

Examination noted one LoZ conductor wire insulation chafed at F5, R/H. What caused the chafing is not known. A photograph shows an overview of the tank unit, F5, R/H with the chafed LoZ wire insulation. A second photograph shows a close-up detail view of the actual chafe location. **See photographs 2 and 3.**

Photograph 2

Photograph 3

A second wire was found chafed at F8, R/H. The chafing had worn through the protective outer sheath, the shield wire insulation and the shield wire itself. The wear had not gone through the underlying conductor insulation. Again, the chafing had occurred at a location where the wires were looped several times through a clamp, adjacent to the tank unit. **See photographs 4, 5, 6 and 7.**



Photograph 4- F8 R/H

Photograph 5- Coiled Wire

The gray mass attached to the wires in photographs 4 and 5 is fuel tank sealant. It is not a condition that is typical of production.

Photograph 6- Chafed Wire

Photograph 7-Detail of Wear

All of the wire harnesses were of the older [silver] style, with silver terminals that were crimped and not soldered. There was contamination evident on all of the terminal/wire junctions.

Of the three ship sets examined, this set appeared to have suffered the most degeneration as a result of multiple factors (e.g. age, maintenance, physical damage, etc.). Several units were submitted with wire segments looped several times through the first, adjacent clamps that were not attached to the units, themselves. This practice may have been initiated in order to support extra wire length. The wire harness sheaths were stained, presumably from exposure to fuel over time. An examination of some of the cut wire ends, attached to the tank units and compensators, noted discoloration and staining of the shield wire which had migrated approximately 12 to 14 inches down the length of the shield.

Some of the tank units displayed physical damage (dents and bent terminals). **See photograph 8**. It was not known, in every case, whether the damage occurred prior, during installation, in the installation or during the removal process. A detailed list of the physical observations is enclosed as Table II, section B.

Photograph 8. F3 L/H
Clamp mount is bent inward into body of tube.

All of the tank units/compensator removed from the R/H (#2) main tank were manufactured in1979. The majority of tank units/compensator removed from the L/H (#1) main tank had been manufactured in the 1970s with the exception of three units. The center tank contained two units manufactured in the 1990s. The wire harness segments, attached to the tank units/compensators, from the R/H and L/H main tanks, were the older style harness; the sheathing was brown in color and the wire was a silver type. In contrast, the wire segments from the center tank probes were of a newer style with green sheathing and nickel wire. There were no part numbers or wire identification on the remaining wire segments (attached to the tank units and compensators) to positively identify the wires, or dates of manufacture.

The manufacturing dates of the tank units and compensator in the #1 L/H tank were as follows:

1968 - qty. 1
1969 - qty. 1
1977 - qty. 2
1979 - qty. 7
1980 - qty. 1

The manufacturing dates of the tank units and compensator in the #2 R/H tank were as follows:

1979 - qty. 12

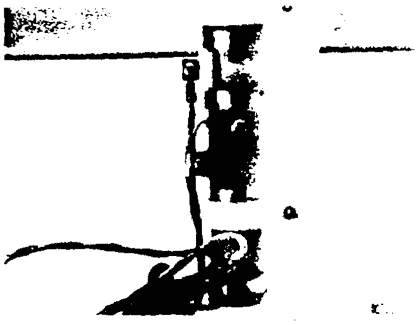
The manufacturing dates of the tank units and compensator in the center tank were as follows:

1977 – qty. 1
1991 – qty. 1
1994 – qty. 1

The airplane was delivered on March 27, 1980.

Some of the units were not original equipment delivered with the airplane. The number of units replaced during the service life of this airplane is not unusual and is considered typical for an airplane of this age. It is possible (although not confirmed) that all of the units in the #2 or right main tank may be original equipment. An examination of all units noted that the tank units/compensators, from the #1 and #2 main tanks, were stained heavily and dirty on the outside of the tubes. In comparison, however, the tank units/compensator from the center tank were relatively clean.

Both main tank wire harnesses were of the older silver style (with brown protective sheath) and were likely original equipment. The center tank wire harness was of the newer nickel style (with green protective sheath) and most likely, was not original equipment. Both (older style) main tank wire harnesses segments, attached to the tank units/compensators, had eyelet terminal ends that had only been crimped. They had not been soldered. There were two styles of eyelet terminals ends that corresponded to the silver or nickel harnesses respectively. The older [silver] wire had rectangular, silver-plated eyelet terminals and the new [nickel] wire had round, nickel-plated eyelet terminals. The nickel harness (center tank only)had nickel-plated, round terminal ends that had been both crimped and soldered. The terminal ends of the nickel wire harness were relatively free of staining or discoloration from corrosion products. Heavy, dark colored contamination (in comparison to others examined) was observed on the older silver wire harnesses, where the exposed copper wire strands projected from the terminal crimps and between the terminal end and heat shrink covering the shield termination. Migration of the corrosion products along the length of the outer tube, downward, away from the terminals, was readily apparent. **See photograph 9**.



Photograph 9. Detail of tank unit F18, L/H showing stain migrating down the tube from LoZ terminal.

Most of the tank units and compensators had some varying amount of green primer (from fuel tank) that had splashed onto the exterior probe body (at the bottom of the units).

Several tank units and wire harnesses had fuel tank sealant adhered to the outer tubes and wires.

Line Number 1221:

A total of 26 tank units , 3 compensators (29 total) and their respective wire harnesses were received for test and analysis from line number 1221. They had been removed from the center and numbers 1 and 2 main tanks. This airplane (737-300) had accumulated 37,200 hours and 26,231 cycles. It had been delivered in April of 1986. It had been in service for 13 years. A detailed part number and serial number list of the items examined is enclosed as Table III, section A.

Examination of the submitted components and wiring noted no anomalies. All of the parts were in very good condition.

The manufacturing dates of the tank units and compensator in the #1 L/H tank were as follows:

1985 - qty. 12
Unmarked – qty. 1

The manufacturing dates of the tank units and compensator in the #2 R/H tank were as follows:

1984 - qty. 1
1985 - qty. 12

The manufacturing dates of the tank units and compensator in the CTR tank were as follows:

1985 - qty. 2

1986 – qty. 1

The airplane was delivered on April 23, 1986. All of the submitted units may be original installation.

An examination of all tank units and compensators noted that they were reasonably clean and only very lightly stained on the outside of the tubes.

The wire harnesses were of the newer nickel style. Contamination by copper, silver/sulfur/sulfide corrosion products was minimal and had not resulted in any anomalous conditions or performance. All wire harness segments attached to tank probes had square, silver plated eyelet terminal ends that had been crimped and **not** soldered. The exposed copper wire strands, in the end of the terminal end crimps, were exhibiting early signs of discoloration from corrosion products. The older silver, square terminal ends were not soldered until 1988 and this airplane had been delivered prior to that. The amount of black colored corrosion products was relatively minor but had initiated on all exposed wire terminal ends examined.

Most of the tank units and compensators had slight amounts of green primer (from fuel tank) that had splashed onto the exterior probe body (at the bottom of the units).

A detailed list of the observations is documented in Table III, section B.

Examination Summary:

A number of the units were not original equipment delivered with the airplanes. Both (older [silver] and newer [nickel] style) main tank wire harnesses segments, attached to the tank units/compensators, had eyelet terminal ends that had been either crimped or both crimped and soldered. There were two styles of eyelet terminals ends that were "mixed" with the old [silver] or new [nickel] harnesses. The silver wire had rectangular, silver-plated eyelet terminals and the nickel wire had round, nickel-plated eyelet terminals. The set from L/N 1221 however, had nickel style harnesses with square, silver terminal ends. Some dark colored contamination was observed on the older wire harnesses, where the exposed copper wire strands projected from the terminal crimps and between the terminal end and heat shrink covering the shield termination. Migration of the corrosion products along the length of the outer tube, away from the terminals, was also apparent in some of the tank units.

Most of the tank units and compensators had some varying amount of green primer (from fuel tank) that had splashed onto the exterior probe body (at the bottom of the units). Several tank units and wire harnesses had fuel tank sealant adhered.

In general, the contamination was progressively more noticeable on the older units, with the exception of the overhauled components removed from line number 527.

TEST RESULTS:

The tank units and compensators were tested for dry capacitance, insulation resistance and high potential characteristics. Due to the fact that all electrical testing was conducted through the attached wires, an exception to the specification requirement was made relative to the high potential testing. SCD 10-61219, reference (a), requires high potential testing at 3000 VDC [**tank units and compensators**]. SCD 10-61827, reference (d), requires a dry dielectric test voltage of 1000 VAC RMS [**FQIS wire harness assembly**]. In order to obtain comparative results in relation to earlier testing of 747 tank units and compensators, the high potential tests were conducted using 1500 VAC. The test using the required 3000 VDC, per paragraph 4.2.24.2 of SCD 10-61219, **for tank units and compensators**, was withheld in order to preserve evidence with the exception of the units removed from line number 527. The results of the insulation resistance tests at 500 VDC and the dielectric tests at 1500 VAC noted a number of units exhibiting lower insulation resistance and dielectric test values in comparison to others.

Line Number 527:

Of the tank units and compensators examined, all met the new part acceptance test specification requirements. The testing disclosed no discrepancies with any parts when testing at 1500VAC. Subsequent exceptional testing at 3000 VDC (exceeding the wire rating), yielded one unit that incurred dielectric breakdown at 2758 VDC within the wire. The wiring attached to F18, R/H, did exhibit a dielectric breakdown between the coaxial conductor and the shield as a result of an isolated case, manufacturing process flaw which allowed a strand of the shield to become entrapped under the heat shrink (adjacent to the end termination), providing a path for conduction under the presence of an extremely high voltage. The wiring is supposed to be tested to only 1000 VAC. The test procedure using 3000 VDC may have damaged the wire under test. 3000 VDC is used as a measure for acceptance of new tank units and compensators, not wire harnesses. The wiring survived prolonged exposure to 1500 VAC with only 0.110 milliamp leakage. This condition is not likely to have resulted in any discrepancy in the airplane installation.

Line Number 640:

Of a total of 27 units tested for insulation resistance using 500 VDC, (6) units failed the insulation resistance test requirement of one megohm minimum between Coax (HiZ) and Shield; (8) units had resistance values between 1.2 to 108.9 megohms; (2) units had resistance values between 3.3 and 7.2 gigohms. The remaining (11) units had resistance values in excess of 10 gigohms. All of the discrepant or lower insulation resistance test values (in comparison to other units) occurred between the Coax (HiZ) to Shield combination. Testing across the remaining combinations, Tank (LoZ) to Shield and Coax to Tank (HiZ to LoZ) yielded no anomalies at all.

Dielectric testing noted 8 units of 27 total exhibiting discrepancies when testing at 1500 VAC. It should be noted that this test value exceeds the wire test value of 1000 VAC and may have caused some stress to the wire. Of the 8 units exhibiting anomalous performance, 7 exceeded the maximum allowable leakage current of 0.5 milliamp when tested at 1500 VAC. (wire requirement of max. 1.5 mA @ 1000 VAC). One unit failed as a result of breakdown between the Coax and Shield. The lowest test anomaly occurred at 641 VAC.

Line Number 1221:

The results of the initial testing at 500 VDC and at 1500 VAC noted no anomalous performance characteristics. Of the tank units and compensators examined, all met the new part acceptance test (747 test) specification requirements. The units/wiring survived prolonged exposure to 1500 VAC with only 0.195 milliamp maximum leakage. The maximum allowable leakage (for the wire), per the reference (d), is leakage current no greater than 1.5 milliamps when testing at 1000 VAC. The higher leakage values (for all units tested) were typically associated with the HiZ (Coax) to Shield wire combination. It was found that the leakage was associated with the wiring and not the unit, itself.

ANALYSIS:

The request for this analysis was made with incomplete background information provided regarding the service history of the airplane/fuel tanks from which the subject tank units/compensators had been removed.

Airplane PK552 (Line Number 640) had accumulated 60,773 hours and 67,895 cycles. The examination of the attached wire segments, their respective terminal ends and tank unit/compensator eyelet terminals, noted a pronounced buildup of a dark colored contamination (in comparison to the other ship sets). This ship set appeared to exhibit the most "age" with respect to condition of parts, test results and with respect to the accumulation of dark deposits. For these reasons, two tank units exhibiting more contamination deposits (in comparison to other units) were selected from this ship set for chemical analysis of the deposits.

Analysis has identified the dark deposits as sulfur corrosion products of copper and silver. See the enclosed Analytical Engineering Report No.: 9-5576-WP-99-021. Findings were consistent and similar to previous chemical analyses of 747 FQIS components. For this reason, chemical analyses were not requested of components removed from line numbers 527 and 1221.

Wire chafing was found in two separate instances with wires attached to two tank units. In one case, the shield insulation/wire had been chafed through and in the second case, the LoZ wire insulation had been chafed into but no conductor was exposed. In both cases, the wires had been looped several times through a clamp (as if to take up slack in extra length). This condition (looped wires) is unique to only line number 640; it was not witnessed in either of the other two ship sets of components/wiring submitted. It is not known whether this unusual routing may have been a result of maintenance practices or original installation. Additionally applied sealant was evident on individual units, wiring and on connectors suggesting that they were applied after original installation.

SUMMARY and DISCUSSION:

Of the tank units and compensators examined, all met the new part acceptance test specification requirements for dry capacitance. They were functionally acceptable. Although a number of insulation resistance and dielectric test discrepancies were noted, they were not likely to have resulted in any discrepant performance in the airplane installation. The degradation of insulation resistance and dielectric strength over time is not unusual or unexpected.

Observations were noted that might warrant further investigation. The most notable finding was the confirmation that contaminants, introduced by the reaction reagents in the fuel with copper, can be conductive. However, the biggest drawback to any meaningful interpretation of any of the results is that the contamination is yet to be fully understood. The contaminant varies by airplane, location, consistency, and composition, among other variables. Any number of other factors may also affect the contamination or its conductivity while in-service. These may include, but are not limited to, pressure altitude, humidity and moisture, temperature, and (wet) fuel exposure. One of the key issues regarding the variation in the contaminant is with regards to the fuel that an airplane is exposed to over time/life. Various fuels contain different additives, different sulfur levels and forms of sulfur as well as other constituents. Exact fuel composition can be different and still meet the requirements for commercial aviation fuel. In addition, maintenance (tank cleaning/inspection, repair and/or alteration) may also add unknown elements into the "picture" as well. Any or all of these variables can affect the make-up of the contamination, its growth rate as well as its conductivity. No obvious correlation between the presence of observable contaminants and the electrical breakdown was observed. Specifically, units that experienced insulation resistance or dielectric strength breakdown appeared to be no more heavily contaminated than units, which did not exhibit any breakdown at all.

A number of additional topics may need to be explored further before any interpretation of the preceding results can be made. These may include, but are not limited to, (1) additional chemical characterization of the contamination deposits, (2) effect of humidity on the electrical properties of the deposits, (3) effect of the presence or absence of liquid fuel and fuel vapor on the electrical properties of the contamination deposits, (4) effect of reduced pressure altitude on the electrical properties of the deposits, and (5) effect of applied voltage on rate and geometry [and location] of the deposition.

The voltages used to test insulation resistance and dielectric properties are far in excess of system voltages that it would seem unlikely that the corrosion related issues would negatively affect system performance in the airplane installation

The preceding information is being submitted to the concerned personnel for action as necessary. This EQA is considered closed.

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ENCLOSURES:

A. Table I, Section A: Identification Table, L/N 527
B. Table I, Section B: Examination Observations, L/N 527
C. Table I, Section C: Dry Capacitance and Insulation Resistance, L/N 527
D. Table I, Section D: Dielectric Tests, L/N 527
E. Table II, Section A: Identification Table, L/N 640
F. Table II, Section B: Examination Observations, L/N 640
G. Table II, Section C: Dry Capacitance and Insulation Resistance, L/N 640
H. Table II, Section D: Dielectric Tests, L/N 640
I. Table III, Section A: Identification Table, L/N 1221
J. Table III, Section B: Examination Observations, L/N 1221
K. Table III, Section C: Dry Capacitance and Insulation Resistance, L/N 1221
L. Table III, Section D: Dielectric Tests, L/N 1221
M. Analytical Engineering Report No. 9-5576-WP-99-021
N. Conductivity Table from American Institute of Physics handbook, 3rd edition.
O. Photographs 1- 9 : Details of findings
P. Photographs 10-33: Representative pictures of tank units and compensators removed from line number 527.

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C

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ENCLOSURES:

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B. Table I, Section B: Examination Observations, L/N 527
C. Table I, Section C: Dry Capacitance and Insulation Resistance, L/N 527
D. Table I, Section D: Dielectric Tests, L/N 527
E. Table II, Section A: Identification Table, L/N 640
F. Table II, Section B: Examination Observations, L/N 640
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O. Photographs 1- 9 : Details of findings
P. Photographs 10-33: Representative pictures of tank units and compensators removed from line number 527.

Table I, Section A

Identification

L/N: 527 Main Tank Units & Compensators

#1 Tank	#2 Tank
F2 L/H	**F2 R/H**
10-61219-1	10-61219-1
S/N 3793 AC	S/N 868 U
391041-05007	391041-05007
2Q80	9/26/67
F3 L/H	**F3 R/H**
10-61219-10	10-61219-10
S/N 1715 K	S/N 793 E
391046-04137	391046-04137
2Q76	2Q68
F4 L/H	**F4 R/H**
10-61219-11	10-61219-11
S/N 1722 L	S/N 4059 N
391046-04136	391046-04136
2Q76	1Q88
F5 L/H	**F5 R/H**
10-61219-12	10-61219-12
S/N 1765 J	S/N 981 E
391046-04135	391046-04135
1Q77	4Q68
F6 L/H	**F6 R/H**
10-61219-13	10-61219-213
S/N 1662 J	S/N 5160 B
391046-04134	391046-05134
2Q76	6/27/91
F7 L/H	**F7 R/H**
10-61219-14	10-61219-14
S/N 1694 M	S/N 629 ?
391046-04133	391046-04133
2Q76	1Q67

F8 L/H 10-61219-15 S/N 1666 J 391046-04132 2Q76	**F8 R/H** 10-61219-15 S/N 1810 J 391046-04132 2Q78
F9 L/H 10-61219-16 S/N 1705 L 391046-04131 3Q76	**F9 R/H** 10-61219-16 S/N 1699 L 391046-04131 2Q76
F10 L/H 10-61219-17 S/N 1682 J 391046-04130 2Q76	**F10 R/H** 10-61219-17 S/N 975 E 391046-04130 4Q68
F11 L/H 10-61219-18 S/N 1715 J 391046-04129 3Q76	**F11 R/H** 10-61219-18 S/N 938 E 391046-04129 4Q68
F12 L/H 10-61219-19 S/N 1704 J 391046-04128 2Q76	**F12 R/H** 10-61219-19 S/N 1703 J 391046-04128 2Q76
F18 L/H 10-61219-20 S/N 1713 J 391046-04138 2Q76	**F18 R/H** 10-61219-20 S/N 713 D 391046-04138 1Q68

Table I, Section B
Examination Observations

L/N 527
Main (#1) & (#2) Tank Units & Compensators

1. **F2 R/H -** 10-61219-1 S/N 868 U	* Old style brown harness * Square silver crimped/soldered terminal ends * Outer tube relatively clean * Cracked insulator block
2. **F2 L/H -** 10-61219-1 S/N 3793 AC	* New style green harness * Round crimped/soldered terminal ends. * Clean outer tube * Some green primer splash at bottom of O.T.
3. **F3 R/H -** 10-61219-10 S/N 793 E	* Old style brown harness * Square silver crimped/soldered terminal ends * Clean outer tube
4. **F3 L/H** 10-61219-10 S/N 1715 K	* Round crimped/soldered terminal ends * Unit is most discolored probe of this ship set * New style green harness
5. **F4 R/H** 10-61219-11 S/N 4059 N	* Square, silver crimped/soldered terminal ends * Old style brown harness * Very clean outer tube * Minor sealant at bottom
6. **F4 L/H** 10-61219-11 S/N 1722 L	* Dent in outer tube * New style green harness * Very dirty on upper ½ of tube * Green primer at base * Round crimped/soldered terminal ends

7. F5 R/H
10-61219-12
S/N 981 E

* Silver, square crimped/soldered terminal ends
* Old style brown harness

8. F5 L/H
10-61219-12
S/N 1765 J

* Dirty exterior tube
* New style green harness
* Round crimped/soldered terminal ends

9. F6 R/H
10-61219-213
S/N 5160 B

* Square silver crimped/soldered terminal ends
* Old style brown wire harness

10. F6 L/H
10-61219-13
S/N 1662 J

* New style green wire harness
* Outer tube discolored heavil
* Round crimped/soldered terminal ends
* Green primer at bottom of probe

11. F7 R/H
10-61219-14
S/N 629 ?

* Old style brown harness
* Square, silver crimped/soldered terminal ends
* Outer tube slightly stained

12. F7 L/H
10-61219-14
S/N 1694 M

* New style green harness
* Round crimped/soldered terminal ends
* Outer tube heavily stained
* Green primer at base of outer tube

13. F8 R/H
10-61219-15
S/N 1810 J

* Very clean outer tube
* Old style brown sheath harness
* Square, silver crimped/soldered terminals

14. F8 L/H
10-61219-15
S/N 1666 J

* Moderately stained outer tube
* New style green harness
* Round crimped/soldered terminals
* Green primer at bottom of tubes

15. F9 R/H
10-61219-16
S/N 1699 L

* Old style brown harness
* Square silver crimped/soldered terminal ends
* Green primer at base

* Slightly discolored outer tube

16. F9 L/H
10-61219-16
S/N 1705 L

* Heavily stained
* New style green harness
* Round crimped/soldered terminal ends
* Green primer at base

17. F10 R/H
10-61219-17
S/N 975 E

* Old style brown harness
* Square silver crimped/soldered terminal ends.
* Outer tube is quite discolored

18. F10 L/H
10-61219-17
S/N 1682 J

* New style green harness
* Round crimped/soldered terminal ends
* Heavy staining on tube.
* Green primer at base
* Cracked insulator block

19. F11 R/H
10-61219-18
S/N 938 E

* Old style brown harness
* Square silver crimped/soldered terminal ends
* Clean outer tube

20. F11 L/H
10-61219-18
S/N 1715 J

* New style green wire harness
* Round crimped/soldered terminals
* Heavily discolored outer tube
* Green primer on bottom of outer tube

21. F12 R/H
10-61219-19
S/N 1703 J

* Old style brown wire harness
* Square silver crimped terminal ends
* Moderately clean outer tube

22. F12 L/H
10-61219-19
S/N 1704 J

* Reasonably clean probe.
* Round style silver eyelet terminals.
* New style green harness
* Some minor green primer at base.

26. F18 R/H 10-61219-20 S/N 713 D	* Old style brown sheath harness. * Square silver crimped terminals * Cracked insulator block
27. F18 L/H 10-61219-20 S/N 1713 J	* New style green harness * Round crimped/soldered terminal ends * Bottom half of tube heavily stained * Green primer at bottom * Moderately stained

Table I, Section C

L/N 527: Dry Capacitance & Insulation Resistance

Tank Position	Dry Capacitance	I.R. Coax to Shield	I.R. Tank to Shield	I.R. Coax to Tank
F2 R/H (-1)	39 pF	>10 Gigohm	> 10 Gigohm	>10 Gigohm
F2 L/H (-1)	39.1 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F3 R/H (-10)	73.2 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F3 L/H (-10)	71.6 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F4 R/H (-11)	73.1 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F4 L/H (-11)	73.9 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F5 R/H (-12)	64.7 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F5 L/H (-12)	64.7 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F6 R/H (-213)	42.2 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F6 L/H (-13)	42.5 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F7 R/H (-14)	23.5 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F7 L/H (-14)	22.6 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F8 R/H (-15)	35 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F8 L/H (-15)	34.8 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F9 R/H (-16)	30.6 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F9 L/H (-16)	30.1 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F10 R/H (-17)	30.8 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F10 L/H (-17)	30.2 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F11 R/H (-18)	35.1 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F11 L/H (-18)	35 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F12 R/H (-19)	26.5 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F12 L/H (-19)	26.4 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F18 R/H (-20)	31.4 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F18 L/H (-20)	31.4 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm

Table I, Section D

L/N 527: Dielectric Tests

Tank Position	1500 VAC Coax to Shield	1500 VAC Tank to Shield	1500 VAC Coax to Tank	3000 VDC Coax to Shield	3000 VDC Tank to Shield	3000 VDC Coax to Tank
F2 R/H	0.082 mA	0.041 mA	0.044 mA	19 Gohm	14 Gohm	23 Gohm
F2 L/H	0.065 mA	0.037 mA	0.042 mA	24 Gohm	14 Gohm	17 Gohm
F3 R/H	0.087 mA	0.053 mA	0.065 mA	500.5 Megohm	19 Gohm	16 Gohm
F3 L/H	0.055 mA	0.037 mA	0.058 mA	37 Gohm	44 Gohm	44 Gohm
F4 R/H	0.093 mA	0.054 mA	0.068 mA	39 Gohm	25 Gohm	26 Gohm
F4 L/H	0.048 mA	0.037 mA	0.059 mA	45 Gohm	38 Gohm	36 Gohm
F5 R/H	0.063 mA	0.042 mA	0.058 mA	297 Megohm	26 Gohm	45 Gohm
F5 L/H	0.075 mA	0.050 mA	0.061 mA	25 Gohm	48 Gohm	40 Gohm
F6 R/H	0.098 mA	0.047 mA	0.048 mA	*	*	*
F6 L/H	0.035 mA	0.027 mA	0.038 mA	32 Gohm	29 Gohm	33 Gohm
F7 R/H	0.052 mA	0.027 mA	0.029 mA	21 Gohm	54 Gohm	34 Gohm
F7 L/H	0.047 mA	0.029 mA	0.029 mA	45 Gohm	42 Gohm	34 Gohm
F8 R/H	0.055 mA	0.032 mA	0.035 mA	41 Gohm	51 Gohm	48 Gohm
F8 L/H	0.073 mA	0.041 mA	0.042 mA	25 Gohm	35 Gohm	38 Gohm
F9 R/H	0.061 mA	0.035 mA	0.035 mA	38 Gohm	32 Gohm	37 Gohm
F9 L/H	0.052 mA	0.029 mA	0.032 mA	52 Gohm	42 Gohm	56 Gohm
F10 R/H	0.041 mA	0.025 mA	0.030 mA	25 Gohm	26 Gohm	27 Gohm
F10 L/H	0.060 mA	0.034 mA	0.035 mA	53 Gohm	42 Gohm	27 Gohm
F11 R/H	0.045 mA	0.028 mA	0.034 mA	6.2 Gohm	39 Gohm	35 Gohm
F11 L/H	0.053 mA	0.033 mA	0.037 mA	31 Gohm	52 Gohm	57 Gohm
F12 R/H	0.052 mA	0.027 mA	0.029 mA	42 Gohm	36 Gohm	47 Gohm
F12 L/H	0.048 mA	0.027 mA	0.029 mA	27 Gohm	36 Gohm	39 Gohm
F18 R/H	0.110 mA	0.051 mA	0.050 mA	<1Mohm @ 2758VDC	17 Gohm	25 Gohm
F18 L/H	0.055 mA	0.032 mA	0.034 mA	35 Gohm	38 Gohm	38 Gohm

* This part was removed and sent to Boeing Field for tests prior to the high potential 3000 VDC test.

Table II, Section A

Identification

L/N 640: Main & Center Tank Units & Compensators

#1 Tank	#2 Tank	Center Tank
F2 L/H	**F2 R/H**	**F14 Ctr.**
10-61219-1	10-61219-1	10-61219-1
S/N 3213 AC	S/N 3515 AC	S/N 4249 AD
391041-05007	391041-05007	391041-05007
2Q77	3Q79	5/94
F3 L/H	**F3 R/H**	**F16 Ctr.**
10-61219-10	10-61219-10	10-61219-44
S/N 1987 K	S/N 2001K	S/N 361 C
391046-04137	391046-04137	391046-299
3Q79	3Q79	8/17/77
F4 L/H	**F4 R/H**	**F17 Ctr.**
10-61219-11	10-61219-11	10-61219-245
S/N 1974 L	S/N 1951 L	S/N 2030 B
391046-04136	391046-04136	391046-245
2Q79	2Q79	1Q91
F5 L/H	**F5 R/H**	
10-61219-12	10-61219-12	
S/N 1515 J	S/N 1992 J	
391046-04135	391046-04135	
4/18/77	2Q79	
F6 L/H	**F6 R/H**	
10-61219-13	10-61219-13	
S/N 1938 J	S/N 1928 J	
391046-04134	391046-04134	
2Q79	2Q79	
F7 L/H	**F7 R/H**	
10-61219-14	10-61219-14	
S/N 1171 J	S/N 1986N	
391046-04133	391046-04133	
4Q69	2Q79	

F8 L/H
10-61219-15
S/N 2155 J
391046-04132
2Q80

F8 R/H
10-61219-15
S/N 1968 J
391046-04132
2Q79

F9 L/H
10-61219-16
S/N 1951 L
391046-04131
2Q79

F9 R/H
10-61219-16
S/N 1974 L
391046-04131
2Q79

F10 L/H
10-61219-17
S/N 1949 J
391046-04130
2Q79

F10 R/H
10-61219-17
S/N 1924 J
391046-04130
2Q79

F11 L/H
10-61219-18
S/N 903 E
391046-04129
4Q68

F11 R/H
10-61219-18
S/N 1974 J
391046-04129
2Q79

F12 L/H
10-61219-19
S/N 1960 J
391046-04128
2Q79

F12 R/H
10-61219-19
S/N 1949 J
391046-04128
2Q79

F18 L/H
10-61219-20
S/N 1968 J
391046-04138
2Q79

F18 R/H
10-61219-20
S/N 1985 J
391046-04138
2Q79

L/N 640: Wire Harness Identification:

Center tank: Assembly P/N: 10-61827-24
Connector: 10-60479-134.
Cinch P/N: CN0940-134
Date Code: 9327A

R or L tank: Assembly P/N: 10-61827-1
(unmarked) Connector: 10-60479-35
Amphenol P/N: 217-101-3
Date Code: 7939-2

L or R tank: Assembly P/N: 10-61827-1 * Heavily coated w/new sealant
(unmarked) Connector: 10-60479-35
Amphenol P/N: 217-101-3
Date Code: 7918-3

Bussing Plugs:

L/H: Plug P/N: 10-60479-137
Cinch P/N: CN0940-137
Date Code: 9340A

Ctr. or R: Plug P/N: 10-60479-31
(unmarked) Cinch P/N: CN0940-31
Date Code: 8921

R or Ctr.: Plug P/N: 10-60479-31
(unmarked) Amphenol P/N: 217-100
Date Code: 7934

Table II, Section B

Examination Observations

L/N 640: Center and Main (#1) & (#2) Tank Units & Compensators

1. **F2 R/H –** 10-61219-1 S/N 3515 AC	* Old style brown harness * Square silver crimped terminal ends * Outer tube moderately stained * Paint splash onto bottom of tube * Some slight discoloration at terminals
2. **F2 L/H –** 10-61219-1 S/N 3213 AC	* Old style brown harness * Square silver crimped terminal ends. * Moderately clean outer tube * Coax/HiZ terminal end bent * LoZ terminal end heavily stained
3. **F3 R/H –** 10-61219-10 S/N 2001K	* Old style brown harness * Square silver crimped terminal ends * Upper ½ of tube stained * Paint splash on bottom of tube * Indentation in outer tube, ½ inch from bottom
4. **F3 L/H** 10-61219-10 S/N 1987 K	* Square silver crimped terminal ends * Unit is most discolored probe * Old style wire harness (brown sheath) * Clamp mount dented inward into tube * Upper 1/3 tube – heavily stained * Lower 2/3 tube – moderately stained * Paint splash on bottom of tube * Coax/HiZ terminal end bent * Dent in lower 1/3 area in outer tube * This unit in "rough" shape
5. **F4 R/H** 10-61219-11 S/N 1951 L	* Square, silver crimped terminal ends * Old style brown harness

* Fuel tank sealant all over top of outer tube
* Upper ¼ outer tube heavily stained
* Terminal/wire junctions dark

6. **F4 L/H**
   10-61219-11
   S/N 1974 L

* Upper 1/3 tube heavily stained
* Old style brown harness
* Lower 2/3 of tube moderately stained
* Green primer at base
* Square, silver crimped terminal ends

7. **F5 R/H**
   10-61219-12
   S/N 1992 J

* Silver, square crimped terminal ends
* Old style brown harness
* Shield wire and HiZ insulation heavily stained
* Upper ½ of outer tube stained heavil
* HiZ terminal bent
* Sealant & paint on lower part of outer tube
* LoZ wire insulation braid chafed through *
* LoZ insulation chafed- no conductor showing *

8. **F5 L/H**
   10-61219-12
   S/N 1515 J

* Fairly clean
* Old style brown harness
* Square, silver crimped terminal ends
* HiZ conductor very darkened
* Heavy black stain at terminals/crimp & insulation
* Stains on top 1/6 of outer tube

9. **F6 R/H**
   10-61219-13
   S/N 1928 J

* Square silver crimped square terminal ends
* Old style brown wire harness
* Upper 1/3 of outer tube is stained heavil
* Paint splashed onto bottom of tube
* Wire insulation dark
* Inner tube wear pattern ½ way around (bottom)

10. **F6 L/H**
    10-61219-13
    S/N 1938 J

* Old style brown wire harness
* Outer tube discolored heavil
* Square, silver crimped terminal ends
* Terminals heavily stained
* Green primer at bottom of probe

11. F7 R/H
10-61219-14
S/N 1986 N

* Old style brown harness
* Square, silver crimped terminal ends
* Outer tube discolored and stained
* Minor paint splash on bottom
* HiZ wire at terminal crimp quite dark

12. F7 L/H
10-61219-14
S/N 1171 J

* Old style brown harness
* Square, silver crimped terminal ends
* Outer tube very clean
* Terminals/wire junctions dark

13. F8 R/H
10-61219-15
S/N 1968 J

* Fuel tank sealant all over top of tube
* Old style brown sheath harness
* Square, silver crimped terminals - dark
* Minor paint splash on bottom

14. F8 L/H
10-61219-15
S/N 2155 J

*Outer tube clean.
* Old style brown harness
* Square, silver crimped terminals
* Terminal/wire junction heavily stained
* Shield wire heavily discolored

15. F9 R/H
10-61219-16
S/N 1974 L

* Old style brown harness
* Square silver crimped terminal ends
* Green primer at base
* Very heavily stained outer tube
* Terminals and wire insulation dark

16. F9 L/H
10-61219-16
S/N 1951 L

* Heavily stained – both tubes
* Old style brown harness
* Square, silver crimped terminal ends
* Lots of green primer at base
* Both crimps blackened
* Shield heavily stained

17. F10 R/H
10-61219-17
S/N 1924 J

* Old style brown harness
* Square silver crimped terminal ends.
* Outer tube is quite discolored
* Paint splash on bottom of tube
* Both terminals, wire insulation darkened

18. F10 L/H
10-61219-17
S/N 1949 J

* Old style brown harness
* Square, silver, crimped terminal ends
* Heavy staining on tube.
* Green primer at base
* Shield wire black
* Terminals/wire insulation black

19. F11 R/H
10-61219-18
S/N 1974 J

* Old style brown harness
* Square silver crimped terminal ends
* Medium staining on tube
* Paint splash on bottom of tube
* LoZ terminal end very dark

20. F11 L/H
10-61219-18
S/N 903 E

* Old style brown wire harness
* Square, silver crimped terminals
* Tube relatively clean
* Shield wire and terminal ends discolored

21. F12 R/H
10-61219-19
S/N 1949 J

* Old style brown wire harness
* Square silver crimped terminal ends
* Medium stained probe
* Wire insulation and crimps black
* Terminal flats are clean
* Paint splash on bottom of outer tube
* Shield wire black

22. F12 L/H
10-61219-19
S/N 1960 J

* Reasonably clean probe.
* Round style silver eyelet terminals.
* New style green harness
* Some minor green primer at base.

23. F14 CTR 10-61219-1 S/N 4249 AD	* New style green wire harness * Round style nickel terminal ends * Terminal ends crimped and soldered * Green paint splashed onto bottom of tube * New style probe base * Very clean tube
24. F16 CTR 10-61219-44 S/N 361 C	* New style harness * Round style nickel terminal ends. * Terminal ends crimped and soldered. * Upper clamp cracked. * Very clean tube and terminals. * Minor paint on bottom of outer tube.
25. F17 CTR 10-61219-245 S/N 2030 B	* New style green wire harness * Tube extremely clean * Round terminal end crimped and soldered
26. F18 R/H 10-61219-20 S/N 1985 J	* Old style brown sheath harness. * Square silver crimped terminals * Shield wire heavily blackened * Outer tube moderately stained * Paint splash on bottom
27. F18 L/H 10-61219-20 S/N 1968 J	* Old style brown harness * Square, silver crimped eyelet terminal ends * Bottom half of tube heavily stained * Green primer at bottom * Wire harness looped 5 times inside clamp * Wire terminals dark with contamination

Table II, Section C

L/N 640: Dry Capacitance & Insulation Resistance

Tank Position	Dry Capacitance	I.R. Coax to Shield	I.R. Tank to Shield	I.R. Coax to Tank
F2 R/H (-1)	39.9 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F2 L/H (-1)	40.6 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F14 CTR (-1)	39.5 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F3 R/H (-10)	72.8 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F3 L/H (-10)	72.9 pF	**Fail 400 Koh**	>10 Gigohms	>10 Gigohm
F4 R/H (-11)	74.2 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F4 L/H (-11)	74.6 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F5 R/H (-12)	66.1 pF	3.3 Gigohm	>10 Gigohm	>10 Gigohm
F5 L/H (-12)	66.0 pF	**Fail 337 Koh**	>10 Gigohm	>10 Gigohm
F6 R/H (-13)	42.8 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F6 L/H (-13)	43 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F7 R/H (-14)	24.9 pF	**1.2 Mohm**	>10 Gigohm	>10 Gigohm
F7 L/H (-14)	23.9 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F8 R/H (-15)	35.2 pF	**13.2 Mohm**	>10 Gigohm	>10 Gigohm
F8 L/H (-15)	35.7 pF	**108.9 Mohm**	>10 Gigohm	>10 Gigohm
F9 R/H (-16)	30.8 pF	**Fail 200 Koh**	>10 Gigohm	>10 Gigohm
F9 L/H (-16)	31.2 pF	7.2 Gigohm	>10 Gigohm	>10 Gigohm
F10 R/H (-17)	31.2 pF	**5.8 Mohm**	>10 Gigohm	>10 Gigohm
F10 L/H (-17)	31.4 pF	**Fail 96 Koh**	>10 Gigohm	>10 Gigohm
F11 R/H (-18)	36.1 pF	**Fail <1Moh**	>10 Gigohm	>10 Gigohm
F11 L/H (-18)	36.2 pF	**5.19 Mohm**	>10 Gigohm	>10 Gigohm
F12 R/H (-19)	27.3 pF	**4.2 Mohm**	>10 Gigohm	>10 Gigohm
F12 L/H (-19)	27.6 pF	**2.45 Mohm**	>10 Gigohm	>10 Gigohm
F18 R/H (-20)	32.1 pF	**2.42 Mohm**	>10 Gigohm	>10 Gigohm
F18 L/H (-20)	32.8 pF	**Fail 59 Koh**	>10 Gigohm	>10 Gigohm
F? CTR (-44)	79.6 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F? CTR (-245)	87.3 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm

Table II, Section D

L/N 640: Dielectric Tests

Tank Position	1500 VAC Coax to Shield	1500 VAC Tank to Shield	1500 VAC Coax to Tank	3000 VDC Coax to Shield	3000 VDC Tank to Shield	3000 VDC Coax to Tank
F2 R/H	0.060 mA	0.035 mA	0.041 mA			
F2 L/H	0.023 mA	0.020 mA	0.033 mA			
F14 CTR	0.095 mA	0.046 mA	0.047 mA			
F3 R/H	0.122 mA	0.070 mA	0.077 mA			
F3 L/H	0.024 mA	0.023 mA	0.058 mA			
F4 R/H	0.091 mA	0.058 mA	0.071 mA			
F4 L/H	0.021 mA	0.020 mA	0.057 mA			
F5 R/H	0.112 mA	0.061 mA	0.070 mA			
F5 L/H	> 0.5 mA 641 V	0.059 mA	0.064 mA			
F6 R/H	0.097 mA	0.053 mA	0.052 mA			
F6 L/H	0.057 mA	0.035 mA	0.043 mA			
F7 R/H	> 0.5 mA @ 1079 VAC	0.040 mA	0.036 mA			
F7 L/H	0.058 mA	0.031 mA	0.031 mA			
F8 R/H	> 0.5 mA @ 682 VAC	0.047 mA	0.046 mA			
F8 L/H	>0.5 mA @ 855 VAC	0.034 mA	0.036 mA			
F9 R/H	>0.5 mA @ 720VAC	0.042 mA	0.040 mA			
F9 L/H	0.026 mA	0.020 mA	0.028 mA			
F10 R/H	Fail arc @ 867 VAC	0.045 mA	0.045 mA			
F10 L/H	>0.5 mA @ 1110 VAC	0.033 mA	0.036 mA			
F11 R/H	>0.5 mA @ 720 VAC	0.042 mA	0.040 mA			

F11 L/H	0.188 mA	0.024 mA	0.031 mA			
F12 R/H	0.066 mA	0.018 mA	0.026 mA			
F12 L/H	0.158 mA	0.044 mA	0.043 mA			
F18 R/H	0.030 mA	0.018 mA	0.029 mA			
F18 L/H	>0.5 mA @ 773 VAC	0.091 mA	0.074 mA			
F? CTR (-44)	0.030 mA	0.027 mA	0.060 mA			
F? CTR (-245)	0.077 mA	0.052 mA	0.075 mA			

Table III, Section A

Identification

L/N 1221: Main & Center Tank Units & Compensators

#1 Tank	#2 Tank	Center Tank
F2 L/H	**F2 R/H**	**F14 CTR**
10-61219-1	10-61219-1	10-61219-1
S/N 5271 AF	S/N 5254 AF	S/N 5538 AG
391041-05007	391041-05007	391041-05007
2Q85	2Q85	1Q86
F3 L/H	**F3 R/H**	**F16 CTR**
10-61219-10	10-61219-10	10-61219-44
S/N 3149 L	S/N 3146 L	S/N 1138 E
391046-04137	391046-04137	391046-299
2Q85	2Q85	3Q85
F4 L/H	**F4 R/H**	**F17 CTR**
10-61219-11	10-61219-11	10-61219-45
S/N 3080 M	S/N 3050 M	S/N 1154 D
391046-04136	391046-04136	391046-45
N/A	4Q84	3Q85
F5 L/H	**F5 R/H**	
10-61219-110	10-61219-110	
S/N 426 A	S/N 443 A	
391046-480	391046-480	
2Q85	2Q85	
F6 L/H	**F6 R/H**	
10-61219-13	10-61219-13	
S/N 3247L	S/N 3255L	
391046-04134	391046-04134	
4Q85	4Q85	
F7 L/H	**F7 R/H**	
10-61219-14	10-61219-14	
S/N 3160 P	S/N 3154 P	
391046-04133	391046-04133	
2Q85	2Q85	

F8 L/H	**F8 R/H**
10-61219-90	10-61219-90
S/N 369	S/N 374
391046-479	391046-479
1Q85	1Q85
F9 L/H	**F9 R/H**
10-61219-16	10-61219-16
S/N 3083 M	S/N 3113 M
391046-04131	391046-04131
2Q85	3Q85
F10 L/H	**F10 R/H**
10-61219-17	10-61219-17
S/N 3165 K	S/N 3145 K
391046-04130	391046-04130
3Q85	3Q85
F11 L/H	**F11 R/H**
10-61219-18	10-61219-18
S/N 3037 K	S/N 3040 K
391046-04129	391046-04129
2Q85	2Q85
F12 L/H	**F12 R/H**
10-61219-19	10-61219-19
S/N 3085 K	S/N 3108 K
391046-04128	391046-04128
2Q85	2Q85
F18 L/H	**F18 R/H**
10-61219-20	10-61219-20
S/N 3168 K	S/N 3188 K
391046-04138	391046-04138
2Q85	2Q85
F21 L/H	**F21 R/H**
10-61219-83	10-61219-83
S/N 337 D	S/N 348 D
391046-83	391046-83
2Q85	2Q85

L/N 1221: Wire Harness Identification

Center tank:	Assembly P/N: 10-61827-14 Connector: 10-60479-35 TRW P/N: CN0940-35 Date Code: 8550
R tank:	Assembly P/N: 10-61827-6 Connector: 10-60479-35 TRW P/N: CN0940-35 Date Code: 8541
L tank:	Assembly P/N: 10-61827-6 Connector: 10-60479-35 TRW P/N: CN0940-35 Date Code: 8704

Table III, Section B

Examination Observations

L/N 1221: Center and Main (#1) & (#2) Tank Units & Compensators

1. **F2 R/H -** 10-61219-1 S/N 5254 AF	* New style green harness * Square, silver crimped terminal ends * Dark stains at LoZ crimp * Minor primer splash on bottom of tube
2. **F2 L/H -** 10-61219-1 S/N 5271 AF	* New style green harness * Square silver crimped terminal ends. * Clean outer tube * Light primer splash on bottom of outer tube * Wires stained at crimps
3. **F3 R/H -** 10-61219-10 S/N 3146 L	* New style green harness * Square silver crimped terminal ends * Very light stained outer tube * Minor primer splash on bottom of tube * Radial wear pattern on inside of inner tube at top * Darkened wires at terminal ends
4. **F3 L/H** 10-61219-10 S/N 3149 L	* Square silver crimped terminal ends * Light stain on outer tube * New style wire green harness * Light primer splash on bottom of tube * Radial wear on inside of inner tube at top
5. **F4 R/H** 10-61219-11 S/N 3050 M	* Square, silver crimped terminal ends * New style green harness * Minor sealant at middle of outer tube * Light staining of outer tube * Terminal/wire junctions dark * Light primer overspray on bottom of O.T.

6. **F4 L/H**
10-61219-11
S/N 3080 M

* Minor sealant on outer tube
* New style green harness
* Light stain of outer tube
* Green primer at base
* Square, silver crimped terminal ends
* LoZ terminal slight corrosion
* Darkened terminal ends/wires
* Data plate loose

7. **F5 R/H**
10-61219-110
S/N 443 A

* Silver, square crimped terminal ends
* New style green harness
* Sealant on outer tube
* Primer splash on bottom of outer tube
* Relatively clean outer tube

8. **F5 L/H**
10-61219-110
S/N 426 A

* Light staining of outer tube
* New style green harness
* Square, silver crimped terminal ends
* Sealant on top and bottom of outer tube
* Wires at terminals dark
* Light primer splash at bottom

9. **F6 R/H**
10-61219-13
S/N 3255 L

* Square silver crimped square terminal ends
* New style green wire harness
* Light staining on outer tube
* Paint splashed onto bottom of tube

10. **F6 L/H**
10-61219-13
S/N 3247 L

* New style green wire harness
* Outer tube lightly stained
* Square, silver crimped terminal ends
* Green primer at bottom of probe

11. **F7 R/H**
10-61219-14
S/N 3154 P

* New style green harness
* Square, silver crimped terminal ends
* Outer tube lightly stained
* Minor paint splash on bottom
* LoZ terminal crimp dark

12. F7 L/H
10-61219-14
S/N 3160 P

* New style green harness
* Square, silver crimped terminal ends
* Light staining of outer tube
* Terminals/wire junctions dark
* Minor primer splash on bottom of outer tube

13. F8 R/H
10-61219-90
S/N 374

* Light staining of outer tube
* New style green harness
* Square, silver crimped terminals
* Minor paint splash on bottom
* 2 wires per terminal (in parallel)
* LoZ terminal dark

14. F8 L/H
10-61219-90
S/N 369

* Outer tube very clean.
* New style green harness
* Square, silver crimped terminals
* 2 wires per terminal (in parallel)
* Minor paint splash on bottom of outer tube

15. F9 R/H
10-61219-16
S/N 3113 M

* New style green harness
* Square silver crimped terminal ends
* Slight amount of green primer at base
* Lightly stained outer tube
* Wires at terminals dark

16. F9 L/H
10-61219-16
S/N 3083 M

* Very lightly stained tubes
* New style green harness
* Square, silver crimped terminal ends
* Light green primer at base
* Both crimps darkened
* Outer tube, anodize coating lightly worn through b contact with wire harness sheath.

17. F10 R/H
10-61219-17
S/N 3145 K

* New style green harness
* Square silver crimped terminal ends.
* Outer tube is lightly stained
* Minor paint splash on bottom of tube
* Exposed wires at terminals darkened

18. F10 L/H
10-61219-17
S/N3165 K

* New style green harness
* Square, silver, crimped terminal ends
* Light staining of outer tube.
* Slight amount of green primer at base
* LoZ terminal has slight corrosion
* Terminals/wire ends are dark

19. F11 R/H
10-61219-18
S/N 3040 K

* New style green harness
* Square silver crimped terminal ends
* Terminal ends & wires darkened
* Paint overspray on top & bottom of tube

20. F11 L/H
10-61219-18
S/N 3037 K

* New style green wire harness
* Square, silver crimped terminals
* Tube lightly stained
* Wires at terminal ends discolored
* Some primer at bottom of outer tube

21. F12 R/H
10-61219-19
S/N 3108 K

* New style green wire harness
* Square silver crimped terminal ends
* Lightly stained outer tube
* Wire insulation at terminals are dark
* Paint splash on bottom of outer tube & on HiZ terminal.

22. F12 L/H
10-61219-19
S/N 3085 K

*Very lightly stained outer tube.
* Square silver, crimped eyelet terminals.
* New style green harness
* Some minor green primer at base.
* Wires at terminals dark.

23. F14 CTR
10-61219-1
S/N 5538 AG

* New style green wire harness
* Square, silver crimped terminal ends
* Dark stain on HiZ terminal
* Green paint splashed onto bottom of tube
* Darkened wire end at LoZ terminal.

24. F16 CTR 10-61219-44 S/N 1138 E	* New style harness * Square, silver crimped terminal ends. * Very light primer on bottom of outer tube * Clean outer tube *Darkened HiZ terminal.
25. F17 CTR 10-61219-245 S/N 1154 D	* New style green wire harness * Outer tube clean * Square, silver crimped terminal ends * Light paint on bottom of outer tube.
26. F18 R/H 10-61219-20 S/N 3188 K	* New style green sheath harness. * Square silver crimped terminals * LoZ wire end at terminal dark. * Paint overspray all over outer tube
27. F18 L/H 10-61219-20 S/N 3168 K	* New style green harness * Square, silver crimped eyelet terminal ends * Light staining of outer tube * Green primer at bottom * Wire terminals dark with contamination
28. F21 R/H 10-61219-83 S/N 348 D	* New style green harness. * Square, silver crimped terminal ends * Very lightly stained outer tube. * Light primer spray on top & bottom of outer tube * Wires dark at terminals.
29. F21 L/H 10-61219-83 S/N 337 D	* New style green harness. * Square, silver crimped terminal ends. * Lightly stained outer tube * Sealant on top & bottom of outer tube. * Primer at bottom of outer tube * Wires dark at terminals.

Table III, Section C

L/N 1221: Dry Capacitance & Insulation Resistance

Tank Position	Dry Capacitance	I.R. Coax to Shield	I.R. Tank to Shield	I.R. Coax to Tank
F2 R/H (-1)	40.0 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F2 L/H (-1)	40.3 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F3 R/H (-10)	72.0 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F3 L/H (-10)	71.6 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F4 R/H (-11)	74.3 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F4 L/H (-11)	74.1 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F5 R/H (-12)	65.9 pF	>10Gigohm	>10 Gigohm	>10 Gigohm
F5 L/H (-12)	65.9 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F6 R/H (-213)	42.9 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F6 L/H (-13)	42.9 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F7 R/H (-14)	24.5 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F7 L/H (-14)	24.3 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F8 R/H (-15)	34.8 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F8 L/H (-15)	34.9 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F9 R/H (-16)	31.1 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F9 L/H (-16)	31.0 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F10 R/H (-17)	31.0 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F10 L/H (-17)	31.2 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F11 R/H (-18)	36.1 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F11 L/H (-18)	35.9 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F12 R/H (-19)	27.2 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F12 L/H (-19)	27.3 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F18 R/H (-20)	32.2 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F18 L/H (-20)	32.4 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F21 R/H (-83)	33.7 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F21 L/H (-83)	33.8 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F14 CTR (-1)	39.6 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F16 CTR (-44)	79.4 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm
F17 CTR (-45)	87.1 pF	>10 Gigohm	>10 Gigohm	>10 Gigohm

Table III, Section D

L/N 1221: Dielectric Tests

Tank Position	1500 VAC Coax to Shield	1500 VAC Tank to Shield	1500 VAC Coax to Tank	3000 VDC Coax to Shield	3000 VDC Tank to Shield	3000 VDC Coax to Tank
F2 R/H	0.082 mA	0.044 mA	0.046 mA			
F2 L/H	0.102 mA	0.049 mA	0.048 mA			
F3 R/H	0.086 mA	0.054 mA	0.068 mA			
F3 L/H	0.087 mA	0.054 mA	0.067 mA			
F4 R/H	0.080 mA	0.050 mA	0.068 mA			
F4 L/H	0.090 mA	0.057 mA	0.069 mA			
F5 R/H	0.086 mA	0.052 mA	0.062 mA			
F5 L/H	0.075 mA	0.049 mA	0.061 mA			
F6 R/H	0.081 mA	0.044 mA	0.047 mA			
F6 L/H	0.195 mA	0.049 mA	0.050 mA			
F7 R/H	0.088 mA	0.042 mA	0.038 mA			
F7 L/H	0.083 mA	0.038 mA	0.035 mA			
F8 R/H	0.110 mA	0.052 mA	0.048 mA			
F8 L/H	0.140 mA	0.056 mA	0.052 mA			
F9 R/H	0.069 mA	0.038 mA	0.037 mA			
F9 L/H	0.083 mA	0.041 mA	0.040 mA			
F10 R/H	0.069 mA	0.038 mA	0.038 mA			
F10 L/H	0.062 mA	0.035 mA	0.036 mA			
F11 R/H	0.077 mA	0.043 mA	0.042 mA			
F11 L/H	0.069 mA	0.038 mA	0.040 mA			
F12 R/H	0.075 mA	0.038 mA	0.036 mA			
F12 L/H	0.049 mA	0.029 mA	0.031 mA			
F18 R/H	0.090 mA	0.044 mA	0.042 mA			
F18 L/H	0.075 mA	0.038 mA	0.039 mA			
F21 R/H	0.076 mA	0.042 mA	0.042 mA			
F21 L/H	0.055 mA	0.033 mA	0.036 mA			
F14 CTR	0.055 mA	0.035 mA	0.040 mA			
F16 CTR	0.044 mA	0.037 mA	0.067 mA			
F17 CTR	0.079 mA	0.057 mA	0.077 mA			

Ronald J. Hinderberger
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BOEING

29 April 1999
B-H200-16677-ASI

Mr. Robert Swaim
National Transportation Safety Board, AS-40
490 L'Enfant Plaza East, SW
Washington, D.C. 20594-0003
Phone: 202-314-6394

By Express Mail

Subject: In-Service FQIS Components and Wiring Examination Report – TWA 747-100, N93119 Accident off Long Island, NY - 17 July 1996

Reference; Boeing Equipment Quality Analysis Report 7564R, dated 28 April 1999

Dear Mr. Swaim:

Enclosed with this letter is a copy of the Reference examination report for the fuel quantity indication system (FQIS) components from two in-service 747 airplanes. The components consisted of a complete shipset of probes, compensators, wiring harnesses and connectors from airplanes RD412 and RG124.

If you have any questions, please do not hesitate to call.

Very truly yours,

for Ronald J. Hinderberger
Director, Air Safety Investigation
Org. B-H200, M/S 67-PR
Telex 32-9430, STA DIR AS
Phone (425) 237-8525
Fax (425) 237-8188

Enclosures: EQA Report 7564R (107 pages), Analytical Engineering Report 9-5576-WP-97-272 (21 pages), Analytical Engineering Report 9-5576-WP-97-318

(13 pages), Analytical Engineering Report 9-5576-WP-97-329 (13 pages), Analytical Engineering Report 9-5576-WP-98-127 (4 pages), Analytical Engineering Report 9-5576-WP-98-135 (13 pages), Analytical Engineering Report 9-5576-WP-98-136 (3 pages), Analytical Engineering Report 9-5576-WP-98-250 (16 pages), and EQA Report 7564R Photographs (58 pages)

Cc: Al Dickinson, NTSB, AS-10 (without enclosures)

BOEING

EQUIPMENT QUALITY ANALYSIS REPORT

BOEING COMMERCIAL AIRPLANE GROUP
Renton, WA

TO:	J. Hulm	04-JU	**EQA NUMBER:**	7564R
CC:	E. Groat	04-JU	**DATE:**	April 28, 1999
	R. Lidicker	04-JU		
	D. Rodrigues	67-PR	**CUSTOMER:**	COR / TLS
	M. Shander	04-JU		
			MODEL NUMBER:	747-200
			AIRPLANE NUMBERS:	RG124 & RD412
			LINE NUMBERS:	293 & 423

SUBJECT: ***Evaluation of In-Service FQIS Components and Wiring.***

IDENTIFICATION:

Part name:	Fuel Tank Units (probes & compensators)
Boeing part numbers:	60B92010-*
Supplier part numbers:	FG420A-*
Serial numbers:	multiple*
Supplier:	Honeywell Inc.
Date codes:	multiple*

* A detailed parts list is provided in Tables II & III.

REFERENCES:

(a) Analytical Engineering Reports, No's.: 9-5576-WP-97-272, 9-5576-WP-97-318 and 9-5576-WP-97-329. Previous test results of tank units/compensators from NWA. This included intentional destructive testing, elevated sulfur and salt water exposure testing.

(b) Analytical Engineering Reports, No's.: 9-5576-WP-98-127, 9-5576-WP-98-135, 9-5576-WP-98-136, and 9-5576-WP-98-250.

BACKGROUND:

Previous limited testing had been performed on some tank unit/compensators received from NWA. The units had been submitted without any associated wiring harnesses. Insulation resistance and dielectric testing of those units disclosed no insulation resistance or dielectric strength breakdowns. The units were functionally acceptable. Destructive testing was performed on several of the units. This consisted of increasing the test voltage until breakdown occurred. Breakdown occurred at voltages in excess of 3000 VAC. The evaluation of these units is detailed in the reference (a) Analytical Engineering Reports, No's.: 9-5576-WP-97-272 and 9-5576-WP-97-318. Subsequent to the preceding tests, one tank unit was subjected to a one month exposure to Jet A with elevated sulfur and a second unit was exposed to Puget Sound sea water for one month. The results of the tests are detailed in the reference (a) Analytical Engineering Report, No.: 9-5576-WP-97-329.

Subsequent to the preceding tests, two complete ship sets of fuel quantity indication system components and related wiring removed from in-service airplanes were submitted for evaluation. The analyses were conducted to evaluate the existing conditions of the components and wiring and to gain a better understanding of the effects of aging upon the FQIS tank components from in-service airplanes. Specific requests were made to preserve the attached wire harness to terminal block configuration.

Initially, a complete ship set of probes, compensators, wiring harnesses and connectors, from RD412, were received. RD 412 had accumulated 72,518 hours and 14,603 cycles. Subsequently, a second ship set was received from RG124. RG124 had accumulated 62,758 hours and 12,688 cycles.

SUMMARY:

The analysis was comprised of detailed visual/microscopic examination, electrical testing, limited temperature/altitude testing, chemical/metallurgical analyses, assessment of condition and determination of any possible issues of concern.

Insulation resistance and dielectric tests were performed with dry parts at sea level at 70 degrees F. Testing was performed in comparison to specification tolerances for acceptance of new parts. In addition, testing was more severe than when testing new parts. Successive dielectric tests were performed on some units using 1500 VAC repeatedly. Specifications typically require that each successive test be performed at a test voltage of 20% less than each preceding test. Test results disclosed issues with regards to degradation of dielectric strength and insulation resistance properties over time, with the wiring harnesses and with some of the tank units, but the effects of these dielectric breakdowns, with regards to system function, is not considered to be significant since the (installation) system voltages are significantly lower than that of the insulation resistance or dielectric strength test voltages (500 VDC and 1500 VAC respectively). However, repeated testing at these high voltages can damage the insulative properties of the components under test such that failures can be introduced by repeated applications of this nature (the testing, itself).

Copper sulfide/sulfate deposits were observed in various concentrations around the terminal strips and the exposed copper wires (primarily at the terminal ends and shield terminations). Some of the copper sulfide/sulfate deposits were found to be conductive under certain conditions. See Analytical Engineering Reports Number: 9-5576-WP-98-136; and 9-5576-WP-98-250.

CONCLUSION:

The most notable finding was the confirmation that some of the contaminants, introduced by the reaction of reagents in the fuel to copper, are conductive. However, the biggest drawback to any meaningful interpretation of any of the results is that the contamination is yet to be fully characterized or understood.

Some conditions were found which were to be expected with aging parts. The tank units and compensators exhibited contamination. The wiring was attached to the terminal block studs in a variety of configurations and orientations. Various wire terminations on some of the units had been reworked after initial installation. Some shield pigtail wires were not terminated correctly. See photographs 1 through 26 for both airplanes.

Neither airplane's FQIS components/wiring were in the original, "as delivered" configuration. A number of components and wire harnesses had been replaced from the original installation. RD412 is believed to have had some rework with the installation of reserve tanks. The wire harnesses were in remarkably good condition with no chafing evident at any locations. Several nicks were found on wire harnesses but these were believed to have occurred either during installation or in the process of removal. Microscopic examination of these areas confirmed that the damaged areas were created by mechanical means and that there was no evidence of electrical arcing. See photographs 27 through 31. No visible evidence of electrical arc was observed on any of the wiring and tank units/compensators as received. All of the submitted tank units and compensators were found to be functionally acceptable. However, when testing to the new part acceptance test requirements of SCD 60B92010, insulation resistance and dielectric strength, several of the units exhibited dielectric breakdown. These breakdown voltages were still sufficiently high enough to not be considered a significant variable with respect to voltages in the system (FQIS) installation or the airplane. The findings were not unusual for units that had been in service and exposed to fuel for a long time.

Dielectric breakdown was found to have occurred between (1) the HiZ and the Shield via the contaminant on the outside of the wire insulation and (2) between LoZ to Shield via the contaminant on the underlying coated copper strip. In either case, it was suspected that the contamination appeared to be the conductive path even though this could not be verified in all instances.

Any interpretation of the correlation of anomalous units to tank location needs to be made with caution. A number of units and wiring harnesses of each ship set had been replaced over time. The condition of the tanks, any repairs, alterations or maintenance the airplane had experienced and other issues, that may have affected the airplane FQIS over the life of the airplanes, remain unknown.

EXAMINATION AND TEST RESULTS:

The examination and testing of the units and wiring consisted of several parts. The dry capacitance values of all tank units and compensators were checked prior to removal from the airplane. The tank units and compensators were re-tested for dry capacitance immediately after arrival and unpacking at EQA. This second check was performed in order to verify the airplane removal, packaging, shipping and unpacking processes to insure the units had not become altered from the time of removal. All dry capacitance values (of both ship sets of tank units and compensators) were consistent with values recorded at the airplane.

For the purposes of presenting the results in a clear manner, the tests and results will be separated by airplane.

The test results were recorded when testing each ship set of tank unit/compensators for insulation resistance and dielectric strength properties. The tests were conducted in relation to specification requirements for acceptance testing per SCD 60B92010, paragraph 4.3.3.3. See test results, Table I. Any successive dielectric test is supposed to be conducted using a source voltage at a value 20% less than each preceding test. An exception to this rule was used when testing the subject components. Successive dielectric tests (for items of specific interest) continued to be performed at a voltage of 1500 VAC. This repeated testing at high voltages can sometimes damage the insulative properties of the component under test such that failures can be introduced by the test itself.

Identification of every unit and wire bundle removed from RD412 is provided in Table II. In addition, observations of note were recorded during initial examination.

Identification of every unit and wire bundle removed from RG124 is provided in Table III. In addition, observations of note were recorded during initial examination.

RD412:

* When interpreting the test values of the compensators and tank units, it should be noted that the tests were conducted through the airplane wire leads still attached (approximately 18 inches long) to the terminals.

- Of a total of 80 tank units and compensators examined and tested, 76 units were functionally acceptable and 3 tank units and 1 compensator exhibited unusual characteristics. Three had low insulation resistance values although none of the values were out of specification. One compensator failed dielectric testing when testing to new part standards.

- The date code breakdown of the removed units was as follows:
  (2) - 1977
  (1) - 1978
  (62) - 1979
  (8) - 1980
  (7) - 1986 *
  * All date code 1986 units had been located in the reserve tanks.

- The low insulation resistance and dielectric strength readings of the three unusual tank units occurred between the HiZ and Shield. Dielectric breakdown of the compensator occurred between HiZ and Shield. High-speed video and still photography captured breakdowns of F58 and F67 during testing. See photographs 32 through 35.

- All four unusual units were 1979 date code.

- All discrepant or unusual readings occurred through the wiring and not the units, themselves. Subsequent testing, after removing the wires from the terminal studs, disclosed no anomalous readings of the tank units and compensator.

- The low insulation resistance values and dielectric breakdown have been attributed to a mildly conductive contaminant film on the wire insulation and terminal blocks. The contaminant was identified as copper sulfides/sulfates with traces of silver and nickel.

- The origin of the copper sulfides/sulfates is exposed copper (primarily from the exposed, terminated wire ends) reacting with sulfur in fuel. A secondary source for sulfur may be the polysulfide sealant used to seal the fuel tanks.

- The tank units and compensators, removed from the reserve tanks, typically exhibited more visible dark deposits than units removed from the main tanks. This finding is unusual with respect to the fact that the reserve tank unit/compensators were newer.

- There was no discernible pattern to tank location with respect to the unusual units. All four unusual units came from different tanks.

- The "unusual" units were from positions: F35 (#2 main tank); F58 (#3 main tank); F67 (#4 main tank); F74 (#4 reserve tank).

- Various wire routing configurations were observed with respect to the wire terminals and the terminal block assembly. Years of maintenance and modifications have resulted in a significant variety of wire routing configurations. A significant number of the configurations were not in accordance with production drawings.

- Of all of the wire harnesses examined, only two appear to be original; the others were all newer. The wires showed no signs of abrasions or wear. A few nick and cut marks of the insulation were observed but exposed shiny copper suggests that this damage occurred recently during the removal process of the harnesses from the airplane.

- Limited altitude/temperature tests were conducted on one "unusual" tank unit (F67). Results of testing with a limited sample suggest that temperature is a more significant variable, as opposed to altitude, with regards to lowering the insulation resistance and dielectric strength values. See Table IV.

- Some units were used to evaluate cleaning methods for the removal of the contamination that had accumulated over time. Initially, isopropyl alcohol was applied with vigorous scrubbing of the contamination on both the wires and terminal blocks. This procedure did not result in higher insulation resistance. In fact, immediately after cleaning with alcohol, the insulation resistance and dielectric strength values decreased (still within specification limits). This was believed to be due to greater dispersion of contaminants, in suspension, across the terminal block. After sufficient drying time was allowed, the values did increase slightly. The drying time required was approximately 12 hours. See enclosed Analytical Engineering Report No.: 9-5576-WP-98-135.

- Some of the units were used as samples to test the effectiveness of potting as a means of possible protection against degradation of insulation resistance and dielectric strength properties. The parts were initially cleaned using isopropyl alcohol, dried and then potted. Initial testing noted slight increase in dielectric strength and insulation resistance properties. Further testing and evaluation of both the cleaning and potting yielded little change in dielectric strength and insulation resistance properties. Tests are on-going to verify the long term integrity of this potting method.

RG124:

* When interpreting the test values of the compensators and tank units, it should be noted that the tests were conducted through the airplane wire leads still attached (approximately 18 inches long) to the terminals.

- Of a total of 80 tank units and compensators examined and tested, 63 units were functionally acceptable, 6 tank units exhibited low insulation resistance between HiZ and Shield and 11 (9 tank units + 2 compensators) failed dielectric test.

- Of the 11 tank units and compensators that failed dielectric testing, 7 failed between HiZ and Shield and 4 failed between LoZ and Shield.

- Of a total of 80 tank units and compensators received, 15 were received with no wires attached to the terminal studs.

- The 7 tank units and compensators that failed dielectric tests between HiZ and Shield failed in the attached wiring and not within the components. Contamination was suspected as the path for breakdown but in some instances, where a visual indication was not evident, the breakdown path could have been internal to the wire around the HiZ shield, ferrule.

- The four tank units and compensator that failed dielectric tests between LoZ to Shield, failed between the Teflon coated copper shield strip, under the terminal blocks and the outer tube. See photograph 58. Manufacturing flaws were observed which allowed exposure of the copper strip, allowing corrosion of the copper to occur. The corrosion was a byproduct of the copper strip being exposed to fuel/sulfur resulting in formation of copper/sulfur corrosion products that can be conductive. See the enclosed Analytical Engineering Report No. 9-5576-WP-98-250.

- The date code breakdown of the removed units was as follows:
  (3) - 1973
  (40) - 1974
  (27) - 1975
  (4) - 1976
  (2) - 1980
  (3) - 1988
  (1) - 1989

- Of the 11 units that failed dielectric tests, 2 failed due to current draw exceeding 0.5 mA of current prior to reaching 1500 VAC (SCD limit). The tester automatically terminated the test on ramp up when draw exceeded 0.5 mA. The other 9 units failed due to dielectric breakdown between either HiZ to Shield or between LoZ to Shield.

- Of the 6 units that had lower insulation resistance, 3 were from the number 2 main tank, 1 from the center tank, one was from the number 3 main tank and 1 was from the number 4 main tank.

- Of the eleven units that failed dielectric tests, 2 were from the number 1 main tank, 1 was from the number 2 main tank, 6 were from the number 3 main tank, 1 was from the number 4 main tank and 1 was from the number 2 reserve tank.

- Other than very minor removal damage, there was no evidence of any chafing or wear damage on any of the wire harnesses. The wire harnesses were in exceptionally good condition.

ANALYSIS DISCUSSION:

Analysis has disclosed that the contaminants, in evidence on both the components and the wire harnesses removed from inside the fuel tanks, are primarily copper/sulfur compounds, specifically copper sulfide and/or copper sulfate. These compounds are corrosion products that form when copper is exposed to sulfur. The primary source for the sulfur is the fuel, itself. Sulfur is present in fuel in several different forms, including free sulfur, mercaptan sulfur, sulfides, disulfides, thiophenes, sulfates, organic sulfate acids, sulfones and sulfoxides. A secondary source (but not considered significant) may be the polysulfide sealant used to seal the tanks. However, the effect of the possible secondary source (i.e., the polysulfide sealant) was not examined during this analysis. The reaction mechanisms between the various forms of sulfur and available copper, as well as controlling variables (e.g. temperature, moisture availability, oxygen availability, pH, pressure, etc.) are unknown. It was also found that the contamination can be conductive. Additional testing of reagents has confirmed that copper (I) sulfide (Cu_2S) is not a conductive material but that copper (II) sulfide (CuS) conducts well. See Analytical Engineering Report No.: 9-5576-WP- 98-136.

The greatest drawback to any consistent, meaningful testing regarding contamination is that samples are not identical and that there are a number of extraneous variables which can influence the conductivity or resistivity of the contaminant, itself. The contamination is in essence, a "soup" or mixture with different concentrations of compounds and percentages of trace elements. The samples differ slightly between different tank units and compensators from the same airplane, at different locations, and between different airplanes, since they have been exposed to various subtle differences in fuels (additives, etc.) over time. There was insufficient sample (in any concentration) of contamination such that a precise determination of percentages of constituents could be made. Most of the identification of the contamination was made by infrared spectroscopy and EDX. Humidity and fuel (wet) would also be expected to influence the properties of the contaminant. These issues were not fully examined in this analysis.

Conductivity of the contamination found on tank units, probes and wiring is not consistent. The dielectric and insulation breakdowns (in relation to new part requirements) displayed various characteristics. One of the primary findings was that the chemical/conductivity characteristics changed with repeated applications of test voltages such that insulation resistance and dielectric strength properties increased. Due to the fact that application of voltage appeared to change the electrical properties of the contamination, interpretation of any subsequent test results or analytical results (based on the tested units) should be made with caution.

SUMMARY and DISCUSSIONS:

Observations were noted that might warrant further investigation. The most notable finding was the confirmation that contaminants, introduced by the reaction reagents in the fuel with copper, can be conductive. However, the biggest drawback to any meaningful interpretation of any of the results is that the contamination is yet to be fully understood. The contaminant varies by airplane, location, consistency, and composition, among other variables. Any number of other factors may also affect the contamination or its conductivity while in-service. These may include, but are not limited to, pressure altitude, humidity and moisture, temperature, and (wet) fuel exposure. One of the key issues regarding the variation in the contaminant is with regards to the fuel that an airplane is exposed to over time/life. Various fuels contain different additives, different sulfur levels and forms of sulfur as well as other constituents. Exact fuel composition can be different and still meet the requirements for commercial aviation fuel. In addition, maintenance (tank cleaning/inspection, repair and/or alteration) may also add unknown elements into the "picture" as well. Any or all of these variables can affect the make-up of the contamination, its growth rate as well as its conductivity. No obvious correlation between the presence of observable contaminants and the electrical breakdown was observed. Specifically, units that experienced insulation resistance or dielectric strength breakdown appeared to be no more heavily contaminated than units, which did not exhibit any breakdown at all.

A number of additional topics may need to be explored further before any interpretation of the preceding results can be made. These may include, but are not limited to, (1) additional chemical characterization of the contamination deposits, (2) effect of humidity on the electrical properties of the deposits, (3) effect of the presence or absence of liquid fuel and fuel vapor on the electrical properties of the contamination deposits, (4) effect of reduced pressure altitude on the electrical properties of the deposits, and (5) effect of applied voltage on rate and geometry [and location] of the deposition.

The preceding information is being submitted to the concerned personnel for action as necessary. This EQA is considered closed.

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ENCLOSURES:

A. Table I. Insulation resistance and dielectric test results of all tank units and compensators removed from RG124 and RD412.

B. Table II. Identification table for all FQIS components received from RD412.

C. Table III. Identification table for all FQIS components received from RG124.

D. Table IV. Limited altitude/ temperature testing of F67 tank unit removed from RD412.

E. Table V. Insulation Resistance/ Dielectric testing of wiring harnesses from RD412.

F. Photographs 1-13, the various wire configurations at the terminal blocks of all compensators and tank units removed from RG124.

G. Photographs 14-26, the various wire configurations at the terminal blocks of all compensators and tank units removed from RD412.

H. Photographs 27-31, damage areas of the wire harnesses.

I. Photographs 32-35, dielectric breakdown of F58 and F67 (RD412) during extended testing.

J. Photographs 36-57, miscellaneous receiving, unpacking, wire harness connectors, and various panels and instruments received from RD412.

K. Analytical Engineering Reports, No's. : 9-5576-WP-97-272, 97-318, 97-329, 98-127, 98-135, 98-136, and 98-250.

Table I. Test Results

Tank Unit Test Results: RG124

Position Number	Insulation Resistance			Dielectric Withstanding		
	HiZ-Shd	LoZ-Shd	HiZ-Loz	HiZ-Shd	LoZ-Shd	HiZ-Loz
No.1 RESERVE						
F1 Comp. No wires	>10 Gohm	>10 Gohm	>10 Gohm	0.032 mA	0.040 mA	0.046 mA
F2 Comp. No wires	>10 Gohm	>10 Gohm	>10 Gohm	0.032 mA	0.036 mA	0.045 mA
F3 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.098 mA	0.050 mA	0.067 mA
F4 Probe No wires	>10 Gohm	>10 Gohm	>10 Gohm	9.27 Na	0.013 mA	0.039 mA
F5 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.184 mA	0.038 mA	0.038 mA
F6 Probe No wires	>10 Gohm	>10 Gohm	>10 Gohm	9.4 Na	0.013 mA	0.032 mA
No.1 MAIN						
F7 Comp.	>10 Gohm	>10 Gohm	>10 Gohm	0.305 mA	0.090 mA	0.084 mA
F8 Comp.	>10 Gohm	>10 Gohm	>10 Gohm	0.172 mA	0.079 mA	0.073 mA
F9 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.151 mA	0.056 mA	0.065 mA
F10 Probe No wires	>10 Gohm	>10 Gohm	>10 Gohm	0.015 mA	>0.5 mA @ 1461 VAC	0.045 mA
F11 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.358 mA	0.079 mA	0.078 mA
F12 Probe	>10 Gohm	>10 Gohm	>10 Gohm	arc@1154 arc@1311	0.089 mA	0.098 mA
F13 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.162 mA	0.056 mA	0.059 mA
F14 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.132 mA	0.064 mA	0.079 mA
F15 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.483 mA	0.091 mA	0.095 mA
F16 Probe No wires	>10 Gohm	>10 Gohm	>10 Gohm	10.27 Na	0.016 mA	0.031 mA
F17 Probe No wires	>10 Gohm	>10 Gohm	>10 Gohm	10.91 Na	0.015 mA	0.042 mA
F18 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.342 mA	0.080 mA	0.088 mA
F19 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.157 mA	0.068 mA	0.085 mA
F20 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.170 mA	0.053 mA	0.056 mA
F21 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.149 mA	0.055 mA	0.059 mA
No.2 MAIN						
F22 Comp	>10 Gohm	>10 Gohm	>10 Gohm	0.187 mA	0.052 mA	0.056 mA
F23 Comp	>10 Gohm	>10 Gohm	>10 Gohm	0.127 mA	0.047 mA	0.052 mA
F24 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.245 mA	0.121 mA	0.127 mA
F25 Probe (SCD = >1 Mohm)	<200M@ 496 VDC					
F26 Probe	<200M@ 488VDC					

F27 Probes	>10 Gohm	>10 Gohm	>10 Gohm	11.65 Na	0.015 mA	0.066 mA
F28 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.148 mA	0.058 mA	0.061 mA
F29 Probe	>10 Gohm	>10 Gohm	>10 Gohm	arc @ 1003VAC		
F30 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.093 mA	0.057 mA	0.072 mA
F31 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.197 mA	0.109 mA	0.114 mA
F32 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.150 mA	0.067 mA	0.082 mA
F33 Probe	<200M					
F35 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.092 mA	0.058 mA	0.105 mA
CENTER FUEL TANK						
F36 Comp	>10 Gohm	>10 Gohm	>10 Gohm	0.289 mA	0.094 mA	0.086 mA
F38 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.183 mA	0.100 mA	0.126 mA
F39 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.156 mA	0.074 mA	0.095 mA
F40 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.165 mA	0.074 mA	0.094 mA
F41 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.306 mA	0.118 mA	0.155 mA
F42 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.165 mA	0.087 mA	0.135 mA
F43 Probe	<200Mohm	>10 Gohm	--			
F44 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.116 mA	0.065 mA	0.128 mA
No.3 MAIN						
F45 Comp	>10 Gohm	>10 Gohm	>10 Gohm	0.169 mA	0.051 mA	0.056 mA
F47 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.142 mA	0.070 mA	0.096 mA
F48 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.134 mA	>0.5 mA @1156 VAC	0.089 mA
F49 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.149 mA	0.067 mA	0.082 mA
F50 Probe No wires	>10 Gohm	>10 Gohm	>10 Gohm	10.24 Na	0.015 mA	0.065 mA
F51 Probe	>10 Gohm	>10 Gohm	>10 Gohm	arc @ 830 VAC		
F52 Probe	<200 Mohm					
F53 Probe	>10 Gohm	>10 Gohm	>10 Gohm	arc @ 1112 VAC		0.065 mA
F54 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.150 mA	0.073 mA	0.095 mA
F55 Probe	>10 Gohm	>10 Gohm	>10 Gohm	arc @ 996 VAC		
F56 Probe	>10 Gohm	>10 Gohm	>10 Gohm	arc @ 1139 VAC		
F58 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.082 mA	arc @ 1222 VAC	
No.4 MAIN						
F59 Comp	>10 Gohm	>10 Gohm	>10 Gohm	arc @ 1077 VAC		
F60 Comp	>10 Gohm	>10 Gohm	>10 Gohm	0.205 mA	0.076 mA	0.072 mA
F61 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.191 mA	0.060 mA	0.068 mA
F62 Probe No wires	>10 Gohm	>10 Gohm	>10 Gohm	9.07 Na	0.015 mA	0.068 mA
F63 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.156 mA	0.057 mA	0.064 mA

F64 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.110 mA	0.058 mA	0.083 mA
F65 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.136 mA	0.057 mA	0.059 mA
F66 Probe	<200 Mohm @ 384VDC					
F67 Probe No wires	>10 Gohm	>10 Gohm	>10 Gohm	0.015 mA	0.017 mA	0.068 mA
F68 Probe No wires	>10 Gohm	>10 Gohm	>10 Gohm	9.0 Na	0.014 mA	0.029 mA
F69 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.154 mA	0.059 mA	0.063 mA
F70 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.143 mA	0.069 mA	0.086 mA
F71 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.147 mA	0.077 mA	0.091 mA
F72 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.212 mA	0.066 mA	0.065 mA
F73 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.116 mA	0.045 mA	0.051 mA
No. 4 RESERVE						
F74 Comp No wires	>10 Gohm	>10 Gohm	>10 Gohm	0.035 mA	0.043 mA	0.049 mA
F76 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.103 mA	0.053 mA	0.068 mA
F77 Probe No wires	>10 Gohm	>10 Gohm	>10 Gohm	0.016 mA	0.018 mA	0.041 mA
F78 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.184 mA	0.015 mA	0.014 mA
F79 Probe No wires	>10 Gohm	>10 Gohm	>10 Gohm	0.014 mA	0.019 mA	0.031 mA
No.2 RESERVE						
F82 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.082 mA	0.039mA	0.042 mA
F83 Probe parallel w/F84	*>10 Gohm	*>10 Gohm	*>10 Gohm	*0.391 mA	*0.045 mA	* 0.046mA
F84 Comp parallel w/F83	*>10 Gohm	*>10 Gohm	*>10 Gohm	*0.093 mA	arc @ 1090 VAC	
No. 3 RESERVE						
F85 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.111 mA	0.040 mA	0.045 mA
F86 Probe *parallel w/ F87	*>10 Gohm	*>10 Gohm	* >10 Gohm	*0.393 mA	*0.104 mA	*0.093 mA
F87 Comp parallel w/ F86	*>10 Gohm	* >10 Gohm	* >10 Gohm	*0.393 mA	*0.104 mA	*0.093 mA

Tank Unit Test Results: RD412

Position Number	Insulation Resistance			Dielectric Withstanding		
	HiZ-Shd	LoZ-Shd	HiZ-Loz	HiZ-Shd	LoZ-Shd	HiZ-Loz
No.1 RESERVE						
F1 Comp.	>10 Gohm	>10 Gohm	>10 Gohm	0.35 mA	0.08 mA	0.08 mA
F2 Comp.	>10 Gohm	>10 Gohm	>10 Gohm	0.18 mA	0.08 mA	0.07 mA
F3 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.07 mA	0.05 mA	0.07 mA
F4 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.10 mA	0.05 mA	0.06 mA
F5 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.12 mA	0.03 mA	0.03 mA
F6 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.19 mA	0.05 mA	0.05 mA
No.1 MAIN						
F7 Comp.	>10 Gohm	>10 Gohm	>10 Gohm	0.15 mA	0.07 mA	0.07 mA
F8 Comp.	>10 Gohm	>10 Gohm	>10 Gohm	0.13 mA	0.07 mA	0.07 mA
F9 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.10 mA	0.05 mA	0.06 mA
F10 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.15 mA	0.06 mA	0.06 mA
F11 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.09 mA	0.05 mA	0.06 mA
F12 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.10 mA	0.06 mA	0.08 mA
F13 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.08 mA	0.04 mA	0.05 mA
F14 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.07 mA	0.05 mA	0.07 mA
F15 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.12 mA	0.06 mA	0.08 mA
F16 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.09 mA	0.04 mA	0.04 mA
F17 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.05 mA	0.05mA	0.05 mA
F18 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.11 ma	0.06 mA	0.08 mA
F19 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.11 mA	0.06 mA	0.08 mA
F20 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.12 mA	0.04 mA	0.05 mA
F21 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.10 mA	0.04 mA	0.05 mA
No.2 MAIN						
F22 Comp	>10 Gohm	>10 Gohm	>10 Gohm	0.22 mA	0.06 mA	0.06 mA
F23 Comp	>10 Gohm	>10 Gohm	>10 Gohm	0.15 mA	0.06 mA	0.05 mA
F24 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.18 mA	0.08 mA	0.10 mA
F25 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.16 mA	0.07 mA	0.09 mA
F26 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.12 mA	0.06 mA	0.07 mA
F27 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.12 mA	0.06 mA	0.08 mA
F28 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.10 mA	0.05 mA	0.05 mA
F29 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.09 mA	0.05 mA	0.06 mA
F30 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.09 mA	0.05 mA	0.07 mA
F31 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.12 mA	0.06 mA	0.08 mA
F32 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.10 mA	0.06 mA	0.08 mA
F33 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.13 mA	0.06 mA	0.07 mA
F35 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.11 mA	0.06 mA	0.11 mA
CENTER FUEL TANK						
F36 Comp	>10 Gohm	>10 Gohm	>10 Gohm	0.15 mA	0.07 mA	0.07 mA
F38 Probe	1.15 Gohm	>10 Gohm	>10 Gohm	0.14 mA	0.07 mA	0.10 mA
F39 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.11 mA	0.06 mA	0.09 mA
F40 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.13 mA	0.07 mA	0.09 mA
F41 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.14 mA	0.08 mA	0.14 mA

F42 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.22 mA	0.10 mA	0.14 mA
F43 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.13 mA	0.07 mA	0.10 mA
F44 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.09 mA	0.07 mA	0.13 mA
No.3 MAIN						
F45 Comp	>10 Gohm	>10 Gohm	>10 Gohm	0.26 mA	0.06 mA	0.06 mA
F47 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.17 mA	0.07 mA	0.09 mA
F48 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.17 mA	0.07 mA	0.10 mA
F49 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.12 mA	0.06 mA	0.07 mA
F50 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.10 mA	0.06 mA	0.08 mA
F51 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.17 mA	0.05 mA	0.06 mA
F52 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.11 mA	0.05 mA	0.07 mA
F53 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.10 mA	0.05 mA	0.07 mA
F54 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.10 mA	0.06 mA	0.08 mA
F55 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.09 mA	0.06 mA	0.08 mA
F56 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.08 mA	0.05 mA	0.07 mA
F58 Probe (SCD = >1 Mohm)	Failed IR <200 Mohm					
No.4 MAIN						
F59 Comp	>10 Gohm	>10 Gohm	>10 Gohm	0.18 mA	0.07 mA	0.07 mA
F60 Comp	>10 Gohm	>10 Gohm	>10 Gohm	0.19 mA	0.08 mA	0.07 mA
F61 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.07 mA	0.06 mA	0.07 mA
F62 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.11 mA	0.05 mA	0.06 mA
F63 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.06 mA	0.06 mA	0.06 mA
F64 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.05 mA	0.04 mA	0.08 mA
F65 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.11 mA	0.05 mA	0.06 mA
F66 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.09 mA	0.05 mA	0.07 mA
F67 Probe (SCD = >1 Mohm)	Failed IR 67 Mohm @ 400 VDC					
F68 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.15 mA	0.04 mA	0.05 mA
F69 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.10 mA	0.04 mA	0.05 mA
F70 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.14 mA	0.06 mA	0.08 mA
F71 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.07 mA	0.05 mA	0.08 mA
F72 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.14 mA	0.05 mA	0.05 mA
F73 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.13 mA	0.05 mA	0.06 mA
No. 4 RESERVE						
F74 Comp	9 Gohm	>10 Gohm	>10 Gohm	Arc @ 713 VAC	0.11 mA	0.10 mA
F76 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.07 mA	0.05 mA	0.07 mA
F77 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.13 mA	0.05 mA	0.05 mA
F78 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.11 mA	0.03 mA	0.04 mA
F79 Probe s	>10 Gohm	>10 Gohm	>10 Gohm	0.22 mA	0.05 mA	0.05 mA
No.2 RESERVE						
F82 Probe	> 10 Gohm	>10 Gohm	>10 Gohm	0.09 mA	0.04 mA	0.05 mA
F83 Probe parallel	*>10 Gohm	*>10 Gohm	*>10 Gohm	*0.35 mA	*0.05 mA	* 0.05mA

w/F84						
F84 Comp parallel w/F83	*>10 Gohm	*>10 Gohm	*>10 Gohm	*0.34 mA	0.08 mA	0.08 mA
No. 3 RESERVE						
F85 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.08 mA	0.04 mA	0.04 mA
F86 Probe	>10 Gohm	>10 Gohm	>10 Gohm	0.11 mA	0.04 mA	0.05 mA
F87 Comp	>10 Gohm	>10 Gohm	>10 Gohm	0.16 mA	0.06 mA	0.06 mA

Airline: **PAL/ATLAS** Airplane Model: **747-2F6** Airplane Variable Number: **RD 412**

Nomenclature: **Fuel Probe** Serial Number: **Q-111**

Boeing Part Number: **60B92010-36** Supplier Part Number: **HONEYWELL FG420A36**

Manufacturer Date: **8/79** Series: **7**

Drawing Number: Revision / Date:

Functional Test Date: **8/79** Installation Position: **F12** Tank Number: **M1**

PACKAGE/BOX MARKINGS	Tank Name:	F Number: F12
Tank Number:	Unknown Numbers: 0136 S/N 223	

TESTING:

1. Dry Capacitance Test: 106.0 Pf
(Using A/P test equipment)

1a. Dry Capacitance Test:
(Using EQA test equipment

	Hi Z to Lo Z	Hi Z to Shield	Lo Z to Shield
2. Insulation Resistance Test:	19 Gigohms	20 Gigohms	22 Gigohms
3. Dielectric Test:	0.08 mA	0.10 mA	0.06 mA

OBSERVATION:

I **Terminal Block Data**

Excessive dark deposits on Hi Z and shield. Darkened copper on Teflon shield.

Hi Z connection: Wire Number: W776-Q111-20 F12

Lo Z connection: Wire Number: 60B40037-906 LO Z F12\F64

Shield connection: Wire Number: W776-Q111-20 F12

I Terminal Block Data

Teflon laminated shield, copper Slightly discolored. Dark deposits on terminal hardware.

Hi Z connection: Wire Number: W524-Q122-20 W524-Q130-20, 61B40524-3

Lo Z connection: Wire Number: LOZ F24

Shield connection: Wire Number: W524-Q122-20 W524-Q130-20, 61B40524-3

Airline: **PAL/ATLAS** Airplane Model: **747-2F6** Airplane Variable Number: **RD 412**

Nomenclature: **Fuel Probe** Serial Number: **Q-37**

Boeing Part Number: **60B92010-26** Supplier Part Number: **HONEYWELL FG420A36**

Manufacturer Date: **2/79** Series: **8**

Drawing Number: Revision / Date:

Functional Test Date: **3/79** Installation Position: **F25** Tank Number: **M2**

PACKAGE/BOX MARKINGS	Tank Name:	F Number: F25
Tank Number: Left wing	Unknown Numbers: 0126 225	

TESTING:

1. Dry Capacitance Test: 117.0 Pf
(Using A/P test equipment)

1a. Dry Capacitance Test:
(Using EQA test equipment

	Hi Z to Lo Z	Hi Z to Shield	Lo Z to Shield
2. Insulation Resistance Test:	21 Gigohms	17 Gigohms	23 Gigohms
3. Dielectric Test:	0.09 mA	0.16 mA	0.07 mA

OBSERVATION:

I Terminal Block Data

Teflon laminated shield, copper clean. Dark deposits on terminal hardware.

Hi Z connection: Wire Number: W524-Q135-20 W524-Q132-20 F25, 69B40524-3

Lo Z connection: Wire Number: LOZ F25

Shield connection: Wire Number: W524-Q135-20 W524-Q132-20 F25, 69B40524-3

Wire Clamp Position: Wire Number:

Clamp stud appears slightly discolored.

II Length of probe

Airline: **PAL/ATLAS** Airplane Model: **747-2F6** Airplane Variable Number: **RD 412**

Nomenclature: **Fuel Probe** Serial Number: **Q-44**

Boeing Part Number: **60B92010-20** Supplier Part Number: **HONEYWELL FG420A20**

Manufacturer Date: **2/79** Series: **8**

Drawing Number: Revision / Date:

Functional Test Date: **2/79** Installation Position: **F26** Tank Number: **M2**

PACKAGE/BOX MARKINGS	Tank Name:	F Number: F26
Tank Number:	Unknown Numbers: 0120 S/N 211	

TESTING:

1. Dry Capacitance Test: 84.1 Pf
(Using A/P test equipment)

1a. Dry Capacitance Test:
(Using EQA test equipment

	Hi Z to Lo Z	Hi Z to Shield	Lo Z to Shield
2. Insulation Resistance Test:	22 Gigohms	17 Gigohms	23 Gigohms
3. Dielectric Test:	0.07 mA	0.12 mA	0.06 mA

OBSERVATION:

I Terminal Block Data

Teflon laminated shield, copper clean. Dark deposits vary in discoloration on terminal hardware.

Hi Z connection: Wire Number: F26 W524-Q128-20, 61B40524-3 F26 W524-Q123-20, 61B40524-3

Lo Z connection: Wire Number:

Shield connection: Wire Number: F26 W524-Q128-20, 61B40524-3 F26 W524-Q123-20, 61B40524-3

Wire Clamp Position: Wire Number:

Clamp stud appears slightly discolored.

II Length of probe

3. Dielectric Test:	0.08 mA	0.10 mA	0.06 mA

OBSERVATION:

I Terminal Block Data

Teflon laminated shield, copper clean. Darkened deposits on terminal hardware.
LoZ Terminal hardware has excessive deposits.

Hi Z connection: Wire Number: F32 W524-Q129-20 F32

Lo Z connection: Wire Number: LOZ F32

Shield connection: Wire Number: F32 W524-Q129-20 F32

Wire Clamp Position: Wire Number:
Clamp stud appears slightly discolored.

II Length of probe

Airline: **PAL/ATLAS** Airplane Model: **747-2F6** Airplane Variable Number: **RD 412**

Nomenclature: **Fuel Probe** Serial Number: **Q-68**

Boeing Part Number: **60B92010-25** Supplier Part Number: **HONEYWELL FG420A25**

Manufacturer Date: **5/79** Series: **8**

Drawing Number: Revision / Date:

Functional Test Date: **5/79** Installation Position: **F33** Tank Number: **M2**

PACKAGE/BOX MARKINGS	Tank Name:	F Number: F33
Tank Number:	Unknown Numbers: 0125 225	

TESTING:

1. Dry Capacitance Test: 76.7 Pf
(Using A/P test equipment)

1a. Dry Capacitance Test:
(Using EQA test equipment

	Hi Z to Lo Z	Hi Z to Shield	Lo Z to Shield
2. Insulation Resistance Test:	22 Gigohms	16 Gigohms	22 Gigohms
3. Dielectric Test:	0.07 mA	0.13 mA	0.06 mA

OBSERVATION:

I Terminal Block Data

Teflon laminated shield, copper Discolored. Darkened deposits on terminal hardware.

Hi Z connection: Wire Number: W524-Q129-20 F33, 61B40524-3 W524-Q167-20 F33, 61B40524-3

Lo Z connection: Wire Number: LOZ F33

Shield connection: Wire Number: W524-Q129-20 F33, 61B40524-3 W524-Q167-20 F33, 61B40524-3

Wire Clamp Position: Wire Number:

Clamp stud appears slightly discolored.

II Length of probe

II Length of probe

Airline: **PAL/ATLAS** Airplane Model: **747-2F6** Airplane Variable Number: **RD 412**

Nomenclature: **Fuel Probe** Serial Number: **Q-14**

Boeing Part Number: **60B92010-16** Supplier Part Number: **HONEYWELL FG420A16**

Manufacturer Date: **2/79** Series: **8**

Drawing Number: Revision / Date:

Functional Test Date: **3/79** Installation Position: **F43** Tank Number: **C**

PACKAGE/BOX MARKINGS	Tank Number:	F Number: F43
Tank Name: CWT	Unknown Numbers:	

TESTING:

1. Dry Capacitance Test: 120.0 Pf
(Using A/P test equipment)

1a. Dry Capacitance Test:
(Using EQA test equipment

	Hi Z to Lo Z	Hi Z to Shield	Lo Z to Shield
2. Insulation Resistance Test:	21 Gigohms	17 Gigohms	22 Gigohms
3. Dielectric Test:	0.10 mA	0.13 ma	0.07 mA

OBSERVATION:

I Terminal Block Data

All terminal hardware very clean.

Hi Z connection: Wire Number: W498-Q137-20 W498-Q136-20, 61B40498-2

Lo Z connection: Wire Number: 60B40037-308 LO Z F43

Shield connection: Wire Number: W498-Q137-20 W498-Q136-20, 61B40498-2

Wire Clamp Position: Wire Number:

Clamp stud clean.

II Length of probe

Airline: **PAL/ATLAS** Airplane Model: **747-2F6** Airplane Variable Number: **RD 412**

Nomenclature: **Fuel Probe** Serial Number: **P-90**

Boeing Part Number: **60B92010-13** Supplier Part Number: **HONEYWELL FG420A13**

Manufacturer Date: **4/80** Series: **7**

Drawing Number: Revision / Date:

Functional Test Date: **4/80** Installation Position: **F44** Tank Number: **C**

PACKAGE/BOX MARKINGS	Tank Number:	F Number: F44
Tank Name: CWT	Unknown Numbers:	

TESTING:

1. Dry Capacitance Test: 183.9 Pf
(Using A/P test equipment)

1a. Dry Capacitance Test:
(Using EQA test equipment

	Hi Z to Lo Z	Hi Z to Shield	Lo Z to Shield
2. Insulation Resistance Test:	18 Gigohms	19 Gigohms	21 Gigohms
3. Dielectric Test:	0.13 mA	0.09 mA	0.07 mA

OBSERVATION:

Airline: **PAL/ATLAS** Airplane Model: **747-2F6** Airplane Variable Number: **RD 412**

Nomenclature: **Fuel Probe** Serial Number: **Q-34**

Boeing Part Number: **60B92010-26** Supplier Part Number: **HONEYWELL FG420A26**

Manufacturer Date: **2/79** Series: **8**

Drawing Number: Revision / Date:

Functional Test Date: **3/79** Installation Position: **F48** Tank Number: **M3**

PACKAGE/BOX MARKINGS	Tank Number: 3	F Number: F48
Tank Name:	Unknown Numbers: 0126224	

TESTING:

1. Dry Capacitance Test: 117.1 Pf
(Using A/P test equipment)

1a. Dry Capacitance Test:
(Using EQA test equipment

	Hi Z to Lo Z	Hi Z to Shield	Lo Z to Shield
2. Insulation Resistance Test:	17 Gigohms	15 Gigohms	19 Gigohms
3. Dielectric Test:	0.10 mA	0.17 mA	0.07 mA

OBSERVATION:

I **Terminal Block Data**

Teflon laminated shield, copper clean.
Discolored terminal hardware.

Hi Z connection: Wire Number: W1178-Q147-20
W1178-Q149-20

Lo Z connection: Wire Number: 60B40037-807 LO Z F48

Shield connection: Wire Number: W1178-Q147-20
W1178-Q149-20

Wire Clamp Position: Wire Number:

Clamp stud discolored.

II Length of probe

Airline: **PAL/ATLAS** Airplane Model: **747-2F6** Airplane Variable Number: **RD 412**

Nomenclature: **Fuel Probe** Serial Number: **Q-47**

Boeing Part Number: **60B92010-20** Supplier Part Number: **HONEYWELL FG420A20**

Manufacturer Date: **2/79** Series: **8**

Drawing Number: Revision / Date:

Functional Test Date: **2/79** Installation Position: **F49** Tank Number: **M3**

PACKAGE/BOX MARKINGS	Tank Number: 3	F Number: F49
Tank Name:	Unknown Numbers: 0120 S/N 212	

TESTING:

1. Dry Capacitance Test: 84.1 Pf
(Using A/P test equipment)

1a. Dry Capacitance Test:
(Using EQA test equipment

	Hi Z to Lo Z	Hi Z to Shield	Lo Z to Shield
2. Insulation Resistance Test:	21 Gigohms	18 Gigohms	23 Gigohms
3. Dielectric Test:	0.07 mA	0.12 mA	0.06 mA

OBSERVATION:

I Terminal Block Data

Teflon laminated shield, copper clean.

1a. Dry Capacitance Test: *(Using EQA test equipment*

	Hi Z to Lo Z	Hi Z to Shield	Lo Z to Shield
2. Insulation Resistance Test:	22 Gigohms	19 Gigohms	25 Gigohms
3. Dielectric Test:	0.07 mA	0.08 mA	0.05 mA

OBSERVATION:

I **Terminal Block Data**

Teflon laminated shield, copper discolored.
Discolored terminal hardware.

Hi Z connection: Wire Number: W1178-Q146-20 W1178-Q170-20

Lo Z connection: Wire Number:

Shield connection: Wire Number: W1178-Q146-20 W1178-Q170-20

Wire Clamp Position: Wire Number:
Clamp stud discolored.

II **Length of probe**

Airline: **PAL/ATLAS** Airplane Model: **747-2F6** Airplane Variable Number: **RD 412**

Nomenclature: **Fuel Probe** Serial Number: **Q-106**

Boeing Part Number: **60B92010-64** Supplier Part Number: **HONEYWELL FG420A64**

Manufacturer Date: **7/79** Series: **2**

Drawing Number: Revision / Date:

Functional Test Date: **7/79** Installation Position: **F58** Tank Number: **M3**

PACKAGE/BOX MARKINGS	Tank Number: 3	F Number: F58
Tank Name: RIGHT WING	Unknown Numbers: 0164 224 1P42792	

TESTING:

1. Dry Capacitance Test: 141.6 pf
(Using A/P test equipment)

1a. Dry Capacitance Test:
(Using EQA test equipment

	Hi Z to Lo Z	Hi Z to Shield	Lo Z to Shield
2. Insulation Resistance Test:	Failed @300V		
3. Dielectric Test:			
4. Insulation Resistance Test:	<200 MOhms		

OBSERVATION:

I Terminal Block Data

Teflon laminated shield, copper discolored.
Discolored terminal hardware.

Hi Z connection: Wire Number: W1178-Q143-20, 61B41178-3

Lo Z connection: Wire Number: 60B40037-807 LO C F58

Shield connection: Wire Number: W1178-Q143-20, 61B41178-3

Wire Clamp Position: Wire Number:

Clamp stud discolored.

II Length of probe

Airline: **PAL/ATLAS** Airplane Model: **747-2F6** Airplane Variable Number: **RD 412**

Nomenclature: **Compensator** Serial Number: **Q-348**

Boeing Part Number: **60B92010-62** Supplier Part Number: **HONEYWELL FG6C4**

Manufacturer Date: **8/79** Series: **3**

Drawing Number: Revision / Date:

Functional Test Date: **8/79** Installation Position: **F59** Tank Number: **M4**

PACKAGE/BOX MARKINGS	Tank Number:	F Number: F68
Tank Name:	Unknown Numbers: 0129 S/N228	

TESTING:

1. Dry Capacitance Test: 52.3 Pf
(Using A/P test equipment)

1a. Dry Capacitance Test:
(Using EQA test equipment

	Hi Z to Lo Z	Hi Z to Shield	Lo Z to Shield
2. Insulation Resistance Test:	20 Gigohms	15 Gigohms	20 Gigohms
3. Dielectric Test:	0.07 mA	0.18 mA	0.07 mA

OBSERVATION:

I Terminal Block Data

Discolored terminal hardware.
Two mechanical ferrules on HIZ exposed.

Hi Z connection: Wire Number: COMP GA HI Z F59 COMP GA HI Z F7\F59 60B40037-906 COMP GA LO Z

Lo Z connection: Wire Number: COMP GA HI Z F7\F59 60B40037-906 COMP GA LO Z

Shield connection: Wire Number: COMP GA HI Z F59 COMP GA HI Z F7\F59 60B40037-906 COMP GA LO Z

Wire Clamp Position: Wire Number:

Clamp stud dicolored.

II Length of compensator

Primer/ paint on outer tube.

Airline: **PAL/ATLAS** Airplane Model: **747-2F6** Airplane Variable Number: **RD 412**

Nomenclature: **Compensator** Serial Number: **Q-364**

Boeing Part Number: **60B92010-62** Supplier Part Number: **HONEYWELL FG6C4**

Manufacturer Date: **8/79** Series: **3**

Drawing Number: Revision / Date:

Functional Test Date: **8/79** Installation Position: **F60** Tank Number: **M4**

PACKAGE/BOX MARKINGS	Tank Number: R4	F Number: F78
Tank Name:	Unknown Numbers: 0108 S/N231	

TESTING:

1. Dry Capacitance Test: 52.4 Pf
(Using A/P test equipment)

1a. Dry Capacitance Test:
(Using EQA test equipment

Shield connection: Wire Number: W1180-Q152-20, 61B41180-5 W1180-Q153-20

Wire Clamp Position: Wire Number:

Clamp stud discolored.

II Length of probe

Airline: **PAL/ATLAS** Airplane Model: **747-2F6** Airplane Variable Number: **RD 412**

Nomenclature: **Fuel Probe** Serial Number: **Q-43**

Boeing Part Number: **60B92010-32** Supplier Part Number: **HONEYWELL FG420A32**

Manufacturer Date: **5/79** Series: **7**

Drawing Number: Revision / Date:

Functional Test Date: **6/79** Installation Position: **F66** Tank Number: **M4**

PACKAGE/BOX MARKINGS	Tank Number: 4	F Number: F66
Tank Name:	Unknown Numbers: 0132 S/N 215	

TESTING:

1. Dry Capacitance Test: 88.1 Pf *(Using A/P test equipment)*

1a. Dry Capacitance Test: *(Using EQA test equipment*

	Hi Z to Lo Z	Hi Z to Shield	Lo Z to Shield
2. Insulation Resistance Test:	30 Gigohms	27 Gigohms	35 Gigohms
3. Dielectric Test:	0.07 mA	0.09 mA	0.05 mA
4. Insulation Resistance Test:			

OBSERVATION:

I Terminal Block Data

Teflon laminated shield, copper discolored.
Discolored terminal hardware.
Perforations in both sleeves over ferrules

Hi Z connection: Wire Number: W1180-Q153-20, 61B41180-5 W1180-Q154-20

Lo Z connection: Wire Number: 60B40037-906 LO Z F14-F66

Shield connection: Wire Number: W1180-Q153-20, 61B41180-5 W1180-Q154-20

Wire Clamp Position: Wire Number:
Clamp stud discolored.

II Length of probe

Airline: **PAL/ATLAS** Airplane Model: **747-2F6** Airplane Variable Number: **RD 412**

Nomenclature: **Fuel Probe** Serial Number: **Q-44**

Boeing Part Number: **60B92010-30** Supplier Part Number: **HONEYWELL FG420A30**

Manufacturer Date: **8/79** Series: **7**

Drawing Number: Revision / Date:

Functional Test Date: **8/79** Installation Position: **F67** Tank Number: **M4**

PACKAGE/BOX MARKINGS	Tank Number: 4	F Number: F67
Tank Name:	Unknown Numbers: 0130 S/N 211	

Shield connection: Wire Number: W1562-unidentifiable Tape F82

Also connected to shield of compenstor F84

Wire Clamp Position: Wire Number:

Clamp stud discolored.

II Length of probe

Inner tube is out of round.

Airline: **PAL/ATLAS** Airplane Model: **747-2F6** Airplane Variable Number: **RD 412**

Nomenclature: **Compensator** Serial Number: **H-1088**

Boeing Part Number: **60B92010-62** Supplier Part Number: **HONEYWELL FG6C4**

Manufacturer Date: **1986** Series: **3**

Drawing Number: Revision / Date:

Functional Test Date: **1986** Installation Position: **F84** Tank Number: **R2**

PACKAGE/BOX MARKINGS	Tank Number: M4	F Number: F69
Tank Name:	Unknown Numbers: 0131 S/N 231	

TESTING:

1. Dry Capacitance Test: 55.1 Pf *(Using A/P test equipment)*

1a. Dry Capacitance Test: *(Using EQA test equipment*

	Hi Z to Lo Z	Hi Z to Shield	Lo Z to Shield
2. Insulation Resistance Test:	17 Gigohms	13 Gigohms	17 Gigohms
3. Dielectric Test:	0.08 mA	0.34 mA	0.08 mA
4. Insulation Resistance Test:			

OBSERVATION:

I Terminal Block Data

All terminal hardware appears clean.
No heat shrink sleeving on mechanical all ferrules.
Termination at HIZ has broken wires and insulation not captured in the terminal lug.

Hi Z connection: Wire Number: COMP GA HI Z F84 W1562-Q1267 COMP GA HI Z F84, COMP GA LO Z
Also connected to HIZ on Probe F83.

Lo Z connection: Wire Number: COMP GA HI Z F84, COMP GA LO Z

Shield connection: Wire Number: COMP GA HI Z F84 W1562-Q1267 COMP GA HI Z F84, COMP GA LO Z
Also connected to shield on Probe F83.

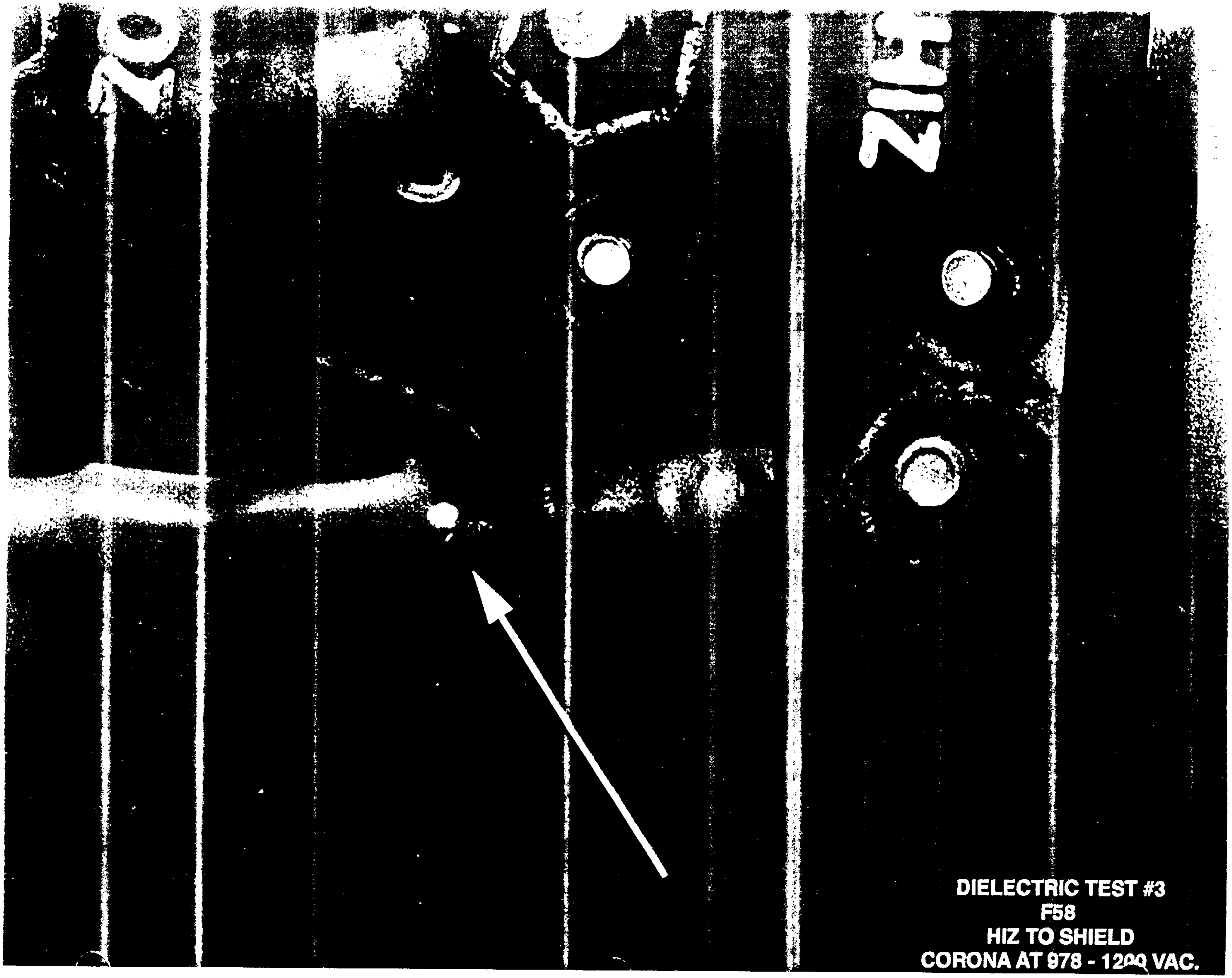
Wire Clamp Position: Wire Number:
Clamp stud clean.

II Length of compensator

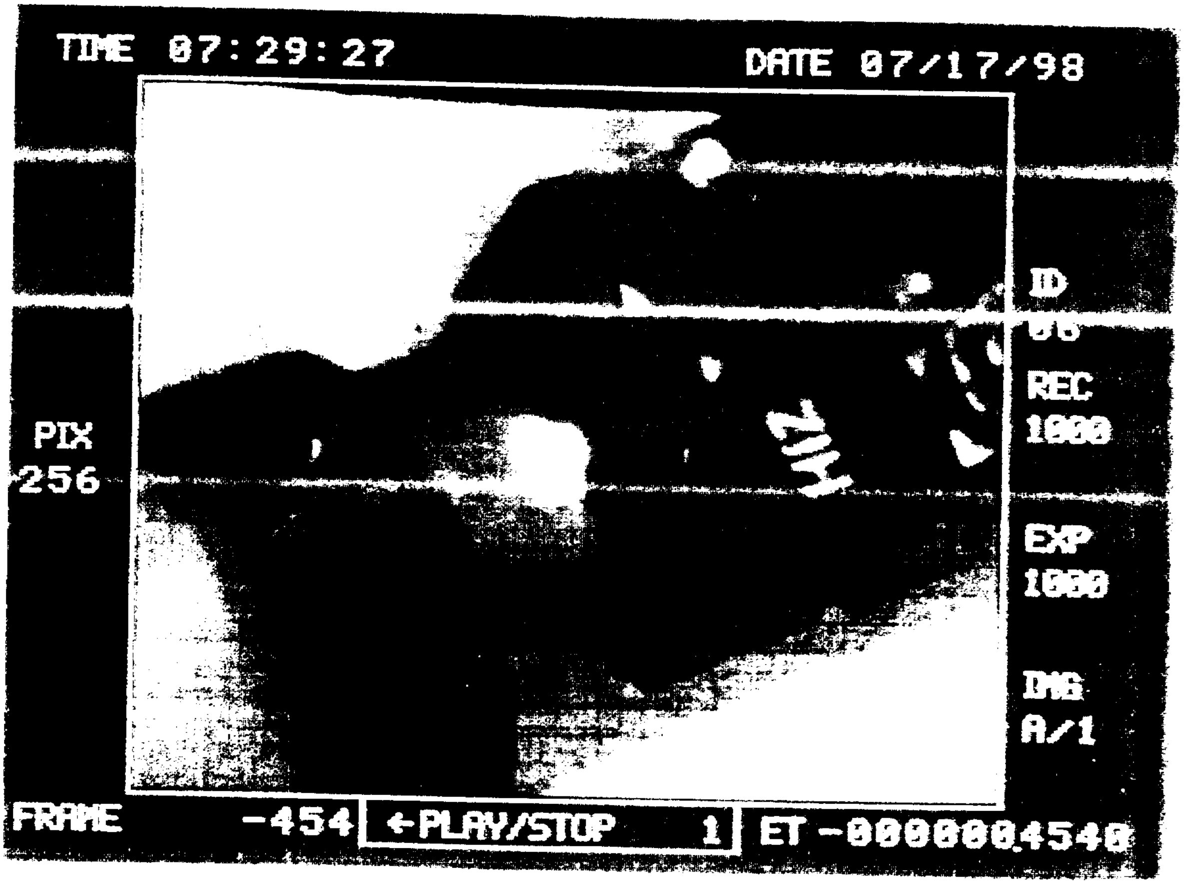
Paint\primer on inner and outer tube.

Airline: **PAL/ATLAS** Airplane Model: **747-2F6** Airplane Variable Number: **RD 412**
Nomenclature: **Fuel Probe** Serial Number: **H-0166**
Boeing Part Number: **60B92010-66** Supplier Part Number: **HONEYWELL FG420A66**
Manufacturer Date: **8/86** Series: **2**
Drawing Number: Revision / Date:
Functional Test Date: **8/86** Installation Position: **F85** Tank Number: **R2**

PACKAGE/BOX MARKINGS	Tank Number: R4	F Number: F79
Tank Name:	Unknown Numbers: 0110 S/N 229	



DIELECTRIC TEST #3
F58
HIZ TO SHIELD
CORONA AT 978 - 1200 VAC.



EQA-561R
PHOTOGRAPHS

ANALYTICAL ENGINEERING REPORT

TO:	J. R. Hulm	04-JU	**NO.:**	9-5576-WP-98-135
CC:	R. S. Breuhaus	0T-72	**ITEM NO.:**	Chem 6533
	S. M. Hatch	0T-62		
	R. J. Lidicker	04-JU	**DATE:**	May 15, 1998
	J. D. Rodrigues	67-PR		
	E. M. Sedenquist	02-EL	**MODEL:**	747

GROUP INDEX: 9-5576 - Analytical Engineering, Chemical/Physical

SUBJECT: Mechanical Removal of Sulfur-Bearing Deposits from FQIS Hardware

REFERENCE: Analytical Engineering Report 9-5576-WP-98-127, Trip Report – Meetings at NTSB Office, April 28 & 29, 1998

BACKGROUND

Air Force personnel report instances in which malfunctioning fuel quantity indicating system (FQIS) components have been restored to proper function by mechanically cleaning them with a brush wetted with isopropyl alcohol (IPA) (Reference). The cleaning operation is believed to remove sulfur-bearing deposits that form on insulating surfaces in service, thereby lowering insulation resistance. In order to evaluate the practicability of the method for treating FQIS components *in situ*, five components with attached wiring from the ship-set removed from airplane RD412 (Atlas) were selected for testing. The purposes of the testing were to visually determine the effectiveness of mechanically cleaning the surfaces and to quantify effects on electrical properties.

CONCLUSIONS

Mechanical cleaning using a nylon brush wetted with IPA solvent, followed by rinsing with IPA, effectively removes much but not all deposit build-up from wire insulation and other exposed surfaces. Cleaning increased insulation resistance (IR) by more than a factor of two in most instances. Dielectric withstanding voltage (DWV) remained essentially unchanged in all but two instances, where modest increases in leakage current were measured. These results provide justification for considering mechanical cleaning as a means of removing deposits that have formed in service. Removal of discolored or damaged heat shrink sleeving might also be considered, since deposits covered by the sleeving could then be removed as well.

EXPERIMENTATION AND RESULTS

The five FQIS probes selected from airplane RD412 (Atlas), listed in Table 1, included two compensators and three probes. The probes were photographed prior to and after cleaning. Cleaning was accomplished by brushing the terminals, wire insulation and connections with a soft nylon bristle brush wetted with IPA, followed by rinsing with a stream of clean IPA.

Views of the parts prior to and following cleaning are presented in Figures 1 through 10. Improvement in appearance at some locations, particularly on the wire insulation, is obvious in every instance. It is also clear that not all discoloration was removable, even from the wire insulation. Nor was it possible to significantly alter the appearance of the heat shrink sleeving.

IR and DWV were measured using a Vitrek 844i Dielectric Tester. Insulation resistance was measured at 500 volts DC. DWV was measured at 1500 volts AC, with a maximum allowable leakage current of 0.5 milli-Amp. Results are presented in Table 2, where values before cleaning represent measurements made at the time the entire ship-set of FQIS components was first characterized. Note that insulation resistance values improved in every case, and by a factor of 2 or more in all but one instance. Dielectric values were essentially unchanged in all but two instances (emboldened). In those two cases, leakage current increased slightly, but remained well below the specified 0.5 milli-Amp limit.

These results indicate that mechanical cleaning will remove deposits sufficiently to improve insulation resistance without damaging the parts.

Prepared by D. Bruce Skoropinski
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Approved by
W. L. Plagemann
M/S 73-09, 234-3025

Electrical Characterization:	J. I. Murphy
Photography:	J. A. Brewer

Table 1. Listing of Hardware Selected for Evaluation of the Effects of Mechanical Cleaning

Probe #	Location
F45 (Compensator)	No. 3 Main
F59 (Compensator)	No. 4 Main
F61	No. 4 Main
F76	No. 4 Main
F79	No. 4 Main

Table 2. Insulation Resistance and Dielectric Withstanding Voltage of the Test Hardware Prior to and Following Mechanical Cleaning

	F45		F59		F61		F76		F79	
	Before	After	Before	After	Before	After	Before	After	Before	After
Insul. Resistance (G-Ohm):										
Hi-Z to Shield	13	26	15	36	17	34	22	61	14	29
Lo-Z to Shield	17	52	20	31	26	57	23	88	17	56
Hi-Z to Lo-Z	17	60	20	62	25	56	22	69	18	54
Dielectric (milli-Amp):										
Hi-Z to Shield	0.26	0.27	0.18	0.18	0.07	**0.18**	0.07	0.07	0.07	**0.22**
Lo-Z to Shield	0.06	0.06	0.07	0.07	0.06	0.06	0.05	0.04	0.05	0.06
Hi-Z to Lo-Z	0.06	0.06	0.07	0.07	0.07	0.06	0.07	0.06	0.05	0.06

Figure 1. Terminations on compensator F45 before mechanical cleaning (4.4X).

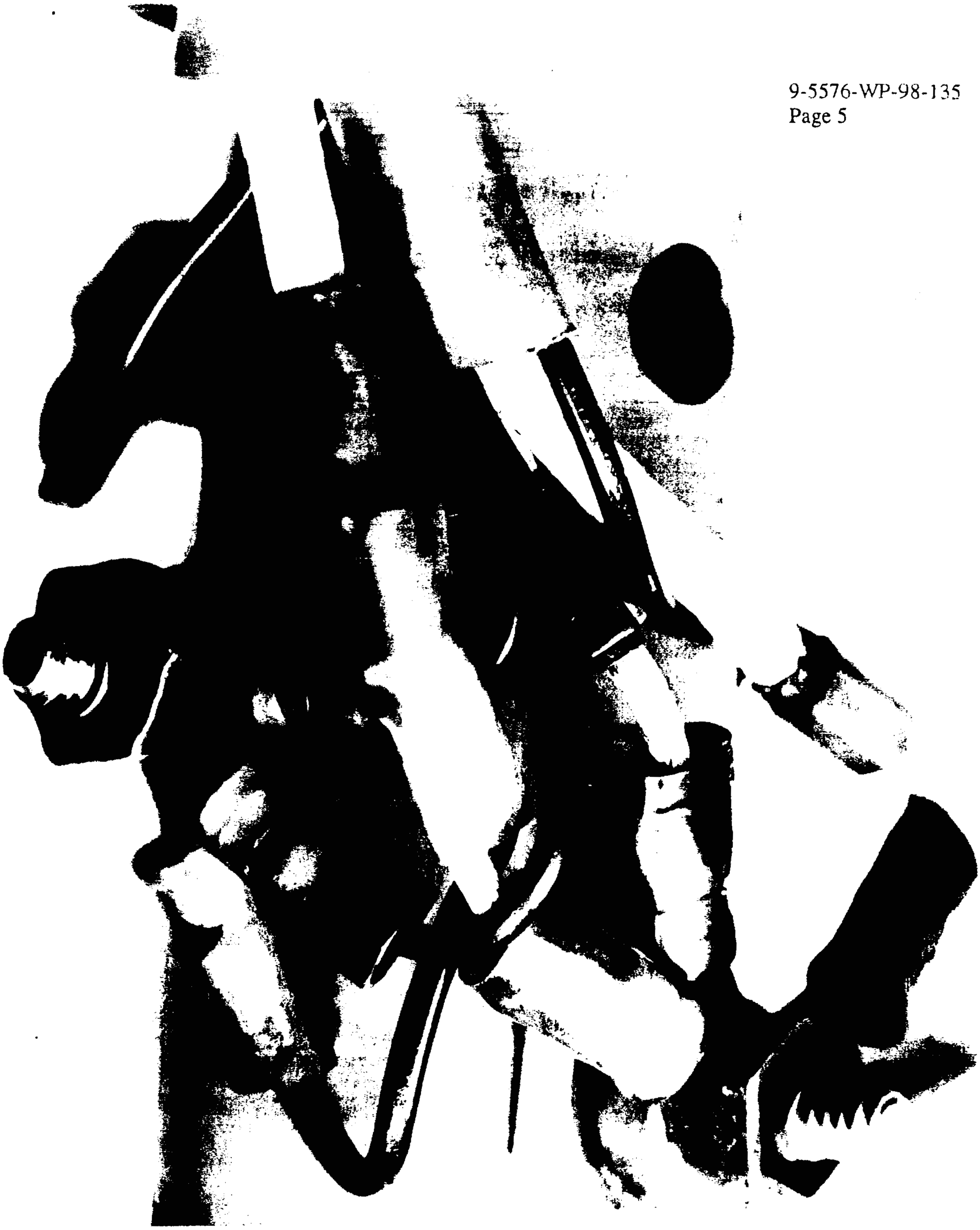

Figure 2. Terminations on compensator F45 after mechanical cleaning (4.4X).

Figure 3. Terminations on compensator F59 before mechanical cleaning (4.2X).

Figure 4. Terminations on compensator F59 after mechanical cleaning (4.2X).

Figure 5. Terminations on probe F61 before mechanical cleaning (3.7X).

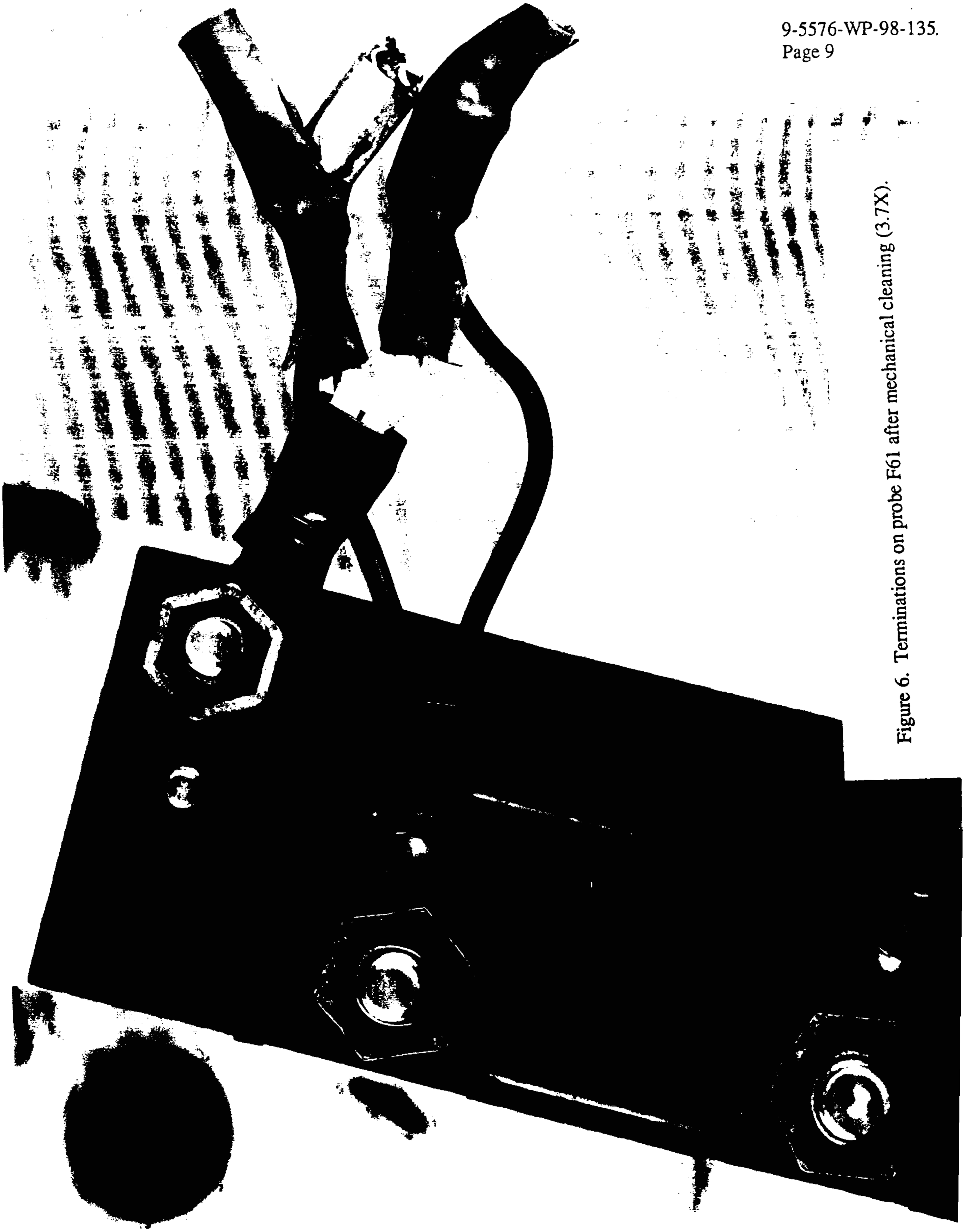

Figure 6. Terminations on probe F61 after mechanical cleaning (3.7X).

Figure 7. Terminations on probe F76 before mechanical cleaning (4.4X).

ANALYTICAL ENGINEERING REPORT

TO: T. M. Mitchell 04-JU

CC:

NO.: 9-5576-WP-97-329

ITEM NO.: Chem 6007

DATE: September 17, 1997

MODEL: 747 Fuels

GROUP INDEX: 9-5576 - Analytical Engineering, Chemical/Physical

SUBJECT: Immersion Testing of Two Fuel Quantity Tank Units

REFERENCE: Analytical Engineering Report 9-5576-WP-97-272, Analysis of Fuel Quantity Tank Units for Copper Sulfide

BACKGROUND

Two fuel tank quantity units previously analyzed for copper sulfide (Reference) have, respectively, completed a one month exposure to Jet A with an elevated sulfur concentration and to Puget Sound sea water. Tank unit F41 was selected for the fuel exposure. No electrical arcing was observed to have occurred during previous testing of tank unit F41, but the laminated copper film in the shield assembly of that unit had been nearly uniformly blackened. In order to preserve the blackened shield laminate for further study in the event that it was discovered to be significant, the shield assembly from F42, which had experienced very minimal arcing, was installed on F41 for the immersion test. Unit F44, with minor arc damage to its shield and outermost tube, was selected for exposure to sea water.

CONCLUSIONS

The electrical properties of fuel quantity tank unit F41 (with the shield assembly from F42) were found to have remained within what appear to be acceptable bounds in spite of the month long exposure to fuel with a high concentration of sulfur. Sulfur compounds of silver, copper and cadmium were present on the terminal assembly, as expected. The sulfur appeared to also have reacted to a slight degree with the laminated copper shield at some locations. If further exposure testing is desired, immersion of a source of additional copper in the test vessel is recommended in order to accelerate the formation of conductive paths, if possible, and to more accurately represent the condition internal to a fuel tank.

Components of the terminal assembly of fuel quantity tank unit F44 were found to have corroded due to exposure to the Puget Sound sea water. Copper sulfide was still present on the Hi-Z terminal block, as it had been prior to immersion in sea water. but additional deposits had formed and the laminated copper shield had been substantially darkened. Electrical arc damage that was present on the assembly prior to immersion was still visible at the end of the exposure test.

EXPERIMENTATION AND RESULTS

The fuel quantity tank units were immersed to a depth sufficient to fully cover the terminal block assemblies. Following immersion, the unit that had been immersed in fuel was characterized electrically. Both units were inspected optically and disassembled for further inspection. Samplings of deposits were characterized chemically.

Tank Unit F41 - High Sulfur Fuel Exposure. Powdered elemental sulfur was mixed with U.S. Oil Jet A fuel at the rate of 0.30 percent by weight, which is the maximum allowable sulfur content for Jet A as listed in ASTM D1655. The sulfur dissolved slowly, and a small quantity remained undissolved at completion of the test. The sulfur-laden fuel and test article remained at ambient conditions of temperature and humidity throughout the test. The tank unit was to be removed from test for an interval of roughly two hours twice daily, excluding weekends, for the duration of the test. Due to manpower difficulties, that schedule was not strictly followed, adding an element of randomness to the cycling. Twenty-one cycles were recorded on the daily log, reported here as Table 1.

The terminal assembly, shown in Figure 1, did not appear to have been significantly changed by the testing. Nor had the individual terminal blocks, which were removed for inspection. Copper within the laminated shield had darkened at some locations where sulfur might have gained entry (Figures 2 and 3).

The capacitance of F41 was determined using an Andeen Hagerling Model 2500A Ultra-Precision Capacitance Bridge. Dielectric properties at 225 VAC were determined for a one minute duration with a Vitrek 944i Dielectric Analyzer; and the insulation resistance was determined at 225 VDC with the Vitrek 944i, also over a one minute duration. Lower than standard test voltages were selected to preclude the possibility of inducing arcing during testing. Results, presented in Table 2, do not indicate that exposure to the fuel was detrimental to the probe. Certainly no paths for leakage current were created by the exposure. Inclusion of wiring or other copper components would likely provide a more realistic scenario for a long-term study, however, since the tank unit itself has no immediate source of copper (for formation of conductive paths based on copper sulfide) other than that which had previously been deposited on the terminal blocks in service.

Electron microprobe elemental surveys of samplings of dark deposits from the Hi-Z terminal block and from a silver-plated nut associated with that terminal block are presented in Figure 4. These data are essentially consistent with past analyses, confirming that sulfur compounds are present on the terminal block assembly and that copper from (in service) sources within the fuel system has been deposited there.

Tank Unit F44 - Puget Sound Sea Water Exposure. The terminal assembly on F44 was continuously immersed in Puget Sound sea water from 3:00 p.m. on August 5 until 2:00 p.m. on September 2. As shown in Figure 5, corrosion of the terminal blocks occurred during the exposure. The Lo-Z outer tube with the terminal assembly removed is shown in Figure 6, and the shield is shown in Figure 7. Note that the laminated copper shield was damaged and darkened by the exposure. Note also that the arc damage that was present prior to the exposure was still evident (Figures 6-8). Figure 9 shows the Hi-Z terminal block as it appeared before and after the sea water exposure. Note that black deposits were still visible after the exposure, but that additional deposits had formed. The orange deposits were found to be rich in iron, sodium and chlorine; and the blue deposits contained copper, sodium, and magnesium. Electron microprobe elemental surveys of dark deposits sampled from the Hi-Z terminal block prior to and after the exposure, presented in Figure 10, show that copper-sulfur compounds were still present on the part.

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W. L. Plagemann
M/S 73-09, 234-3025

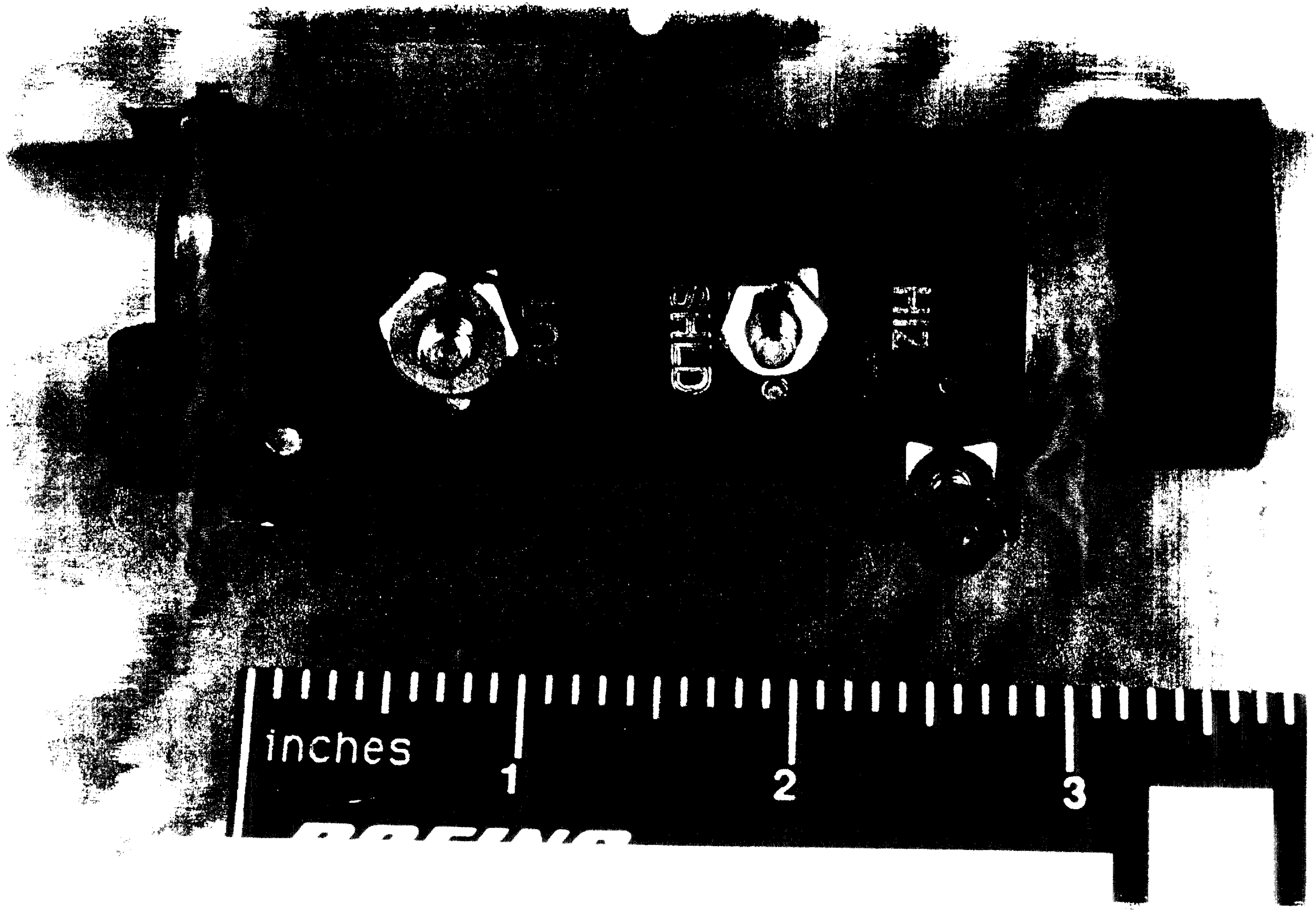
Electron Microprobe Analysis: J. C. Wessel
Photography: J. A. Brewer

Table 1. High-Sulfur Fuel Immersion Test for Tank Unit F41:
Daily Schedule for Removal from Fuel, Exposure to Atmosphere

	First Daily Cycle			Second Daily Cycle		
Date	Time Out	Time In	Duration (hrs.)	Time Out	Time In	Duration (hrs)
8/5/97 (Begin Test)					1: 00 p.m.	
8/11/97	10:00 a.m.	12:00 p.m.	2:00	1:00 p.m.	2:55 p.m.	1:55
8/12/97	6:40 a.m.	8:40 a.m.	2:00	11:00 p.m.	2:02 p.m.	3:02
8/13/97	7:00 a.m.	9:20 a.m.	2:20	12:42 p.m.	2:45 p.m.	2:03
8/14/97	6:05 a.m.	8:05 a.m.	2:00	9:25 a.m.	11:25 a.m.	2:00
8/15/97	11:00 a.m.	2:30 p.m.	3:30			
8/18/97	2:00 p.m.	3:40 p.m.	1:40			
8/19/97	9:40 a.m.	11:50 a.m.	2:10			
8/20/97	7:10 a.m.	3:00 p.m.	7:50			
8/21/97	9:15 a.m.	11:15 a.m.	2:00			
8/22/97	6:45 a.m.	9:00 a.m.	2:15	12:35 p.m.	2:45 p.m.	2:10
8/27/97	6:20 a.m.	8:20 a.m.	2:00			
8/28/97	5:40 a.m.	7:40 a.m.	2:00	9:00 a.m.	10:35 a.m.	1:35
8/29/97	5:30 a.m.	7:40 a.m.	2:10	11:30 a.m.	3:20 a.m.	3:50
9/2/97	5:40 a.m.	7:40 a.m.	2:00	12:05 p.m., Test Complete		

Table 2. Capacitance, Insulation Resistance and Dielectric Properties
of Fuel Quantity Tank Unit F-41 (with Shield from F-42) after High Sulfur Fuel Exposure

Measurement	F-41/42
Capacitance (pico-Farads):	192.9
Dielectric (leakage current, micro-amps):	
Hi-Z to Lo-Z	16 to 17
Hi-Z to Shield	5.05
Lo-Z to Shield	5.75
Insulation Resistance (giga-ohms):	
Hi-Z to Lo-Z	3.8
Hi-Z to Shield	7 to 11
Lo-Z to Shield	7 to 11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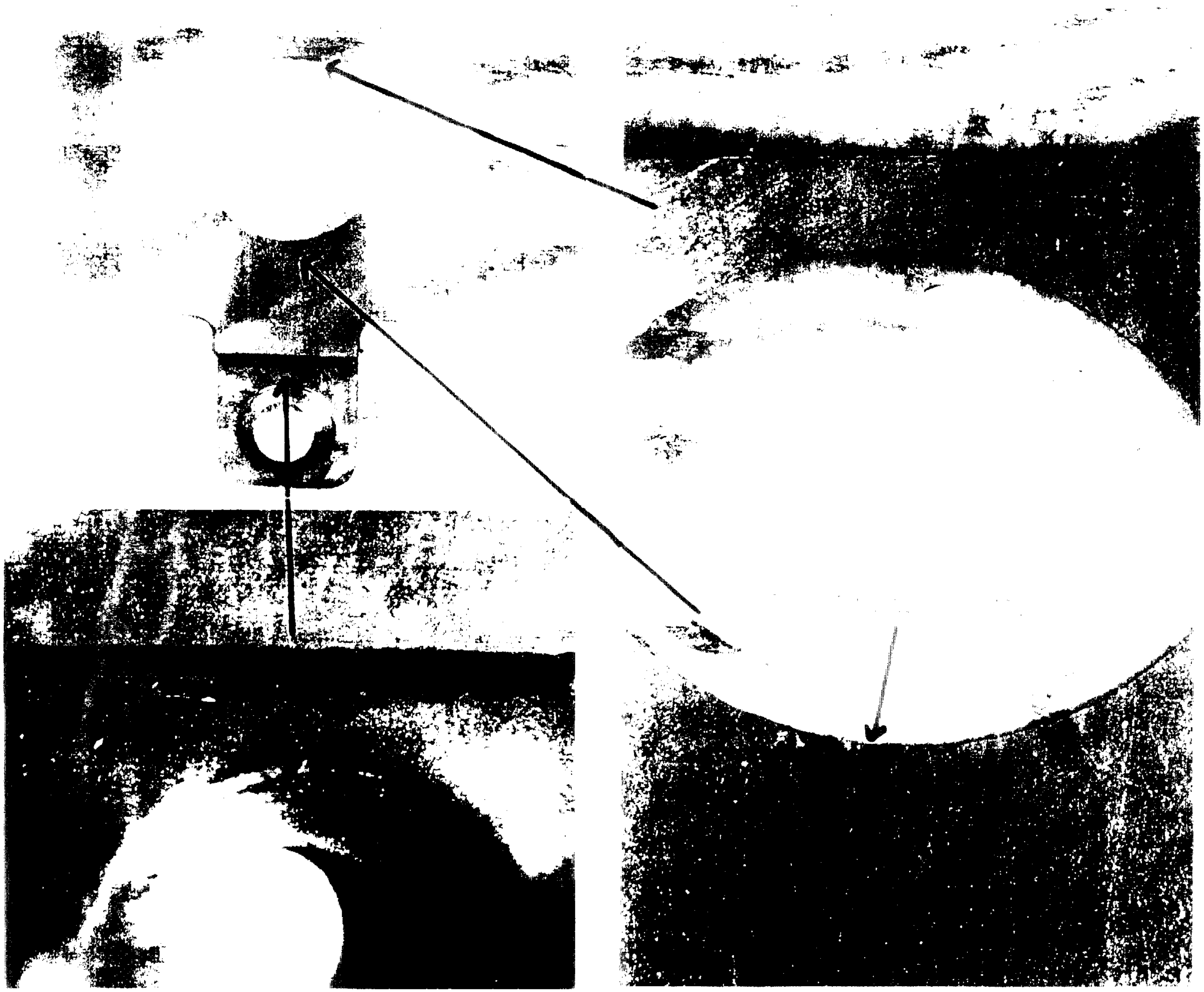

Figure [illegible] copper shield from the [illegible] was used in the [illegible]

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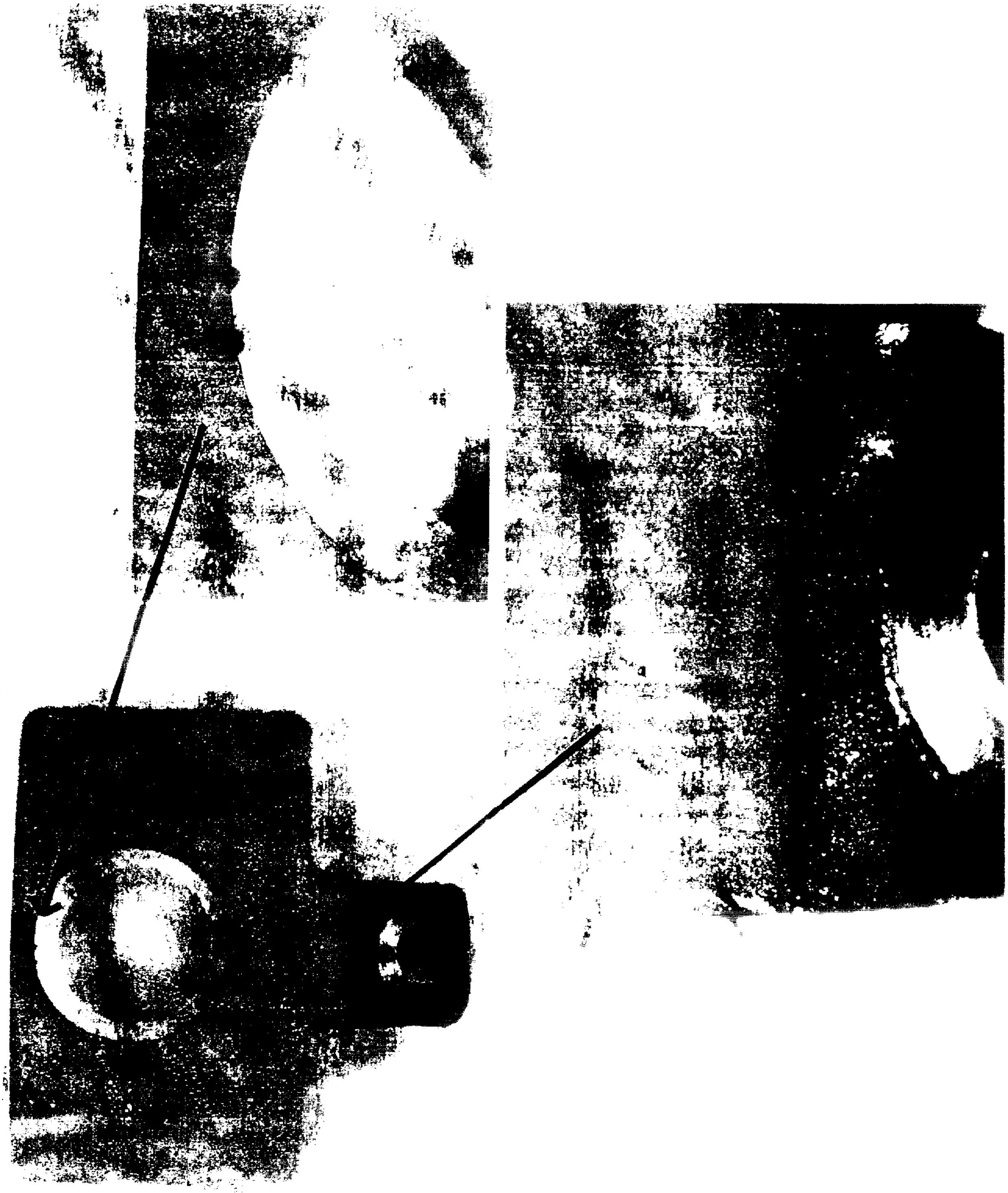

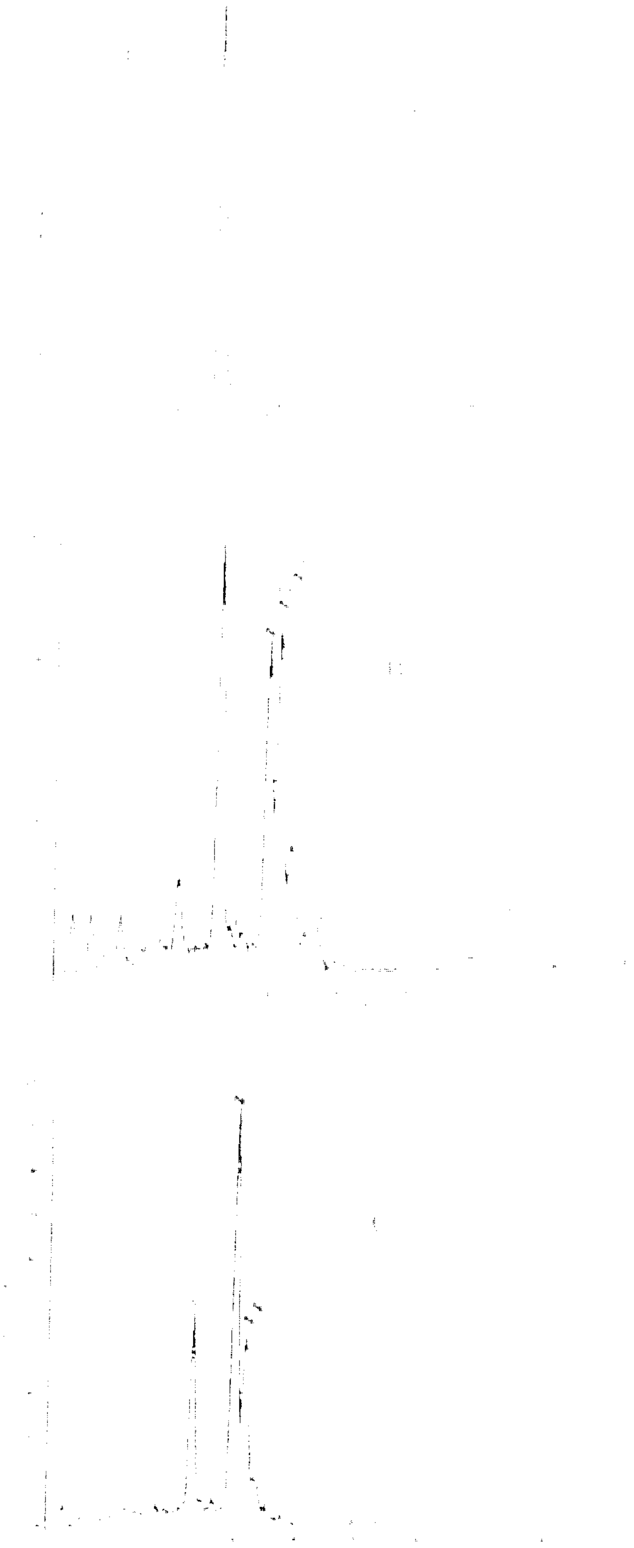

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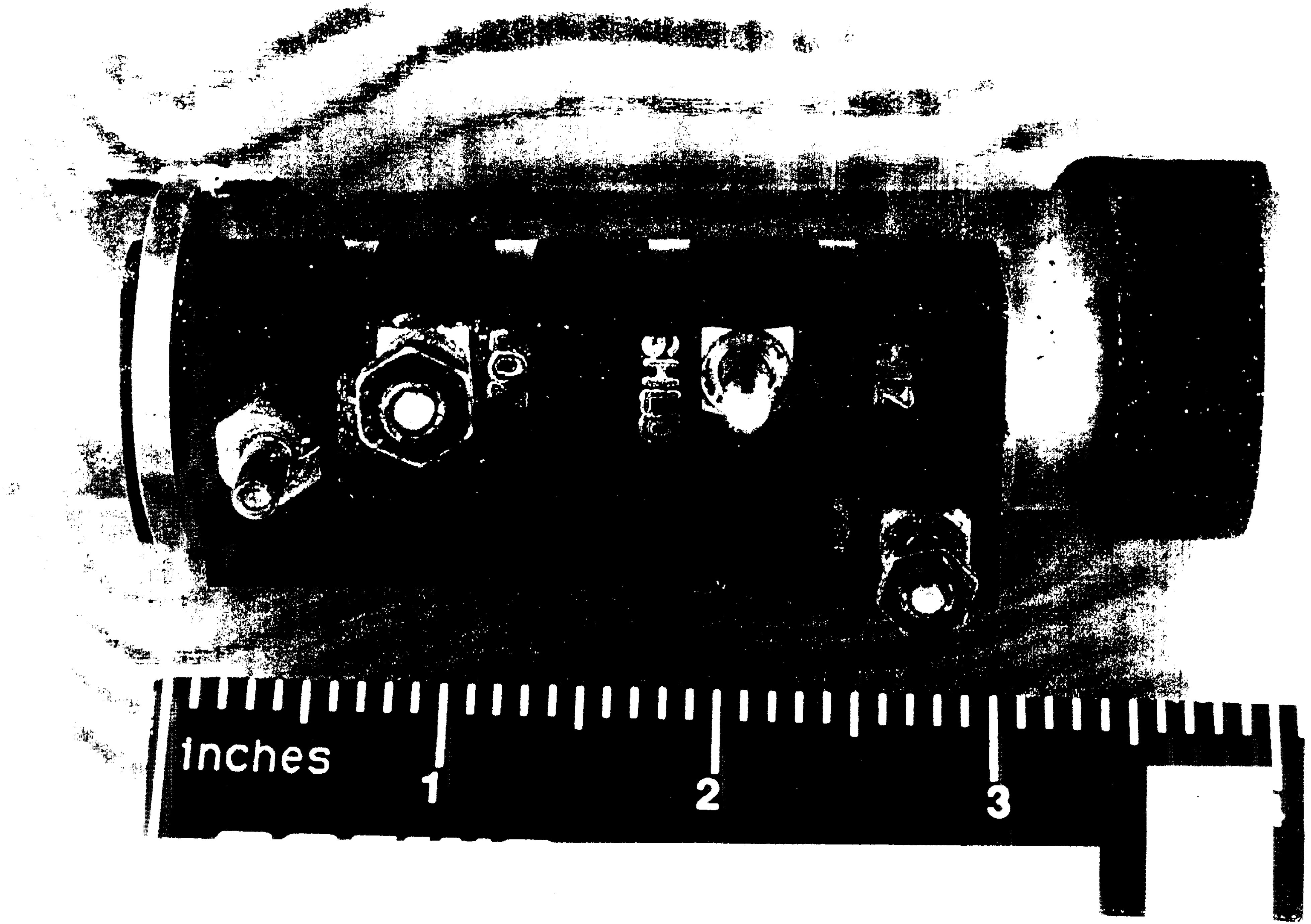
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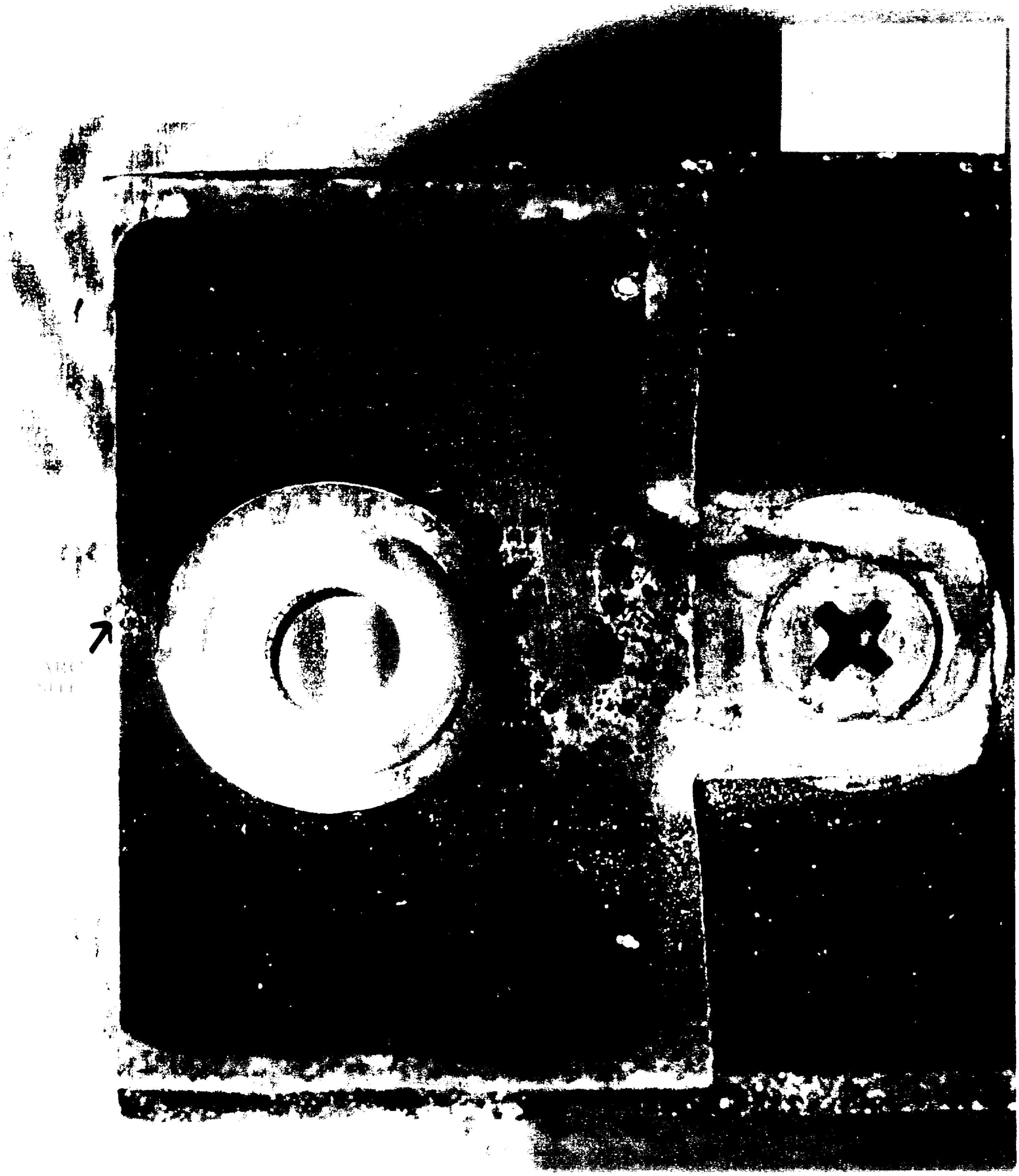

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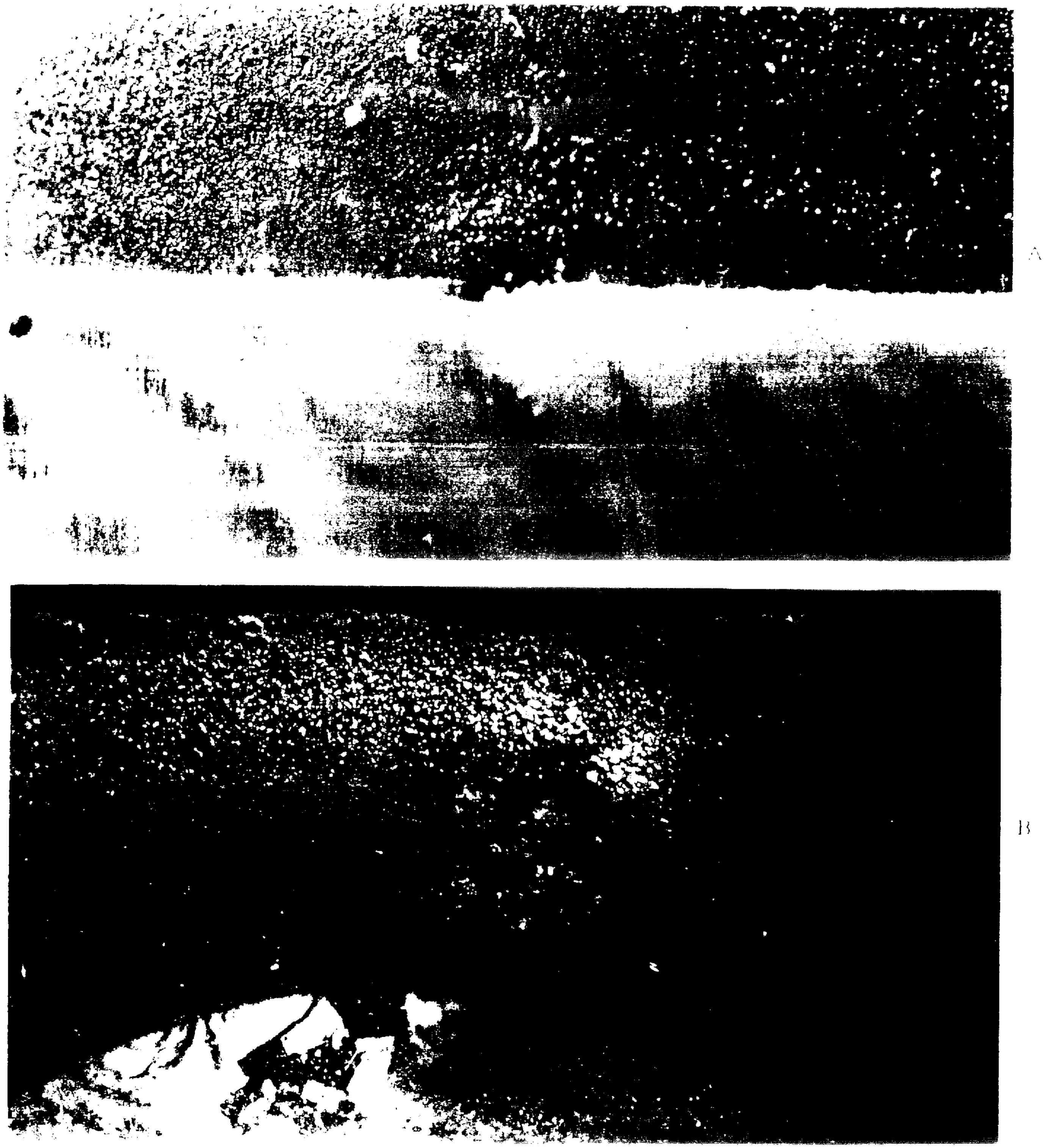
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ANALYTICAL ENGINEERING REPORT

TO:	J. R. Hulm	04-JU	**NO.:**	9-5576-WP-98-136
CC:	R. J. Lidicker J. D. Rodrigues	04-JU 67-PR	**ITEM NO.:**	Chem 6533
			DATE:	May 20, 1998
			MODEL:	747

GROUP INDEX: 9-5576 - Analytical Engineering, Chemical/Physical

SUBJECT: Sulfide Deposits - Recommendations for Testing

REFERENCE: Analytical Engineering Report 9-5576-WP-98-127, Trip Report – Meetings at NTSB Office, April 28 & 29, 1998

BACKGROUND

The NTSB has requested input regarding recommendations for additional analysis and testing of the properties of sulfur-bearing deposits that form on some airplane fuel system hardware in service (Reference). The following are offered in response to this request.

RECOMMENDATIONS

The following topics are suggested for additional investigation:

(1) Additional chemical characterization of the deposits
(2) Effect of humidity on electrical properties of deposits
(3) Effect of the presence or absence of liquid fuel and fuel vapor on the electrical properties of deposits
(4) Effect of reduced pressure (altitude) on electrical properties of deposits
(5) Effect of applied voltage on rate and geometry of deposition

DISCUSSION

Chemical Characterization. Better chemical characterization would enable improved modeling of deposits using reagent chemicals. Modeling using reagents might prove to be important in light of the fact that examples of service hardware exhibiting anomalous behavior will be limited in number, and should be tested with caution to avoid loss of information. Suitable synthetic mixtures mimicking behavior of authentic deposits could greatly expand the scope of testing that could be accomplished, since test set-up and development could be carried out solely with the model material.

Preliminary tests with reagents indicate that copper (I) sulfide (Cu_2S) is not a conductive material, but that copper (II) sulfide (CuS) conducts quite well. In the preliminary test, reagent sulfide powders were placed on one-inch Teflon® squares in a strip about 1/8 to 1/4 inch wide. The strip of powder was flattened slightly with a scalpel blade, and a few drops of Frekote spray silicone release agent were added to help the powder remain immobile on the Teflon®. Test leads terminated with alligator clips were attached to the edges of the sample squares so that each contacted one end of the powder strip. Using a Vitrek 944i Dielectric Tester, the insulation resistance (IR) across the Cu_2S was measured to be 121 GΩ at 500 VDC. The IR test failed on the CuS, with an over-current condition occurring at 93 VDC during the voltage ramp (test conditions were a 100 Volt per second ramp with a 1 MΩ minimum resistance allowed). Dielectric withstanding voltage (DWV) was measured with the same instrument. At 1500 VAC, an acceptable leakage current of only 5 μamp was measured across the Cu_2S, but the test failed due to over-current at less than 20 volts when the CuS was tested.

Previous analyses have revealed that copper and sulfur are the main constituents of the deposits in most instances. Knowing if CuS is present in the deposits and at what percentage could prove to be particularly important in developing a reagent model. It might also be useful to know if and how much sulfate is present, what particular silver compounds are common, and if ammonium or other salts have formed. X-ray diffraction is recommended if enough deposit can be collected from service hardware to accomplish the analysis. If the deposits are crystalline rather than amorphous, X-ray diffraction should provide information as to the specific identity and oxidation state of the chemical components. If insufficient sample is available or results are inadequate, chemical spot tests to try to confirm the presence of sulfide, sulfate and ammonium are recommended as well.

In general, surface analysis (X-ray photoelectron spectroscopy or XPS, Auger electron spectroscopy and secondary ion mass spectroscopy or SIMS) is not recommended for this problem. There are exceptional instances where these methods might prove to be useful, such as the terminal strip that was analyzed by XPS and SIMS under the direction of the NTSB (Reference). In that case, the deposits affected electrical performance even though they consisted of a thin film, and insufficient sample was present for energy dispersive X-ray spectroscopy (which examines the sample to a depth of about 1 to 2 μm) or other relatively "bulk" techniques.

True surface techniques examine only the outermost several molecular monolayers, providing chemical information to a depth of only 5 to 10 nanometers. Most materials that have been exposed to environment for any length of time will yield a fairly strong carbon signal due to organic compounds that are adsorbed from atmosphere. Samples that have been handled or that have resided in the vicinity of lubricants will typically have an even stronger carbon signal. In either case, brief to lengthy sputtering with an argon ion beam to expose the surface of interest is usually required. For a sample that has been in a fuel environment, many organic and other compounds that are unrelated to the deposits or their harmful effects are expected to be detectable by surface analysis, and will likely confuse results.

Effects of Environment. IR and DWV measurements through deposits are recommended under varying conditions of relative humidity, in the presence and absence of liquid and vapor phase fuel, and at pressures representing expected airplane altitude cycling. If possible, modeling using a synthetic reagent matrix should be carried out prior to testing service hardware. These tests will provide a comparison of electrical properties of deposits under various potential service conditions with values obtained in an ambient laboratory environment, shedding additional light on voltage required to precipitate an electrical discharge through the deposits. Humidity and altitude testing can be done in ordinary environmental chambers, but suitable protected equipment will be necessary for testing in the presence of fuel.

Effects of Applied Voltage. This would be a long-term test with doubtful results. To be successful, an accelerated means of generating deposits representative of those that form in service would be required. A considerable method development effort would probably be involved. However, knowing whether or not applied voltage augments deposit formation, and if voltage affects location of deposition, could be key in decisions regarding rework and future design.

Prepared by D. Bruce Skoropinski
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Approved by
W. L. Plagemann
M/S 73-09, 234-3025

IR and DWV Experiments: J. I. Murphy

ANALYTICAL ENGINEERING REPORT

TO: T. M. Mitchell	49-57	**NO.:**	9-5576-WP-97-318
CC:		**ITEM NO.:**	Chem 6112
		DATE:	September 2, 1997
		MODEL:	747

GROUP INDEX: 9-5576 - Analytical Engineering, Chemical/Physical

SUBJECT: Analysis of Fuel Compensator P/N 60B92010-62, S/N W-180

BACKGROUND

The subject compensator, stamped with manufacture and functional test dates of October, 1973, was submitted for inspection for evidence of electrical arcing and identification of contaminants/deposits. Determination of the capacitance, insulation resistance and dielectric properties was also requested, but with the test potential limited to 225 volts to avoid inducing arcing during test.

CONCLUSIONS

No evidence of electrical arcing was found at any location on the compensator. Deposits under and around the terminal block consisted of machining fragments of a 2000-series aluminum alloy and a variety of other particles, including at least one fragment of a corrosion-resistant steel alloy. Deposits/corrosion products at most other locations on the terminal block assembly and on internal connections were composed of the sulfides of copper, cadmium and silver. Tin was also present in some deposits, as was a relatively low concentration of organic constituents. Sleeving around crimped wire terminals that attached to the Lo-Z and Hi-Z tubes appeared to have rubbed against the interior of the shield tube to generate wear debris. However, analysis revealed that deposits at those sites did not consist of wear debris, but were instead composed primarily of copper sulfide, where the copper most probably originated from the wire strands.

No measurable conductive path existed between the shield and the terminals to the Lo-Z and Hi-Z tubes, in spite of the copper sulfide deposits on and around the sleeving. The capacitance of the compensator was measured to be 0.03 pico-Farads greater than the specification upper limit of 53.16 pF. The Hi-Z-to-shield insulation resistance and dielectric leakage current were somewhat anomalous, although the insulation resistance was still in the mega-ohm range (see Table 1). These results suggest that additional disassembly and inspection might be of value.

EXPERIMENTATION AND RESULTS

The part was inspected optically, then disassembled for further inspection for arc damage or other anomalies. Samplings of contaminants/deposits were analyzed by infrared microspectroscopy and/or electron microprobe.

Optical Inspection for Electrical Arc Damage. Upon disassembly, a good deal of metallic debris was found under the terminal block assembly (Figure 1). Although the reflective character of the metallic particles suggested the possibility of arc damage, closer examination revealed particulate metallic debris at the reflective locations. At magnifications up to 50X, no evidence of electrical arcing was observable at any location.

Identification of Deposits - Exterior Surfaces. The general debris (gray deposits) indicated in Figure 1B is represented by the electron microprobe elemental survey in Figure 2A, which shows that it consists of a complex mixture of particulate material. Individual metallic particles were lifted from each of the locations shown in Figure 1B, C and D for identification by electron microprobe. All but one particle were identified as a 2000-series aluminum alloy such as 2024 (Figure 2B). The single exception was identified as a corrosion-resistant steel alloy (2C). An electron micrograph of a grouping of the metallic particles, presented in Figure 3, indicates that they consist primarily of machining debris.

Orange deposits were present on the surface of the polytetrafluoroethylene (PTFE) insulator sheet that mated to the underside of the terminal assembly (Figure 4A). The associated electron microprobe elemental survey (4B) is indicative primarily of cadmium sulfide. Although cadmium sulfide does not absorb appreciably in the mid-infrared spectral region, the infrared spectrum of the substance (4C) had several distinct absorptions. The methyl/methylene functional group stretching absorptions (2800 to 3000 wavenumbers) were not decreased by rinsing the deposit with solvent, indicating that an organic component is included in the orange substance. The bands near 1450 and 1550 wavenumbers together are probably indicative of a carboxylate salt generated by reaction of the cadmium (most likely plating on the bolt) with a carboxylic acid. The native carboxylic acid content of fuel is expected to be negligible, but carboxylic acids are known metabolic by-products of organisms that sometimes exist particularly in any water phase in fuel tanks. The absorption near 1100 wavenumbers in 4C indicates the presence of sulfate.

Results similar to those in Figure 4 were obtained for orange deposits at other locations on the terminal block assembly (Figure 5A). Dark deposits on the terminal blocks consisted primarily of copper sulfide (5B), while the small (silver-plated) nuts used to mount the terminal blocks to the assembly were coated with silver sulfide (5C).

Identification of Deposits - Internal to Tubes. Other anomalies were observed on the interior surfaces of the compensator unit. A streak of gray material was present on the innermost (shield) tube where a plastic mounting bracket was attached to the tube (Figure 6A). Analysis indicated that the gray substance consisted primarily of aluminum wear product (6B), but further disassembly to expose the edge of the tube would be required to confirm that. The origin of the low concentration of lead in the gray deposit (indicated in 6B by the width of the overlapping sulfur peak and confirmed by wavelength dispersive X-ray spectroscopy) has not been determined. The Delrin plastic bracket material was not detectable in the deposit.

Corrosion was present where shielding for the wiring to the Hi-Z terminal connected to the interior of the shield tube (Figure 7A). Sulfides of copper and possibly of tin were indicated (7B). Corrosion was also present on internal connections at the end of the compensator opposite the terminal block (Figure 8A and B). Again, sulfides of copper, cadmium and silver were detected, as was some tin. Note in 8C and D that the red sleeving appeared to have rubbed against the interior surface of the shield tube to generate deposits (the connection to the Lo-Z tube appeared to still be in contact with the interior of the shield tube, while the sleeving associated with the Hi-Z connection did not). However, results for samplings lifted from the interior of the tube and from the sleeve were indicative primarily of copper sulfide, a small quantity of organic material and other substances such as sulfate (Figure 9), but not of aluminum wear product. The copper conductor strands of the wire are the most likely source of the copper.

Determination of Electrical Properties. The terminals shown in Figure 8 connected to the Hi-Z and Lo-Z tubes. In order to determine if a measurable electrical path had been established to the shield tube via the deposits, the resistances between the shield terminal in the terminal block area and the connections shown in Figure 8 were measured. Resistance values of greater than 1 mega-ohm (the limit of the instrument used for the measurement) were obtained (see Table 1). These results show that, in a dry state, no conductive path exists between the shield tube and the terminals.

The terminal block assembly was reattached to the compensator in its original configuration for determination of the capacitance, insulation resistance and dielectric properties of the part. Capacitance was determined using an Andeen Hagerling Model 2500A Ultra-Precision Capacitance Bridge. Dielectric properties at 225 VAC were determined for a one minute duration with a Vitrek 944i Dielectric Analyzer; and the insulation resistance was determined at 225 VDC with the Vitrek 944i, also over a one minute duration. A compensator which had been tested previously (S/N L0495, MFD SEP 1983) was re-tested as a reference. Results, presented in Table 1, show that the capacitance of the compensator was very close to but slightly greater than the specification value. The insulation resistance and dielectric leakage current between the Hi-Z terminal and the shield were somewhat anomalous, although the insulation resistance was still in the mega-ohm range. The insulation resistances represent the lowest values observed during the test interval.

Although no evidence of electrical arcing was observed, results of electrical characterization suggest that additional disassembly and inspection might be of value.

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Table 1. Capacitance, Insulation Resistance and Dielectric Properties of the Compensator, Compared to a 1983 S/N Part

Measurement	S/N W-180	S/N L0495	Spec. Value
Capacitance (pico-Farads):	53.19	52.65	52.64 ± 0.52
Dielectric (leakage current, micro-amps):			
Hi-Z to Lo-Z	6.66	6.09	
Hi-Z to Shield	260	4.54	
Lo-Z to Shield	6.07	4.77	
Insulation Resistance (mega-ohms):			
Hi-Z to Lo-Z	370	11,000	
Hi-Z to Shield	5.6	12,000	
Lo-Z to Shield	420	11,000	

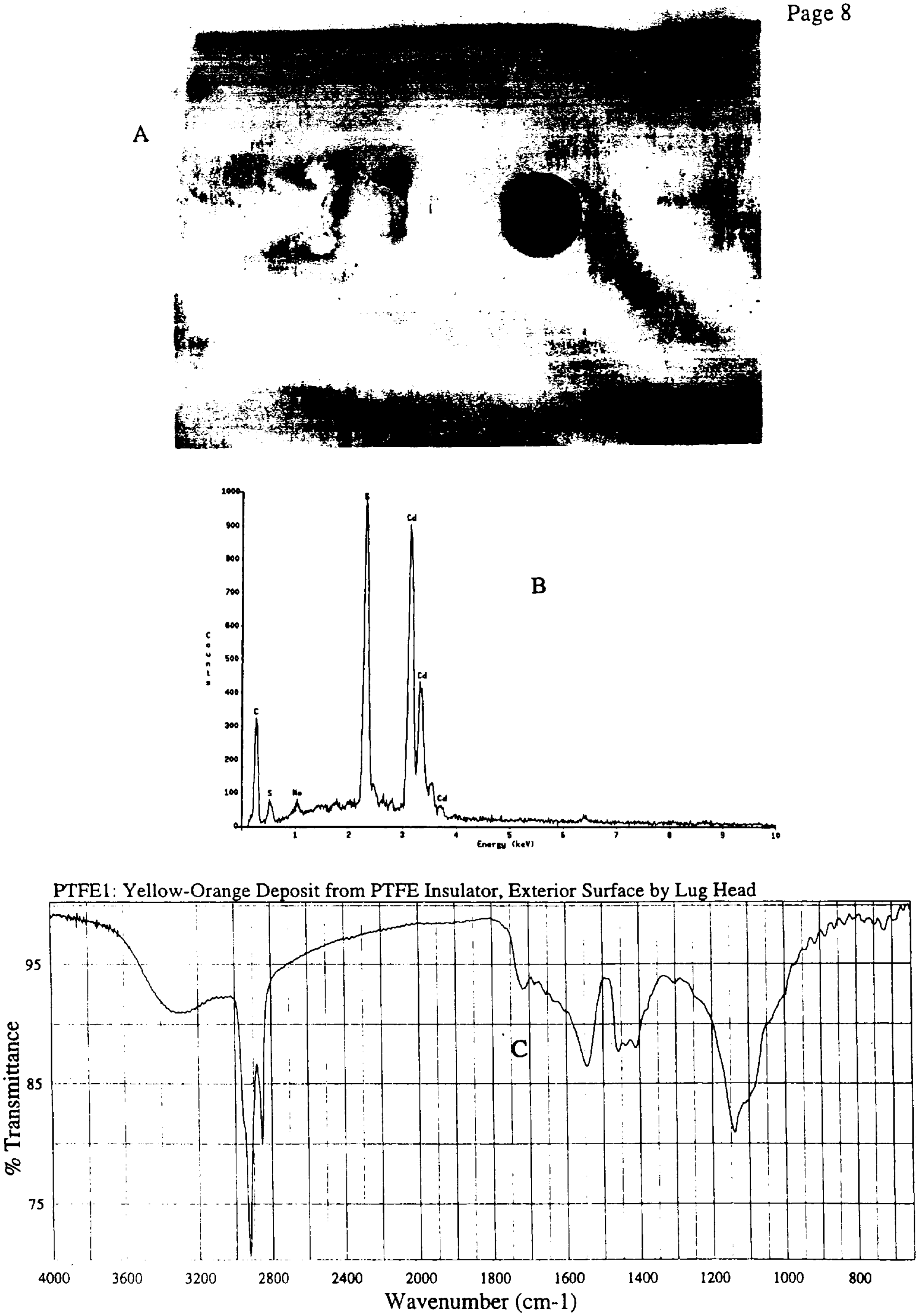


Figure 4. (A) Orange deposits on the surface of the PTFE insulator sheet that separated the terminal block assembly from the shield tube (2.3X). (B) An electron microprobe elemental survey and (C) infrared spectrum of the deposits shown in (A).

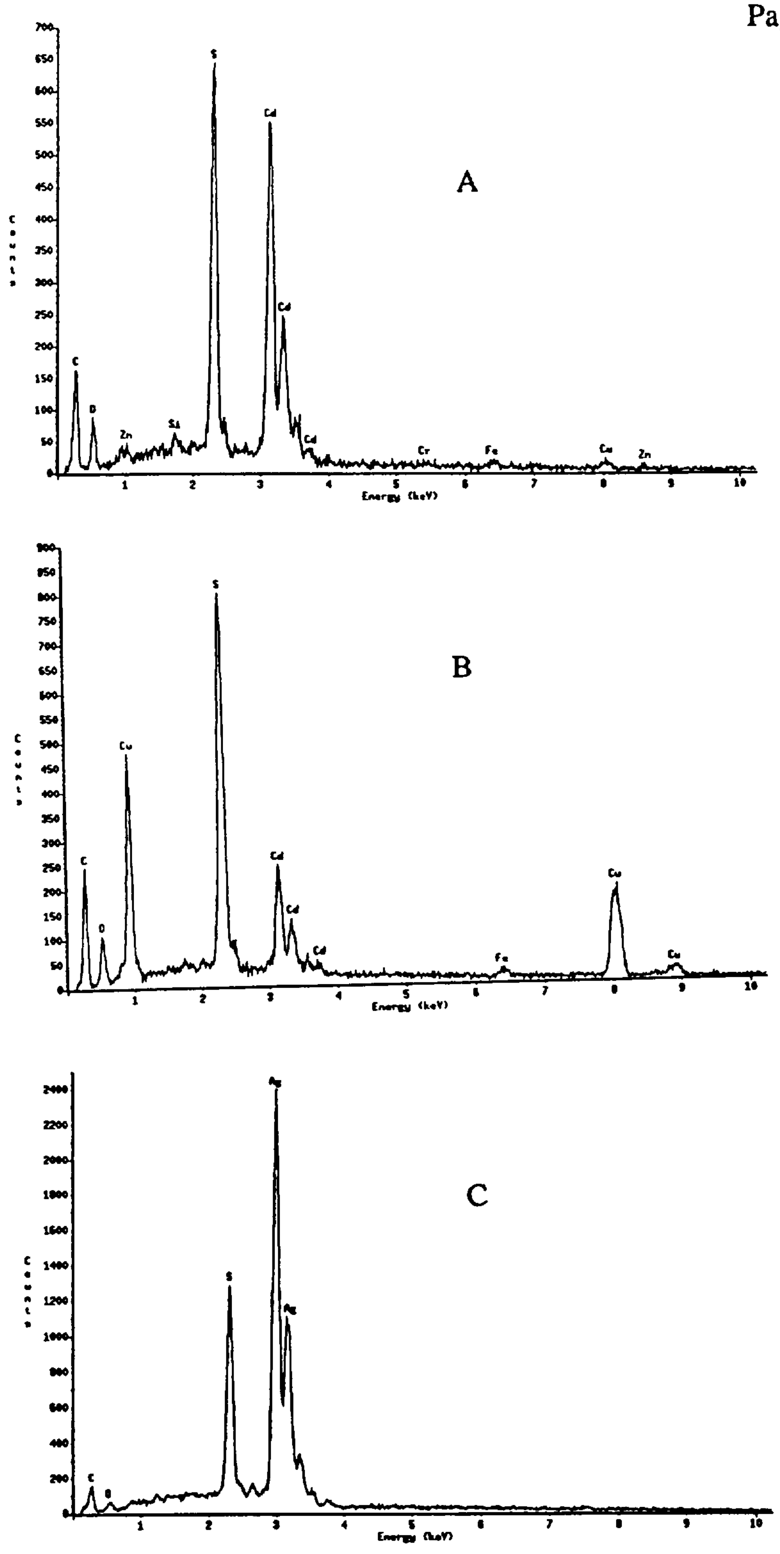
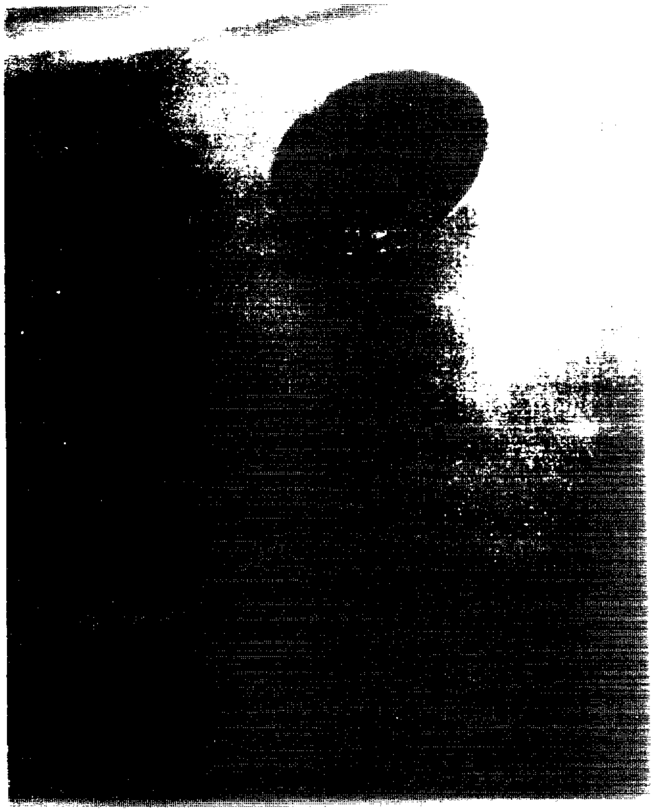
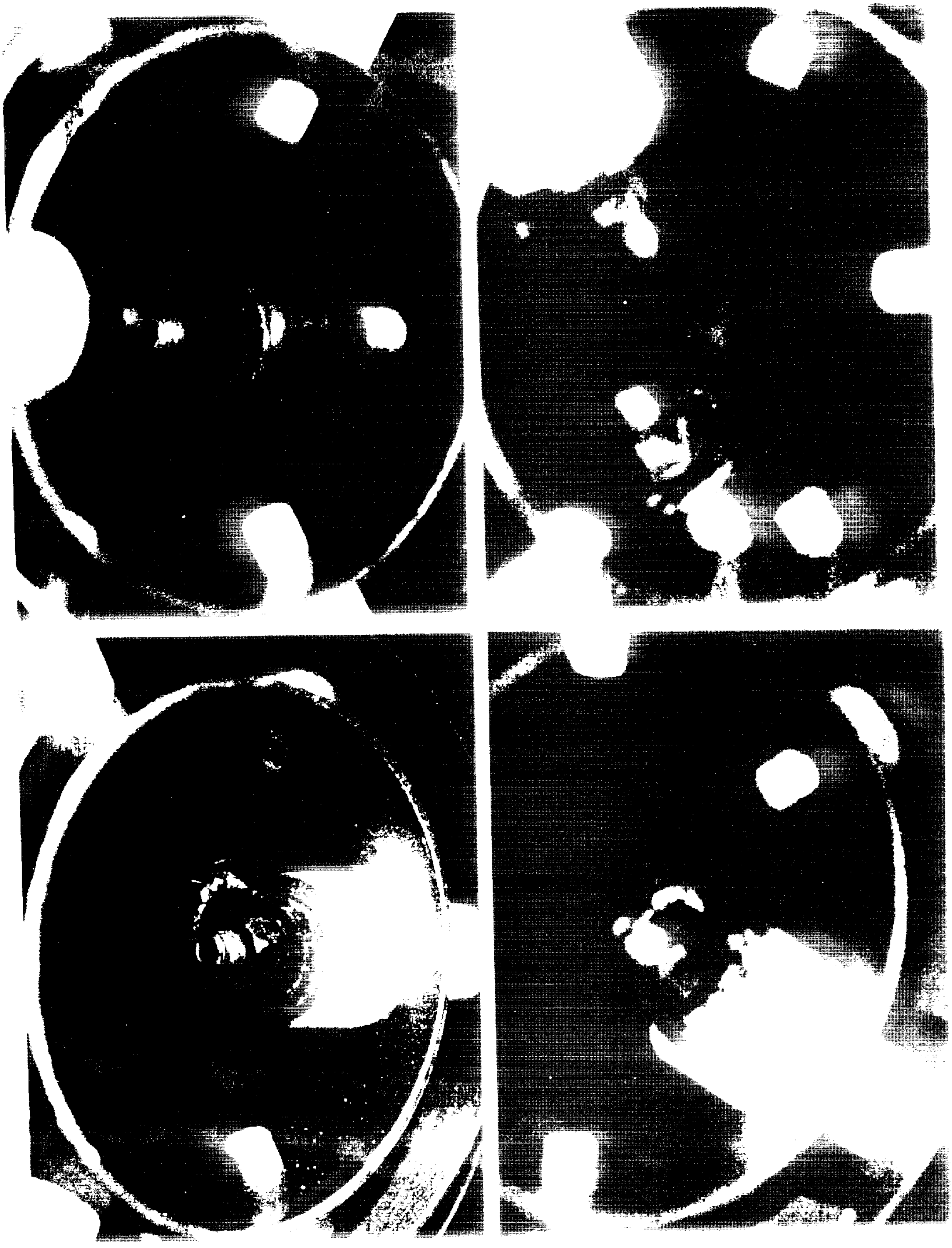


Figure 5. Electron microprobe elemental surveys of (A) orange deposits and (B) dark deposits from the shield terminal block, and (C) black material from the surface of the shield terminal hold-down nut.





Film Residues on Fuel Quantity Indicator System Fuel Tank Components (Materials Analysis)

18 October 1999

Evaluation Report
(43499TAO/NTSB)

Report No. AFRL/MLS 99-68

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EXECUTIVE SUMMARY

Fuel probes, compensators, wiring and terminal strips removed from 747 aircraft were submitted. Many of these components exhibited thin-film residues that were subjected to various voltage breakdown tests. In earlier AFRL evaluation reports the residues were found to be a mixture of materials, specifically copper, silver and sulfur. Residue films on component surfaces were probed and exhibited resistance values from more than 30 megohms to the low kilohm range. The films were fragile, with resistance values altered by physical probing or after the application of a voltage across the film surfaces.

Breakdown of the thin films was noted when voltages between 10 and 200 volts were impressed upon selected samples. Residue films with resistance values in the kilohm range would readily break down at 175 volts or lower values. Residue films from fuel probe terminal blocks also exhibited arc track damage after impressing voltage across their surfaces.

A single, short-duration, 170-volt pulse was applied across two points on a terminal strip residue film. This produced an arc discharge event. An audible popping sound, accompanied by a flash of light, signaled the discharge event. The event was captured on videotape and the energy level discharged during event was calculated to be 2,740 millijoules. The discharge event physically damaged the film. In two other 170-volt breakdown tests, arc events were also captured on videotape. The calculated energy discharges were in the low millijoule ranges (1-20) and the films apparently were not physically damaged.

During limited testing, laboratory-fabricated carbon films ignited flammable vapors in a test fixture. A single short duration 170-volt breakdown pulse produced calculated energy discharge levels between 1100 and 2400 millijoules. Breakdown tests were also conducted on fuel terminal blocks and wire terminals exhibiting conductive (low kilohm range) thin film residues. The tested residues did not ignite the flammable vapor. The maximum energy discharged during testing in flammable vapors was 4.6 millijoules. Significantly higher energy levels were required to ignite the vapor mixture, since vapors in the laboratory test fixture were not at the concentration required for minimum energy ignition.

ACKNOWLEDGMENTS

The author wishes to thank Messrs. Dale Hart, John Ziegenhagen and Richard Reibel (The University of Dayton Research Institute) and David Johnson and Ms. Abigail Cooley (AFRL/MLSA) for their expert technical support, videography and photography, and Ms. Marianne Ramsey (AFRL/MLSA) for expert manuscript preparation.

TABLE OF CONTENTS

Film Residues on Fuel Quantity Indicator System
Fuel Tank Components

PURPOSE

Characterize voltage breakdown and energy dissipation across residues found on fuel quantity instrumentation system (FQIS) fuel tank components.

FACTUAL DATA

Surface analysis techniques were used to determine the composition of the black residues on submitted fuel probe terminals, wiring and barrier strips. Residue composition included copper, silver, sulfides and sulfates. Surface analysis results are given in evaluation report AFRL/MLS 99-2, dated 26 January 1999.

The National Transportation Safety Board (NTSB) submitted Boeing 747 aircraft fuel probe terminal blocks, wiring and terminal barrier strips (evaluation report AFRL/MLS 99-33). Examples of components selected for analysis are shown in figures 1, 2, 3 and 4. Due to limited sample availability, and the desire to control compositional and electrical characteristics, laboratory fabricated films were used for preliminary evaluation. Results are given in appendix A. After developing a test circuit, preliminary voltage breakdown and impressed energy calculations were made on selected FQIS components. These results are given in appendix B.

Energy Calculations Using Capacitive Discharge Test

After reviewing initial results in appendices A and B, a new circuit was designed to better quantify the energy being injected into the residue films under test. Capacitors were charged to a predetermined voltage level and then discharged through the film under test between the spring-loaded probes. The capacitors were charged using AC line voltage connected to an autotransformer. A diode provided rectification. A digital voltmeter monitored the voltage in the capacitors both before and after discharge. The circuit schematic and test set-up is shown in figures 5 and 6, respectively. The energy delivered to the sample through the probes was calculated using the voltage remaining in the capacitor after discharge. The equation used was

$$E = 1/2C(V_i^2 - V_f^2)$$

where E is the energy in Joules, C is the capacitance, V_i is the initial capacitor voltage and V_f is the final capacitor voltage after the film discharge event. Two parallel connected 125uf capacitors (250uf equivalent capacitance) were used as charging capacitors. A Hewlett Packard ance analyzer set at five hertz gave an equivalent measured capacitance of 290uf. A single-pole, double-throw (SPDT) switch was used to charge the capacitors and then discharge them through the probes. A digital multimeter was used to measure the resistance of the area between the probes before and after each test. A test fixture was fabricated to hold the fuel probes and two probe manipulators (highlighted box, figure 6). The manipulators allowed precise positioning of the spring-loaded probes on the surface of the fuel probe terminal blocks or other areas. The probes and contact area were positioned under an optical microscope equipped with a video camera connected to a conventional, standard-speed recorder.

Preliminary discharge testing demonstrated electrical contact could not be maintained between the probes and the residue film. Breakdown of the residue between the probes was desired. This was facilitated by applying conductive silver paint to the surface of the residue. The silver paint increased the contact surface area, lowered the contact resistance and offered a buffer zone between the probe tips and residue.

The discharge characteristics were evaluated between probes suspended in air, imposed on a high resistance area of residue and on a conductive region of residue film. The freestanding probes allowed the capacitor to discharge from 50 to 48 volts in 100 seconds. Conductive silver traces approximately one millimeter (mm) part were placed on a terminal block residue that exhibited a high resistance (fuel probe A-119). The resistance between the traces was too high to be measured by the multimeter. The capacitor discharged from 50 to 40 volts in 10 seconds. Resistance remained very high after the test, beyond the range of the meter. The test was repeated twice with essentially the same results. Conductive silver traces were placed 1.1 mm apart on area of the A-119 terminal block that exhibited a conductive residue (figure 7). Initial resistance was three kilohms. The capacitor discharged from 50 to 3 volts in 5 seconds. Using the capacitance energy equation the energy discharged by the capacitor was 359.7 millijoules. Resistance after the test measured 10 kilohms. No damage on the surface between the probes could be seen under the microscope. A summary of discharge test results, using a calculated energy discharge over five seconds, is given in table 1. An arc event was not captured on the standard-speed videotape recording.

Terminal Strip Testing

Since many of the conductive fuel probe residues had already been probed during earlier breakdown tests, a terminal barrier strip with significant residue deposits was selected for additional discharge testing. The barrier strip was reported to have low resistance values between terminals and was submitted by the NTSB. An analysis of the terminal strip is given in evaluation report AFRL/MLS 99-33.

The terminal strip contained five terminal lugs (figure 8). Note residues between the terminals. Before testing, the resistance values between terminals were measured using a multimeter. Resistance between terminals 1 and 2 and between 4 and 5 were above the range of the multimeter. Resistance between terminals 2 and 3 measured 2.5 megohms; terminals 3 and 4 measured 120 kilohms. The residue film between terminals 3 and 4 was initially probed and exhibited resistance values between 1.2 to 4 kilohms with an approximate 1-mm spacing.

Two dots of conductive silver paint were applied to another area of high conductivity between terminals 3 and 4, points 1 and 2 (figure 9). The spacing between the dots was approximately 0.9 mm. The capacitor discharged from 100 to 98.9 volts in 10 seconds. Using the capacitance energy equation ($E = 1/2C(V_i^2 - V_f^2)$, $C = 290X10^{-6}$) andthe energy discharged by the capacitor was 31.72 millijoules. The resistance was 0.6 kilohms before the test and the circuit measured open after the test. No physical damage was noted. A resistance of 1.3 kilohms was obtained by adjusting the probes and the discharge test was repeated. It was noted the resistance reading remained very stable and only varied slightly in the hundredths of a kilohm. Typically, resistance readings varied in the tenths of a kilohm. The capacitor discharged from 100 to 96.3 volts in 10 seconds. Using the capacitance energy equation, the energy discharged by the capacitor was 105.3 millijoules. After the test, a review of the videotape showed a possible arc track event had occurred on the residue film during the discharge. Before and after photographs are shown in figures 9 and 10. A digitized copy of the videotape is included as exhibit 1. A single arc was captured across the residue. The damaged film surface is shown in a videotape frame that was captured as a still photograph (figure 11). The resistance after the test was beyond the meter range (>30 megohms). A measurable resistance could not be obtained by adjusting the probes. This implies the breakdown occurred through the film and not only in the area contacted by the probes.

Short Duration Energy Discharge Test Circuit

The videotape of the above film breakdown event shows breakdown can occur over a short duration (milliseconds). The discharge circuit was modified to capture discharge voltage and current waveforms of short duration (milliseconds) breakdown events (figure 12). A digital oscilloscope and high-speed video camera capable of recording 100 frames per second were used to capture breakdown or arcing events. A breakdown voltage approaching 170 volts was selected for most follow-on tests. This would be the peak voltage available on a single phase of 120 volt, three-phase aircraft power.

Additional silver dots were applied to residue areas on the terminal strip (figures 13 and 14). The areas were probed to determine resistance values. Voltage was then applied while simultaneously videotape recording and capturing the discharge event with an oscilloscope. Energy was calculated by multiplying the captured voltage and current waveforms and integrating the resulting power waveform or by using the voltage discharged by the capacitor. Several tests were conducted, the distance between spots being in the range of 1 to 1.6 millimeters with resistance values between 400 ohms and several kilohms. Results are shown in table 2. The waveforms captured with the oscilloscope are shown in figures 15, 16 and 17. For event 2, the current waveform was not captured because the current was too high for the selected range. Arc events can be seen in the videotape clip (exhibit 2). On the oscilloscope, event 2 produced a large arc. Small arcs can be seen emanating from a probe in events 1 and 3. These arc events lasted less than two milliseconds. A single arc was captured for each event. A spark and audible "pop" was noted when the breakdown occurred during event 2. The imaging area of the video camera was saturated by the light energy released by the arc. Significant surface damage was noted only after event 2 (figure 18). Testing on the terminal strip was halted to conserve residue sites for ignition testing in jet fuel. Material analyses were conducted on the terminal strip residues, particularly the effect of conductive silver paint on the residue surfaces. Results are presented in appendix D.

Energy Discharge Tests in a Flammable Vapor

Energy discharge tests were conducted on conductive thin film samples to determine if flammable vapors could be ignited by a voltage breakdown event. Initially, laboratory fabricated samples were tested to establish procedures and energy levels necessary to ignite flammable vapors. Fuel probe residues were then evaluated. The capacitive discharge circuit shown in figure 12 was used to provide the energy to create an arc or voltage breakdown event. The event was recorded with an oscilloscope and high speed videotape system (100 frames per second).

Laboratory-pure carbon films were created by sputtering microscope slide cover slips using an AnaTech LTD CDS II Carbon Sputtering System. After the carbon was deposited conductive silver paint dots are applied spaced approximately 5.0 mm. Silver-plated copper wire leads were attached with conductive silver paint (figure 19). After attaching wires, excess carbon film was scraped away to increase the current density between the contact points (figure 19).

The test vessel was a partially sealed 150-mm diameter transparent plastic culture dish whose volume (dish and lid) was approximately 0.35 liters. It was not sealed to allow air to mix with the vapors. The film sample was placed upright to increase exposure to flammable vapors. The carbon-coated glass slides were placed in the culture dish. Instrumentation and a film under test are shown in figure 20.

The flammable liquid selected for the testing was lighter fluid, a blend of 18 percent Hexane and 82 percent Naphtha. This material could be easily introduced as a liquid that would then evaporate, creating a flammable mixture in air. According to the materials safety data (MSD) sheet on the selected lighter fluid, the flash point of the lighter fluid is 5.6°C. The reported explosive limit is between one to seven percent. Ignition tests were initially conducted using a small piezoelectric igniter. Five drops of lighter fluid, heated to 30 to 35°C for three minutes, consistently ignited vapors.

Six tests were conducted using the laboratory-prepared carbon films with resistance values between 660 ohms and 4.7 kilohms. The capacitors were charged to 170 VDC. The fuel vapors ignited in three out of six attempts. The events were recorded with a high-speed video system and oscilloscope (figures 21, 22 and 23). The videotape was digitized and ignition examples are offered in exhibit 2. A summary of test results is given in table 3. The first two tests were part of the setup process. Event 6 was the application of 250 volts to the test sample used in event 5. Although an arc was produced, the vapors did not ignite. The energy impressed onto the sample was calculated by two methods. The first method captured voltage and current waveforms on the oscilloscope. As before, the energy was calculated using the procedure in appendix C. A second method was to use the difference between the initial and final voltage remaining in the capacitors after the arc event. Testing was halted after obtaining three ignition events. Variation in energy readings was due to several factors. In event 7, the current probe amplifier was saturated, due to the selected amplifier range, and the actual current level was not captured.

The next sets of tests were conducted on components from submitted fuel probes. Three insulated lug terminals were removed from the probes. The insulation on these terminals had a conductive black residue. Conductive silver paint stripes were applied to the residue to enhance the contact connection, and silver-plated copper wires were attached using conductive silver paint (figure 24). The initial resistance values of these films were between 725 and 3.8 kilohms. The films were tested in the same manner as the previous carbon films. There were no ignition events and the impressed energy was between 2.5 and 4.6 millijoules. Similar tests were also conducted on four terminal blocks with conductive residue. The resistance values of these films were between 0.72 and 3.1 kilohms. There were no ignition events and the impressed energy was between 1.1 and 4.2 millijoules. The results are given in table 4. A captured waveform is shown in figure 25. There were no electrical arcs captured on the videotape for events 10 through 16.

Summary of Findings

Laboratory films of copper sulfide, specifically cupric sulfide (CuS), were created that exhibited resistance values in the low to high kilohm range. Cupric sulfide (Cu_2S) films exhibited resistance values in the 10^{12}-ohm range. Silver Sulfide (Ag_2S) bulk resistance was measured and found to be in the low megohm (10^6) range.

The laboratory fabricated CuS films were subjected to voltage breakdown tests. Single half-wave sinusoidal voltage pulses were applied to the samples with peak voltages in the range of 59 to 178 volts. Breakdown was noted when the captured current pulse exhibited spikes or did not follow the voltage waveform. Peak currents as high as 600 milliamperes were recorded across the film samples. Visual inspection revealed no physical damage or evidence of arcs on test sample surfaces. Film resistance changed dynamically during and after the test. The resistance values typically dropped by several orders of magnitude up to the breakdown event and then would rise to a level above the original value.

Residue films on fuel quantity instrumentation components (fuel probes, compensators, wiring and terminal strips) were electrically probed. Residues exhibited resistance values in the low kilohm range, using a 1/8-inch (3.2mm) probe separation. Residue films were then subjected to voltage breakdown tests. The films exhibited voltage breakdown characteristics when half-wave sinusoidal (1.25 millisecond duration) voltage pulses were applied. Voltage breakdown peak values were between 8 and 147 volts. Peak current values were as high as 12 milliamperes, but were typically in the range of 2 to 5 milliamperes. There were no electrical arcs or physical damage noted during or after testing. A dynamic (changing) resistance was noted during and after the voltage breakdown events. The breakdown appeared to be occurring at the interface of the spring-loaded probe and residue. The residue films were fragile; slight probe movement or pressure changes would change the resistance values. Resistance values were also significantly changed by the application of a voltage across the films.

The energy applied to the residue films was measured during the application of a half-wave voltage pulse. Residue films were obtained from fuel probe Lo-Z terminals and the terminal blocks beneath these terminals. Voltage as applied to spring-loaded probes separated approximately 1/8 inch (3.2mm) apart. The peak voltage was approximately 175 volts. In two tests, arc track sites were noted between the electrical test probes. Both events had some of the highest energy dissipation values calculated (6.5 and 1.46 millijoules). In many tests, there were multiple breakdown events during voltage application.

A capacitive discharge circuit was next connected to probed residue sites. Conductive silver paint was applied to the residue films to improve the contact interface. A materials analysis of residues with silver paint indicated the applied silver had not bridged the residue area under test. A terminal strip with significant amounts of residue film was selected for testing. When probed, the residues on the terminal strip exhibited very stable and low resistance values. In the initial circuit, capacitors were discharged across the surface of the films for several seconds. An arc across the residue surface was captured on videotape. This occurred during a discharge event calculated to be 103 millijoules occurring over a 10-second period. The arc physically damaged the test-site. The resistance of the affected residue was now over 30 megohms. The videotape showed the actual breakdown occurred over a short duration (milliseconds).

Additional discharge tests on the terminal strip were conducted using a capacitive circuit capable of producing a single short duration 170-volt pulse over several milliseconds. Conductive silver dots were applied, with a separation between 1 and 1.6 mm. In one test, a popping sound and flash of light signaled the discharge. The event was captured on videotape and the energy level discharged during the event was calculated to be 2,420 millijoules. The arc discharge released enough light to completely saturate the video camera image capturing circuits. The breakdown event lasted approximately 10 milliseconds. The test damaged the residue film. In two other 170-volt breakdown tests, arc events were also captured on videotape. The calculated energy discharges were in the low millijoule ranges (1-20) and there was no apparent physical damage to the residue films.

During limited testing, laboratory-fabricated carbon films ignited vapors in a test fixture filled with a flammable vapor. A capacitive circuit capable of producing a single, short duration 170-volt pulse over several milliseconds was used to initiate the breakdown event. Calculated energy discharge levels were between 1100 and 2400 millijoules. In each of the three ignition events, burning vapors created sufficient gas pressure to raise the lid from the test chamber. A maximum energy discharge of 150 millijoules was calculated. An arc was observed in two tests, however, the vapors did not ignite.

Residue films on terminal lugs and terminal blocks were instrumented and also placed in the flammable vapor environment. They had resistance values in the low kilohm range. No ignitions were noted and the maximum energy discharged was 4.6 millijoules over 2.0 milliseconds. Significantly higher energy levels were required to ignite the vapor mixture, since vapors in the laboratory test fixture were not at the concentration required for minimum energy ignition.

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PUBLICATION REVIEW: This report has been reviewed and approved.

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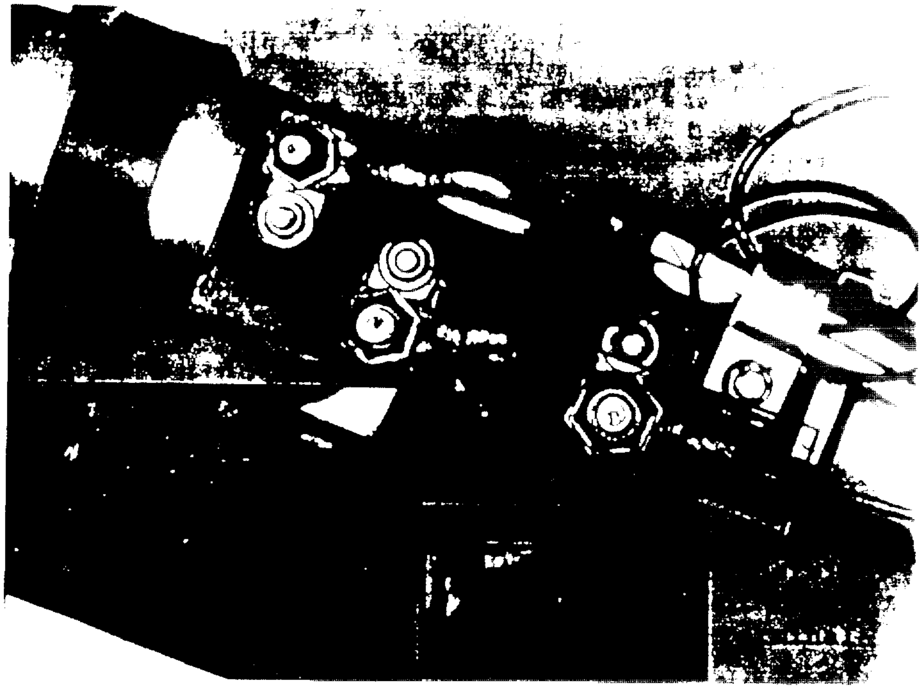
FIGURES



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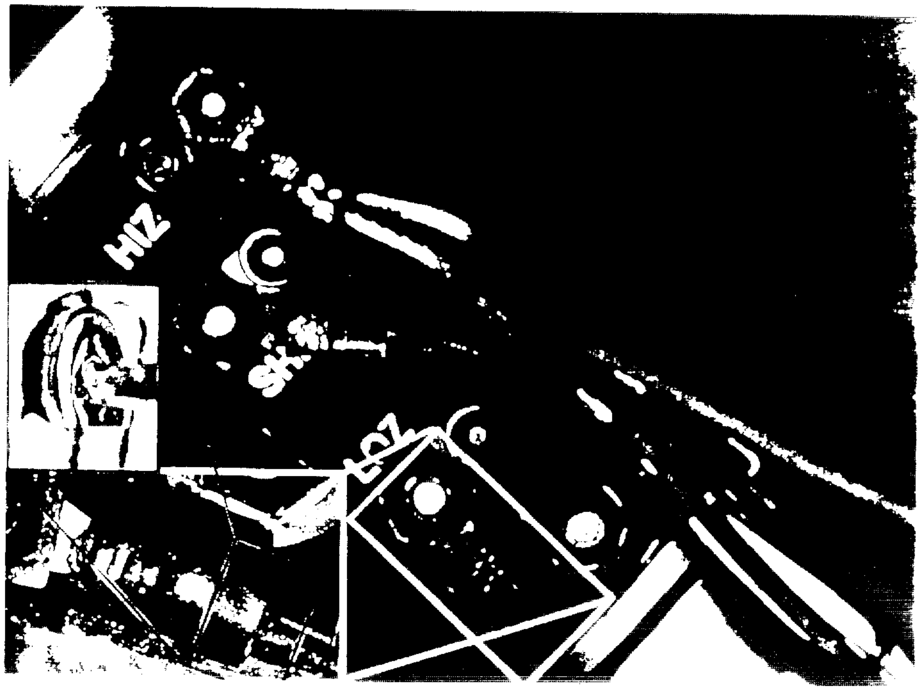

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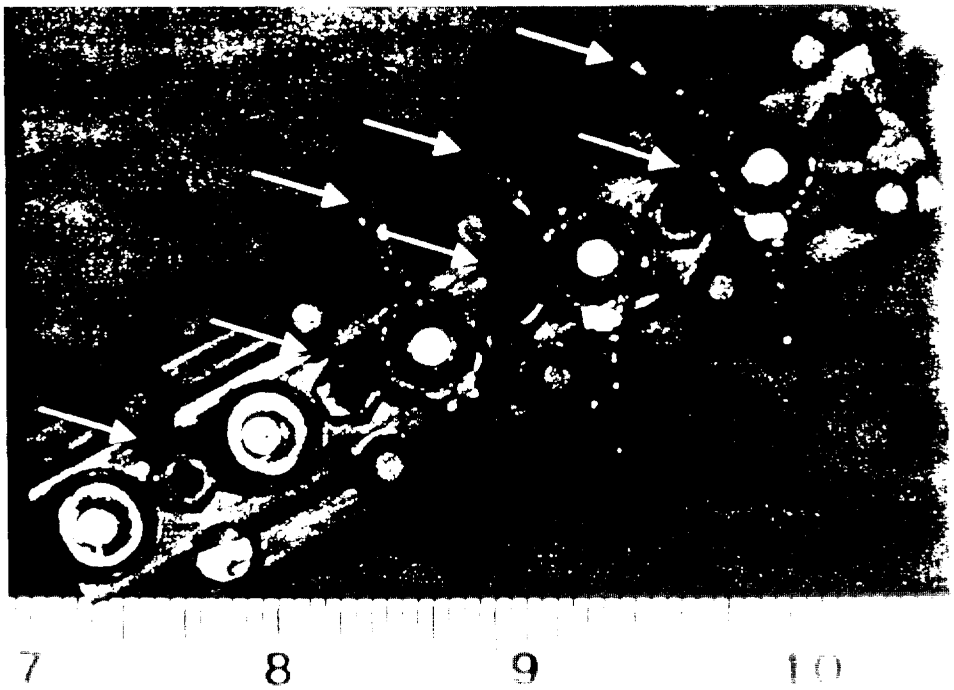

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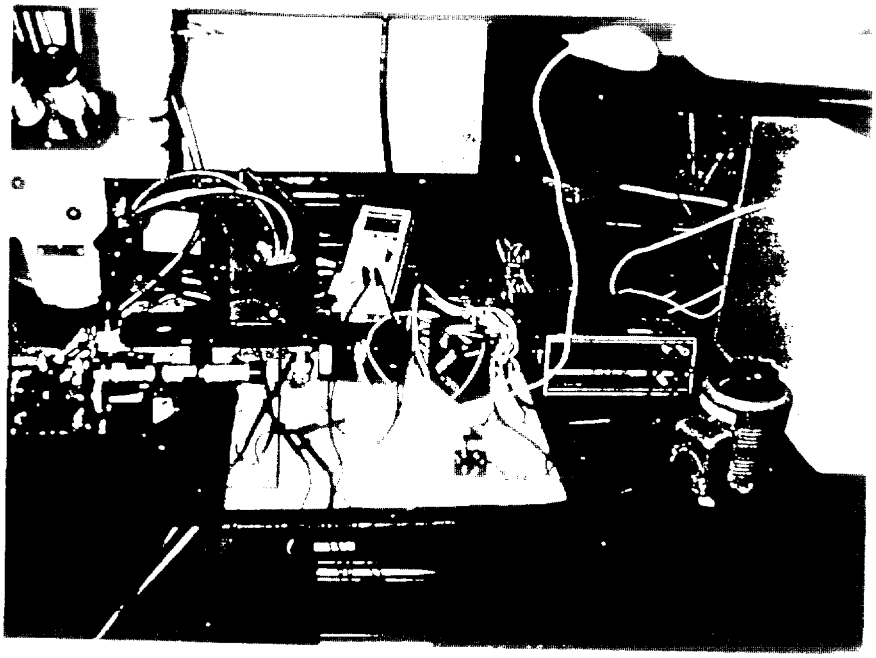

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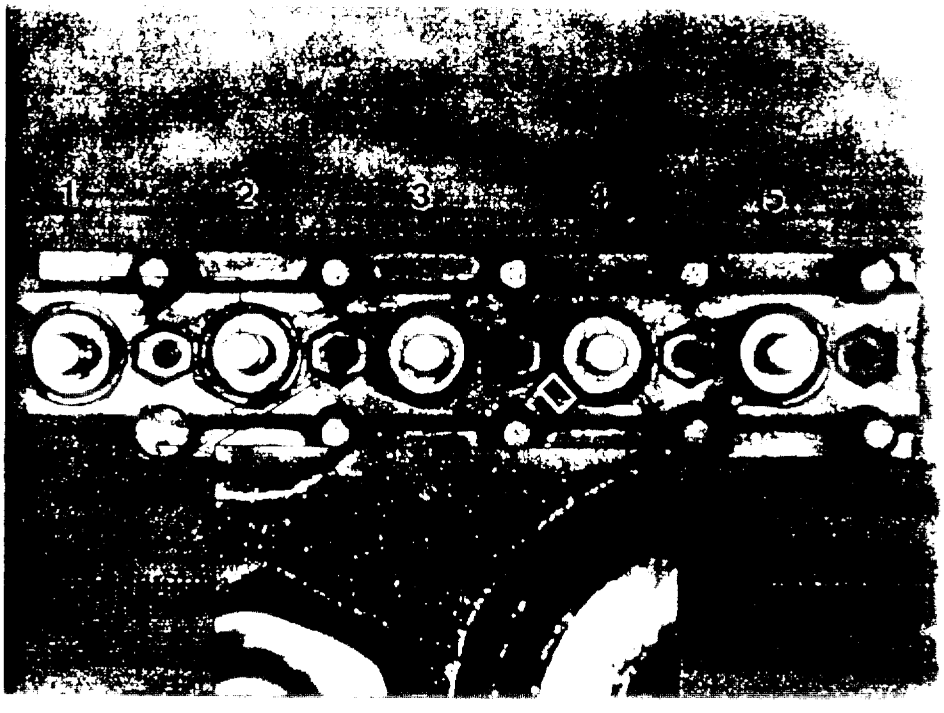

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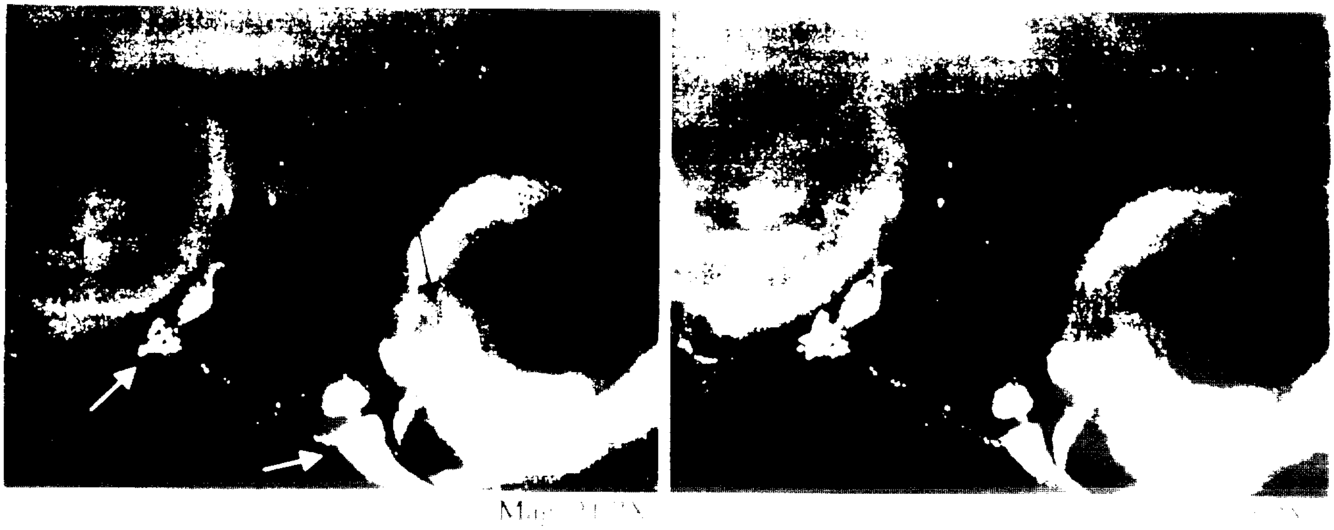

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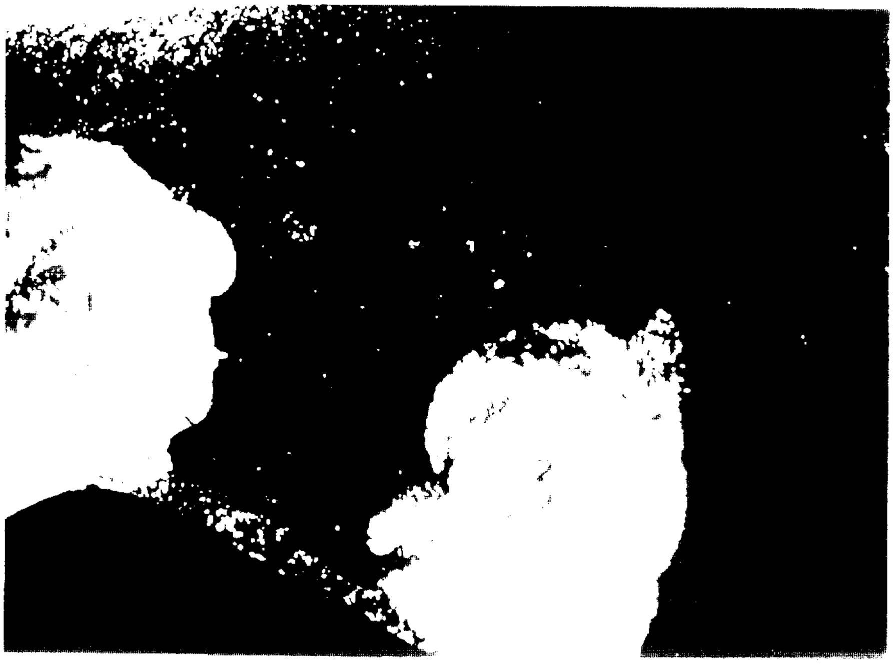

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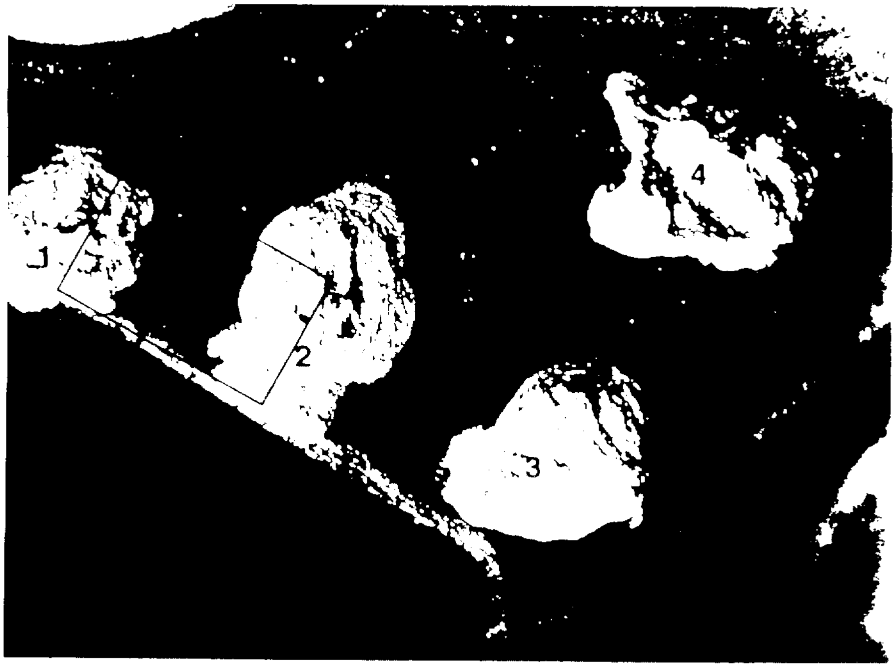


Figure 13. Test sites between barrier strip terminals 3 and 4. The labeled silver dots correspond to table 2, events 1 and 2. Box shows an area analyzed with EDS, appendix D.

Mag: 15X

Figure 14. Test sites between terminals 2 and 3. Insert is a close up of test area after event 8 in table 2.

Mag: 6.2X

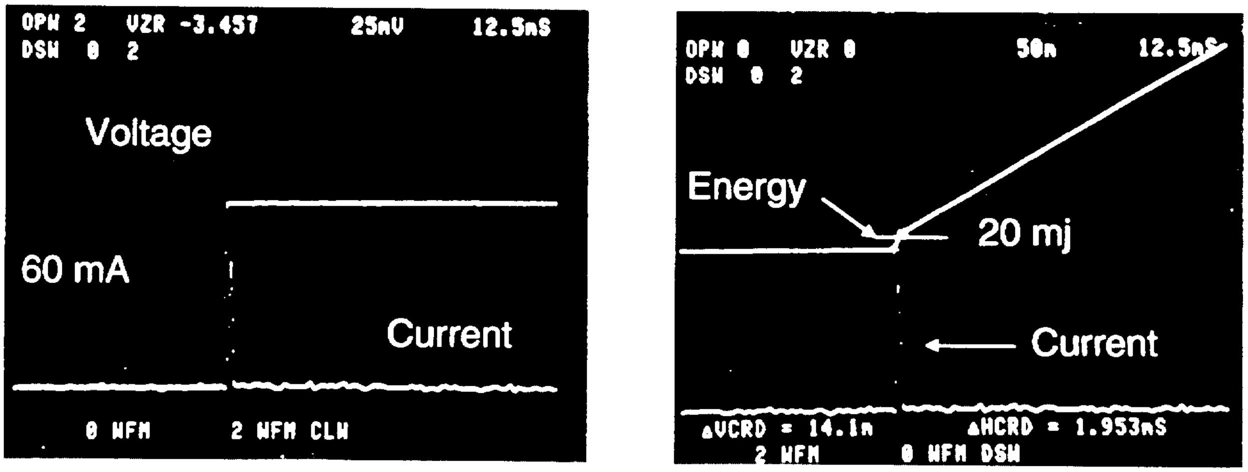


Figure 15. Barrier strip discharge event 1 (table 2), terminal area 3 and 4, points 2 and 4 (figure 13)
Initial resistance 0.4 kilohms, applied voltage: 170V
Arc Event: Small arc (exhibit 2)
Current 60 mA peak for 2 milliseconds, voltage (final): 130V
Arc energy based on waveform calculation: 20 millijoules

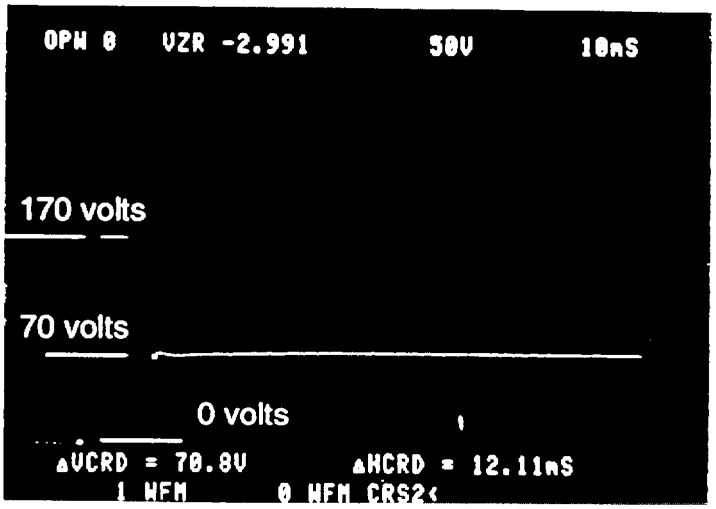


Figure 16. Event 2 (table 2) terminal area 3 and 4, points 3 and 4 (figure 13)
Initial resistance 2.2 kilohms, applied voltage: 170V
Arc Event: Large arc (exhibit 2 and figure 18)
Current event not captured
Arc energy = $.5C(V_1^2 - V_2^2) = .5(290E\text{-}6)(170^2 - 100^2) = 2{,}740$ millijoules, voltage drop of 100 volts in 10 milliseconds

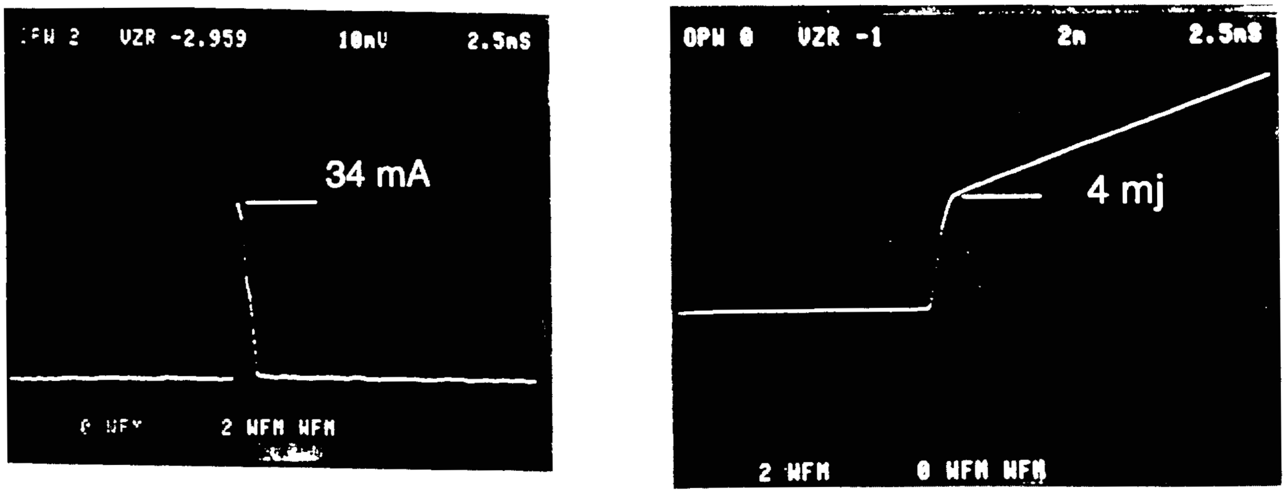


Figure 17. Event 3 (table 2) terminal area 2 and 3, points 10 and 11 (figure 14)
Initial resistance 3.3 kilohms, applied voltage - 170V
Arc Event - Small arc (exhibit 2)
Arc current 34mA peak for 1 millisecond, voltage (final) - 170V
Arc energy based on waveform calculation 4 millijoule

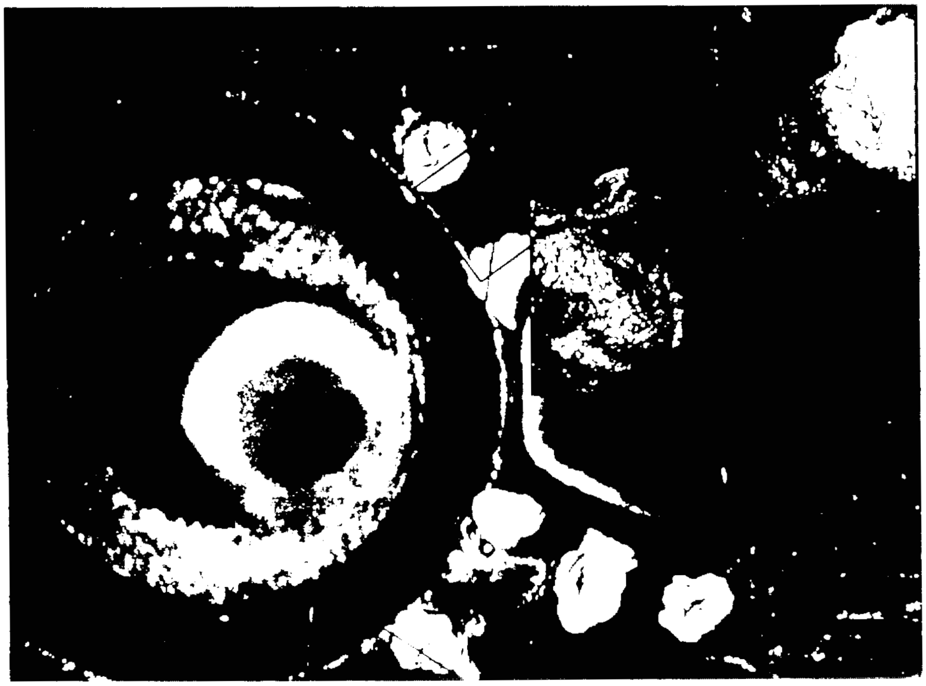


Figure 18. Discharge damage noted between terminals 3 and 4 after test event 2. Note the large damage site (insert). EDS analysis was conducted in the red box area.

Mag. 6.3X

Figure 19. Laboratory prepared carbon-thin film (left) created for ignition testing. Laboratory prepared film (right) with excess carbon film after a discharge test (table 3, event 7).

Mag: 7X

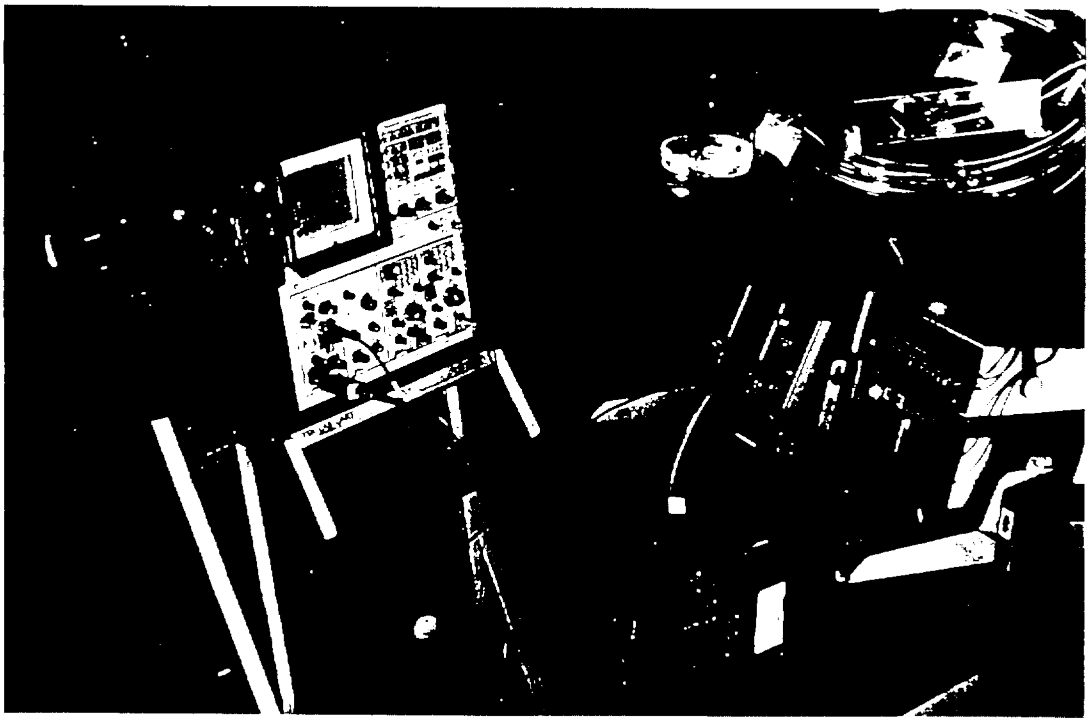


Figure 20. Test setup used to ignite a flammable vapor. A close up of the test vehicle is shown in the insert.

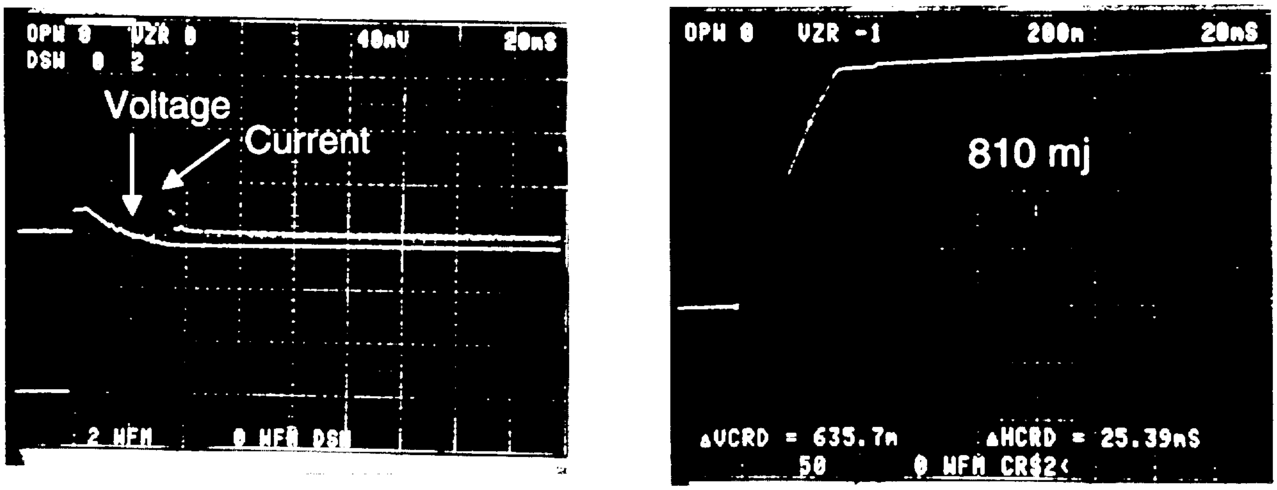


Figure 21 Event 7 (table 3) Container heated to 30 C
Initial film resistance 2.3 kilohms, applied voltage 170V
Five drops of lighter fluid, dwell period three minutes, arc ignited vapors
Arc current 160 mA peak for 40 milliseconds, ending voltage 140 volts
Arc energy = .5C(V1² − V2²) = .5(290E-6)(170² − 140²) = 1,348 millijoules
Oscilloscope trace energy calculation = 810 millijoules
Actual current level not captured due to instrumentation scaling

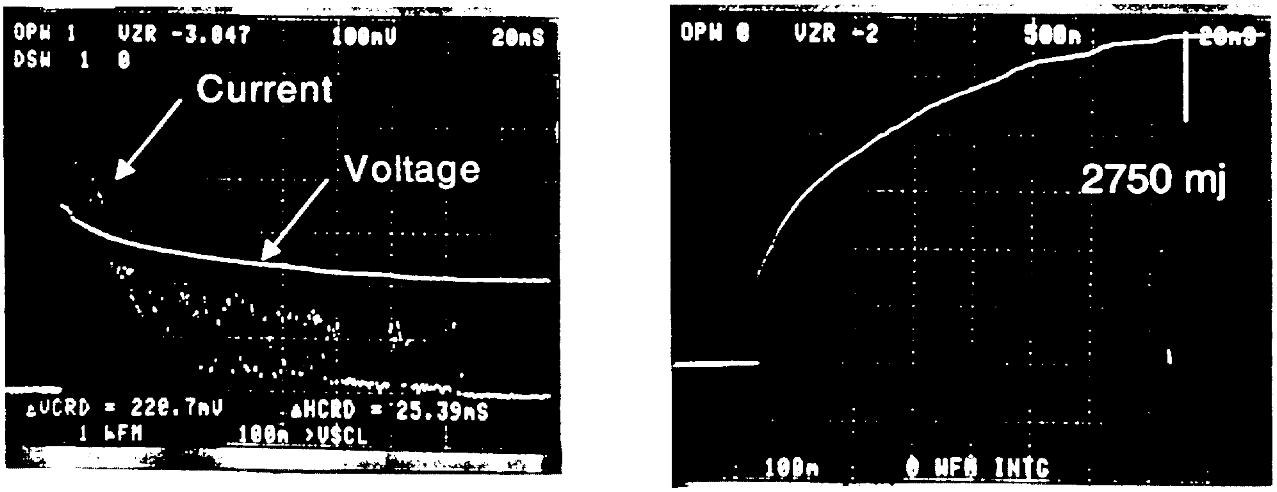


Figure 22 Event 8 (table 3) container heated to 30 C
Initial film resistance 622 ohms, applied voltage 170V
Five drops of lighter fluid, dwell period three minutes, arc ignited vapors
Arc current 500 mA peak for 150 milliseconds, ending voltage 110 volts
Arc energy = .5C(V1² − V2²) = .5(290E-6)(170² − 110²) = 2,436 millijoules
Oscilloscope trace energy calculation = 2750 millijoules

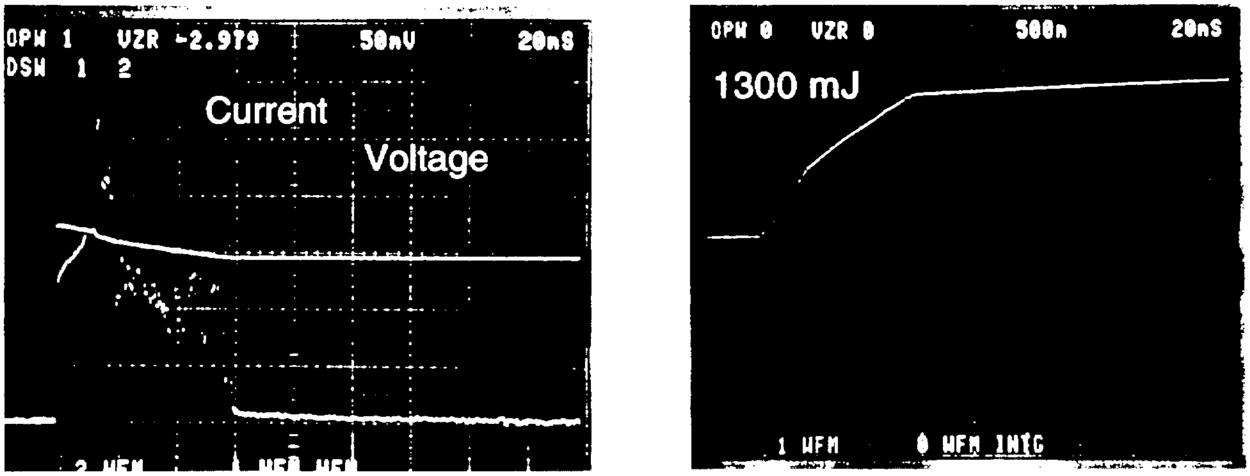


Figure 23. Event 9 (table 3) container heated to 30 C
Initial film resistance 2.2 kilohms, applied voltage = 170V
Five drops of lighter fluid, dwell period three minutes, arc ignited vapors
Arc current 300 mA peak for 60 milliseconds, ending voltage 145 volts
Arc energy = $.5C(V_i^2 - V_f^2) = .5(290E\text{-}6)(170^2 - 145^2) = 1{,}142$ millijoules
Oscilloscope trace energy calculation = 1300 millijoules

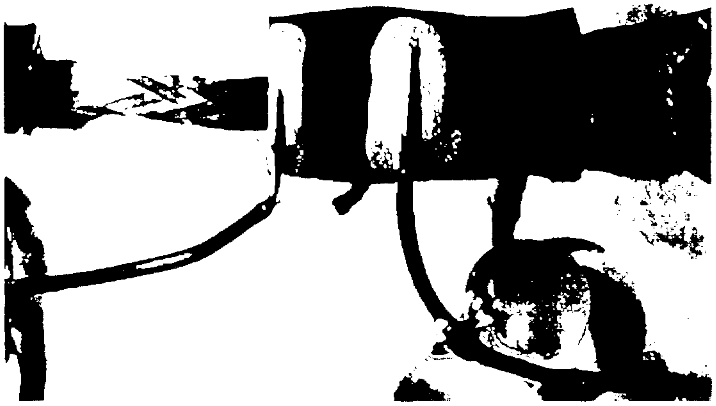


Figure 24. High Z terminal from FG420A29 S/N A110. Two millimeter separation with two kilohm resistance

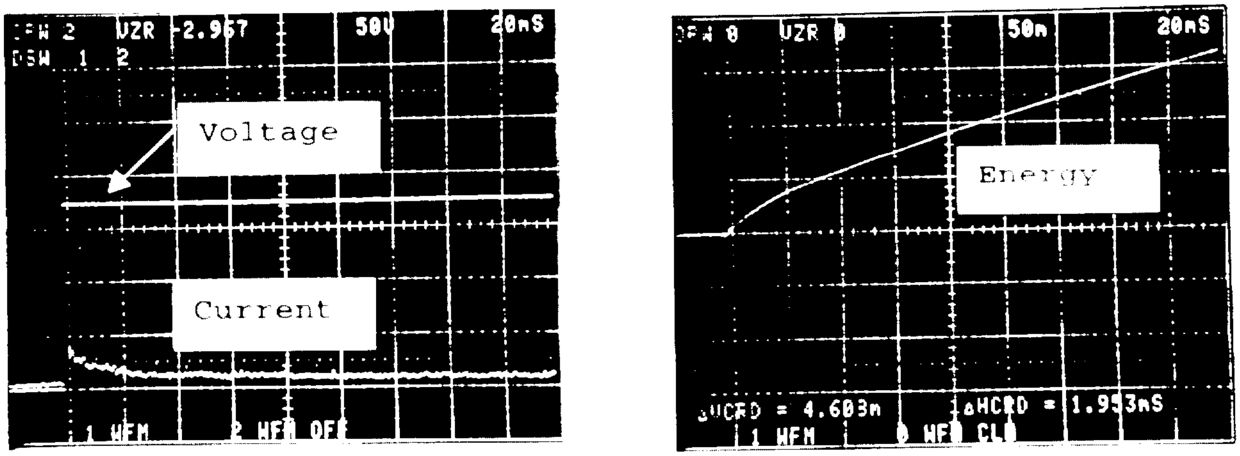


Figure 25. Event 12 from table 4, FG420A29S/N A110 wire terminal residue. The peak current was 28mA over a two millisecond duration. The energy impressed across the film was 12 millijoules (mJ).

TABLES

Table 1

Discharge Results for Terminal Block FG420A23 A-119

Test Condition	Initial/Final Resistance ohms	Starting/Ending Voltage Five Second Period	Calculated Energy Discharge[1]
Probes in air	Open[2]	50V/49.9V	1.4 mjoules
Probes on residue	open[2]	50V/45V	67.4 mjoules
Probes on residue	3 K/10K	50V/3V	359.7 mjoules
Probes on residue	8.4K/11.6K	50V/6V	355.8 mjoules
Probes on residue	4.7K/18K	50V/8V	351.8 mjoules
Probes on residue	5K/open[2]	100V/80V	520.5 mjoules

[1] $E = 1/2C(V_i^2 - V_f^2)$, $C = 290X10^{-6}$

[2] Multimeter reads open above 30 megohms

Table 2

Discharge Tests Conducted on the Residue Found on the Submitted Terminal Strip

Event	Initial/Final Resistance (kilohms)	Applied Voltage (volts)	Peak Current (mA)	Calculated Energy (millijoules)	Comments
1	0.4/-	170	60	20[3]	Terminal strip area 3 and 4 points 2 and 4 (1.6mm), breakdown noted on videotape (figure 15)
2	2.2/open[1]	170	-	2,740[2]	Terminal strip area 3 and 4 points 3 and 4 (1mm apart), large breakdown noted on videotape (figures 16 and 18)
3	3.3/open[1]	170	34	4[3]	Terminal strip area 2 and 3 points 10 and 11 (1.2mm apart), breakdown noted on videotape (figures 17 and 14)

[1] Multimeter reads open above 30 megohms

[2] $E = 1/2C(V_i^2 - V_f^2)$, $C = 290X10^{-6}$

[3] Energy determined by capturing voltage and current waveforms and integrating over time (see appendix one for procedure)

Table 3

Lab Film Voltage Discharge Ignition Test Results in Lighter Fluid

Event	Conditions	Voltage Initial/Final	Energy	Observations
3	5 drops, 35°C, 3min. Film – 3.1 KΩ	170/-[3]	-[3]	Carbon film arced No ignition
4	5 drops, 35°C, 3min. Film – 4.0 KΩ	170/-[4]	150mJ[1]	Carbon film arced No ignition
5	5 drops, 35°C, 3min. Film – 4.7 KΩ	170/-[4]	80mJ[1]	Carbon film arced No ignition
7	5 drops, 30°C, 3min. Film – 2.3 KΩ	170/140 over 40 msec.	810mJ[1] 1348mJ[2]	Carbon film arced Ignition noted (figure 21)
8	5 drops, 30°C, 3min. Film – 0.62 KΩ	170/110 over 150 msec.	2750mJ[1] 2436mJ[2]	Carbon film arced Ignition noted (figure 22)
9	5 drops, 30°C, 3min. Film – 2.2 KΩ	170/145 over 60 msec.	1300mJ[1] 1142mJ[2]	Carbon film arced Ignition noted (figure 23)

[1] Energy determined by capturing voltage and current waveforms and integrating over time (oscilloscope function)

[2] Energy = $1/2C(V_i^2-V_f^2)$, C= $290X10^{-6}$

[3] waveforms not captured

[4] waveforms not recorded

Table 4

Fuel Probe Component Voltage Discharge Ignition Test Results in Lighter Fluid

Event	Component Tested	Conditions	Voltage Initial/Final	Energy/ Time	Observations
10	FG4200A36 S/N A110 Hi-Z wire lug	5 drops, 30°C, 3min. Film – 3.8 KΩ	170/170	3.3 mJ[1] 2.0 msec	No arc or ignition 12mA peak current
11	FG420A18 S/N 85 Hi-Z wire lug	5 drops, 30°C, 3min. Film – 1.0 KΩ	170/170	2.5 mJ[1] 2.0 msec	No arc or ignition 10 mA peak current
12	FG420A29 S/N A110 Hi-Z wire lug	5 drops, 30°C, 3min. Film – 2.0 KΩ	170/170	4.6 mJ[1] 2.0 msec	No arc or ignition 28 mA peak current (see figure 25)
13	FG420A26 Z116 Terminal Block	5 drops, 30°C, 3min. Film – 3.1 KΩ	170/170	1.8 mJ[1] 3.5 msec	No arc or ignition 6 mA peak current
14	Fg420A30 S/N 118 Terminal Block	5 drops, 30°C, 3min. Film – 2.4 KΩ	170/170	1.1 mJ[1] 3.1 msec	No arc or ignition 7 mA peak current
15	Fg420A18 S/N A85 Terminal Block	5 drops, 30°C, 3min. Film – 2.4 KΩ	170/170	1.9 mJ[1] 4.3 msec	No arc or ignition 8 mA peak current
16	FG420A17 S/N A101 Terminal Block	5 drops, 30°C, 3min. Film – 0.72 KΩ	170/170	4.2 mJ[1] 2.3 msec	No arc or ignition 7 mA peak current

[1] Energy determined by capturing voltage and current waveforms and integrating over time (oscilloscope function)

APPENDICES

Appendix A

Preliminary Voltage Breakdown Evaluation Using Laboratory Prepared Test Films

Reagent-grade quantities of copper sulfide in both cupric sulfide (CuS) and cuprous sulfide (Cu_2S) forms and silver sulfide (Ag_2S) were obtained and pulverized to form a powder (figure 1). Chemical properties for compounds of interest are given in table 1. A distilled water suspension was used to disperse materials onto an isopropyl alcohol (IPA)-cleaned bare epoxy circuit board. The two copper compounds readily formed suspensions while the silver compound would not readily form a suspension. After drying overnight, deposits of varying thicknesses were observed for the copper compounds (figure 2). Table 2 describes the created films.

Table 1

Chemical Properties of Compounds of Interest [1]

Compound	Color/ Consistency	Source	Chemical Desig- nation	Melting Point	Solubility
Copper Sulfide (Cupric Sulfide)	Black powder	Mineral form- Covellite	CuS	103°C	Soluble in nitric acid Insoluble in water
Copper Sulfide (Cuprous Sulfide)	Black powder	Mineral form- Chalcocite	Cu_2S	1100°C	Soluble in nitric acid Insoluble in water
Copper sulfate (Cupric Sulfate)	Blue White -Dry		$CuSO_4\,H_2O$		Soluble in water
Silver Sulfide	Grayish black		Ag_2S	825°C	Soluble in nitric acid Insoluble in water

[1] The Condensed Chemical Dictionary, Tenth Edition, 1981.

Resistance values of films were measured with a pair of gold-plated, spring-loaded, flat-end probes (0.062 inches or 1.57 mm in diameter). The probes were mounted in a plastic block to maintain a 1/8-inch (3.2 mm) spacing from inside edge to edge. Measurements were made by placing the probes perpendicular to the film surface and compressing the spring-loaded contacts by about 50 percent. Consistent and repeatable measurements could be obtained in this manner. Measurements were made using a Hewlett-Packard HP 3466A digital multimeter for the more conductive samples, and a Hewlett-Packard HP4329A High Resistance Meter (set to 10 VDC) for the samples of higher resistivity (figure 3).

Three areas were measured on each sample with the appropriate meter and an average value calculated. Results are given in table 2. These results revealed the CuS is more conductive than the Cu_2S films. Since Ag_2S films could not be formed by suspension, the resistance value of a clump of pure silver sulfide was measured. A digital multimeter (HP 3466A) with 1/8 inch spaced probes gave resistance values in the range of 3-5 megohms.

Table 2

Description of Laboratory Created Samples and Measured Resistance Values

Sample Area	Description	Measured Resistance (ohms) [1]
A	A very thick deposit of CuS with mud-cracking	3.67 KΩ (1)
B.	A fairly thick deposit of Cu_2S, not as thick as A Evenly distributed	2.1×10^{12} Ω (2)
C.	A fairly evenly distributed deposit of Cu_2S, thinner than B	2.7×10^{12} Ω (2)
D	Uneven deposit of CuS, one area fairly thick labeled D2	D1 7.4 KΩ (1) D2 108 Ω (1)
E	Thin evenly deposited area of CuS	1.6×10^{12} Ω (2)
F	Bare circuit board - no deposit	4.2×10^{12} Ω (2)
G	Deposit of mixture of 0.35g CuS/5ml water (added later)	0.5KΩ -3MΩ (1)

[1] The reported values are an average of three readings using either the HP 3466A Digital Multimeter (1) or the HP4329A High Resistance Meter set at 10 VDC (2)

Films Placed on Test Coupons

Test coupons were prepared using sections of glass-epoxy printed circuit boards with parallel copper traces spaced at various distances. The traces were approximately 1 mm wide and 8 mm long and were terminated in copper-lined holes to which leads could be soldered. Spacing between the traces was 0.5 mm, 2 mm and 7.5 mm. After leads were soldered in place, the surfaces of the boards and traces were cleaned with isopropyl alcohol (IPA) using cotton swabs to remove rosin flux and other contaminants. Before applying the copper and sulfur suspension mixture, a dam was formed with a silicone bead to contain the mixtures (figure 4).

Resistance readings were taken of the board surfaces across the traces before applying deposits using a Hewlett Packard 4329A High Resistance Meter (set to 100 VDC) connected to the leads. The readings were allowed to stabilize for one minute. Results are given in table 3.

Table 3

Initial Resistance Values between Circuit Board Traces

Sample Description	Measured Resistance
Coupon with 7.5 mm spacing between traces	$1.6 \times 10^{13}\ \Omega$
Coupon with 2.0 mm spacing between traces	$2 \times 10^{14}\ \Omega$
Coupon with 2.0 mm spacing between traces	$8 \times 10^{13}\ \Omega$
Coupon with 0.5 mm spacing between traces	$6 \times 10^{14}\ \Omega$

Preparation of Films Using Cupric Sulfide (CuS) and Water

An analytical balance was used to weigh out 0.035g of CuS, which was then mixed with 5 ml of distilled water. The mixture was stirred and sonicated to aid in the suspension process. Samples of the mixture were poured onto a coupon with the 7.5 mm trace spacing and onto a coupon with a pair of 2 mm spaced traces. After allowing the samples to air dry, measurements were made using a HP 3466A Digital Multimeter. Resistance was initially recorded and then allowed to stabilize for one minute. Since the reading continued to change, the leads were reversed and the measurements were repeated. The films were probed directly using probes with a 1/8-inch spacing. Three measurements were made with the HP 3466A multimeter giving values of 7.5KΩ, 7.7KΩ and 32.1KΩ. Additional results are given in table 4.

Table 4

Resistance Measurements of CuS between PWB Traces (HP3466A@10 VDC)

Sample Description	Measured Resistance (ohms) Initial	Measured Resistance (ohms) Final
Coupon with 7.5mm trace spacing:	30.6K -	1M 440K
Coupon with three leads, 2mm spacing:		
left pair	200KΩ 80K	1MΩ 410K
right pair	300K 200K	500K 600K

Mixtures of CuS, Cu_2S and water were poured on additional circuit board samples with copper traces at various distances. A silicone dam was placed around the traces. The surface of the circuit board was then cleaned with IPA as before. Resistance measurements were made and the lead wires soldered to the traces. Measurements were made with a HP3466A Digital Multimeter or a HP4329A High Resistance Meter set at 10 volts, depending on the amount of resistance present on the particular sample. A configured test sample is shown in figure 4. In some cases, the films were built up in several layers in an attempt to lower the resistance between the traces (figure 5). Results are given in Table 5.

Table 5

Resistance Values for Various Films of CuS and Cu_2S

Sample Description	Measured Resistance
Sample #1 (traces spaced 7.5 mm, 0.35g CuS/5ml water)	66KΩ 88KΩ (leads reversed)
Sample #2 (traces spaced 7.5 mm, 0.35g CuS/10ml water)	3.1MΩ 2.9MΩ (leads reversed)
Sample #3 (layer #1) (A-B traces spaced 2.5 mm, 0.35g CuS/5 ml water):	240KΩ 270KΩ (leads reversed)
Sample #4 (layer #1) (B-C traces spaced 0.5 mm, 0.35g CuS/5 ml water):	2.7MΩ 15MΩ (leads reversed)
Sample #5 (layer #1) (C-D traces spaced 2 mm, 0.35g CuS/5 ml water):	220KΩ 270KΩ (leads reversed)
Sample #6 (layer #1) (A-D traces spaced 5 mm, 0.35g CuS/5 ml water):	10MΩ 4MΩ (leads reversed)
Sample #7 (layer #2)(A-B traces spaced 2.5 mm, 0.35g CuS/5 ml water):	240KΩ 260KΩ (leads reversed)
Sample #8 (layer #2) (B-C traces spaced 0.5 mm, 0.35g CuS/5 ml water):	600KΩ 500KΩ (leads reversed)
Sample #9 (layer #2) (C-D traces spaced 2 mm, 0.35g CuS/5 ml water):	100KΩ 490KΩ (leads reversed)
Sample #10 (layer #2) (A-D traces spaced 5 mm, 0.35g CuS/5 ml water):	2 MΩ 600KΩ (leads reversed)

Electrical Breakdown Tests

A circuit was designed to evaluate voltage breakdowns when a sinusoidal source was applied to the laboratory-created films. A Wavetek Model 95 Arbitrary Waveform Generator was used to directly control a California Instruments Model 3001TCA AC power source. One half of a 400-hertz sinusoidal power cycle (1.25 millisecond duration) was applied to the films under test. The peak voltage could be varied between 0 and 200 volts. Current was limited with a 200 ohm resistor in series with the voltage output circuit. The maximum current output at 200 volts with the test probes shorted was one ampere. Current was monitored using a Phillips PM9355 current probe. This was connected to a Tektronix 7854 sampling and digitizing oscilloscope, which was fitted with a camera, 7A26 and 7A19 vertical amps and a 7B87 horizontal time base. The oscilloscope captured the voltage and current probe outputs. The sample under test was connected with a single-pole-double-throw (SPDT) switch so that it could be connected to either the impressed voltage or a HP3466A digital multimeter to record the resistance value of the sample under test. Electrical measurements were made using gold-plated, spring-loaded, flat-tipped probes or wires soldered to copper strips. The schematic and test set-up is shown in figures 6 and 7. The voltage was increased across the films under test until breakdown was noted on the oscilloscope. Voltage breakdown was noted when the current pulse exhibited spikes or did not follow the voltage waveform.

Voltage was applied to the coupon containing samples 8 (B and C) and 9 (C and D) in table 5 (figure 5). Results are shown in table 7. An oscillograph of a breakdown event is shown in figure 8. Optical inspection did not reveal physical film damage (figure 9). The current would typically rise and reach a peak value and then drop to near zero. As can be seen from table 7, the resistance of the film changes dynamically during and after the application of the voltage. The initial resistance changes to a dynamic resistance and then returns to a value that may be higher or lower than the initial resistance. The voltage breakdown event or events correspond to the peak current level measured. Dynamic resistance was calculated by dividing the peak voltage (at the peak current value) by the peak current.

Table 7

CuS Film Voltage Breakdown Results

Sample	Initial Resistance	Voltage at Breakdown	Peak Current	Dynamic Resistance[1]	Final Resistance
8A (0.5mm)	400K	59V	75mA	790	24K
8B	49K	63V	100mA	630	38K
8C	34K	107V	125mA	860	66K
8D	41K	149K	150mA	990	25K
8E	105K	172 V	150mA	1.2K	300K
8F	300K	178V	600mA	300	500K
9A (2mm)	580K	60 V	70mA	860	4.5K
9B	75K	102V	200mA	510	5.5K
9C	5K	117V	200mA	585	20K
9D	50K	142V	300ma	470	100K
9E	70K	173V	200mA	860	328K

[1] Resistance calculated by dividing the voltage at breakdown by the peak current.

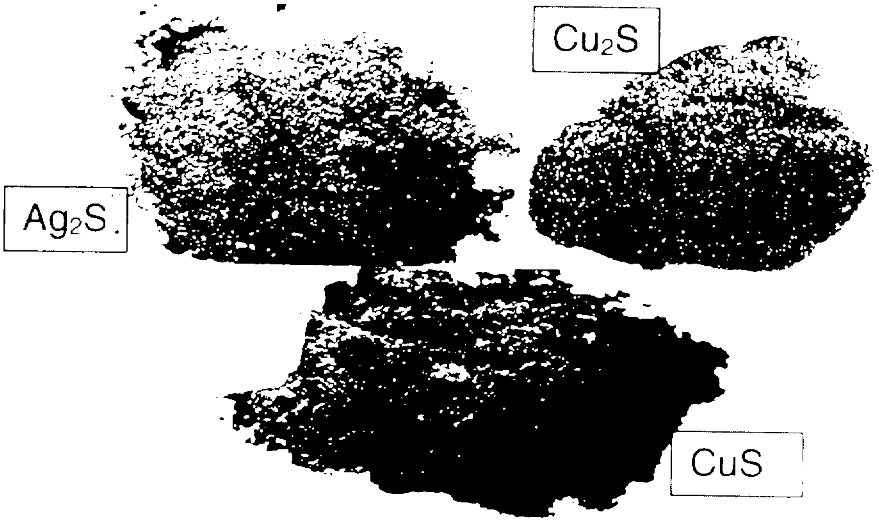


Figure 1. Examples of compounds selected for evaluation.

Figure 2. Test vehicle with laboratory deposited films. Table 2 gives the label identification.

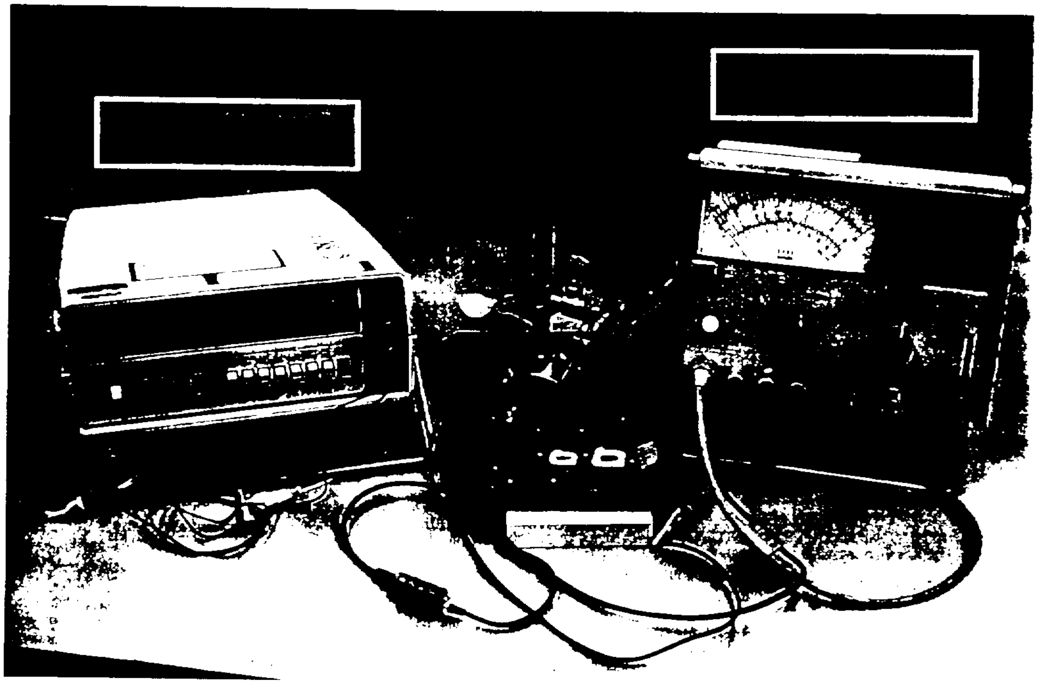


Figure 3. Test setup used to measure resistance of films.

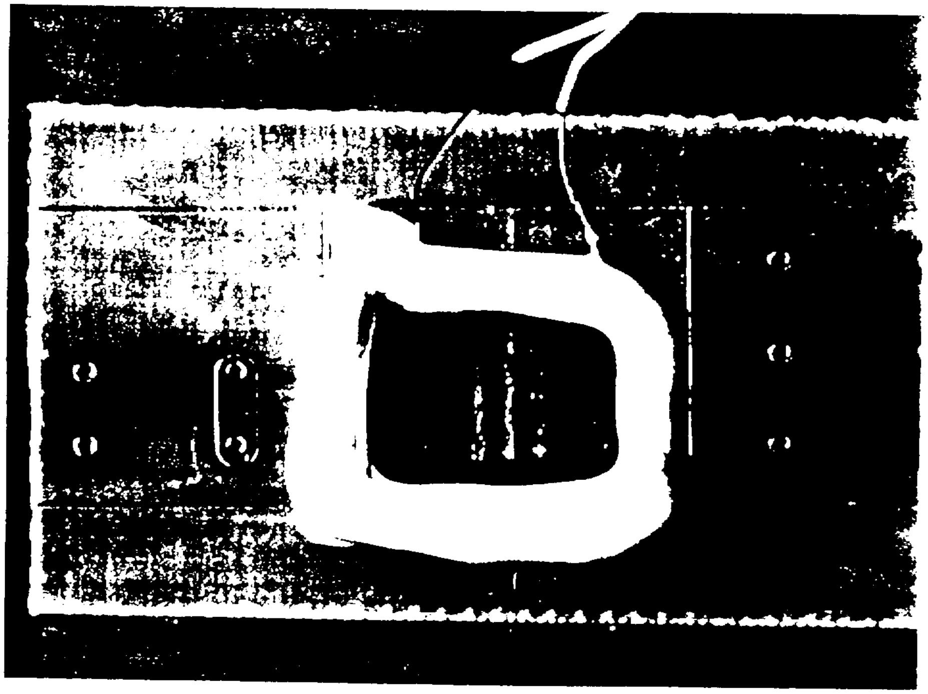


Figure 4. Test sample used to evaluate created films. A silicone bead contained the liquid that was evaporated and formed a film.

Mag. 2.9X

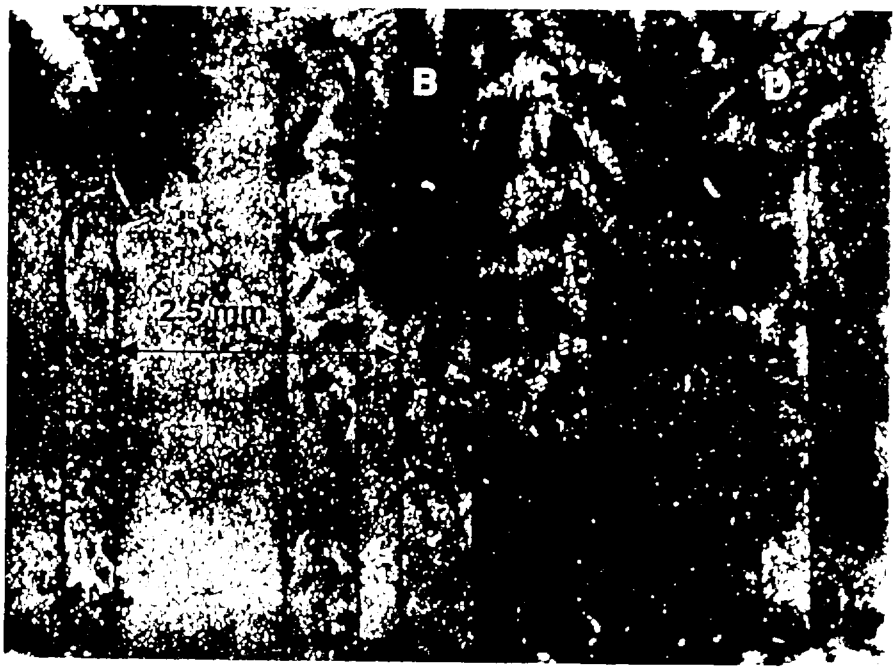


Figure 5. CuS film deposited between circuit board traces. Breakdown tests were conducted between B and C and C and D traces.

Mag. 11.3X

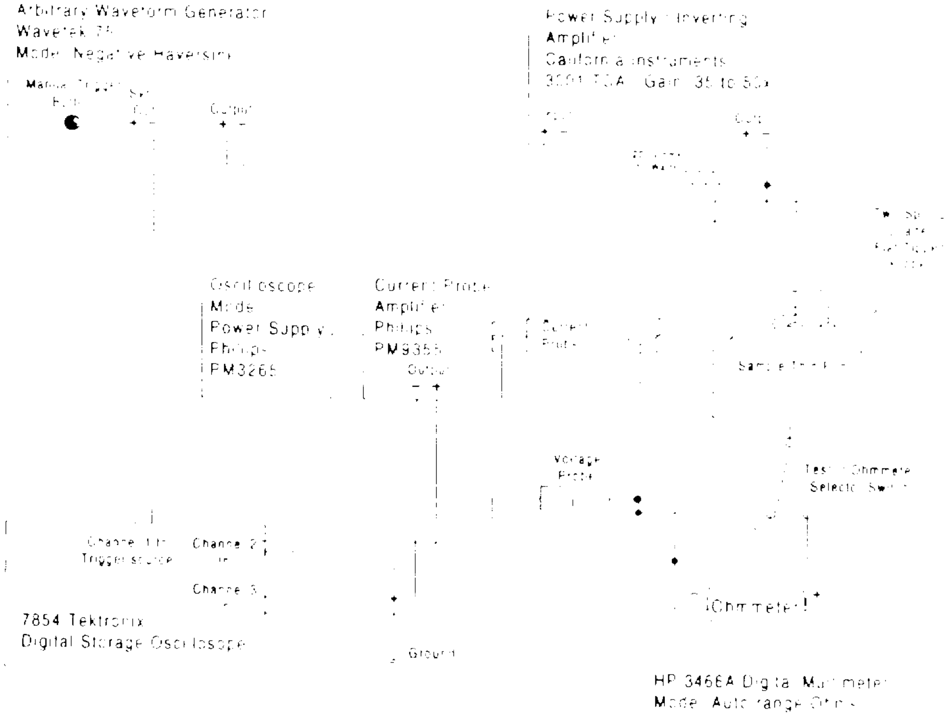


Figure 6. Modified circuit schematic that can apply up to a 200-volt haversine waveform (1.25 msec) to film samples.

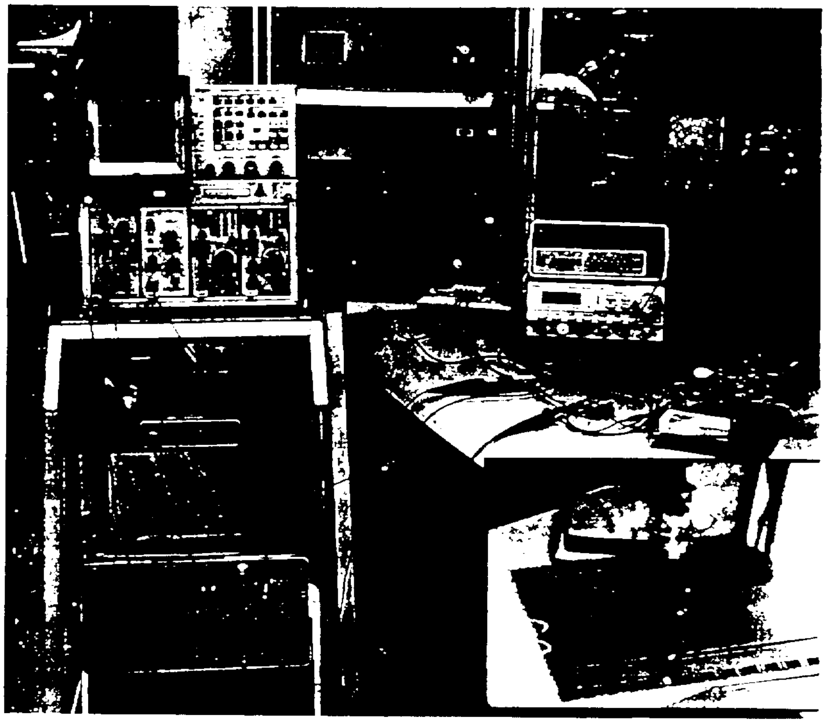


Figure 7. Test setup used to conduct voltage breakdown tests up to 200 volts. The inset shows a sample under test.

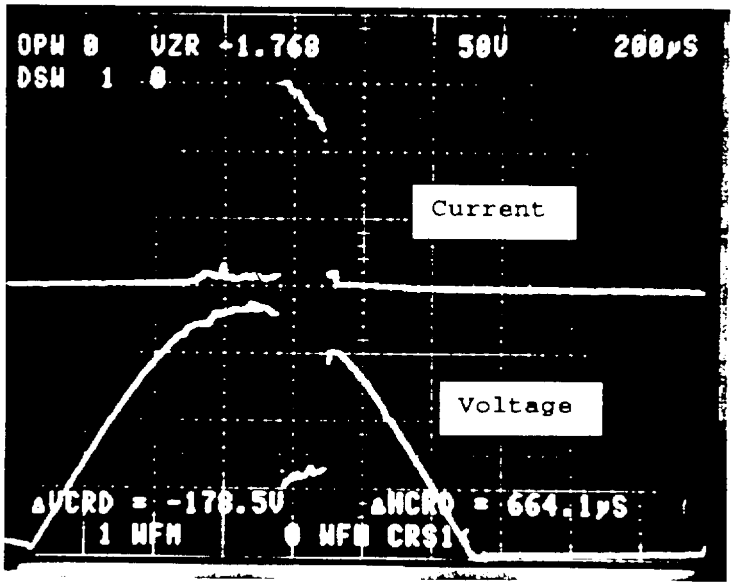


Figure 8. Oscillograph of voltage breakdown event (178 volt and 600mA peak, red arrows) from CuS film on circuit traces 0.5mm apart (table 7, test 8F).

Figure 9. CuS film deposited between circuit board traces after voltage breakdown test (figure 12). No surface damage was noted.

Mag. 11.3X

Appendix B

Preliminary Voltage Breakdown and Impressed Energy Calculations of Fuel Quantity Instrumentation System Components

The following fuel probes were initially selected for voltage breakdown tests, based on the presence of black residues on terminal blocks and on wire terminals: P/N FG420A23 S/N A-119, Aircraft 93117 P/N F40 S/N Z-116, P/N FG420A18, S/N A-85, and P/N FG420A12 S/N Z-119. Examples of residues are given in figures 1,2 and 3 of the main report and figures 1, 2 and 3 of this appendix.

Most of the probes selected had inspection tags. A typical example is given below:

Fuel Qty Unit
Evergreen Air Center, Incorporated B-747
Pinal Air Park, Marana, AZ
FAA Approved Repair Station Number ERKR675D
Removed from Aircraft S/N 1995B/N134TW
Customer: Flight Director, Inc.
Job Number: 10-1073-02-0001
Date: 6-1-98
Removed by M. Stephanson 102023
P/N FG 420A23 S/N A-119
BAC P/N 60B92010-23

Resistance measurements were attempted using a digital multimeter with the spring-loaded probes spaced 1/8 inches apart (figure 4). An area on the insulated terminal lug (Lo-Z terminal) of fuel probe P/N FG420A23 S/N A-119 measured 1.2 to 2.5 kilohms (figure 3). The resistance varied from spot to spot, but was generally low enough to be tested for breakdown. Slight movement of the electrical probes would cause the resistance value to change. The probes were typically adjusted several times until a low and stable resistance value was obtained. The voltage breakdown circuit described in appendix A, figure 6 was used in testing. Voltage was gradually increased until the current indicated a possible breakdown. The first breakdown occurred at 8 volts, with a current of 3 milliamps (figure 5). Resistance before this particular test was 3.05 kilohms. After the test, the resistance was in the megohm range. A summary of the test results is given in table 1. The initial, dynamic and final resistance was recorded. The peak current and the voltage at that value were used to calculate the dynamic resistance (R=V/I). For many cases, when breakdown was noted, the dynamic resistance was lower than the initial and final resistance value. The final resistance would eventually stabilize, as noted in the table. Slight probe movement or pressure would typically re-establish a low resistance path. This implies the voltage breakdown is occurring underneath the spring-loaded probe contacts, rather than in the residue film between the contacts. Optical inspection did not reveal any arc tracking or other signs of breakdown in the residue film between the electrical contacts.

Table 1

Voltage Breakdown Test Results for Insulated Connector Lug (Low-Z Terminal) of Fuel Probe P/N FG420A23, S/N A119

Test	Initial/ Dynamic[6] Resistance (kilohms)	Peak Voltage/ Voltage at Peak Current (volts)	Peak Current (mA)	Resistance After/Stabilized (kilohms)	Comments
1	3.6/5.7	1.7/1.7	0.3	3.2	No breakdown
2	3.2/1.9	4.5/4.5	2.4	3.1	No breakdown
3	3.1/2.7	10/8	3	Megohms[1]/2.9[2]	Breakdown (Figure 5)
4	2.9/-[7]	15	2	Megohms[1]/5.2[2]	Breakdown
5	5.2/-[7]	8	2	5.2	No breakdown
6	5.2/-[7]	13.7	3	5.4	No breakdown
7	5.9/5.1	23.1/18	3.5	Open[1]/18/11[2]	Breakdown
8	11.5/-[7]	23.4	2.5	15/12[2]	Breakdown
9	12/-[7]	28.3	3	16/14[2]	Breakdown
10	13.7/-[7]	37.8	4	18/11.7[3]	Breakdown
11	11.7/8.4	47.8/42	5	Open[1]/27/15[2]	Breakdown
12	11.7/12	63/60	5	50[1]/14[4]	Breakdown (figure 5)
13	14.2/16.6	72.7/58	3.5	Open[1]/17K[2]	Breakdown
14	14/8.5	97.7/85	10	Open[1]/29[4]/23[5]	Breakdown (figure 6)
15	21.3/11.2	122.1/90	8	250[1]/22[2]	Breakdown
16	21.2/-[7]	147	5	5M[1]/25[2]	Breakdown
17	25/11.2	172.4/135	12	12M[1]/12M[5]	Breakdown (figure 6)

[1] Probe contacts adjusted
[2] Resistance stabilized after 5 minutes
[3] Resistance stabilized after 15 min.
[4] Resistance stabilized after 30 min.
[5] Resistance stabilized after 60 min.
[6] Dynamic resistance--voltage at peak current/peak current
[7] Waveforms not stored

Calculation of Energy Voltage Breakdown Events

Energy developed during the applied voltage pulses was calculated using the Tektronix Model 7854 oscilloscope waveform algorithms. The calculation process is described in appendix C. Testing was conducted with the circuit shown in appendix A, figure 6. The residue on the insulated Lo-Z terminal lug from fuel probe P/N FG420A23, S/N A-119 was again used for these tests. Tests were conducted as before, raising the voltage incrementally until sufficient voltage was present to cause a voltage breakdown, based on the oscillograph of the event. An apparent breakdown occurred at 140 volts with a peak current of 5.2 milliamps (figure 7). The resistance value before the test was 13 kilohms, after the test, 1 megohm and after adjusting probe contact pressure, 19 kilohms. The dynamic resistance was calculated as 26.9 kilohms (140V/5.2mA). Using the waveform algorithm functions on the oscilloscope, voltage and current waveforms were multiplied together to produce a power waveform that was then integrated over time (1.25 msec) to give an energy value of 0.24 millijoules (figure 7).

Another area on the insulted terminal exhibited an apparent breakdown at 172.9 volts and peak current of 17 mA. The initial resistance for this test was 16 kilohms. At the end of the test, the resistance was 260 kilohms. The dynamic resistance was calculated to be 10.2 kilohms (172.9V/17mA). The energy impressed on the sample was calculated to be 1.1 millijoules (figure 8).

Fuel Probe 93117 F40 S/N Z-116

A fuel probe from Aircraft 93117 exhibited residues on the insulated terminal lug (Lo-Z terminal) and on the terminal block beneath the lug (Figure 9). Contact probes were applied to the insulated terminal. A 199.2 volt pulse produced a peak current of 7.5 milliamps across the residue (figure 10). Energy was calculated to be .42 millijoules (Figure 11). Initial resistance was 15.7 kilohms and after the test the resistance was 237 kilohms. Dynamic resistance was calculated to be 26.6 kilohms (199.2V/7.5mA)

Additional tests were conducted in different areas with the results summarized in table 2. The residue film surface had no visible damage from the discharge events.

Table 2

Energy Discharge Results for Residues Found on Fuel Probe 93117 F40 S/N Z-116

Test	Initial/ Final Resistance (kilohms)	Peak Voltage/ Voltage at Peak Current (volts)	Peak Current (mA)	Dynamic Resistance[4] (ohms)	Calculated Energy[3] (millijoules)	Comments
1	15.7/237	199.2/199.2	7.5	26.6	0.42	Insulated lug, (figure 10)
2	5.9/13	176.8/90	11	8.2	0.14	Terminal block,under lug (figure 11)
3	7/330[1]/130	174.1/135	13.5	10	.49	Terminal block,under lug (figure 12)
4	10/200[1]/30	175.8/175.8	4.8	36.6	0.29	Terminal block,under lug (Figure 13)
5	13/open[2]	175.8/172	11.8	14.6	0.63	Terminal block,under lug (Figure 14)

[1] Contact probes adjusted

[2] Above 30 megohms

[3] Energy determined by capturing voltage and current waveforms and integrating over time (see appendix C for procedure)

[4] Dynamic resistance- voltage at peak current/peak current

Fuel Probe P/N FG420A18, S/N A-85

Fuel probe P/N FG420A18, S/N A-85 was selected for testing. Residues were noted on the terminal block under the Lo-Z terminal lug (main report, figure 2). The test procedure on residue films was used as before and the results are given in table 3. The residue film surface had no visible damage from the discharge events.

Table 3

Energy Discharge Results for Residues Found on Fuel Probe FG420A18 S/N A-85

Test	Initial/Final Resistance (kilohms)	Peak Voltage/ Voltage at Peak Current (volts)	Peak Current (mA)	Dynamic Resistance[2] (kilohms)	Calculated Energy[3] (millijoules)	Comments
1	5.8/open[1]	175.8/160	24	17.6	0.43	Terminal block, under lug Breakdown (Figure 15)
2	3.3/open[1]	173.8/170	35	4.8	0.39	Terminal block, under lug Breakdown (Figure 16)
3	9.2/open[1]	174.3/160	13.5	11.8	0.63	Terminal block, under lug Breakdown (Figure 17)

[1] Above 30 megohms

[2] Dynamic resistance--voltage at peak current/peak current

[3] Energy determined by capturing voltage and current waveforms and integrating over time (appendix C for procedure)

Fuel Probe P/N FG420A23, S/N A-119

Fuel probe P/N FG420A23, S/N A-119 was tested. Again, the area under the Lo-Z terminal lug on the terminal block was chosen, due to the presence of residues (figure 18). Very low resistance readings were recorded on this sample. The test procedure on residue films was used as before and the results are given in table 4. As was noted in earlier testing, voltage breakdown (a current spike) typically occurred before the voltage peaks. The current would rapidly rise, peak and then fall to a level near zero (figure 19). In some cases there were multiple breakdowns. Optical inspection after testing revealed a possible arc track across a residue film in two of the voltage breakdown events (figures 24 and 25). The arc track appeared to emanate from a contact probe.

Table 4

Energy Discharge Results for Residues Found on Fuel Probe P/N FG420A23, S/N A-119 Under The Lo-Z Terminal Wire Terminal Block

Test	Initial/Final Resistance (kilohms)	Peak Voltage/ Voltage at Peak Current (volts)	Peak Current (mA)	Dynamic Resistance[3] (kilohms)	Calculated Energy[2] (millijoules)	Comments
1	1.9/2.4	174.3	40	-	-	Terminal block, under lug
2	1.7/open[1]	174.3/162	59.8	2.7	0.55	Terminal block, under lug, Breakdown (figure 19)
3	3.6/open[1]	174.3/155	60	2.6	1.46	Terminal block, under lug, Breakdown, surface damage noted (figures 20 and 24)
4	1.6/open[1]	173.8/60	30	1.5	-	Terminal block, under lug, Breakdown, data lost energy not calculated (figure 21)
5	4.9	175.5/145	42	3.4	-	Terminal block, under lug, Breakdown, data lost energy not calculated (figure 21)
6	3.4/8.5	168/-	40	-	-	Terminal block, under lug, data lost energy not calculated
7	7.9	170.9/-	20	-	1.1	Terminal block,under lug, Breakdown
8	4.4/open[1]	171.9/158	34	4.6	1.9	Terminal block,under lug, Breakdown (figure 22)
9	5.2/5500	175.3/-	22	-	1.2	Terminal block,under lug, Breakdown
10	1.5	159.2	80	2.0	6.5	Terminal block,under lug, Breakdown, film damage noted (figures 23 and 25)

[1] Resistance above 30 megohms

[2] Energy determined by capturing voltage and current waveforms and integrating over time (see appendix C for procedure)

[3] Dynamic resistance- voltage at peak current/peak current

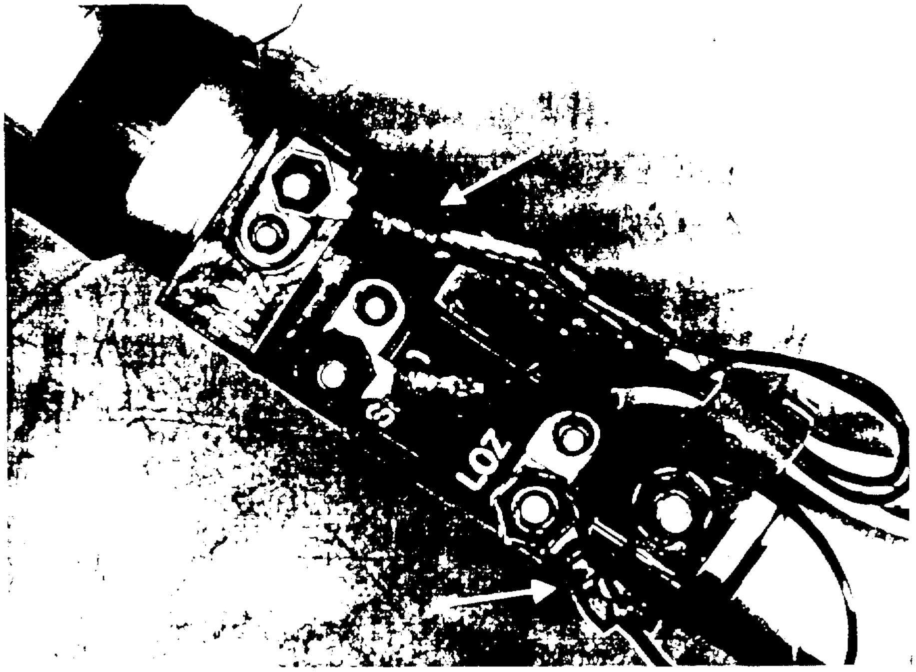


Figure 1 Fuel probe FG420A12 Z119. Note residues on the Hi Z and Lo Z wire terminals (arrows)
Mag 1.1X

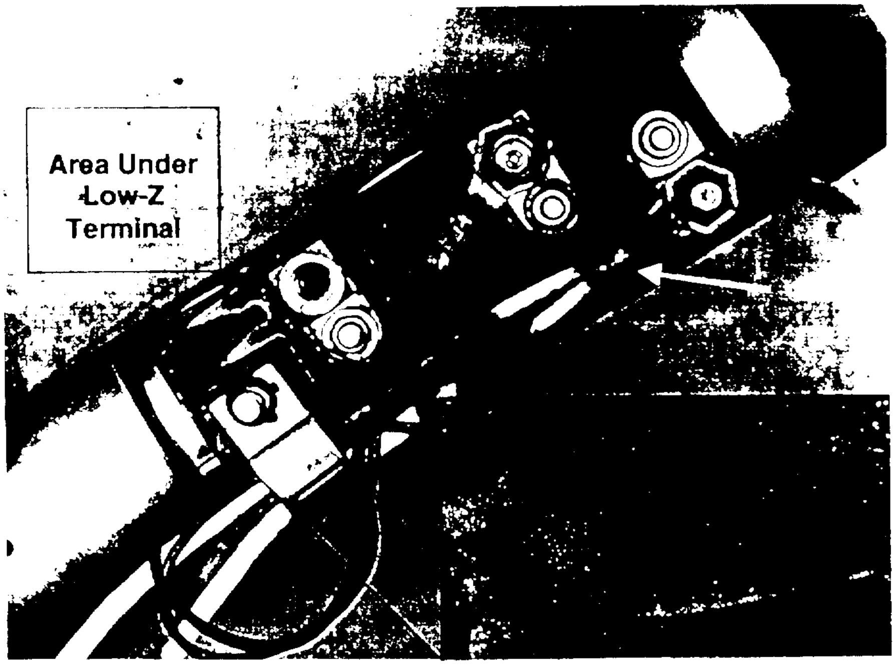


Figure 2 Fuel probe FG420A18, S/N A-85. Note residues on terminals (arrow) and on the terminal block (insert)

Mag 1.1X

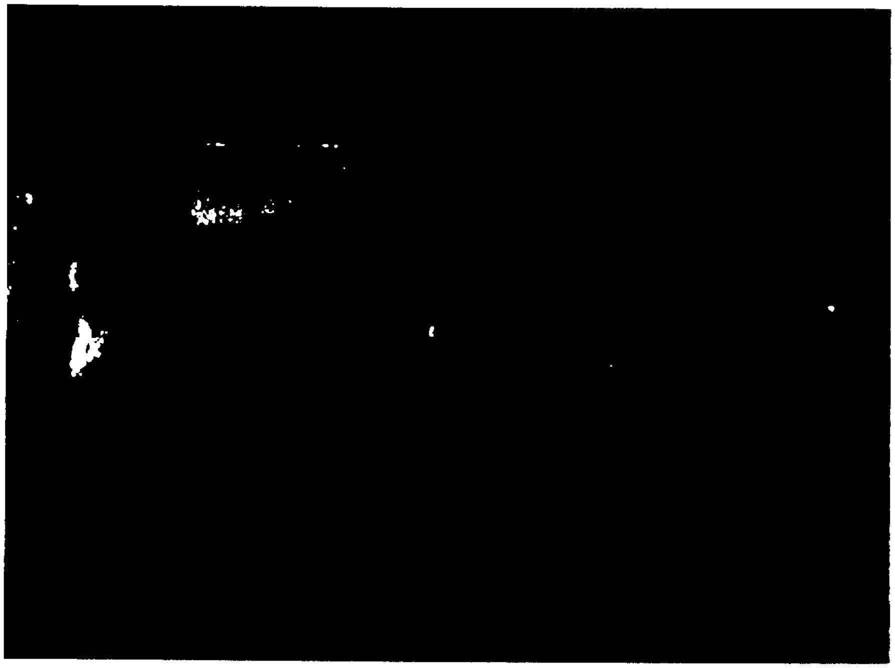


Figure 3 Fuel probe P/N FG420A23 A-119 Lo-Z wire terminal Note black residue

Mag 8.9X

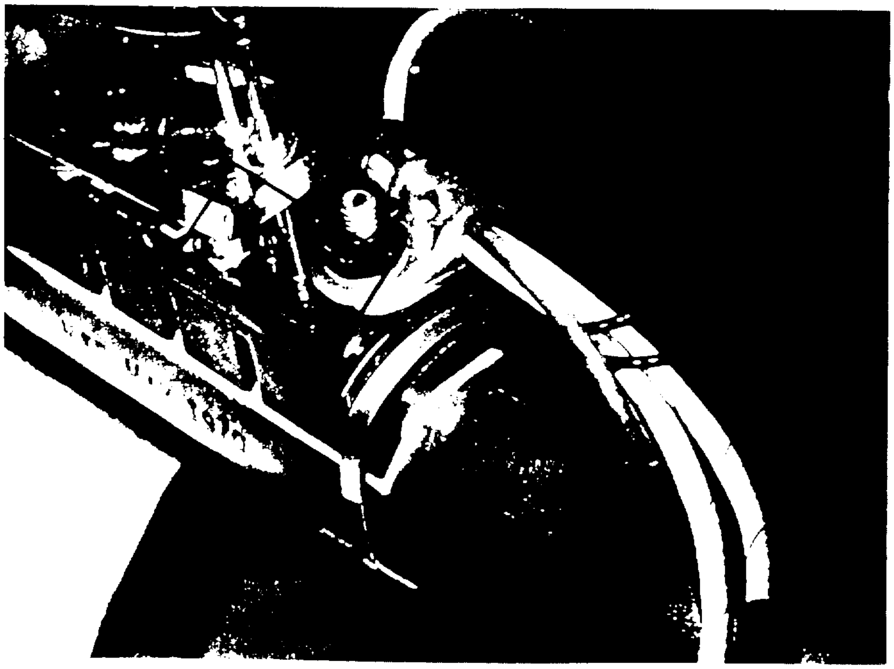


Figure 4 Contact probes (red box) used to impress a voltage on residue films

Mag 1.1X

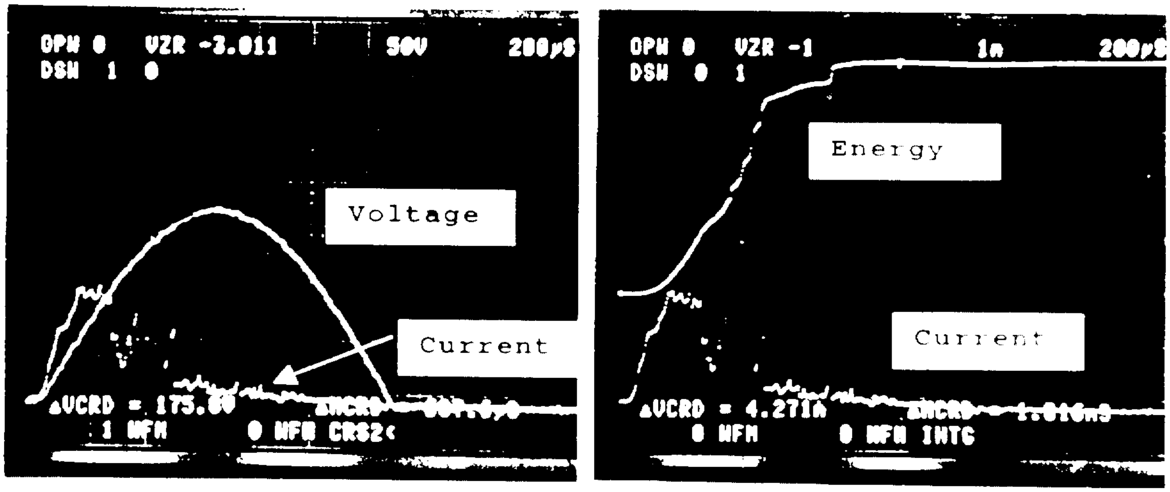


Figure 15. Voltage breakdown on the FG420A18 A 85 terminal block underneath the Lo-Z terminal. Peak breakdown values (red arrows) were 160V and 24mA (left) and calculated energy was 0.43 mJ (right, conversion factor 0.1X).

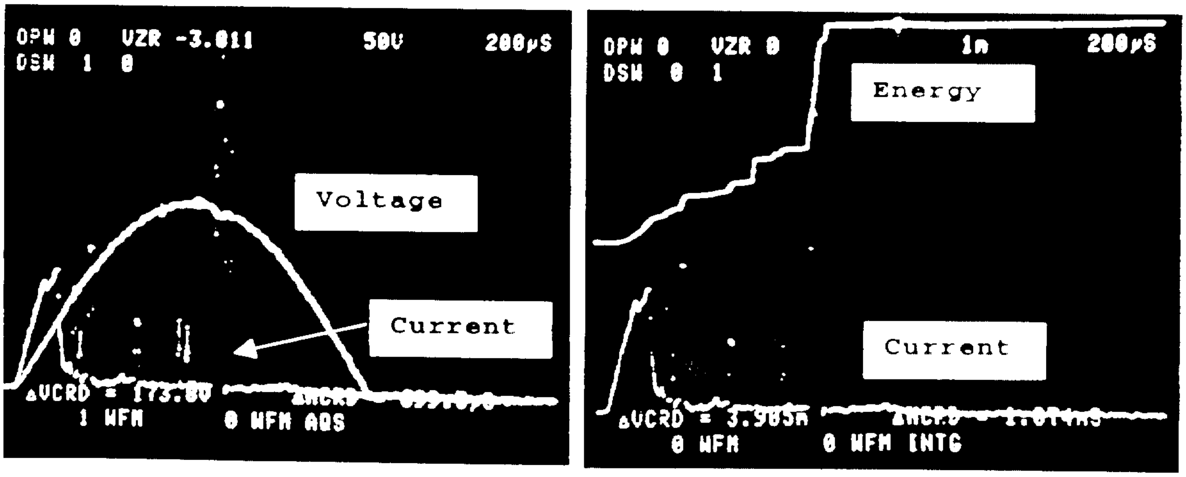


Figure 16. Voltage breakdown on the FG420A18 A 85 terminal block underneath the Lo-Z terminal. Peak breakdown values (red arrows) were 170V and 35mA (left) and calculated energy was 0.39 mj (right, conversion factor 0.1X).

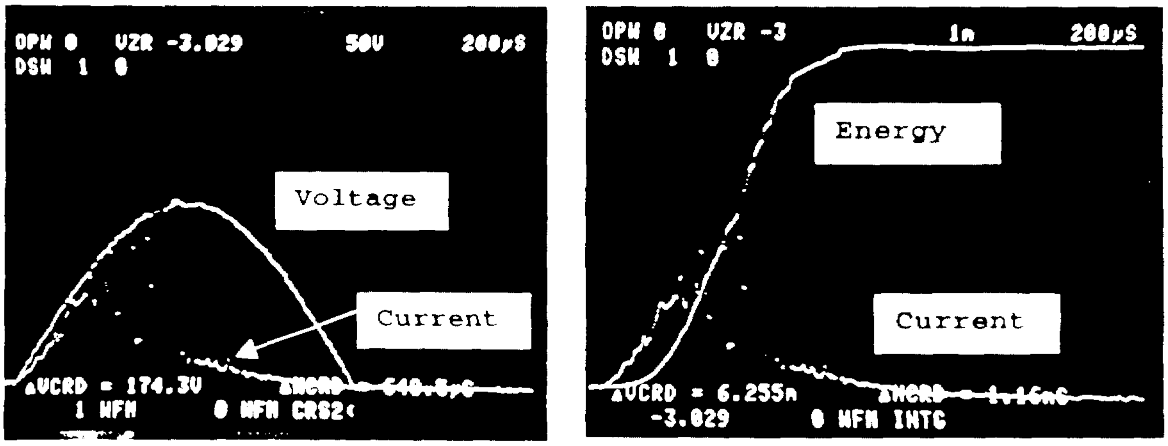


Figure 17. Voltage breakdown on the FG420A18 A-85 terminal block underneath the Lo Z terminal. Peak breakdown values (red arrows) were 160V and 13.5mA (left) and calculated energy was 0.63 mJ (right, conversion factor = 0.1X)

Figure 18. Fuel probe P/N FG420A23 S/N A-119 residue area under the Lo-Z terminal lug on the terminal block.

Mag: 8X

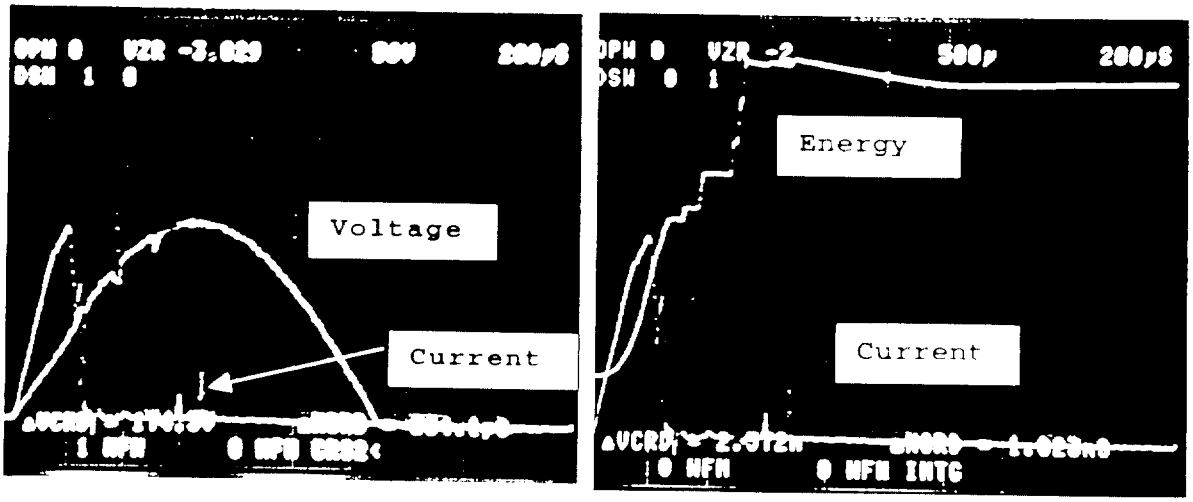


Figure 19. Voltage breakdown on the P/N FG420A23 S/N A-119 residue area under the Low-Z terminal lug on the terminal block. Peak breakdown values (red arrows) were 162V and 59.8mA (left) and calculated energy was 0.55 mJ (right, conversion factor 0.2X).

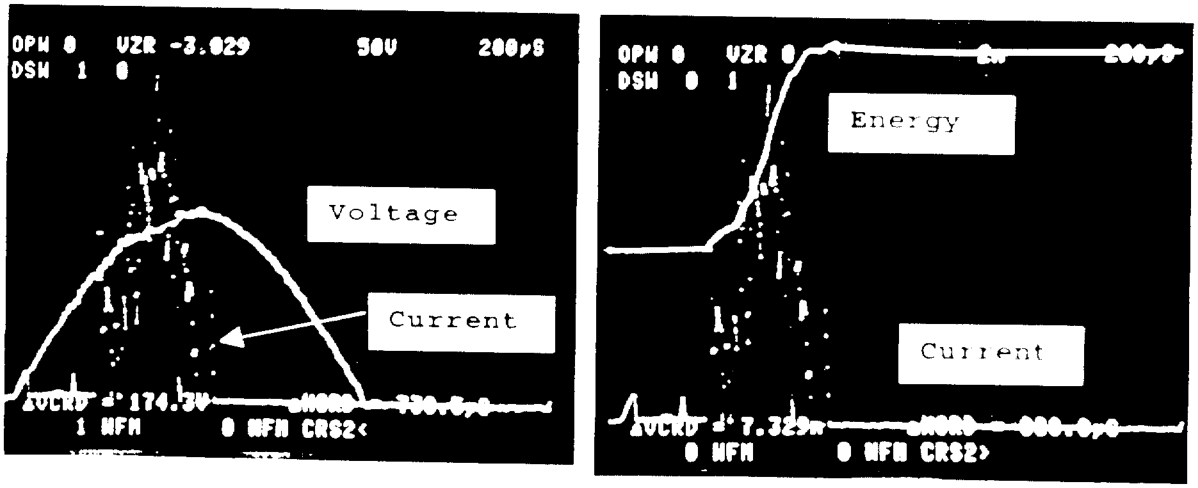


Figure 20. Voltage breakdown on the P/N FG420A23 S/N A-119 residue area under the Low-Z terminal lug on the terminal block. Peak breakdown values were 155V and 60mA (left) and calculated energy was 1.46 mJ (right, conversion factor 0.2X).

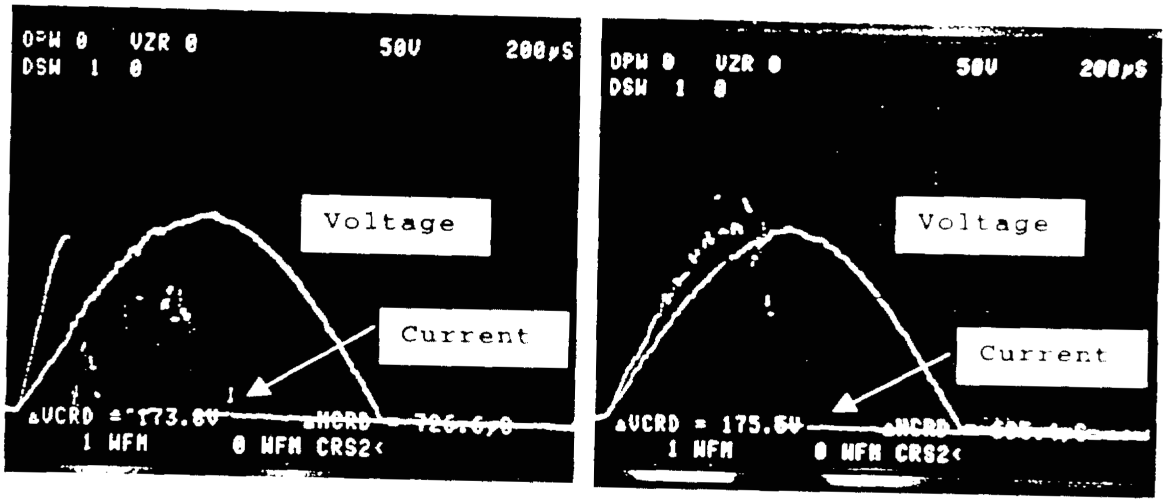


Figure 21. Voltage breakdown on fuel probe FG420A23 S/N A 119 residue area under the Low-Z terminal lug on the terminal block. Peak breakdown values for events were 60V and 30mA (left) and 145V and 42mA (right).

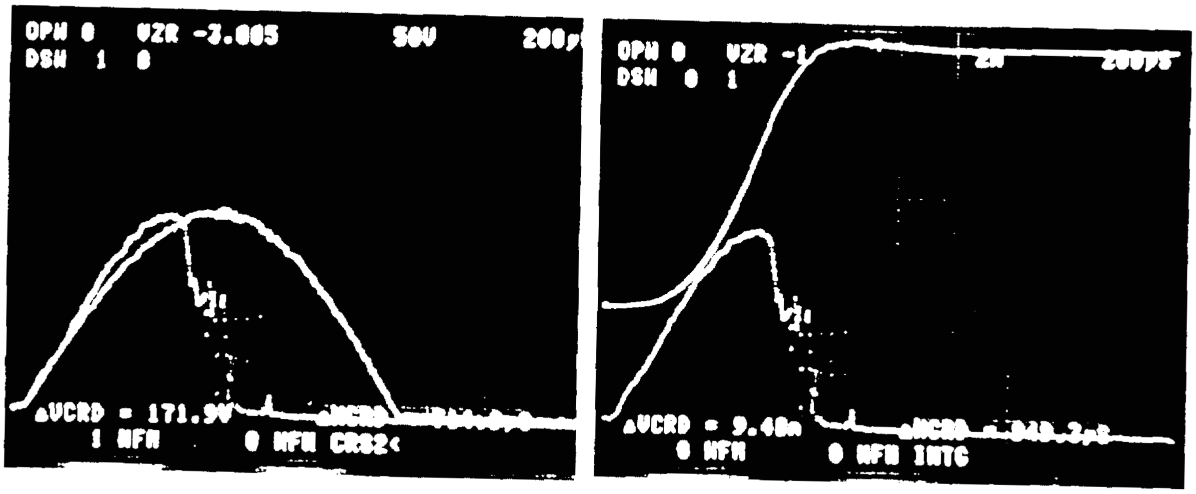


Figure 22. Voltage breakdown on the P/N FG420A23 S/N A 119 residue area under the Low-Z terminal lug on the terminal block. Peak breakdown values were 158V and 34mA (left) and calculated energy was 1.9 mJ (right, conversion factor 0.2X).

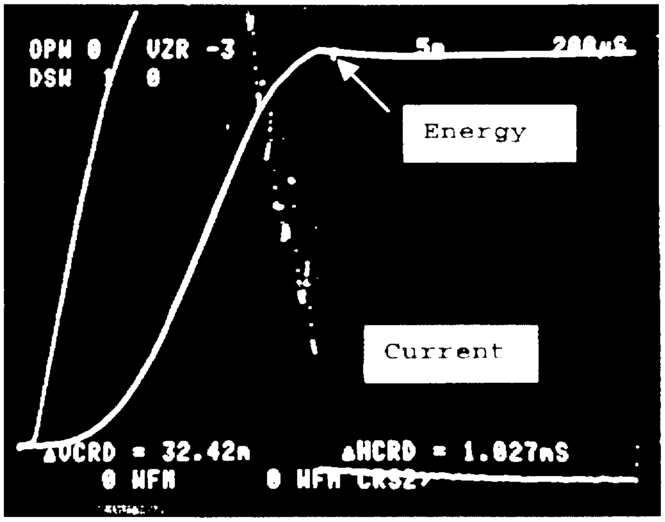


Figure 23 Voltage breakdown on fuel probe FG420A23 S/N A 119 residue area under the Low Z terminal lug on the terminal block. Peak breakdown values were 159.2 V and 80mA (estimated) (left) and calculated energy was 6.5 mJ (right, conversion factor 0.2X)

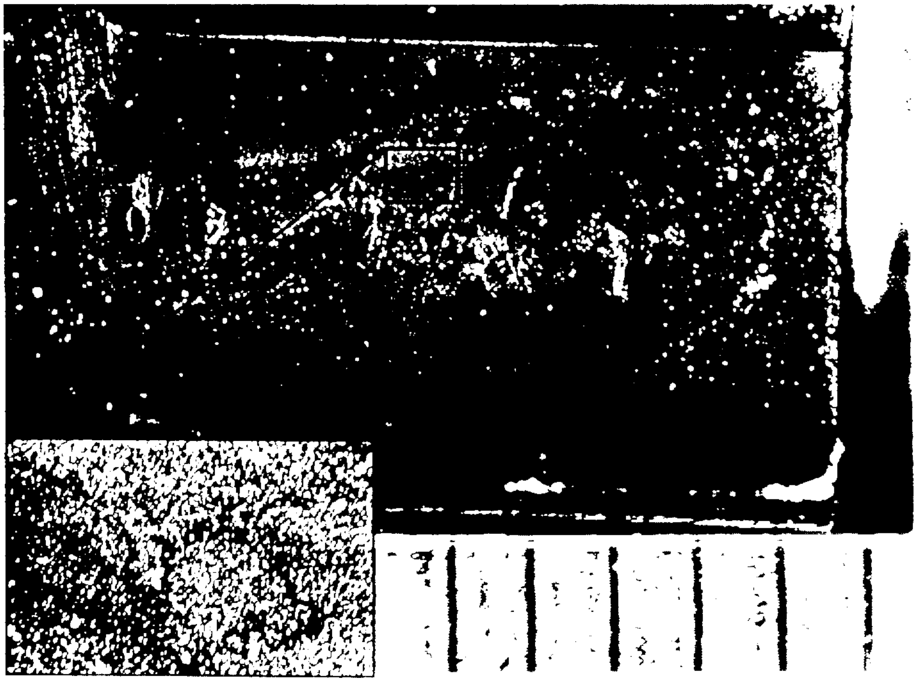


Figure 24 Voltage breakdown damage (insert) on fuel probe FG420A23 S/N A 119 residue area under the Low-Z terminal lug on the terminal block after test 3 (see table 4 event 3)

Mag 6.8X

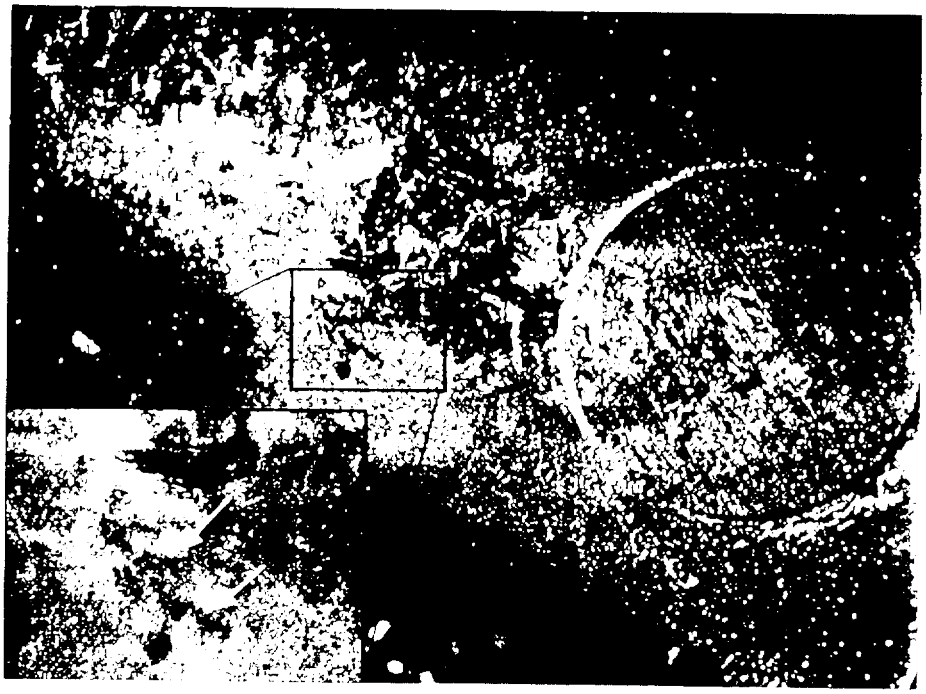


Figure 25. Voltage breakdown damage (arrows) on fuel probe FG420A23 S/N A-119 residue area under the Low-Z terminal lug on the terminal block after test 10 (see table 4, event 10).

Mag: 10.2X

Appendix C

Procedure Used to Calculate Energy Discharged

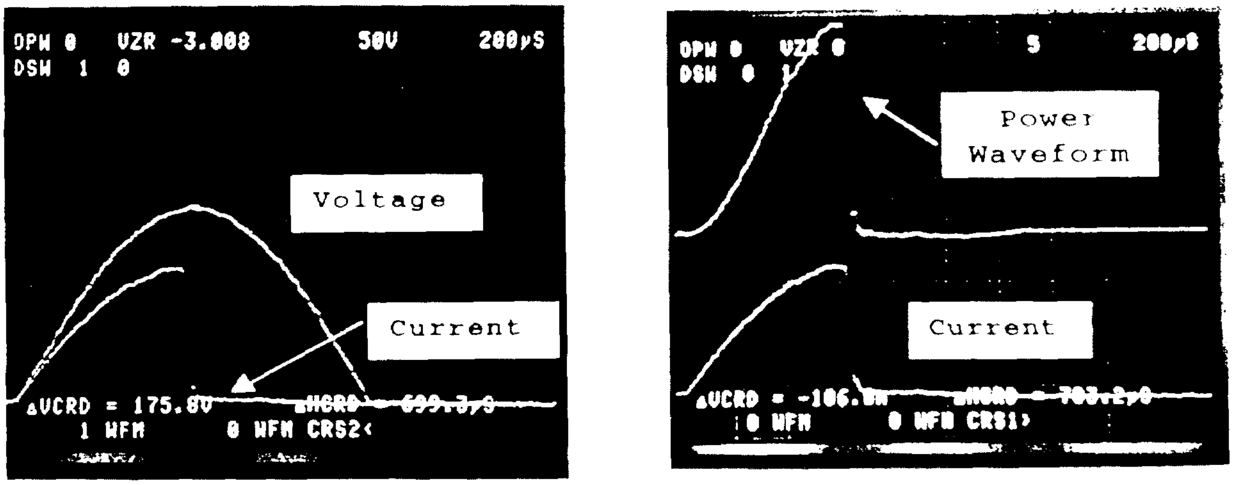


Figure 1 The voltage and current waveforms were acquired using a Tektronix Model 7854 sampling and digitizing oscilloscope sampling with 256 points (left). The voltage (50 volts/div) and current (5mA/div) were captured using the test setup shown in figure 6, appendix A. A 200 microsecond per division time base was used. The two waveforms were multiplied together using the oscilloscope calculator functions, giving a power (P=V x I) waveform (right). Scaling for the power waveform is 500 milliwatts per division.

unable to me

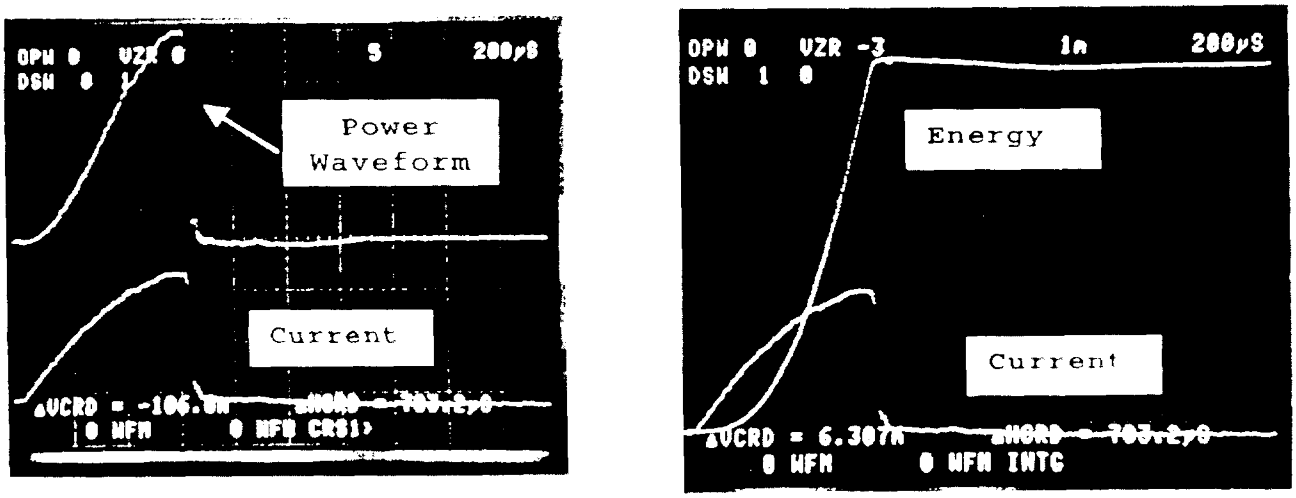


Figure 2 Integrating the power waveform (area under the curve, left) using the oscilloscope integration function gives an energy waveform (right). Integration was calculated internally using the trapezoidal rule. The oscilloscope calculation gave an energy value of 0.63mJ, after applying a conversion factor of 0.1. A 0.1 conversion factor is required to properly scale the current for the internal oscilloscope calculation. For this test the current probe amplifier (that converts the current to a voltage output) was set to 5 mA per division and the input into the oscilloscope at 50 mV per division. (5 mA/50 mV gives a 0.1 scaling factor.)

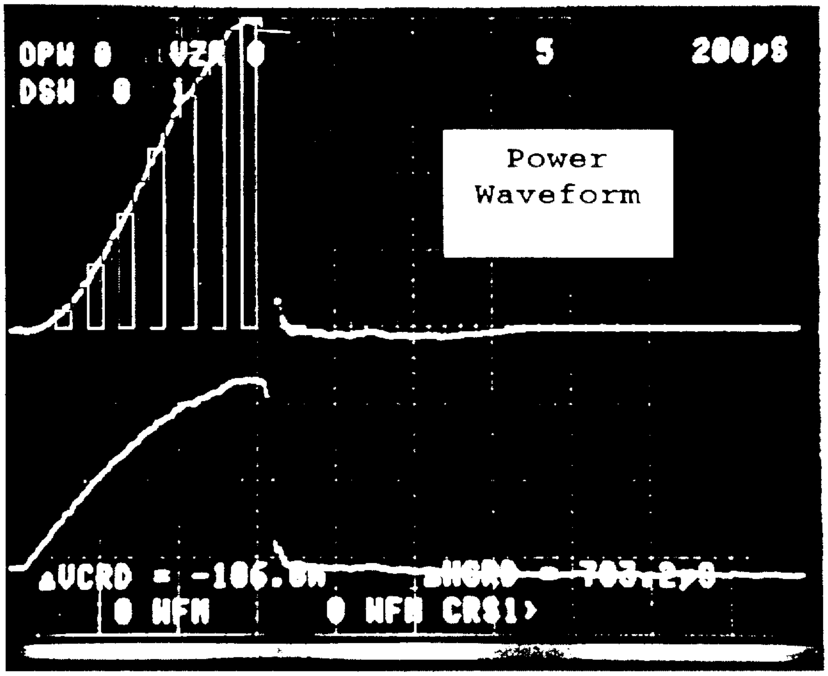


Figure 3. An alternate pictorial method for calculating the energy is given above using the power waveform. Summation of the area (height x width) of the rectangles under the curve is given in table 1 below. The height for each rectangle is the estimated vertical output of the oscilloscope waveform (multiplied amplitudes of the voltage and current or instantaneous power). The width is the unit of time (in this case 40 microseconds). The pictorial example gives an energy value of 0.632 mJ which correlates well with the oscilloscope calculated energy level of 0.63 mJ.

Table 1

Estimated Area Under the Power Wave form Which is Also the Energy

Area	Estimated Height	Width	Energy (H*W)	Energy Summation
1	.15	40E-6	6E-6	6E-6
2	.25	40E-6	10E-6	16E-6
3	.4	40E-6	16E-6	32E-6
4	.6	40E-6	24E-6	56E-6
5	.75	40E-6	30E-6	86E-6
6	.95	40E-6	38E-6	124E-6
7	1.15	40E-6	46E-6	170E-6
8	1.35	40E-6	54E-6	224E-6
9	1.5	40E-6	60E-6	284E-6
10	1.6	40E-6	64E-6	348E-6
11	1.8	40E-6	72E-6	420E-6
12	1.9	40E-6	76E-6	496E-6
13	2.0	40E-6	80E-6	576E-6
14	1.4	40E-6	56E-6	632E-6

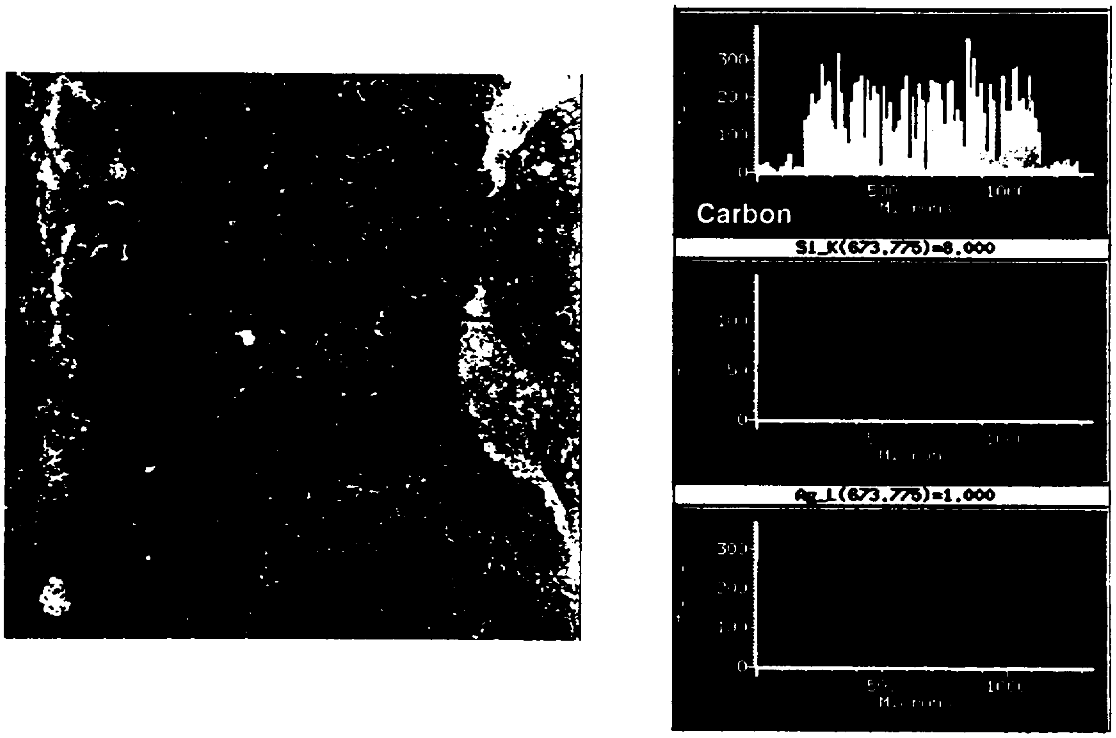
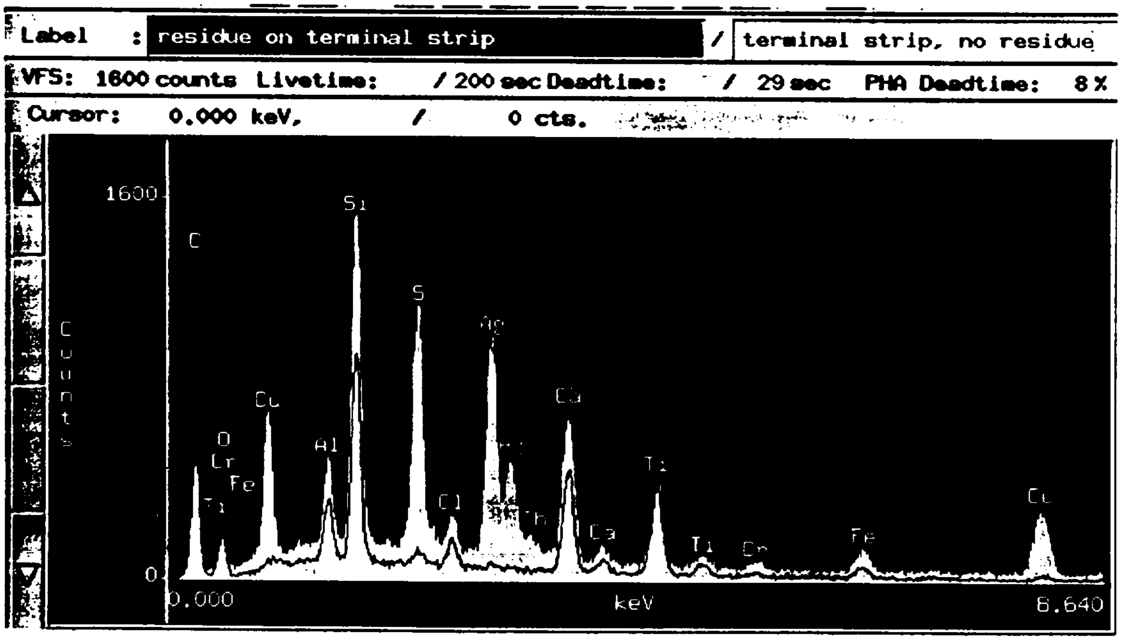


Figure 1. SEM micrograph of carbon stub (left) with silver dots and corresponding EDS line scan (right). The black reference (left) was the line scanned, red line corresponds to the vertical yellow line in spectra.


Label : residue on terminal strip / terminal strip, no residue

VFS: 1600 counts Livetime: / 200 sec Deadtime: / 29 sec PHA Deadtime: 8 %

Cursor: 0.000 keV, / 0 cts.

Figure 2. EDS spectra comparison between a nonresidue (red outline) and residue area (yellow area). Areas analyzed are shown in figure 8, main report. Note the absence of silver (Ag), copper (Cu), and sulfur (S) peaks in the nonresidue area.

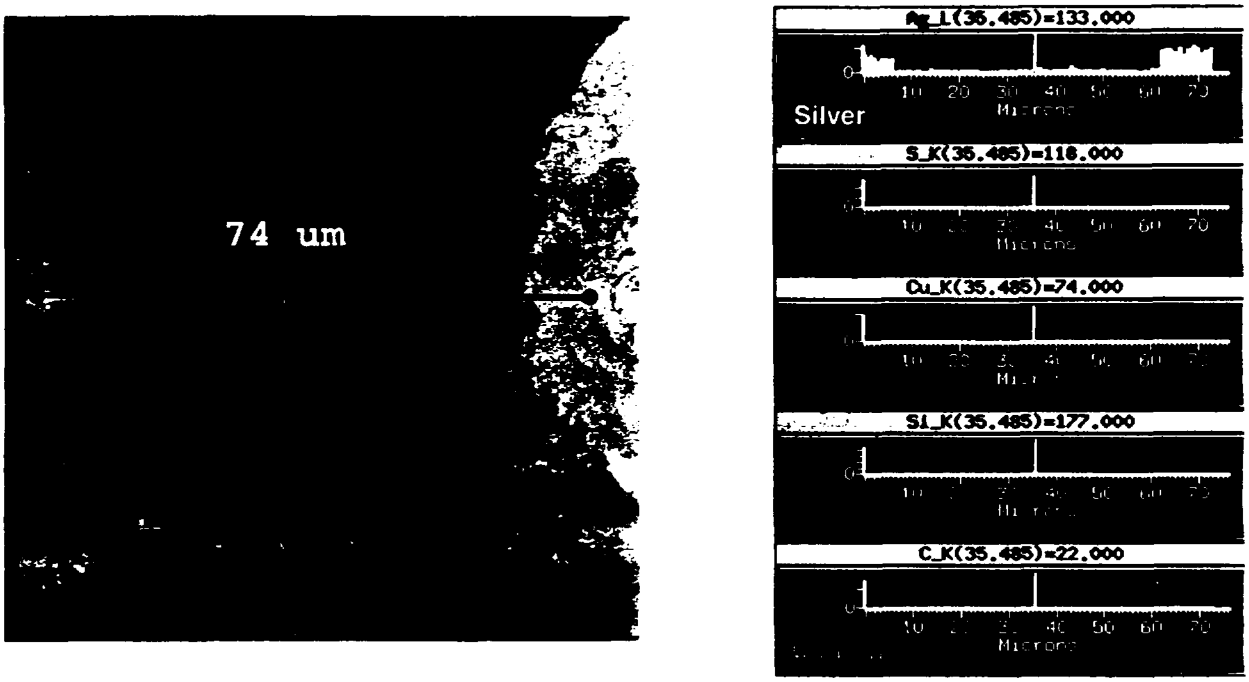


Figure 3. SEM micrograph and EDS line scan of a terminal strip with silver dots (see figure 18, main report). The black reference line (left) was the line scanned and red line corresponds to the vertical white line in spectra.

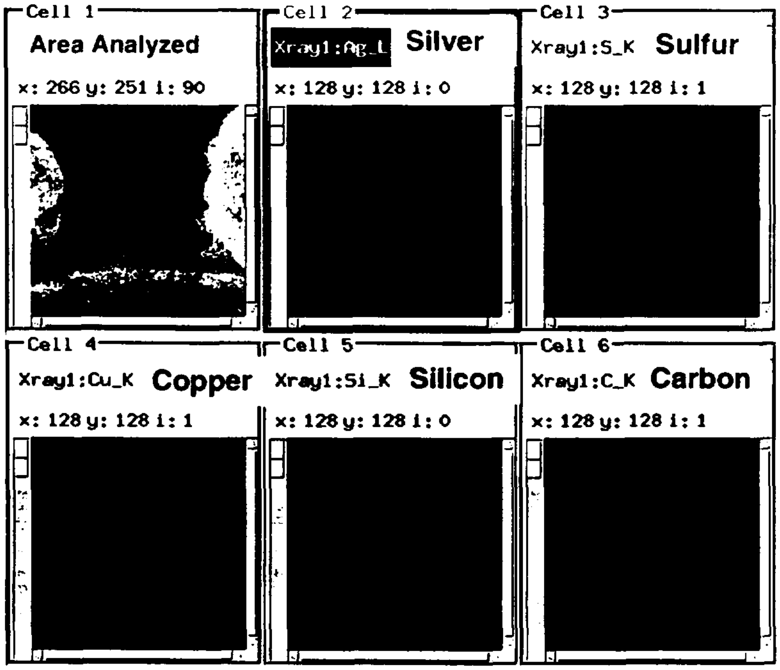


Figure 4. EDS map of a terminal strip with silver dots (see figure 18, main report). Note that silver is the primary element found in the silver dot area. Silver was also found between the silver dots but associated with copper and sulfur.

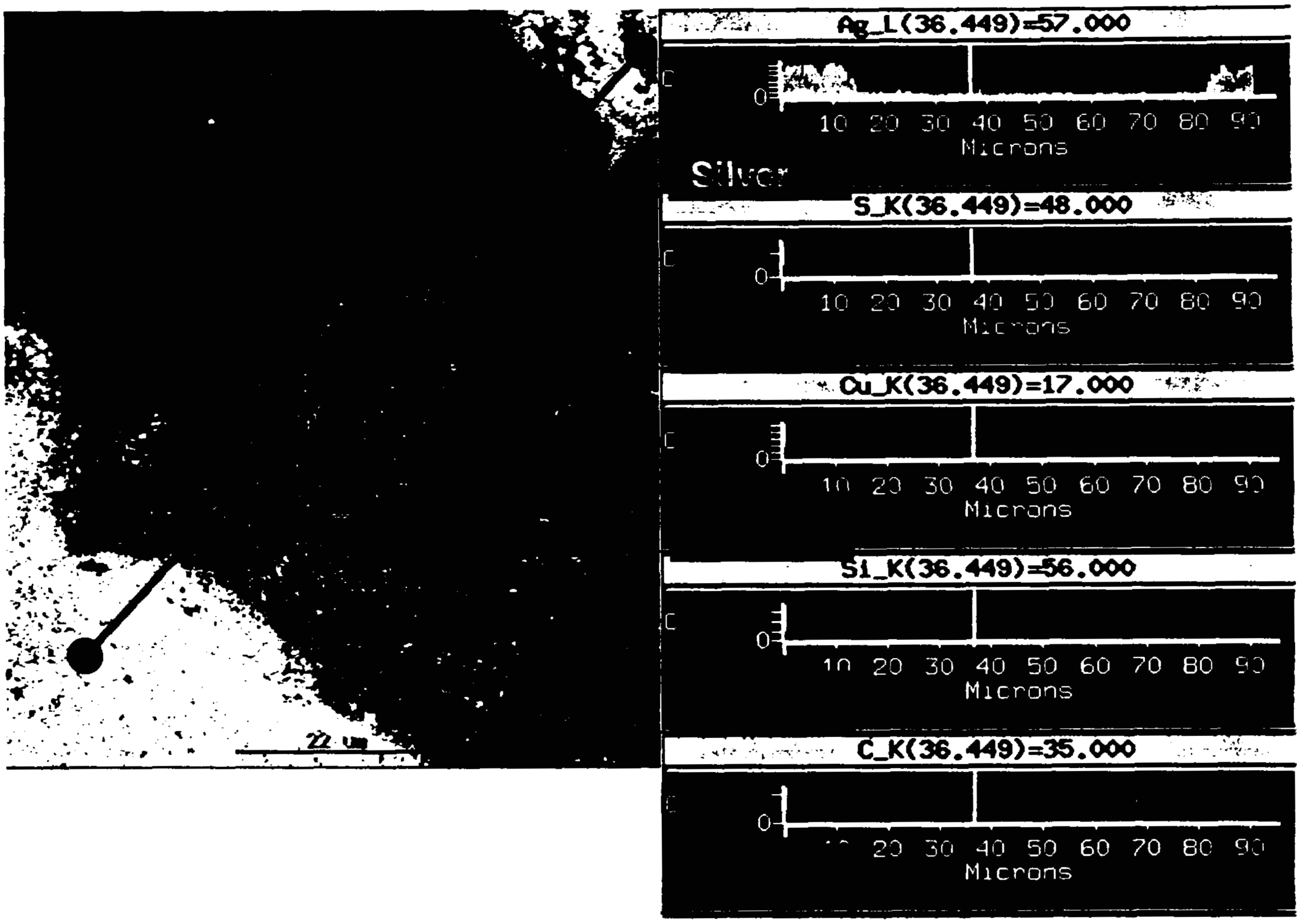


Figure 5. SEM micrograph and EDS line analysis of arc track site (see figure 13 in main report) between terminals 2 and 3 and points (silver dots) 1 and 4. The black reference line (left) was the line scanned (red line corresponds to the vertical white line in spectra).

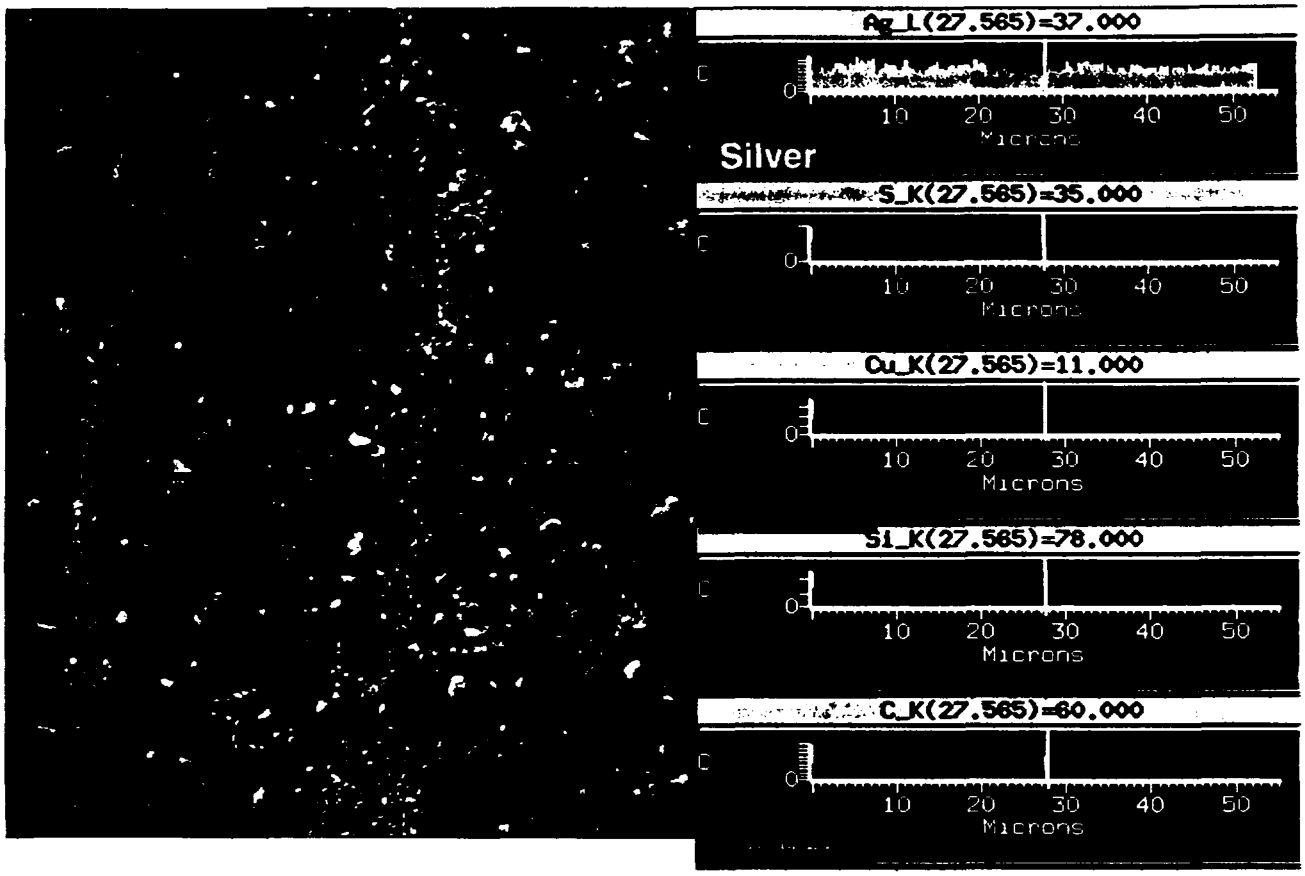


Figure 6. SEM micrograph close-up and EDS line scan of arc track site. The black reference line (left) was the line scanned (red line corresponds to the vertical white line in spectra).

EVALUATION REPORT FEEDBACK

We are striving to improve our performance in supporting our customers and would appreciate a few moments of your time to complete the brief questionnaire concerning the attached evaluation report. Your input will greatly assist us in judging how effectively we have helped you and how to best improve our support in the future. **Mail** to AFRL/MLSA, 2179 12th Street, Building 652, Room 122, Wright-Patterson Air Force Base, Ohio 45433-7718, or **fax** to 937-656-4600.

Evaluation Report Number: AFRL/MLSA 99-68
Title: Film Residues on Fuel Quantity Indicator System Fuel Tank Components
Author: SLENSKI

	Yes	Partly (explain)	No (explain)
Did our evaluation report provide the information you requested/needed? If not, what additional information do you require?________________	☐	☐	☐
Did the report contain sufficient detail and adequate pictorial coverage?	☐	☐	☐
Was adequate testing conducted and were the conclusions fully supported? If not, please explain.	☐	☐	☐
If requested, were adequate updates received during the investigation?	☐	☐	☐
Was the time frame for completion adequate?	☐	☐	☐
Were our analysts responsive? Helpful?	☐	☐	☐
How will our report be of help to you?	☐	☐	☐

What cost benefits are expected as a result of our findings?________________

Other "nontangible" benefits.________________

Specific actions taken as a result of this report.________________

Recommendations for improvement.________________

Name of Respondent________________
Company Name or Symbol/Telephone________________Date________________

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- **Failure Analysis/Accident Investigation**
  - **Structural**
  - **Electronic**
  - **Chemical**

- **Consultations on**
  - **Materials/Process Specifications**
  - **Physical and Mechanical Metallurgy**
  - **Materials and Component Failure Analysis**
  - **Electronics and Packaging**
  - **Adhesive Bonding and Nonmetallic Materials**
  - **Welding and Joining**

- **Nondestructive Inspection**

- **Electrostatic Discharge (ESD) Testing**

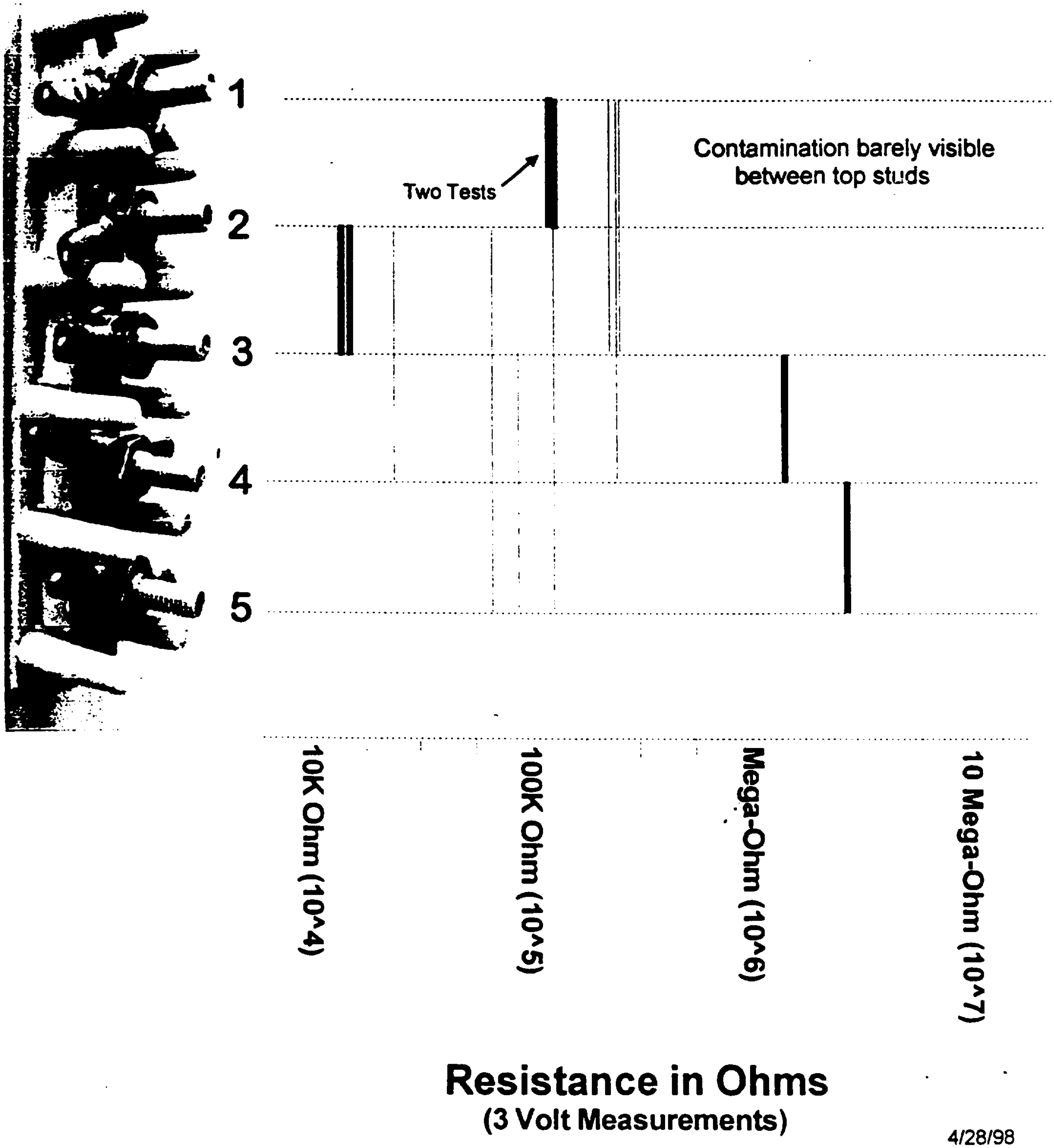
- **Air Force Electrostatic Discharge Control Policy OPR**

- **ESD Material Qualifications/Acceptance Testing**

- **ESD Material Process Specs/Standards**

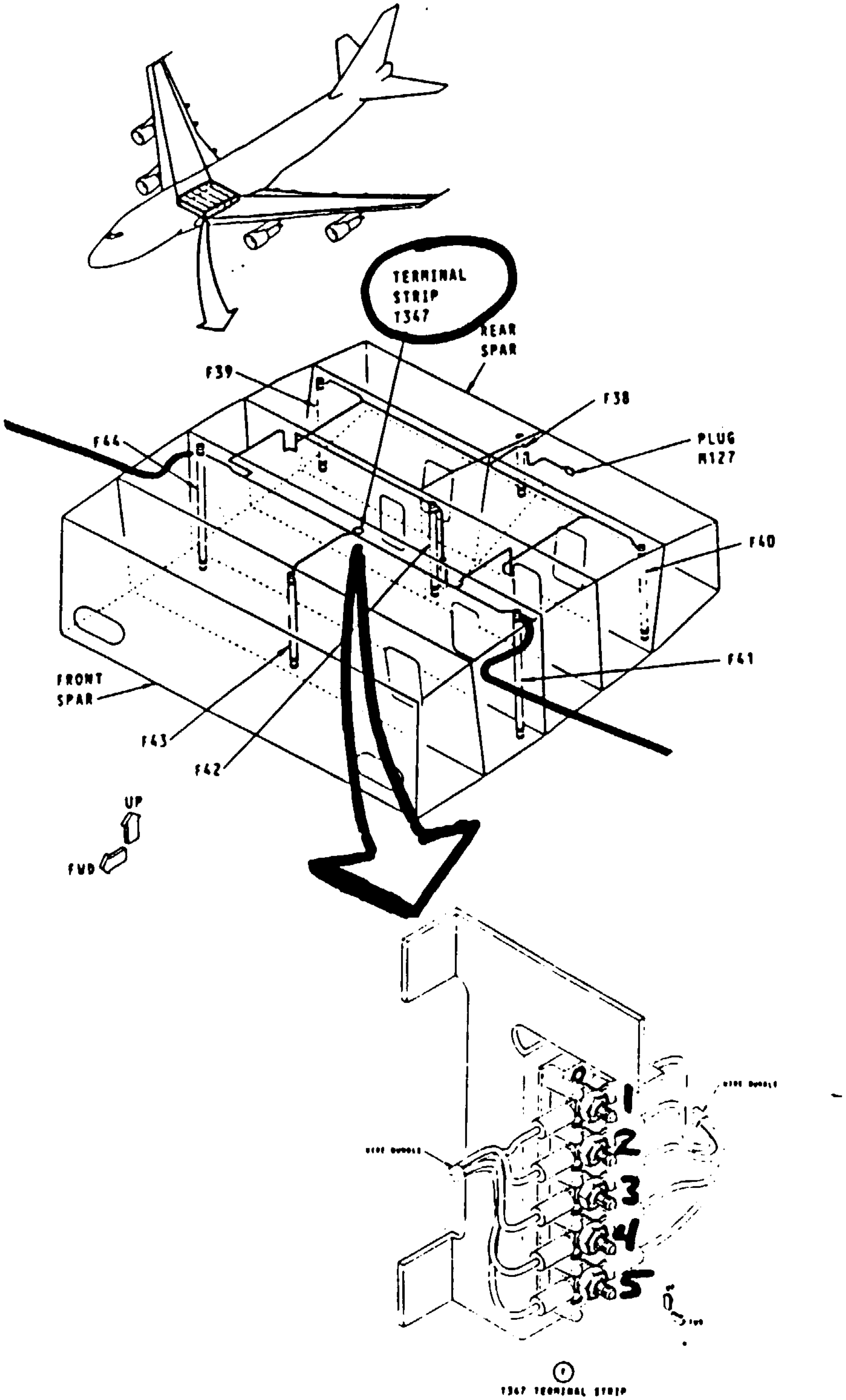
- **Environmental Test and Evaluation**

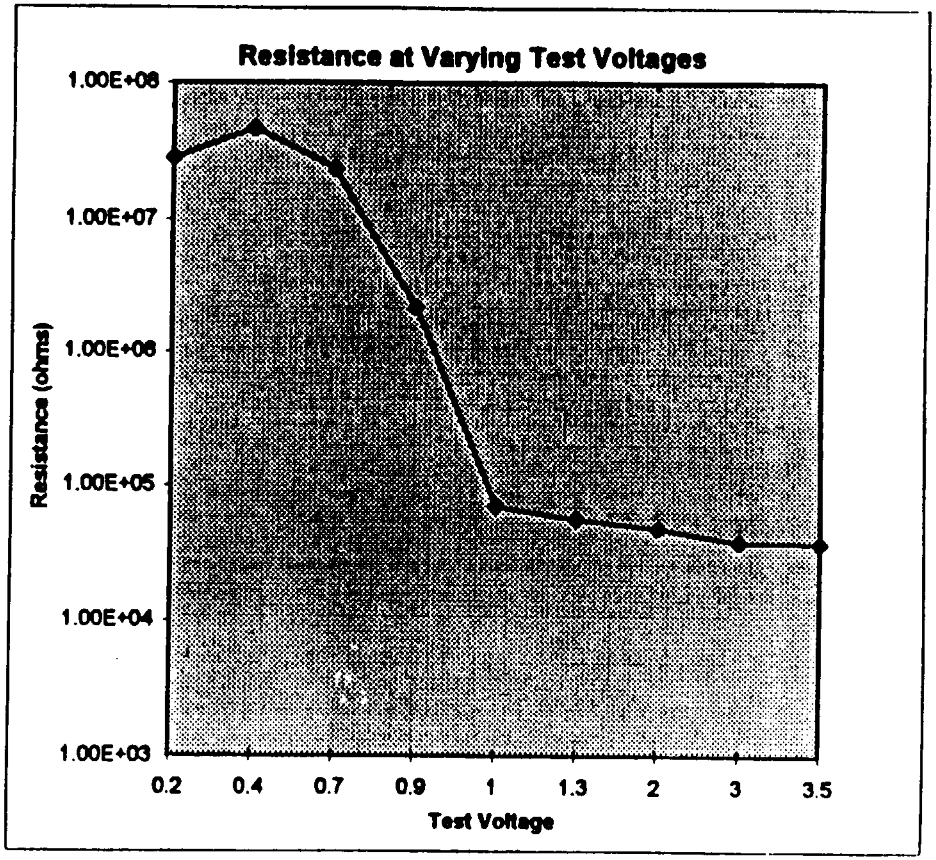
Resistance Found Between Terminal Strip Studs
Terminal Strip Removed From B-747 4/9/98



4/28/98

Varying voltages between terminals 2 & 4:





Data:

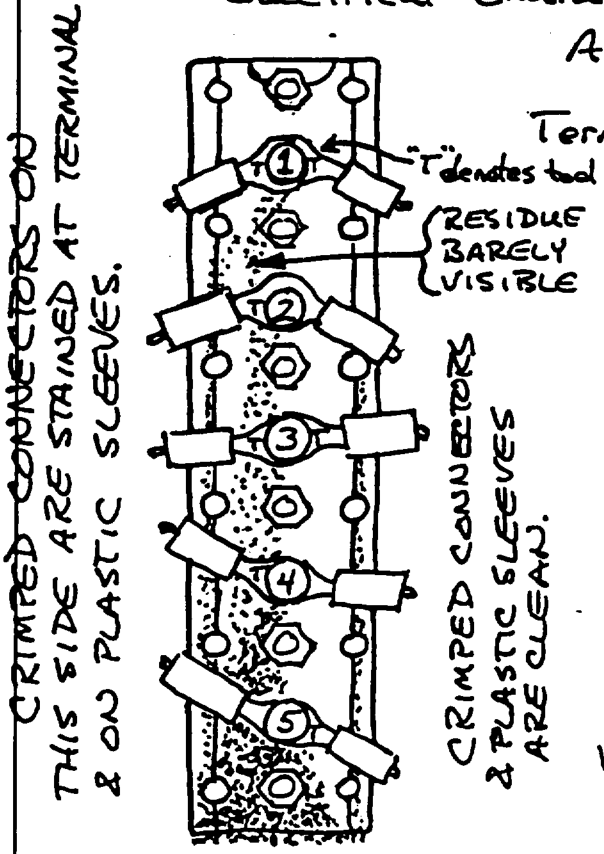
Test Voltage	Ohms
0.2	2.75E+07
0.4	4.50E+07
0.7	2.30E+07
0.9	2.20E+06
1	7.00E+04
1.3	5.62E+04
2	4.80E+04
3	3.80E+04

Exam of [redacted] CWT Terminal Strip (MS27212-2-5) at AFRL by David Johnson & Robert Swaim.

Equipment: Electrostatic Lab Hewlett Packard 4339B High Resistance Meter set to maximum limit of 25V & 500 μA.

Electrical Characterization:

At 3 volts:



Terminal 1-2 = $1.3 \times 10^5\ \Omega$ (1st test)
$1.52 \times 10^5\ \Omega$ (2nd test)
1-3 = 3.4×10^5
2.7×10^5
1-4 = 3.25×10^5
1-5 = 1.3×10^5
4.0×10^5 (Didn't allow bleed ti
2-3 = 2.25×10^4
2.05×10^4
2-4 = 3.8×10^4
3.73×10^4 @ 3.5V
2-5 = 8.2×10^4
3-4 = 2.06×10^6
3-5 = 9.4×10^4
4-5 = 4.0×10^6

Dots indicate visible residue on surface of grey plastic.

Varying voltage between terminals 2 & 4:

.2v = 2.75×10^7
.4v = 4.5×10^7
.7v = 2.3×10^7
.9v = 2.2×10^6
1.0v = 7.0×10^4
1.3v = 5.62×10^4
2.0v = 4.80×10^4
3.0v = 3.80×10^4 } FROM ORIGINAL
3.5v = 3.73×10^4 } TEST SERIES (ABOVE)

PLAN FOR THIS PART IS TO:
1. TOF-SIMS at Evans East on 4/20/98 to examine residue.
2. XPS at Wright-Patt AFRL on 4/23/98 " " "
3. Review data at NTSB ~~[illegible]~~ with parties on 4/29/98.

Surface Analysis of 747 Aircraft Fuel Probe and Wiring
(Materials Analysis)

26 January 1999

Evaluation Report
(43499TMO NTSB)

Report No. AFRL/MLSA 99-2

AUTHOR(S)

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Wright-Patterson Air Force Base, Ohio 45433-7718

REQUESTER(S)

Bob Swaim
NTSB, Office of Aviation Safety (AS-40)
490 L'Enfant Plaza East, SW
Washington D.C. 20594

DISTRIBUTION STATEMENT F: Further dissemination only as directed by The National Transportation Safety Board (NTSB) (26 January 1999) or DoD higher authority.

EXECUTIVE SUMMARY

Surface analysis was conducted on a 747 aircraft fuel probe exhibiting residues on the terminal block and associated wiring. Surface analysis using photoelectron spectroscopy (XPS) verified that residues on the probe terminal block and wiring were similar in composition. Residue composition included copper, silver, sulfides and sulfates. Residue and nonresidue areas contained oxygen, carbon and sulfur.

ACKNOWLEDGMENTS

As is usual for this type of investigation, the efforts of others are critical to its success. The author would like to thank Mr. David Johnson (AFRL/MLSA) for technical support and photography, Dr. John Grant of the University of Dayton Research Institute for the surface analysis evaluation, and Ms. Marianne Ramsey (AFRL/MLSA) for manuscript preparation.

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Surface Analysis of 747 Aircraft Fuel Probe and Wiring

PURPOSE

Identify elemental composition of residues found on fuel probe surfaces and associated wiring.

BACKGROUND

Fuel probes and their associated wiring were removed from a 747 aircraft and submitted for inspection and analysis by the National Transportation Safety Board (NTSB). Documentation submitted with the Evergreen fuel probes is given in appendix A.

FACTUAL DATA

The submitted probes were examined with an inspection microscope capable of 10X-70X magnification and sorted. Probes that exhibited significant residues on surfaces or wiring damage as noted in evaluation report WL/MLS 97-102 dated 30 October 1997 were of primary interest. A probe exhibiting residues from the Evergreen group (identified as 420A14 SN Z-60) was selected for analysis. The fuel probe is shown in figures 1 and 2. Before the optical inspection, the electrical resistance between all combinations of the Hi-Z, Lo –Z and ground wire terminal posts was measured with a Hewlett Packard 4339B high resistance meter set at 200 volts dc. All values were in excess of $1X10^9$ ohms. Surface residues on the terminal block and wiring was electrically probed using a HP 4329A high resistance meter set at 500 volts dc. The resistance values varied between 10^8 and 10^{13} ohms (figures 1 and 13, appendix B). Surface analysis was conducted with photoelectron spectroscopy (XPS). The XPS results are presented in appendix B.

Summary of Findings

Only areas in or near residue areas exhibited detectable concentrations of copper and silver. Higher concentrations of sulfur were found in residue areas when compared to nonresidue sites. For areas in or near residues sulfur was present in at least two states, as a sulfate and sulfide. The copper in residue areas exhibited mixed chemical states (metal, oxides, sulfides or sulfates). Concentrations of oxygen, carbon, sodium and lead were similar for both residue and nonresidue areas. With respect to the terminal block, fluorine and silicon were only found in the nonresidue areas.

PREPARED BY

GEORGE A. SLENSKI
Electronic Failure Analysis
Materials Integrity Branch
Systems Support Division
Materials and Manufacturing Directorate

PUBLICATION REVIEW: This report has been reviewed and approved.

MICHAEL F. HITCHCOCK, Branch Chief
Materials Integrity Branch
Systems Support Division
Materials and Manufacturing Directorate

FIGURES

APPENDICES

APPENDIX A

DOCUMENTATION RECEIVED WITH FUEL PROBES

National Transportation Safety Board
Office of Aviation Safety
Southwest Regional Office
6500 N. Pontatoc Road
Tucson, AZ 85718-1620
(310) 380-5668
(520) 529-8086
FAX: (520) 529-8013

June 1, 1998

Air Force Research Laboratory
C/O George Slenski
2179 Twelfth Street. Suite 1 Bldg.652/Rm 33
Wright Patterson AFB
Dayton, Ohio 45433-6533

Per Bob Swaim's instructions, enclosed are several fuel probes and associated wiring from one aircraft which was located at Evergreen Air Center, Marana, AZ.

The details on this particular aircraft are as follows:

Carrier:	TWA
Aircraft:	Boeing 747-156
S/N:	19958
ID	N134TW
Age:	11/10/70
# Of Hours:	92,141
Last "D" Check	2/21/94
Last known flight	1/13/97

I will be sending any subsequent samples under different cover, as they are still pulling fuel probes and compensator's from different aircraft.

Sincerely,

Debbie Childress
Air Safety Investigator

SHIPPING REQUEST

To: Material Control

DATE: 6-1-98

From: NTSB

Subject: Shipping Request

PLEASE SHIP THE FOLLOWING ITEMS AS INDICATED:

QTY	UNIT	PART NUMBER	DESCRIPTION	S/N	W/O#	P/O#
	See Attached Sheet					

SHIP TO:
Air Force Research Laboratory
c/o George Slenski
2179 Twelfth St., Suite 1, Bldg. 652, Room 33
Wright-Patterson AFB, Dayton, OH 45433-6533

SHIP VIA FedEx PREPAID (X) COLLECT ( ) Account #1567-1347-3

INSURE. YES (X) NO DECLARED VALUE. $500.00

SPECIAL INSTRUCTION OR MARKINGS.
Packing labor & material charged to: Work Order 10-1073-02-0001

SIGNATURE

EXT 5455

REQUIRED SHIPPING DATE: 6/2/98

EVERGREEN **PACKING LIST** **ACFT** SN-19958/N134T

WO#- 10-1073-02-0001

NOMENCLATURE	PART NUMBER	ALT P/N	SERIAL NO.	QTY
Fuel Qty. Unit, RW	FG420A18	60B92010-18	A-88	1
Fuel Qty. Unit, RW	FG420A39	60B92010-39	A-158	1
Fuel Compensator, RW	FG6C2	60B92010-50	Z-655	1
Fuel Qty. Unit, RW	FG420A17	60B92010-17	A-102	1
Fuel ~~Qty.~~ Compensator RW	FG6C2	60B92010-7	A-491	1
Fuel Qty Unit, RW	FG420A30	60B92010-30	Z-49	1
Fuel Qty. Unit, RW	FG420A31	60B92010-31	Z-121	1
Fuel Qty. Unit, RW	FG420A32	60B92010-32	A-117	1
Fuel Qty Unit, LW	FG420A9	60B92010-9	A-171	1
Fuel Compensator, LW	FG6C2	60B92010-50	Z-656	1
Fuel Qty Unit RW	FG420A33	60B92010-33	Z-3	1
Fuel Qty. Unit	FG420A37	60B92010-37	Z-26	1
Fuel Compensator, LW	FG6C2	60B92010-50	Z-772	1
Fuel Compensator, RW	FG6E1	60B92010-63	W-405	1
Fuel Qty. Unit	FG420A29	60B92010-29	A-110	1
Fuel Qty. Unit, LW	FG420A10	60B92010-10	Z-73	1
Terminal Block, Fuel Compensator	MS27212-2-4		NSN	4
Fuel Compensator, LW	FG6C2	60B92010-50	Z-775	1
Fuel Qty Unit, LW	FG420A11	60B92010-11	Z-229	1
Fuel Qty Unit, RW	FG420A19	60B92010-19	A-125	1
Fuel Qty. Unit, RW	FG420A20	60B92010-20	A-174	1
Fuel Qty. Unit, RW	FG420A24	60B92010-24	A-127	1
~~OUTBD AILERON~~	~~317C130-4~~	~~60B[illegible]~~	~~718[illegible]~~	~~1~~
Fuel Qty Unit	FG420A34	60B92010-34	A-155	1
Fuel Qty. Unit	FG420A38	60B92010-38	A-109	1
Fuel Qty. Unit	FG420A36	60B92010-36	A-126	1
Fuel Qty. Unit	FG420A35	60B92010-35	A-146	1
Fuel Qty. Unit	FG420A40	60B92010-40	Z-8	1
Fuel Qty. Unit	FG420A35	60B92010-35	A-25	1
Fuel Qty Unit	FG420A39	60B92010-39	A-106	1
Fuel Qty. Unit	FG420A38	60B92010-38	A-118	1
Fuel Qty. Unit	FG420A36	60B92010-36	A-110	1

DATE ____________ **BOX** ________ PAGE ____

EVERGREEN **PACKING LIST** **ACFT** SN-19958/N134TW

WO#: 10-1073-02-0001

NOMENCLATURE	PART NUMBER	ALT P/N	SERIAL NO.	QTY
Fuel Qty. Unit	FG420A18	60B92010-18	A-85	1
Fuel Qty. Unit	FG420A33	60B92010-33	A-100	1
Fuel Qty. Unit	FG420A19	60B92010-19	A-118	1
Fuel Qty. Unit	FG420A32	60B92010-32	A-106	1
Fuel Qty. Unit	FG420A31	60B92010-31	A-115	1
Fuel Qty. Unit	FG420A34	60B92010-34	A-121	1
Fuel Qty. Unit	FG420A30	60B92010-30	A-118	1
Fuel Qty. Unit	FG420A17	60B92010-17	A-101	1
Fuel Compensator	FG6E1	60B92010-63	W-402	1
Fuel Compensator	FG6C2	60B92010-50	Z-201	1
Fuel Compensator	FG6C2	60B92010-50	Z-625	1
Fuel Compensator	FG6E1	60B92010-63	W-401	1
Terminal Block, Fuel Compensator	MS27212-2-4		NSN	2
Fuel Qty. Unit	FG420A20	60B92010-20	A-152	1
Fuel Qty. Unit	FG420A21	60B92010-21	A-122	1
Fuel Qty. Unit	FG420A23	60B92010-23	A-124	1
Fuel Qty. Unit	FG420A26	60B92010-26	Z-52	1
Fuel Qty. Unit	FG420A25	60B92010-25	A-64	1
Fuel Qty. Unit	FG420A26	60B92010-26	Z-40	1
Fuel Qty. Unit	FG420A25	60B92010-25	A-133	1
Fuel Qty. Unit	FG420A24	60B92010-24	A-123	1
Fuel Qty Unit	FG420A64	60B92010-64	T-133	1
Fuel Qty. Unit	FG420A64	60B92010-64	T-127	1
Fuel Qty Unit	FG420A23	60B92010-23	A-119	1
Fuel Qty. Unit	FG420A22	60B92010-22	Z-94	1
Fuel Qty. Unit	FG420A22	60B92010-22	Z-93	1
Fuel Qty Unit	FG420A21	60B92010-21	A-123	1

DATE ________ **BOX** ________ PAGE ____

EVERGREEN **PACKING LIST** **ACFT** N134TW/SN:19958

WO #: 10-1073-02-0001

NOMENCLATURE	PART NUMBER	ALT P/N	SERIAL NO.	QTY
Fuel Qty. Unit	FG420A40	60B92010-40	Z-9	1
Fuel Qty. Unit	FG420A15	60B92010-15	Z-57	1
Fuel Qty. Unit	FG420A13	60B92010-13	Z-120	1
Fuel Qty. Unit	FG420A16	60B92010-16	Z-54	1
Fuel Qty. Unit	FG420A12	60B92010-12	Z-100	1
Fuel Qty. Unit	FG420A12	60B92010-12	Z-119	1
Fuel Qty Unit	FG420A14	60B92010-14	Z-60	1
Fuel Qty Unit	FG420A13	60B92010-13	Z-108	1
Fuel Compensator	~~FG6C2~~ FG6C2	60B92010-50	Z-776	1
Fuel Compensator	FG6C2	60B92010-50	Z-612	1
Terminal Block, Fuel Compensator	MS27212-2-4		NSN	1

DATE ____________ **BOX** ________ PAGE _____

APPENDIX B

SURFACE ANALYSIS OF 747 AIRCRAFT FUEL PROBE AND WIRING

Appendix B

SURFACE ANALYSIS OF 747 AIRCRAFT FUEL PROBE AND WIRING

From: John T. Grant (UDRI/MLBT)
Phone: 937 255 6603
Fax: 937 258 8075

To: David H. Johnson (MLSA)
George A. Slenski (MLSA)

Fuel Probe 420A14 SN Z-60 and a Hi-Z lead wire were analyzed using x-ray photoelectron spectroscopy (XPS/ESCA) at the Air Force Research Laboratory. The XPS equipment used was a Surface Science Instruments' M-Probe. This instrument has a monochromatic aluminum x-ray source and a hemispherical sector electron energy analyzer, and is used to measure the binding energies of electrons in the atoms that are in the several outermost atomic layers of the specimen. These measurements of electron binding energies are used to identify the elements present in this outermost region of the specimen, and in many cases the measurement provides information about the chemical state of the elements. All elements except hydrogen and helium are detectable, with a detectability limit of about 0.1 to 1 atomic percent.

FUEL PROBE BODY

The fuel probe was mounted on an aluminum specimen holder with a few strands of nickel wire to hold it in place. The nickel wire touched the fuel probe only at its edges. Powder-free gloves were used to handle the fuel probe, and the top surface of the probe was not touched in any manner. Specimen handling is important due to the high surface sensitivity of the XPS measurement. The size of this fuel probe was such that it could just fit through the insertion port of the XPS system. The analysis is done in ultra high vacuum, and the outgassing of the fuel probe caused the gas pressure in the XPS system to rise to the upper limit where the fuel probe could just be analyzed.

XPS analysis was performed at several regions on the fuel probe. The regions examined are shown as 1, 2, and 3 on the photograph of the fuel probe, Figure 1. Each region analyzed covered a surface area of 400 μm x 1000 μm. Region 1 is in the central portion of one of the metallic-looking deposits on the fuel probe, region 2 is away from, but near, this visible deposit, and region 3 is near the central portion of the probe itself. XPS survey scans covering a binding energy range of 0 to 1200 eV are shown for regions 1, 2, and 3 in Figures 2, 3, and 4, with the 0 to 250 eV region expanded for clarity in Figures 5, 6, and 7, respectively. The elements detected are marked on the spectra. It should be noted that the intensities of the peaks for different elements are not related directly to their relative concentrations in the surface region, but the concentrations can be calculated from the peak areas. The calculated atomic concentrations of the detected elements are given in Table 1.

Table 1. Concentrations (in atomic percent) of elements detected at regions 1, 2, and 3, identified on the fuel probe in Figure 1. Note that concentrations might not add to 100 percent due to rounding.

	ATOMIC CONCENTRATION		
ELEMENT	REGION 1	REGION 2	REGION 3
C	57	70	68
O	25	22	20
S	8	3	1.5
N		3	2
F			6
Si			2
Na	1	1.5	1
Ag	4	0.5	
Cu	5	0.7	
Pb	0.1	0.2	0.1

It can be seen that the metallic-looking deposit (region 1) contains silver, copper, and a higher concentration of sulfur than elsewhere on the probe. The concentrations of these elements are significantly lower near the visible deposit (region 2), with no silver or copper detected near the center of the probe (region 3). A small concentration of lead was found at all regions examined. Fluorine and silicon were detected near the center of the probe, nitrogen was found in regions 2 and 3, and sodium was found in all three regions. Carbon and oxygen were found at all regions, and their concentrations are typical for something that has been exposed to the environment. The fuel probe was not cleaned in any manner before the analysis.

Some information about the chemistry can be obtained from the binding energies of the measured peaks. Separately acquired XPS spectra of carbon 1s, sulfur 2p, copper 2p, silver 3d, and lead 4f electronic shells from region 1 are shown in Figures 8, 9, 10, 11, and 12, respectively. The carbon spectrum in Figure 8 shows structure on the high binding energy side of the main peak. This structure has been fit with two peaks, with the lower binding energy peak being typical for ether and hydroxyl groups, and the higher binding energy peak being typical for carbonyl and carboxyl groups. The intensities of these two peaks are similar, and together comprise about 30 percent of the total carbon signal. The sulfur spectrum in Figure 9 shows two distinct chemical states, and these are typical for a sulfide (structure on the right) and a sulfate (structure on the left). The copper spectrum (Figure 10) is typical for mixed chemical states, perhaps metal, oxides, sulfide, or sulfate. Silver, unfortunately, does not show a significant shift in binding energy with changes in chemistry. The lead spectrum (Figure 12) shows an energy typical for a sulfite or a sulfate. (A handbook reference was not available for lead sulfide). Note that the atomic concentration of sulfur found at region 1 is of the right magnitude for the formation of these sulfur compounds, and that the sulfate peak is about one-third less intense than the sulfide. The sulfur spectrum at regions 2 and 3, on the other hand, show a dominance of the sulfate peak over any sulfide (see Figures 5, 6, and 7).

Fuel probe wire

A section of the fuel probe Hi-Z lead wire near the fuel probe terminal was cut out for XPS analysis, as shown in Figure 13. This section of the wiring showed a dark deposit on the insulation, and it was mounted on an aluminum specimen holder with a small, gold-coated clamp to expose the dark deposit.

An XPS survey scan of the dark region is shown in Figure 14, with an expanded view of the 0 to 250 eV binding energy range in Figure 15. The calculated atomic concentrations for the elements detected are listed in Table 2. It can be seen that the dark region contains silver, copper, and sulfur with smaller concentrations of sodium, and lead. The fluorine is probably from the Teflon™ insulation on the wire.

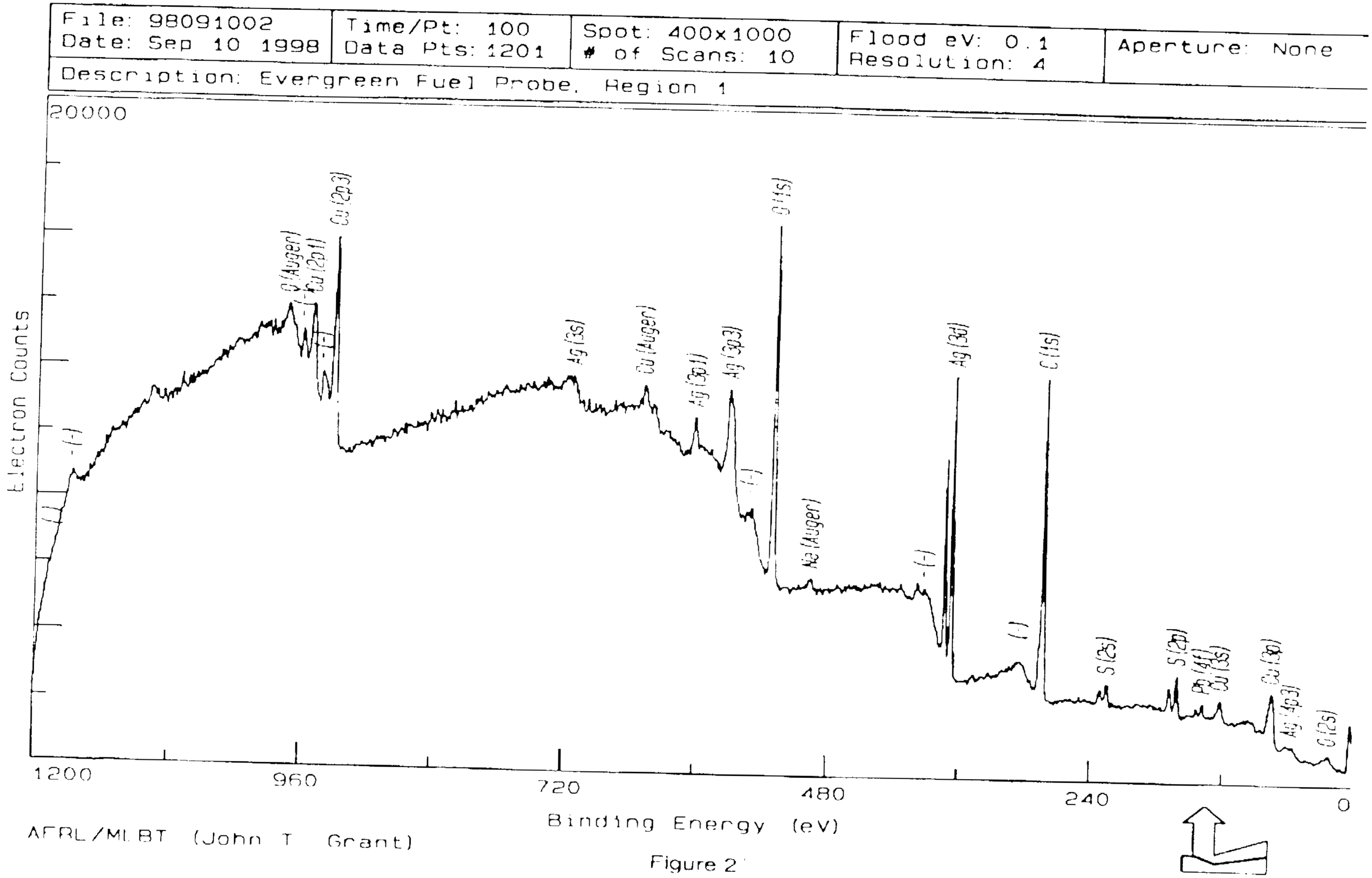
Table 2. Concentrations (in atomic percent) of elements detected at the dark deposit on the fuel probe Hi-Z lead wire. Note that concentrations might not add to 100 percent due to rounding.

ELEMENT	DARK DEPOSIT
C	55
O	24
S	6
F	6
Na	1.5
Ag	5
Cu	2
Pb	0.1

Again, information about the chemistry can be obtained from the binding energies of the measured peaks. Separately acquired XPS spectra of carbon 1s, sulfur 2p, copper 2p, silver 3d, and lead 4f electronic shells are shown in Figures 16, 17, 18, 19, and 20, respectively. The carbon spectrum in Figure 16 shows some structure on the high binding energy side of the main peak. This is similar to that found on the fuel probe terminal block (figure 8), however, there is an additional peak 8 eV from the main carbon peak. Again, two peaks are required to fit the structure near the main carbon peak, with the lower binding energy peak being typical for ether and hydroxyl groups, and the higher binding energy peak being typical for carbonyl and carboxyl groups. The relative intensity of the higher binding energy peak is somewhat lower than that of the lower binding energy peak. The third peak, about 8 eV from the main carbon peak, is due to C-F_3 bonding, probably from the underlying Teflon™ insulation. The presence of CF_3 is confirmed by the correct ratio of the atomic concentrations of the third carbon peak (two atomic percent) and the fluorine peak (six atomic percent). The three small carbon peaks comprise about 30 percent of the total carbon signal. As before, the sulfur spectrum (Figure 17) shows two distinct chemical states, and these are typical for a sulfide (structure on the right) and a sulfate (structure on the left). The copper spectrum (Figure 18) is typical for mixed chemical states, perhaps metal, oxides, sulfide, or sulfate. As mentioned earlier, silver does not show a significant shift in binding energy with changes in chemistry. As before, the lead spectrum (Figure 20) shows an energy typical for a sulfite or a sulfate. Again, note that the atomic concentration of sulfur is of the right magnitude for the formation of these sulfur compounds, and that the sulfate peak is about one-third less intense than the sulfide. (Note that all the XPS peaks from the wire are shifted by about 2.5 eV lower binding energy due to electrical charging of the wire during analysis).

Summary

Visible deposits on Fuel Probe 420A14 SN Z-60 and the Hi-Z lead wire were examined by XPS, and found to contain silver, copper, sodium, lead, and sulfur, in addition to the expected carbon and oxygen. The measured binding energies were used to provide information about possible surface chemistries.



File: 98091002
Date: Sep 10 1998
Time/Pt: 100
Data Pts: 1201
Spot: 400x1000
# of Scans: 10
Flood eV: 0.1
Resolution: 4
Aperture: None
Description: Evergreen Fuel Probe, Region 1

AFRL/MLBT (John T Grant)

Figure 2

File: 98091001
Date: Sep 10 1998

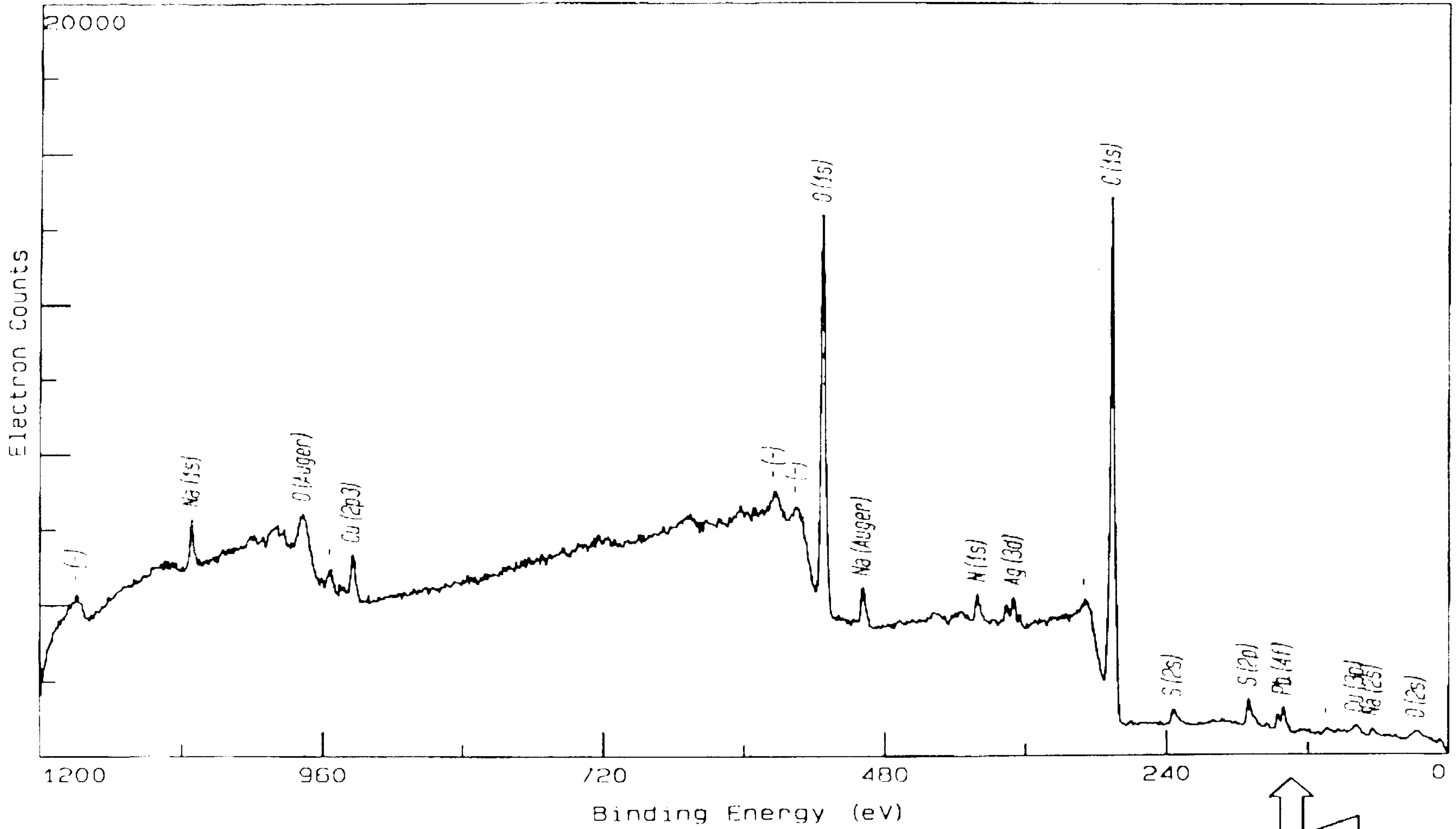
Time/Pt: 100
Data Pts: 1201

Spot: 400x1000
# of Scans: 10

Flood eV: 0.1
Resolution: 4

Aperture: None

Description: Evergreen Fuel Probe, Region 2



AFRL/MLBT (John T. Grant)

Figure 3

File: 98091004 Date: Sep 10 1998	Time/Pt: 100 Data Pts: 1201	Spot: 400x1000 # of Scans: 10	Flood eV: 0.1 Resolution: 4	Aperture: None

Description: Evergreen Fuel Probe, Region 3

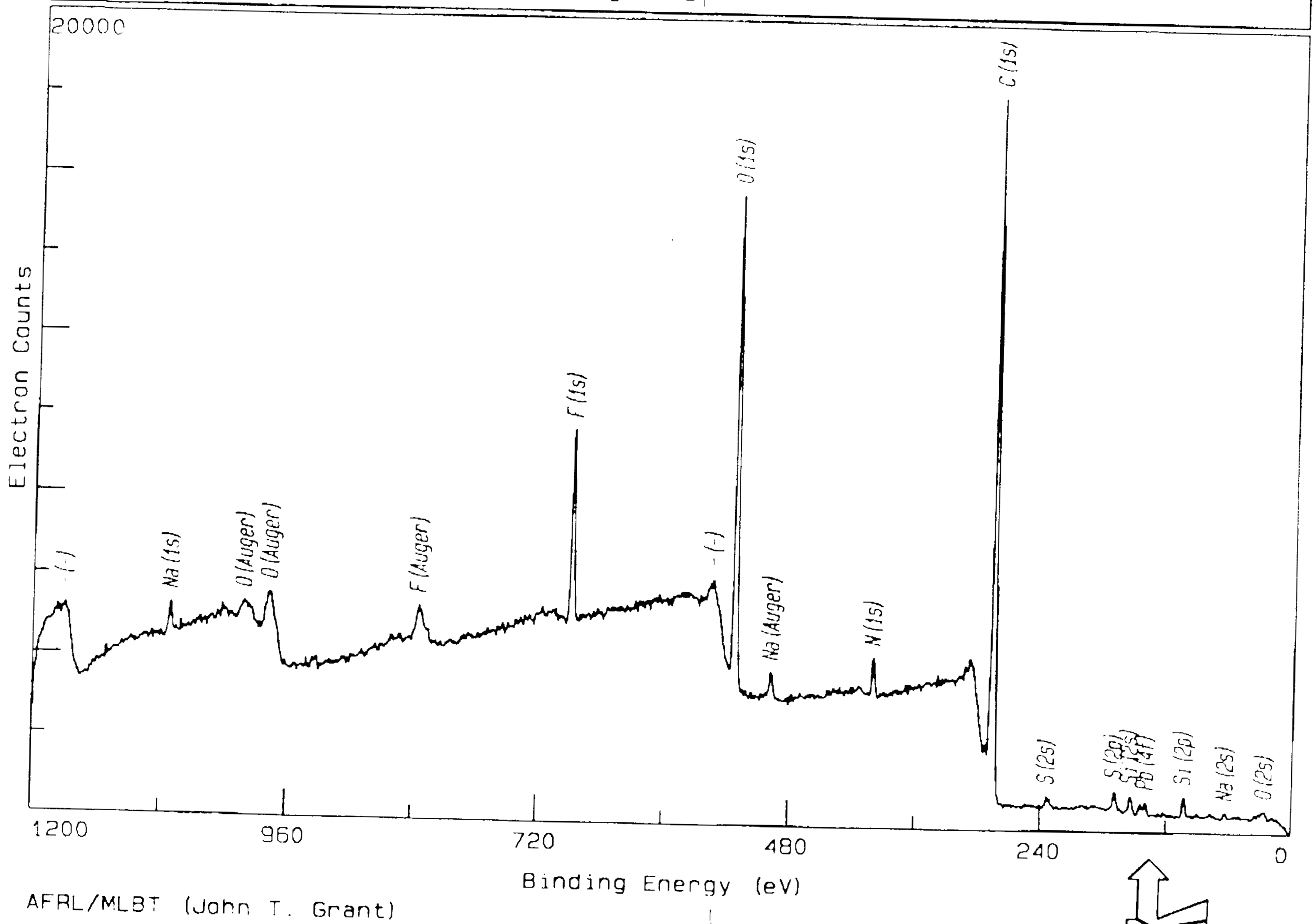
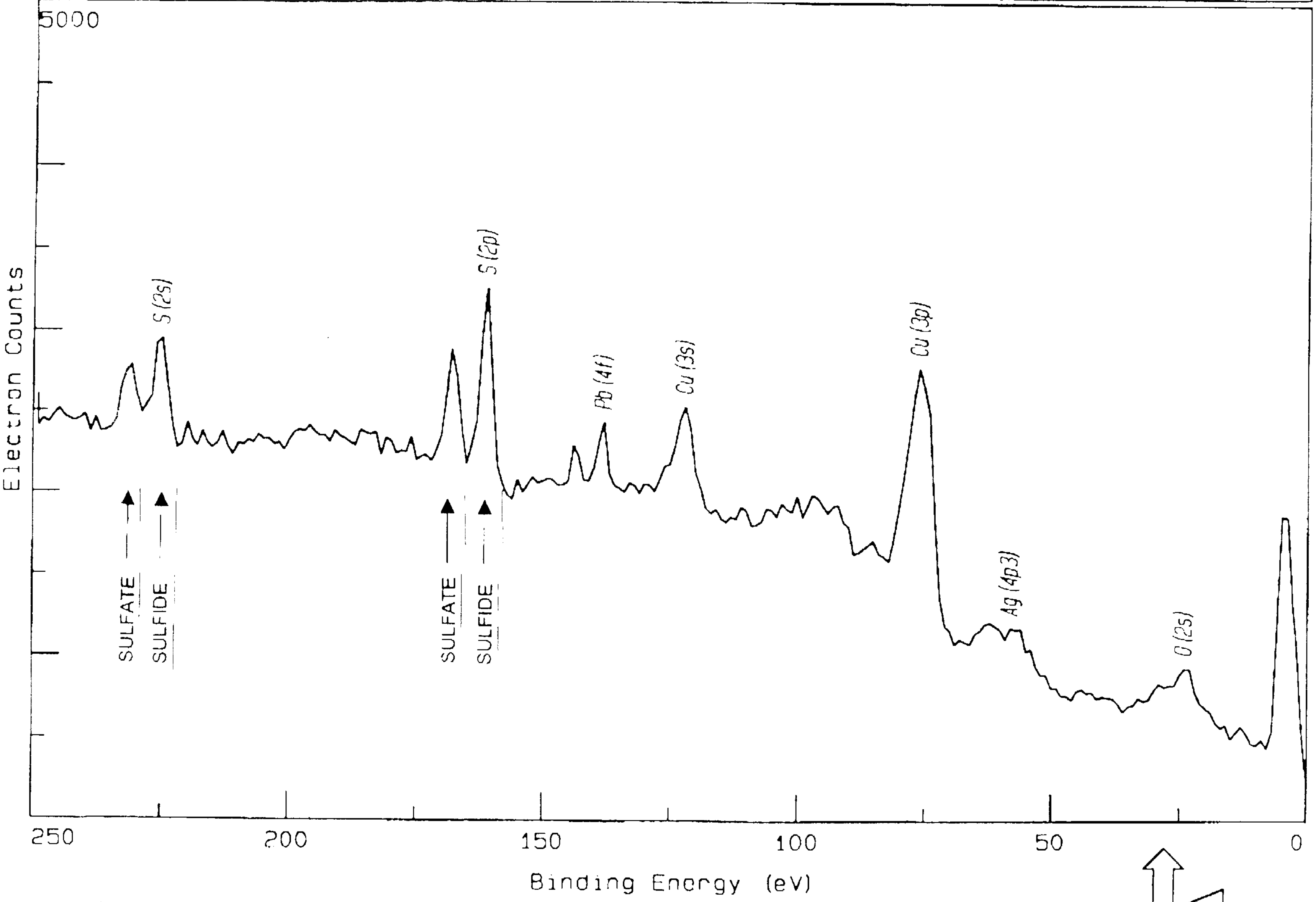


Figure 4

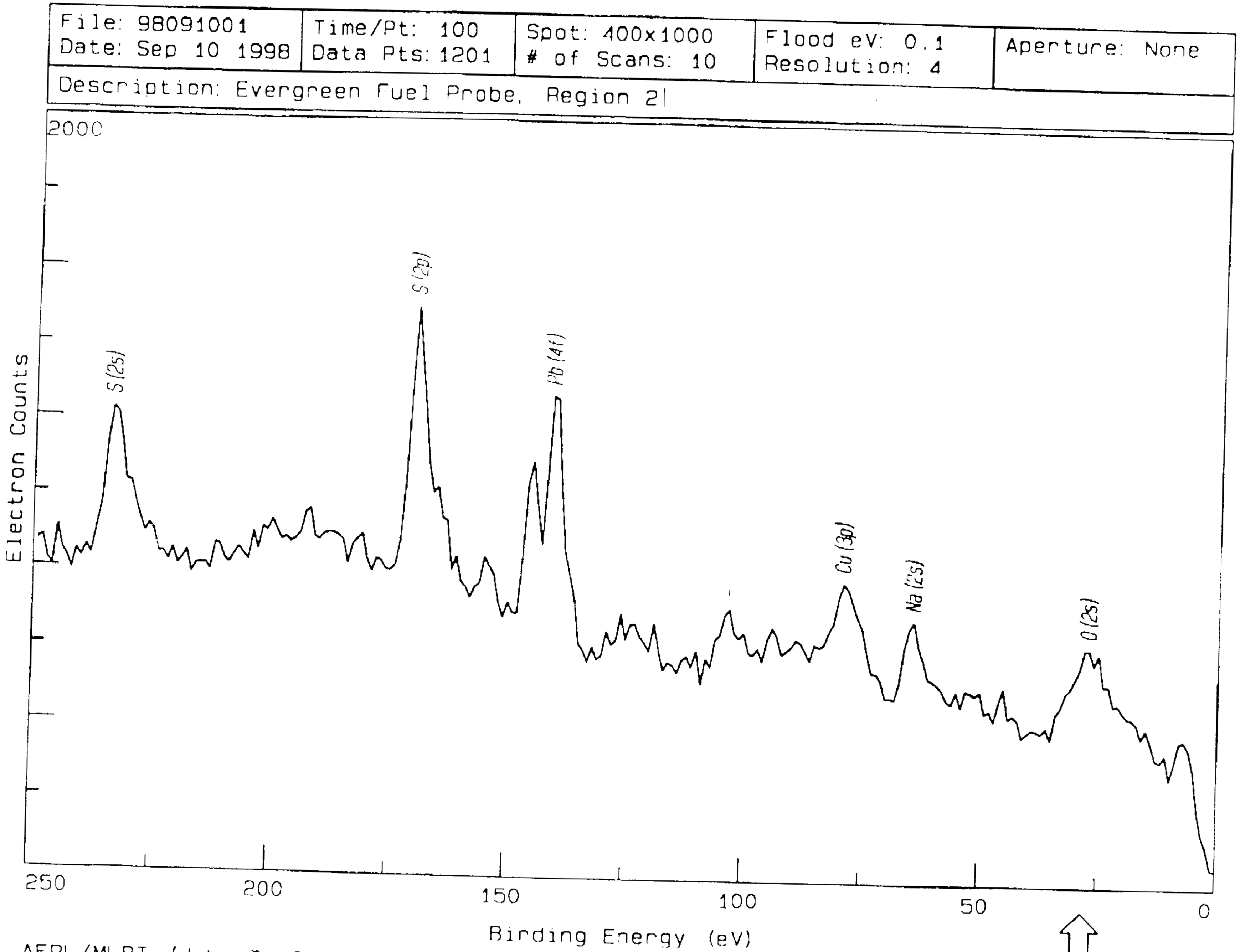
File: 98091002 Date: Sep 10 1998	Time/Pt: 100 Data Pts: 1201	Spot: 400x1000 # of Scans: 10	Flood eV: 0.1 Resolution: 4	Aperture: None

Description: Evergreen Fuel Probe, Region 1



AFRL/MLBT (John T. Grant)

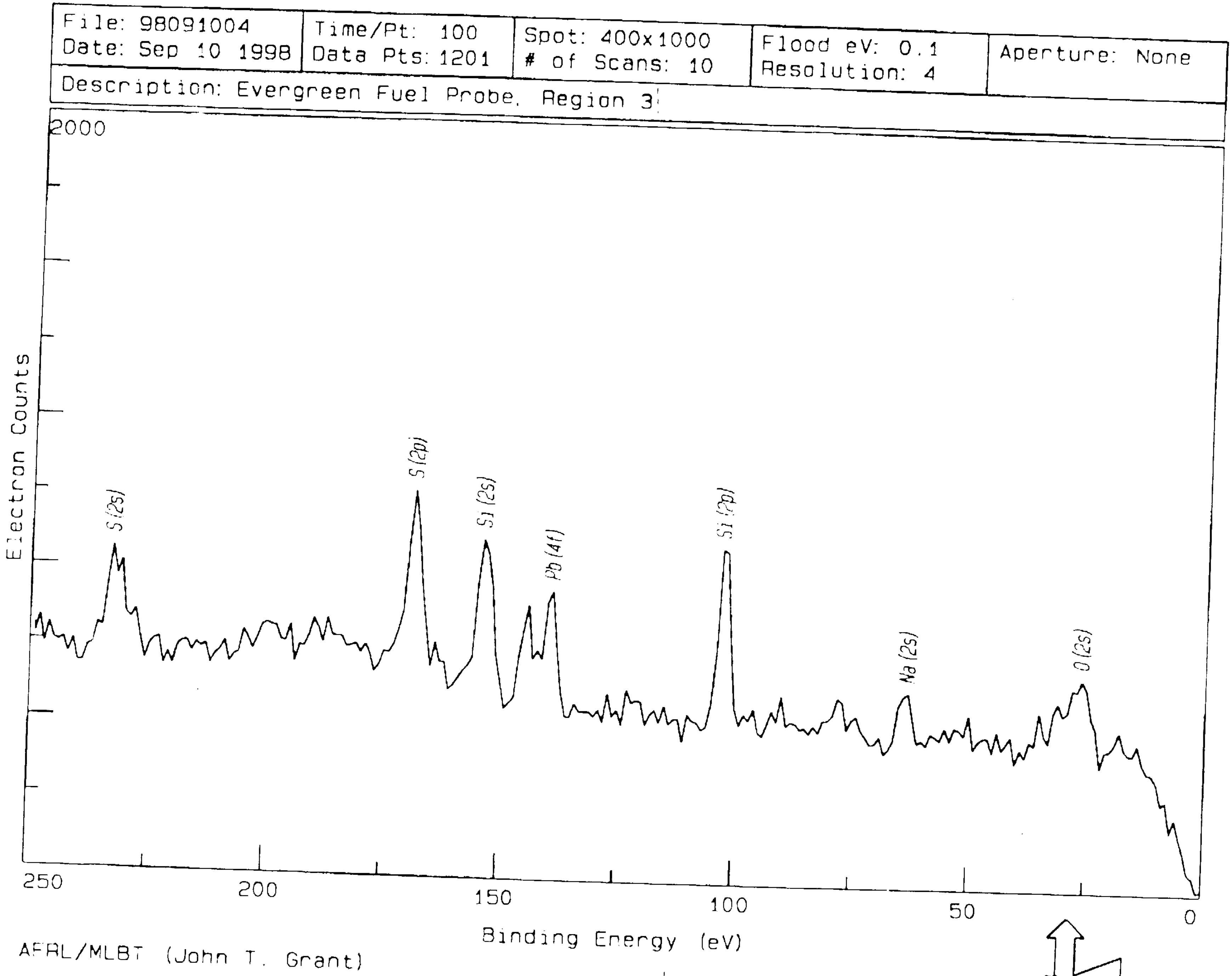
Figure 5



File: 98091001
Date: Sep 10 1998
Time/Pt: 100
Data Pts: 1201
Spot: 400x1000
# of Scans: 10
Flood eV: 0.1
Resolution: 4
Aperture: None
Description: Evergreen Fuel Probe, Region 2

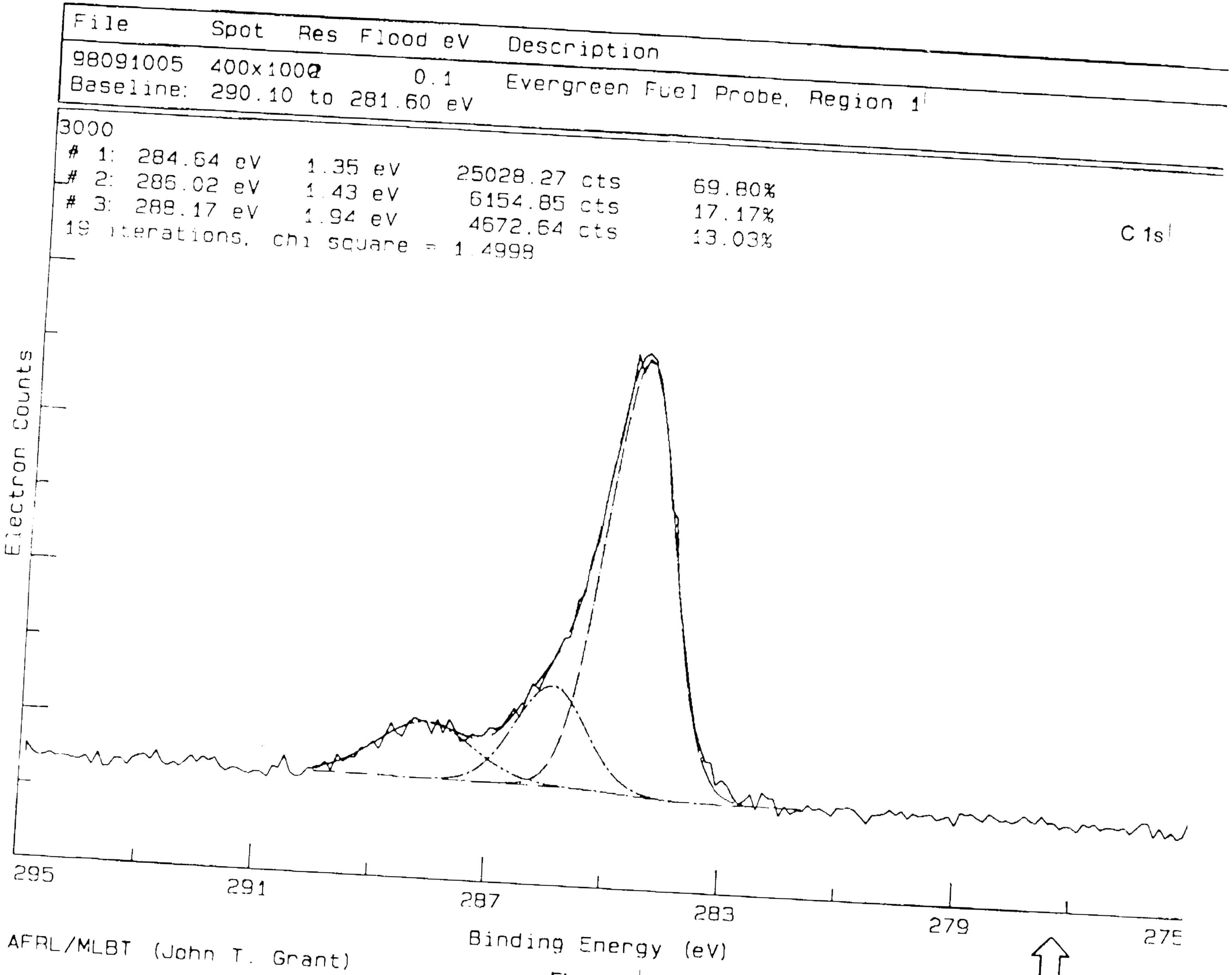
AFRL/MLBT (John T. Grant)

Figure 6



File: 98091004
Date: Sep 10 1998
Time/Pt: 100
Data Pts: 1201
Spot: 400x1000
# of Scans: 10
Flood eV: 0.1
Resolution: 4
Aperture: None
Description: Evergreen Fuel Probe, Region 3

Figure 7



File	Spot	Res	Flood eV	Description
98091005	400x1000		0.1	Evergreen Fuel Probe, Region 1

Baseline: 290.10 to 281.60 eV

3000

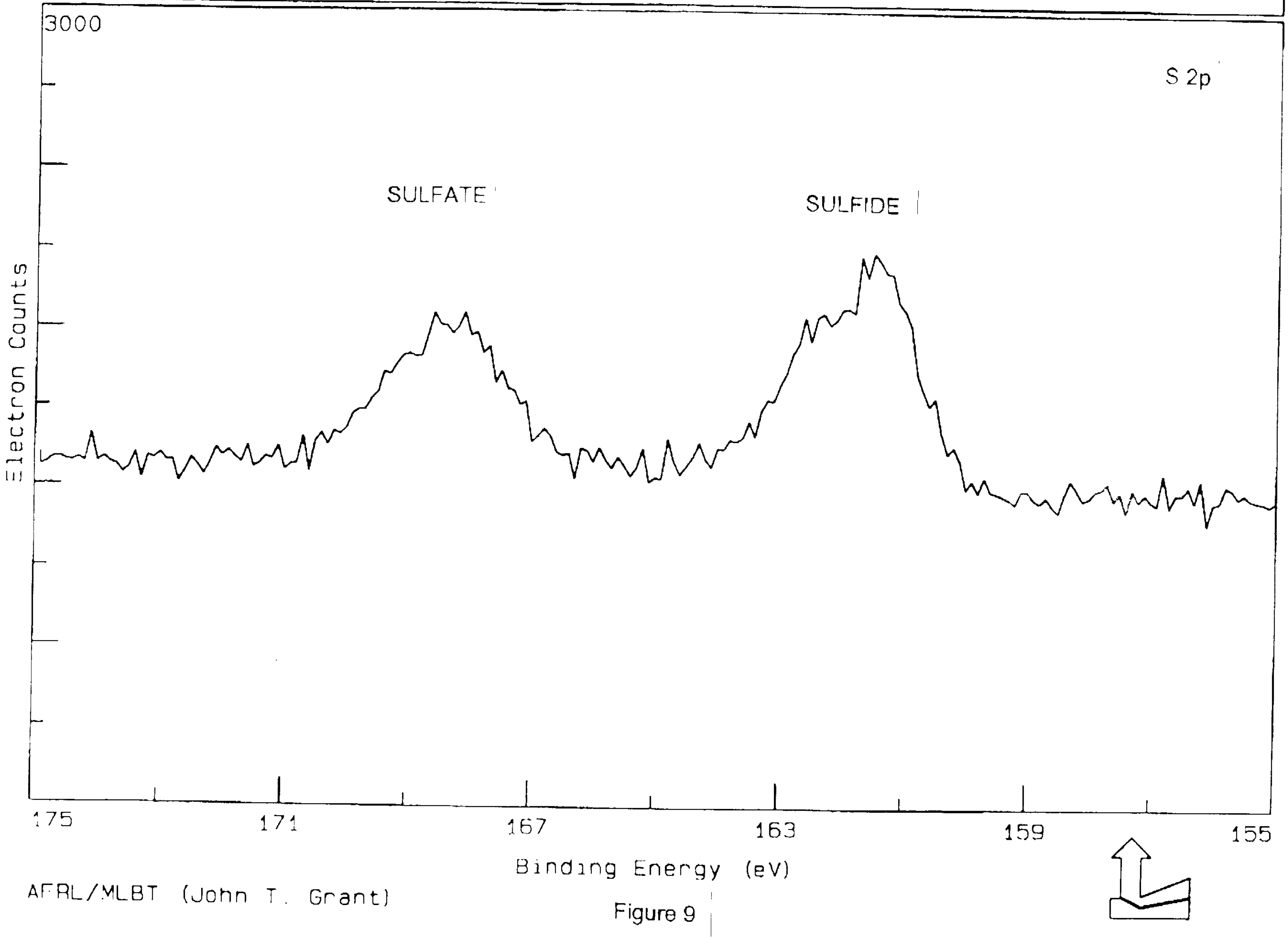
# 1:	284.64 eV	1.35 eV	25028.27 cts	69.80%
# 2:	286.02 eV	1.43 eV	6154.85 cts	17.17%
# 3:	288.17 eV	1.94 eV	4672.64 cts	13.03%

19 iterations, chi square = 1.4998

Figure 8

File: 98091005 Date: Sep 10 1998	Time/Pt: 100 Data Pts: 201	Spot: 400x1000 # of Scans: 40	Flood eV: 0.1 Resolution: 2	Aperture: None

Description: Evergreen Fuel Probe, Region 1

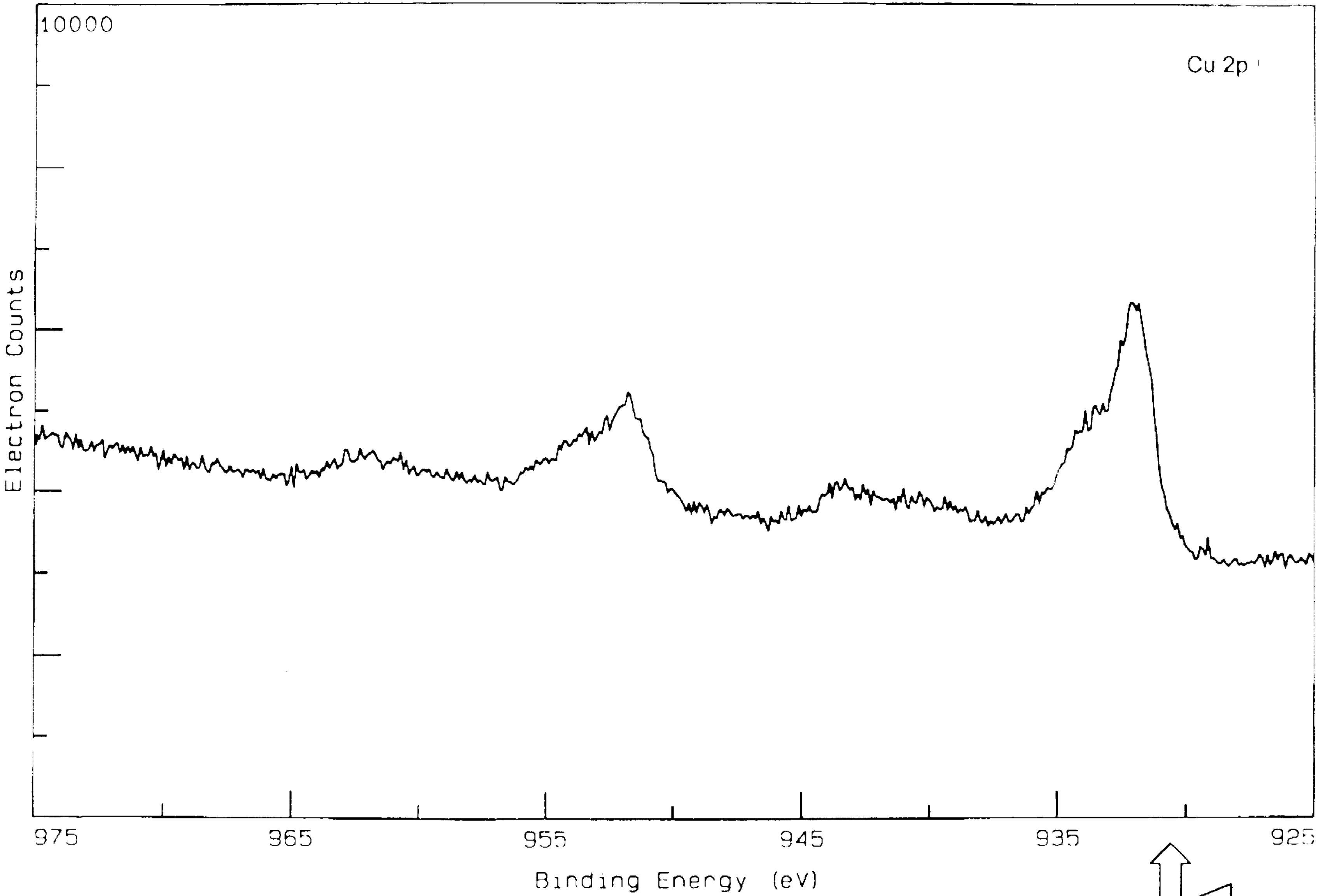


AFRL/MLBT (John T. Grant)

Figure 9

File: 98091005 Date: Sep 10 1998	Time/Pt: 100 Data Pts: 501	Spot: 400x1000 # of Scans: 20	Flood eV: 0.1 Resolution: 2	Aperture: None

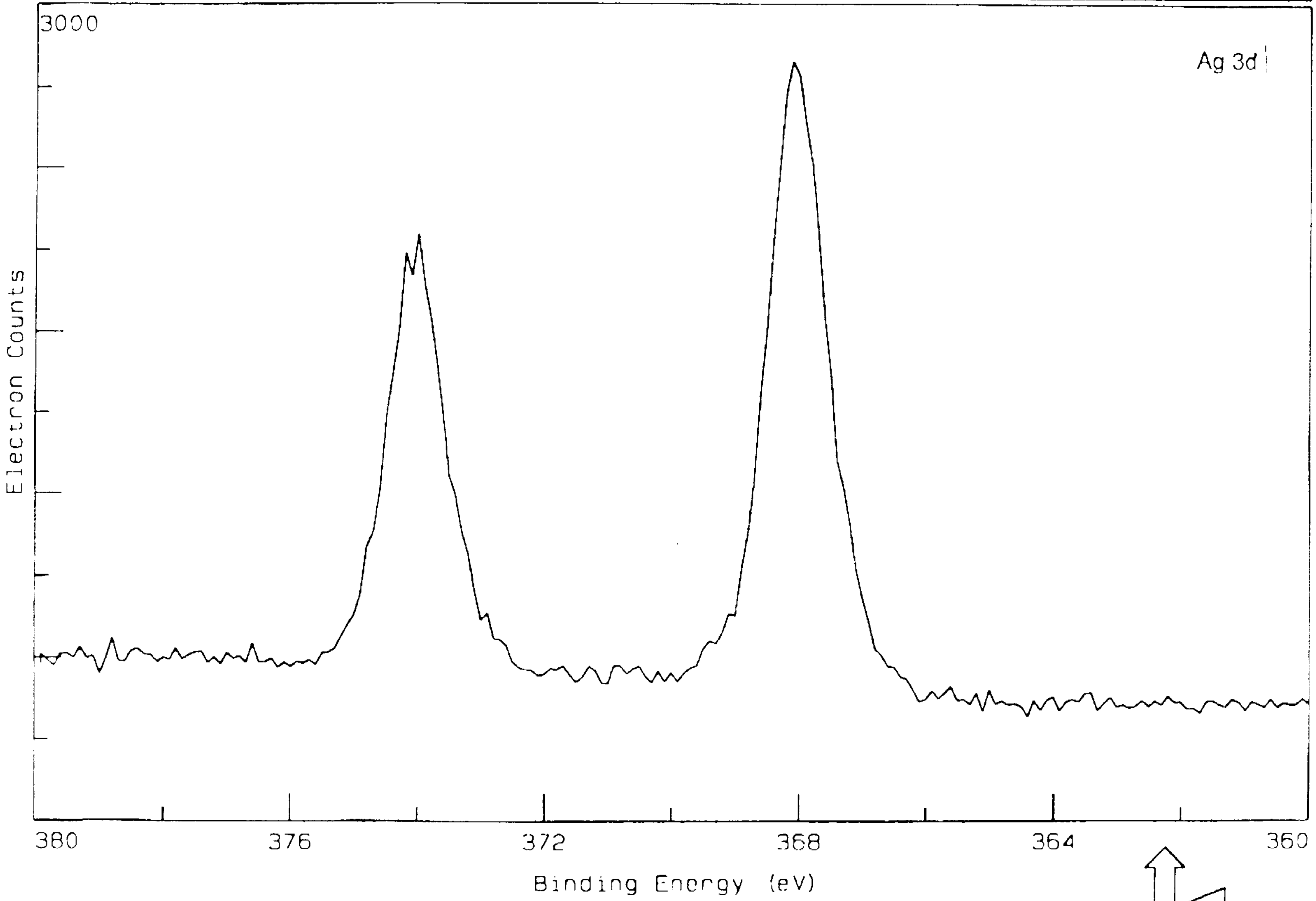
Description: Evergreen Fuel Probe, Region 1



AFRL/MLBT (John T. Grant)

Figure 10

File: 98091005 Date: Sep 10 1998	Time/Pt: 100 Data Pts: 201	Spot: 400x1000 # of Scans: 10	Flood eV: 0.1 Resolution: 2	Aperture: None
Description: Evergreen Fuel Probe, Region 1				

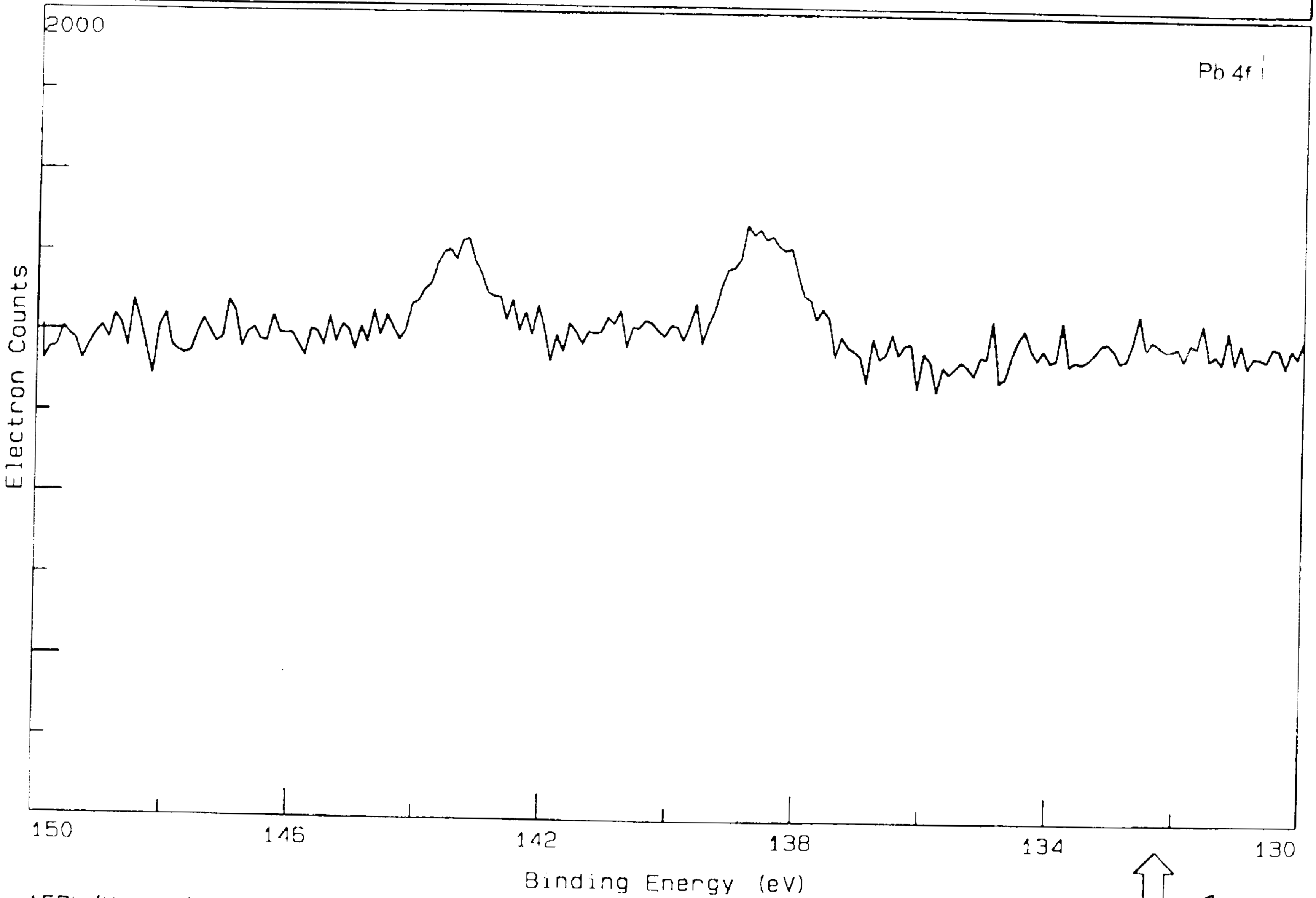


AFRL/MLBT (John T. Grant)

Figure 11

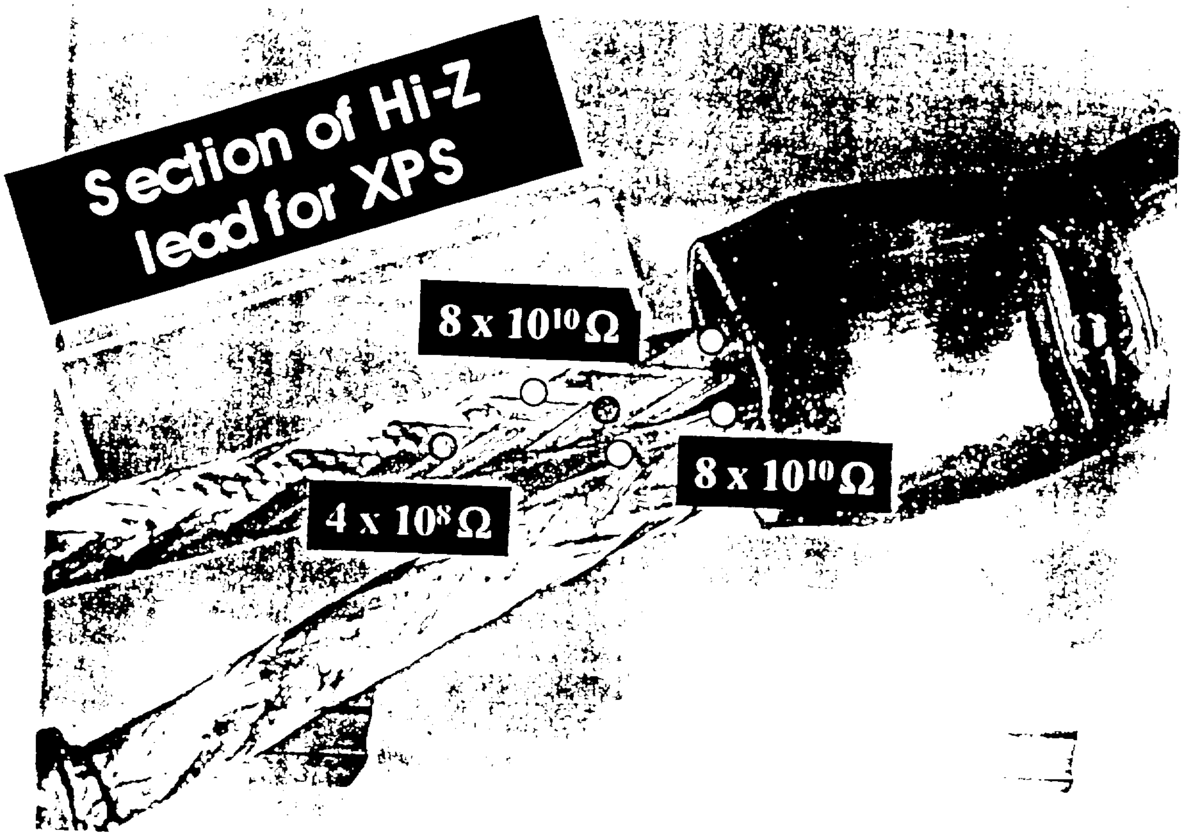
File: 98091005 Date: Sep 10 1998	Time/Pt: 100 Data Pts: 201	Spot: 400x1000 # of Scans: 40	Flood eV: 0.1 Resolution: 2	Aperture: None

Description: Evergreen Fuel Probe, Region 1



AFRL/MLBT (John T. Grant)

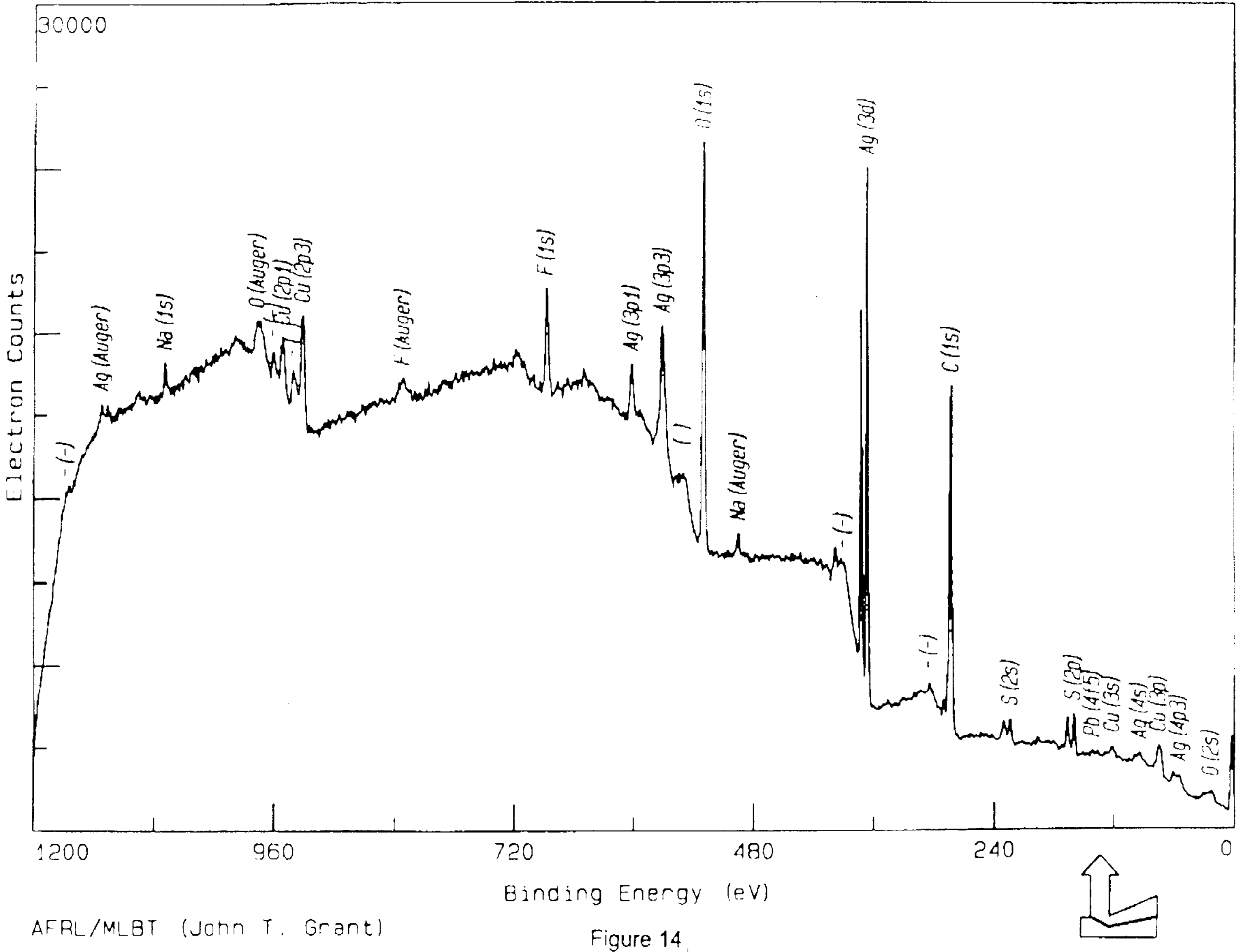
Figure 12



Evergreen Fuel Probe 420A14 SN Z-60
Measured surface resistance values and locations
HP 4339B High Resistance Meter
The section outlined in white was removed for XPS analysis
Figure 13

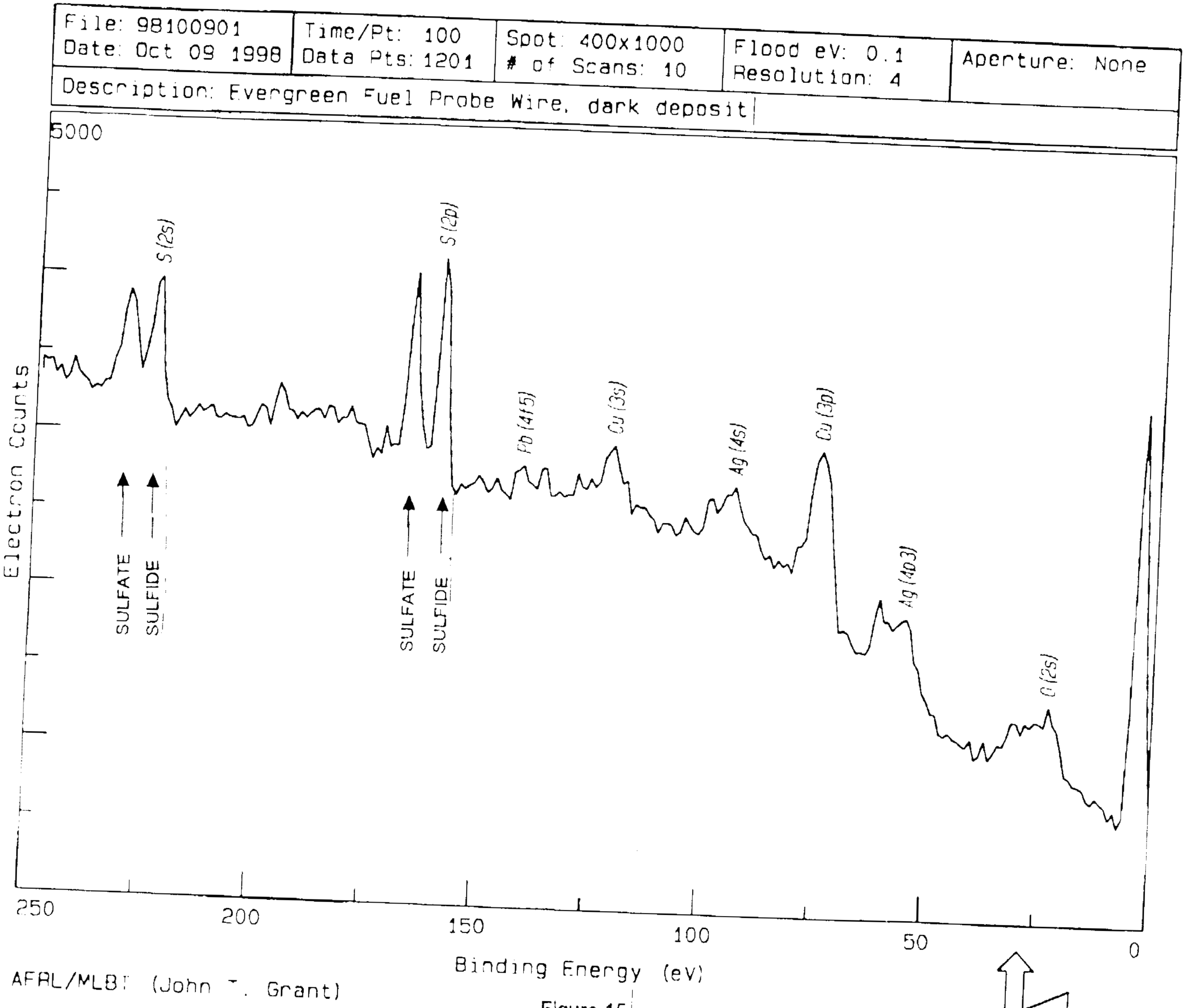
AFRL/MLSA
David Johnson
[illegible]

File: 98100901 Date: Oct 09 1998	Time/Pt: 100 Data Pts: 1201	Spot: 400x1000 # of Scans: 10	Flood eV: 0.1 Resolution: 4	Aperture: None
Description: Evergreen Fuel Probe Wire, dark deposit				



AFRL/MLBT (John T. Grant)

Figure 14



File: 98100901

Date: Oct 09 1998

Time/Pt: 100

Data Pts: 1201

Spot: 400x1000

# of Scans: 10

Flood eV: 0.1

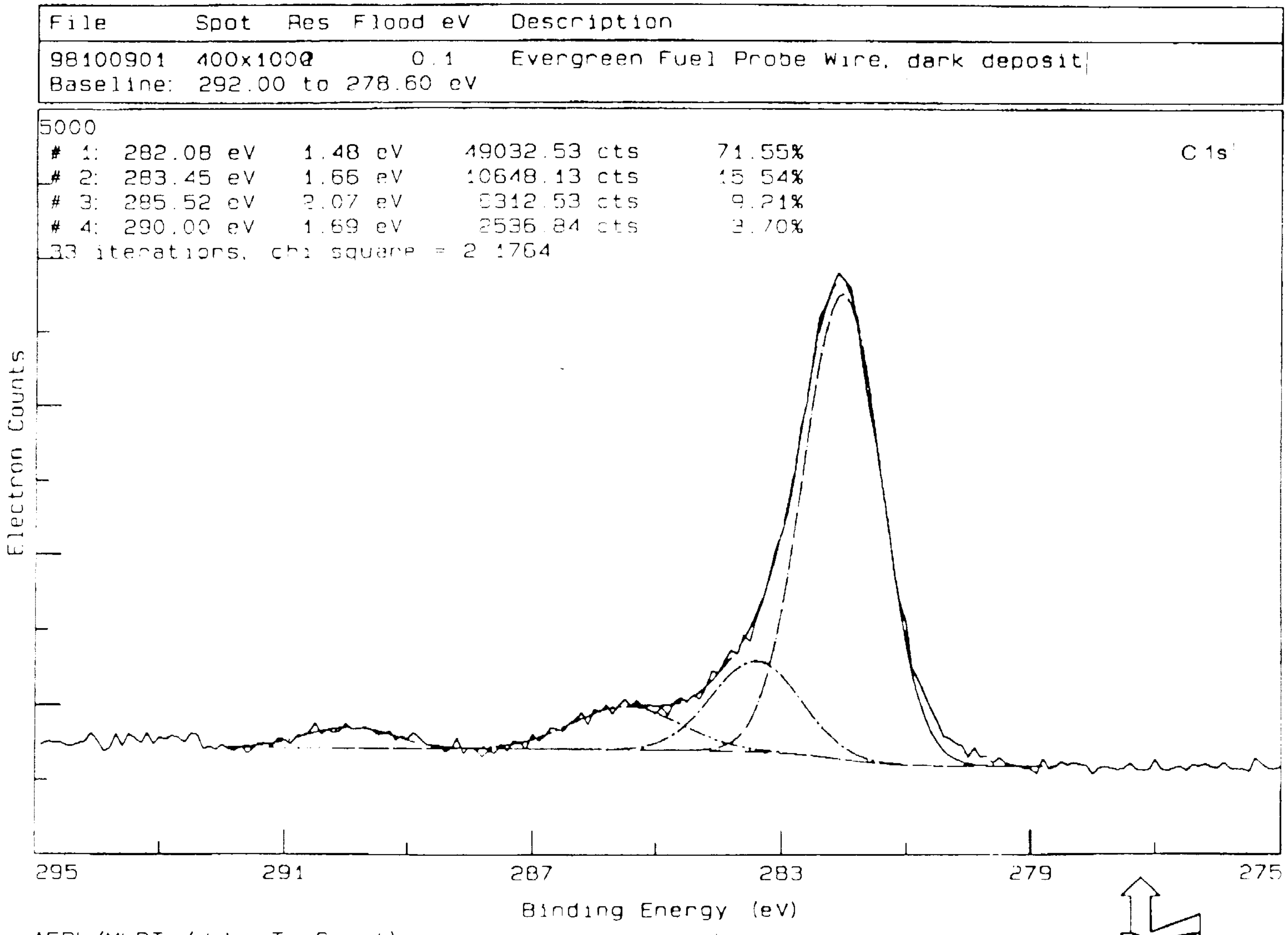
Resolution: 4

Aperture: None

Description: Evergreen Fuel Probe Wire, dark deposit

AFRL/MLBT (John T. Grant)

Figure 15



File Spot Res Flood eV Description

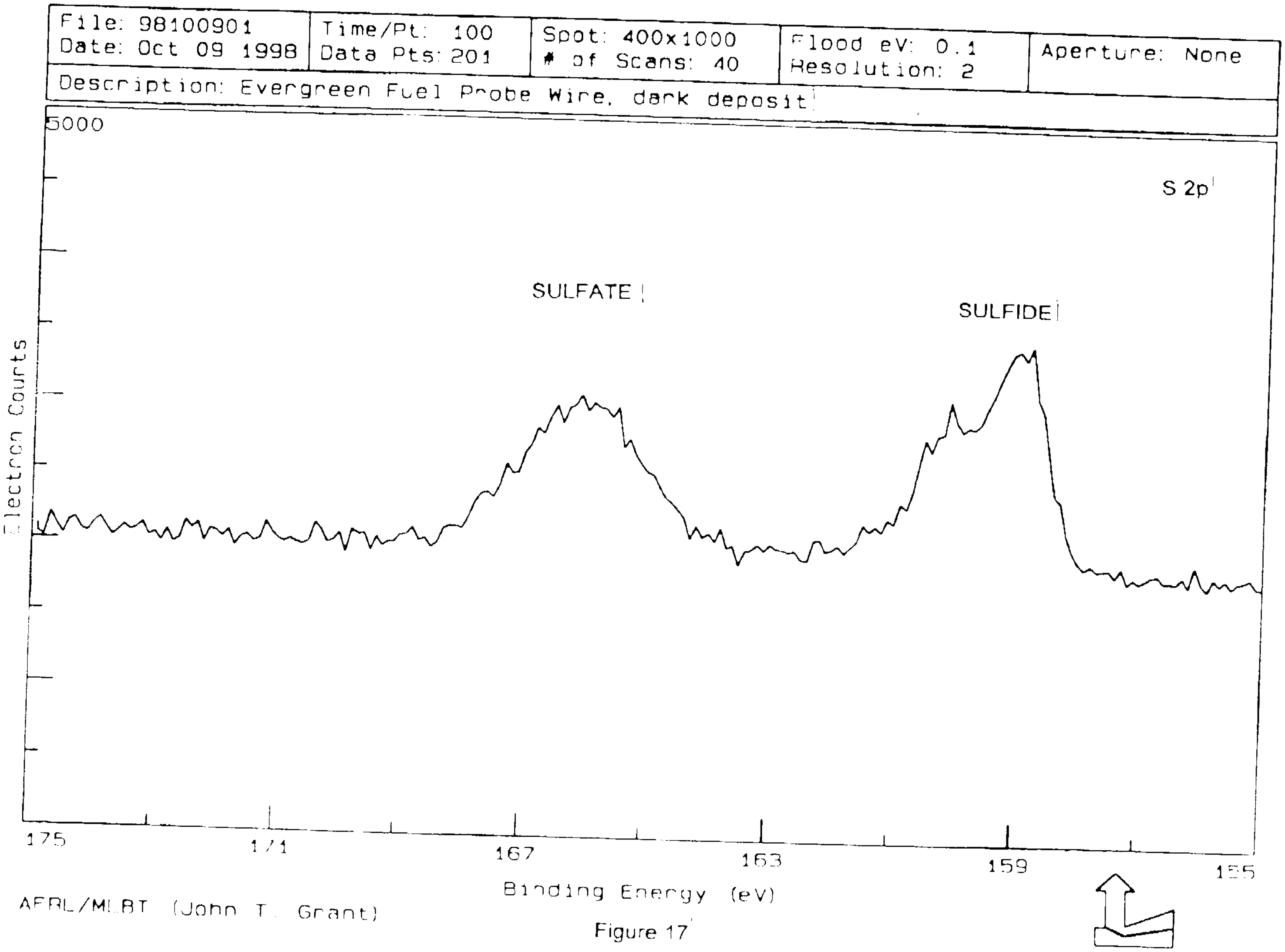
98100901 400x1000 0.1 Evergreen Fuel Probe Wire, dark deposit

Baseline: 292.00 to 278.60 eV

# 1:	282.08 eV	1.48 eV	49032.53 cts	71.55%
# 2:	283.45 eV	1.66 eV	10648.13 cts	15.54%
# 3:	285.52 eV	2.07 eV	6312.53 cts	9.21%
# 4:	290.00 eV	1.69 eV	2536.84 cts	3.70%

33 iterations, chi square = 2.1764

Figure 16



File: 98100901
Date: Oct 09 1998

Time/Pt: 100
Data Pts: 201

Spot: 400x1000
# of Scans: 40

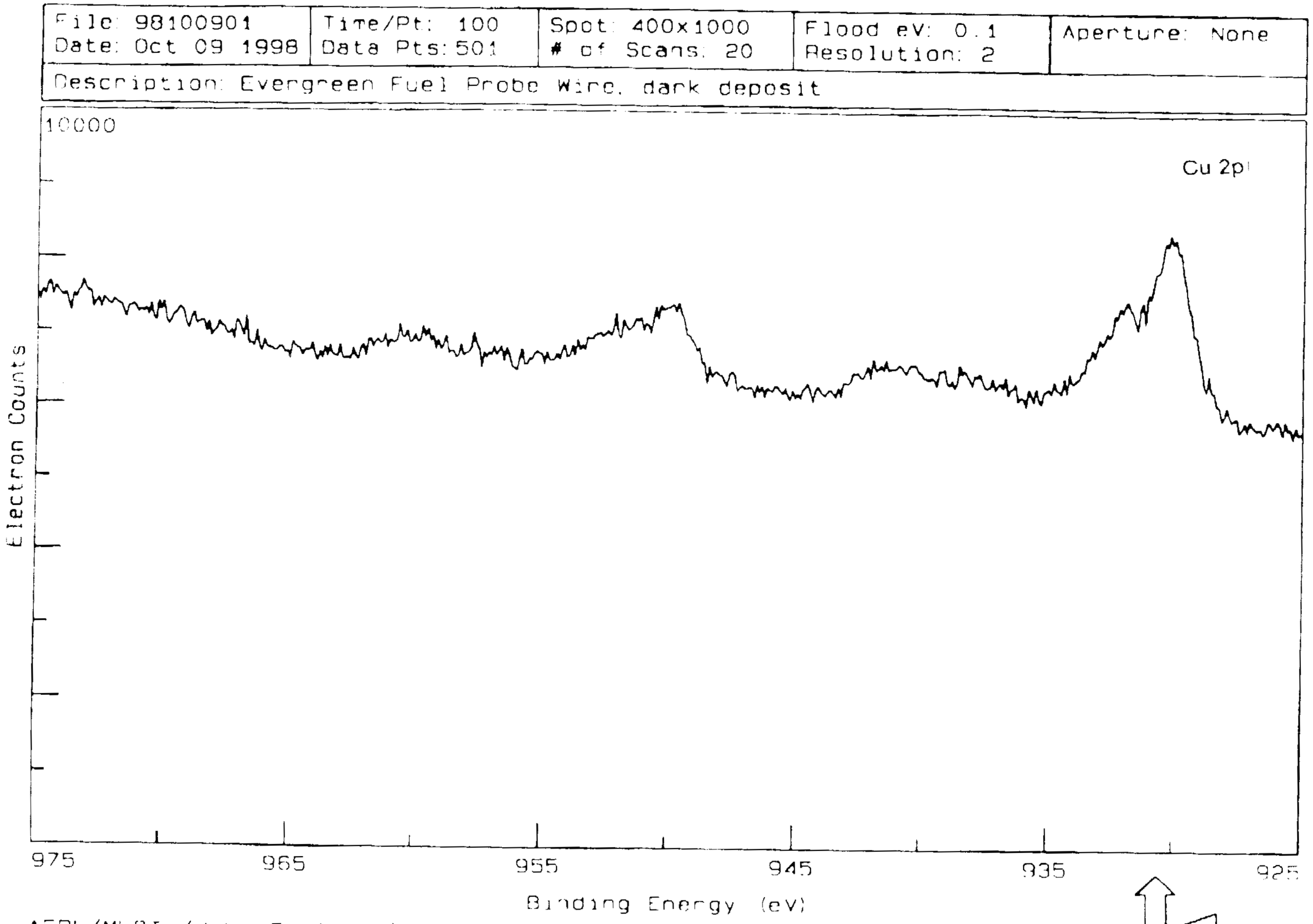
Flood eV: 0.1
Resolution: 2

Aperture: None

Description: Evergreen Fuel Probe Wire, dark deposit

AFRL/MLBT (John T. Grant)

Figure 17



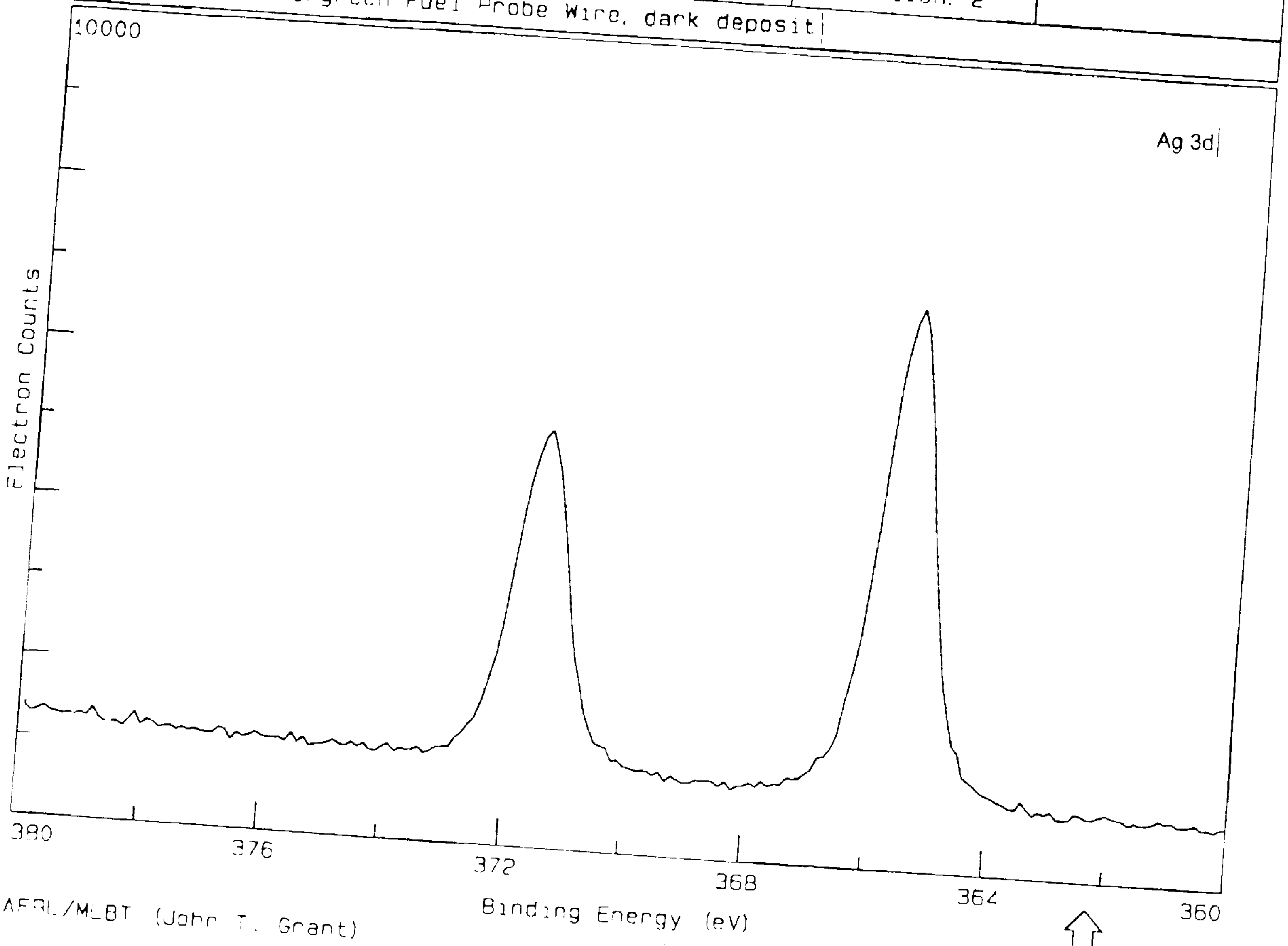
File: 98100901 Date: Oct 09 1998	Time/Pt: 100 Data Pts: 501	Spot: 400x1000 # of Scans: 20	Flood eV: 0.1 Resolution: 2	Aperture: None

Description: Evergreen Fuel Probe Wire, dark deposit

AFRL/MLBT (John T. Grant)

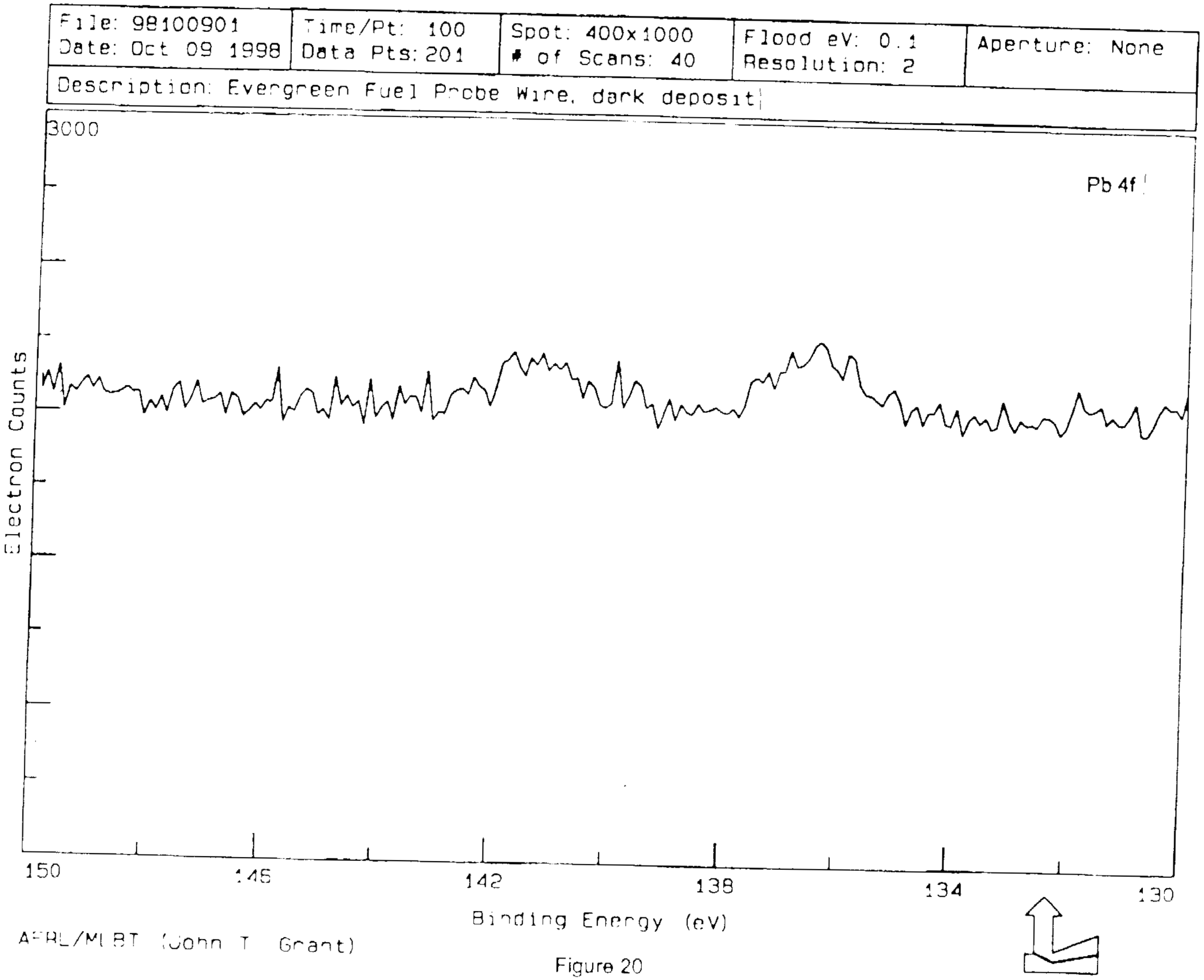
Figure 18

File: 98100901
Date: Oct 09 1998
Time/Pt: 100
Data Pts: 201
Spot: 400x1000
# of Scans: 10
Flood eV: 0.1
Resolution: 2
Aperture: None
Description: Evergreen Fuel Probe Wire, dark deposit



AFRL/MLBT (John T. Grant)

Figure 19



File: 98100901
Date: Oct 09 1998
Time/Pt: 100
Data Pts: 201
Spot: 400x1000
# of Scans: 40
Flood eV: 0.1
Resolution: 2
Aperture: None
Description: Evergreen Fuel Probe Wire, dark deposit

Figure 20

Aircraft Fuel Quantity Indicator System
Component Inspection
(Materials Analysis)

21 June 1999

Evaluation Report
(43499TMO/NTSB)

Report No. AFRL/MLS 99-33

AUTHOR(S)

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DISTRIBUTION STATEMENT F: Further dissemination only as directed by National Transportation Safety Board, 21 June 1999, or DoD higher authority.

EXECUTIVE SUMMARY

Examination of 747 aircraft fuel probes, terminal strips and wiring revealed the presence of fuel residues and damaged wire insulation. Residues were noted near terminals and where damage exposed wire conductors.

High resistance values (greater than 10^{11} ohms) were measured between fuel probe terminations. The submitted terminal strip exhibited low resistance values (10^{4} ohm range) between terminals. Direct probing of fuel probe and terminal strip residue films gave resistance values in the low kilohm range. Residues were rich in copper, silver and sulfur compared to nonresidue areas.

Candidate fuel probe and terminal strip areas were identified for subsequent voltage breakdown tests. The findings of this report were consistent with the earlier evaluation report on 747 fuel probes, AFRL/MLS 97-102, dated 30 October 1997.

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LIST OF FIGURES

Aircraft Fuel Quantity Indicator System Component Inspection

PURPOSE

Evaluate residues and other anomalies found on submitted 747 fuel quantity indicator system (FQIS) components.

BACKGROUND

This is a follow-on activity to evaluation report WL/MLS 97-102 on fuel probe and compensator fragments from TWA flight 800 and FQIS components from a non-mishap 747 aircraft. The National Transportation Safety Board (NTSB) provided additional nonmishap 747 FQIS components for inspection and analysis of residues found on part surfaces. The components were from a 747-156 aircraft (serial number 19958, ID N134TW, number of hours = 92,141). A list of received materials is given in appendix A. It was reported aircraft N134TW was being prepared for salvage when the FQIS components were removed.

FACTUAL DATA

The following processes were used to inspect components and identify samples for possible electrical breakdown testing:

- Visual inspection and photo-documentation
  - Identify damage and/or heavy residue accumulation
- Electrical resistance measurements
  - Terminal-screw-to-terminal-screw resistance measurements (Appendix B tables 1 and 2 for typical data)
  - Sorting criteria of less than one megaohm resistance used to identify components for electrical breakdown testing
- Surface resistance measurements
  - Point-to-point high resistance measurement of surface residue stains
  - Sorting criteria of less than 100 kilohms resistance used to select units for electrical breakdown testing

The terminal-to-terminal electrical measurements of the probes listed in appendix A were all above 10 megaohms. Typical fuel probes received for analysis are shown in figures 1 and 2.

Figures 3 through 9 show typical mechanical damage to fuel probe and compensator wiring. This was typical of the wiring damage found throughout the inspected fuel probes.

Figures 6 through 37 (appendix C) show typical examples of residues observed on terminal block surfaces and wiring. Residues were noted near terminals and exposed wire conductors. Direct probing of fuel probe residues gave resistance values in the low kilohm resistance range with occasional values as low as a several hundred ohms. Examples of surface resistance measurements taken where film residues were present can be found in Appendix B, Table 4. Direct probing measurements in areas with and without visible residues are given in figures 12 and 33. Measured resistance values in areas without visible residues were in the 10^8 to 10^{14} ohm range. Residues were noted to be fragile and resistance values were dependent on test fixture probe size and pressure. Residue resistance values would change when various voltages were applied.

The submitted terminal strip exhibited low resistance values (10^4 ohm range) between terminals (appendix B, table 3). The terminal strip has five screw terminals to which ten wires are connected. The strip was initially received with the crimp-on terminals in place. The wires had been cut to remove the terminal strip without loosening the nuts on the terminal post. Terminal post combinations 2 to 3, 2 to 4, 2 to 5 and 3 to 5 had resistance values between 20.5 kilohm to 94 kilohm when measured at 3.5v using Hewlett Packard 4339B high resistance meter. Following terminal-to-terminal resistance measurements, the terminal strip was sent to an outside lab for a surface analysis method not available at AFRL. The crimp-on terminals were removed before time-of-flight secondary ion mass spectroscopy (TOF-SIMS) surface analysis. When the terminal strip was returned to MLSA, the terminal-to-terminal resistance measurements had increased to values between 120 kilohms and 9.5 megohms using a Hewlett Packard 4339B high resistance meter at 3 volts.

Surface analysis using X-ray Photoelectron Spectroscopy (XPF) and scanning electron microscope (SEM) Energy Dispersive Spectroscopy (EDS) identified copper, silver, and sulfur in residue regions (figures 35 through 39). Probes were segregated for follow-on voltage and energy breakdown tests based on residue build-up and surface resistance probing.

DISCUSSION(S)

Initially, the intent was to sort probes and compensators using DC high resistance measurements to identify units on which to perform electrical breakdown testing. There were no probes or compensators identified with terminal-to-terminal resistance values less than 1×10^7 ohms. The center wing tank (CWT) terminal strip (figures 29 through 32 and 38) did exhibit low resistance values before the wire crimp-on ring terminals were removed. Direct probing of residues found on various fuel system components also gave resistance in the low kilohm ranges.

Direct probing was used to identify candidate samples for voltage breakdown tests. Fuel probe terminal blocks, fuel probe wiring, and terminal strip areas were selected using this method. Residues were typically found on terminal block surfaces at locations where silver-plated copper wire was exposed to jet fuel (figures 6 through 12). Typical sites were beneath the crimp-on terminals at the end of the Hi-Z, Low-Z and shield pigtail wires. Residues were also found on wire insulation where insulation damage exposed the core conductor or shielding braid to fuel. Examples of such damage sites and associated residue stains are shown in figures 6 through 9. Surface resistance measurements were also taken at several areas where the presence of residues was not visually detected. The measured surface resistance values at sites with residue stains were typically in the low kilohm range, with occasional values as low as a few hundred ohms observed. Resistance values in areas without visible residue stains were in the 10^8 to 10^{14} ohm ranges.

SUMMARY OF FINDINGS

Examination of 747 aircraft fuel probes, terminal strips and wiring revealed the presence of fuel residues and damaged wire insulation. Residues were noted near terminals and areas of damaged and exposed wire conductors. Insulation damage was the result of the fuel probe terminal block clamping arrangement. Residues were rich in copper, silver and copper compared to nonresidue areas. These films are most likely the result of silver-plated copper wire coming in contact with fuel. Residues and wire insulation damage found on FQIS components from retired aircraft N134TW are similar to those found in evaluation report number WL/MLS 97-102, 747 Fuel Probe Evaluation--A/C N93119 TWA Flight 800 (failure analysis) dated 30 October 1997.

High resistance values (greater than 10^{11} ohms) were measured between fuel probe terminations. The submitted terminal strip initially exhibited low resistance values (10^4-10^7 ohm range) between terminals. Terminal-to-terminal resistance values increased to over 10^6 ohms after wires were moved and the terminal was shipped and handled during surface analysis. Direct probing of fuel probe and terminal strip residues gave resistance values in the low kilohm ranges. Resistance values were typically unstable and changed value if the residues were disturbed or if the test fixture probe pressure was changed. Handling during probe removal and shipping is also suspected of have disturbed residues and accounted for the higher resistance values than would have been observed otherwise between probe and compensator terminal posts.

Additional terminal barrier strips were received for analysis. These terminal strips exhibited minimal residues and high resistance values between terminals. Serveral of the attached crimped wire terminals were coated with residues (figure 27 and 6C, appendix C). Typically, crimped terminals with residues have had residues on the adjacent terminal block or strip. The observed inconsistency may be the result of the barrier strips being replaced during an earlier maintenance action.

Findings of this report were consistent with the earlier evaluation report on 747 fuel probes, AFRL/MLS 97-102, dated 30 October 1997. Fuel probes exhibiting residues were selected for electrical breakdown testing. Results of electrical breakdown testing will be presented in a subsequent MLSA report.

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PUBLICATION REVIEW: This report has been reviewed and approved.

Michael Hitchcock

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FIGURES

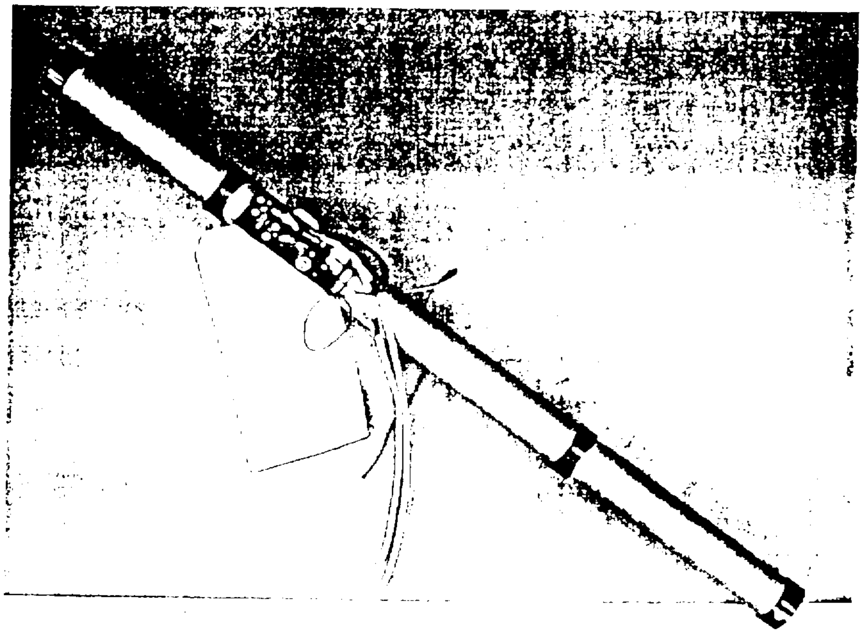

Figure 1. Typical as-received condition of a fuel quantity indication system probe (Model No. FG420A36, Serial No. A-110 from Boeing 747 N134TW).

Mag: 0.25X

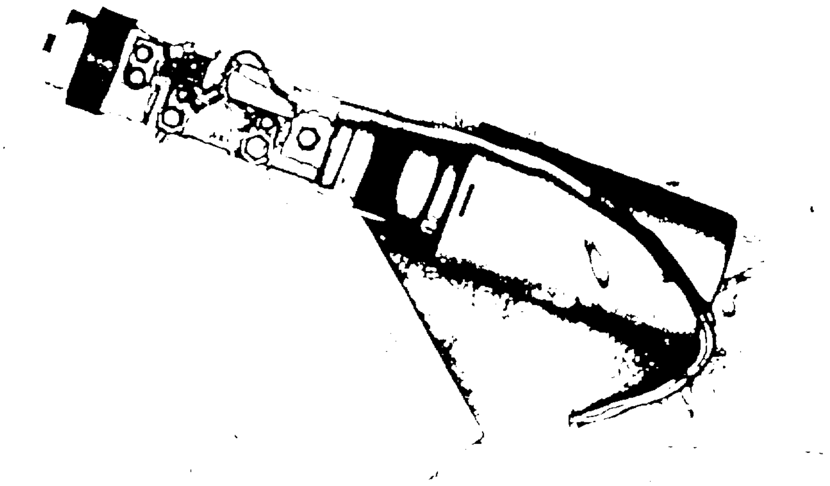

Figure 2. Typical as-received condition of a fuel quantity indication system compensator (Model No. FG6C2, Serial No. Z-612 from Boeing 747 N134TW).

Mag: 0.48X

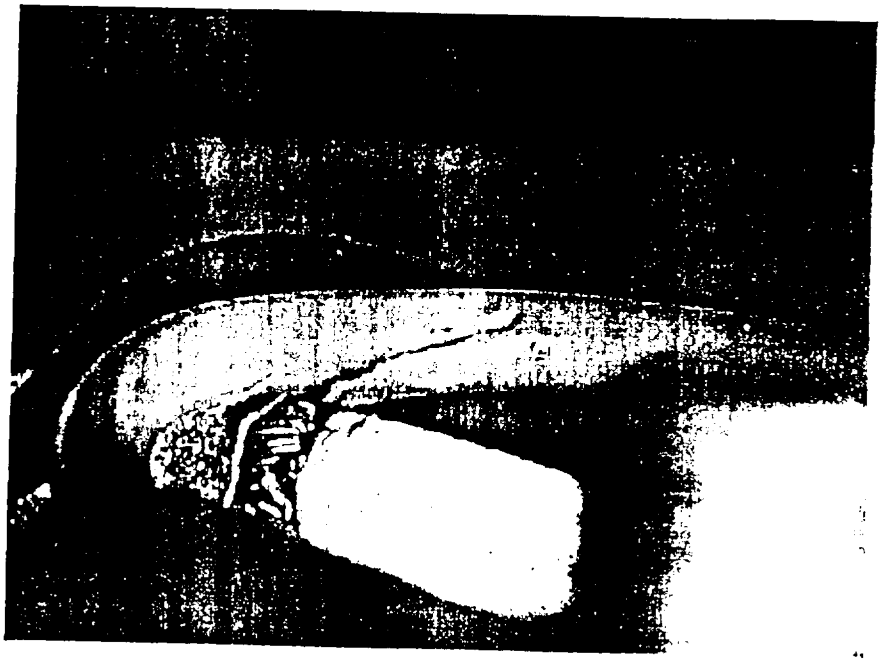

Figure 3. Optical inspection. Example of damaged observed to PTFE wire insulation (compensator: Model No. FG6C2, Serial No. Z-612 from Boeing 747 N134TW).

Mag: 8.2X

Figure 4. Optical inspection. Example of damage to PTFE wire insulation caused by steel strain relief clamp (fuel probe: Serial No. Z-26 from Boeing 747 N134TW).

Mag: 6.3X

Figure 5. Example of damage to PTFE wire insulation caused by steel strain relief clamp (fuel probe: Model No. FG420A24, Serial No. A-123 from Boeing 747 N134TW as seen in figure 5).

Mag: 3X

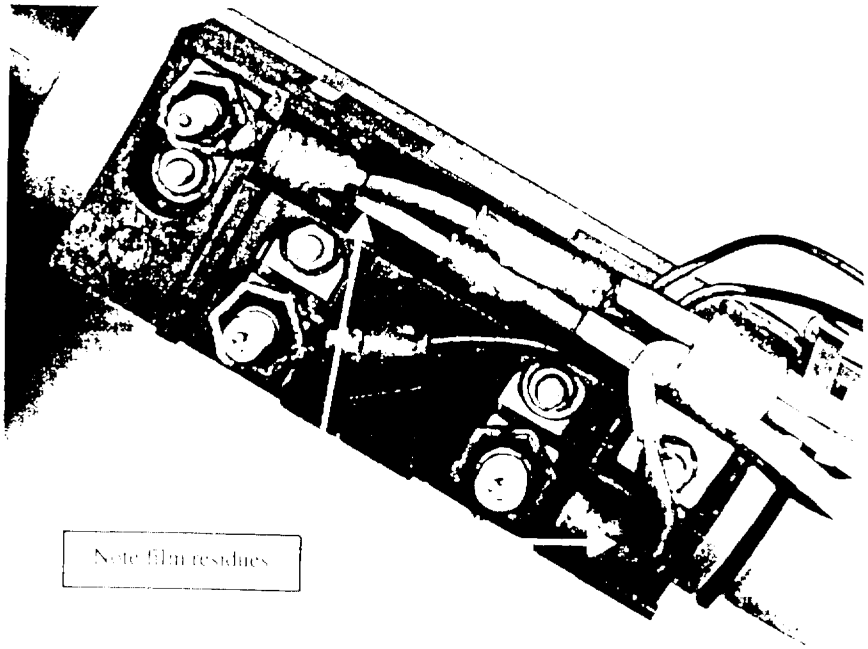

Figure 6. Typical as received condition of fuel probe terminal block from 747, tail number N134TW (FG420A24, Serial No. A-123)

Mag: 1.3X

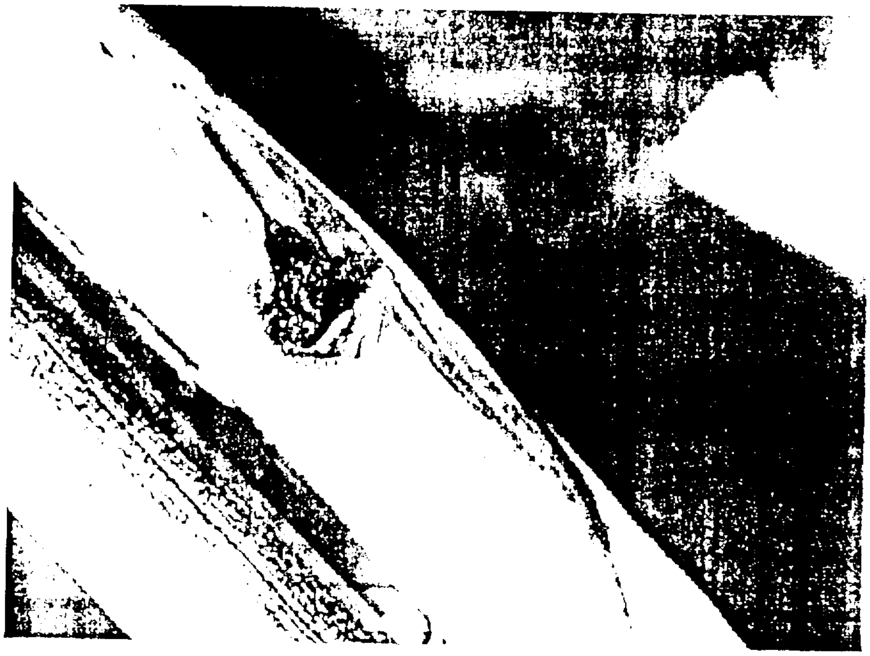

Figure 7. Optical inspection. Example of damage to PTFE wire insulation (fuel probe: Model No. FG420A24, Serial No. A 127 from Boeing 747 N134TW)

Mag: 10.7X

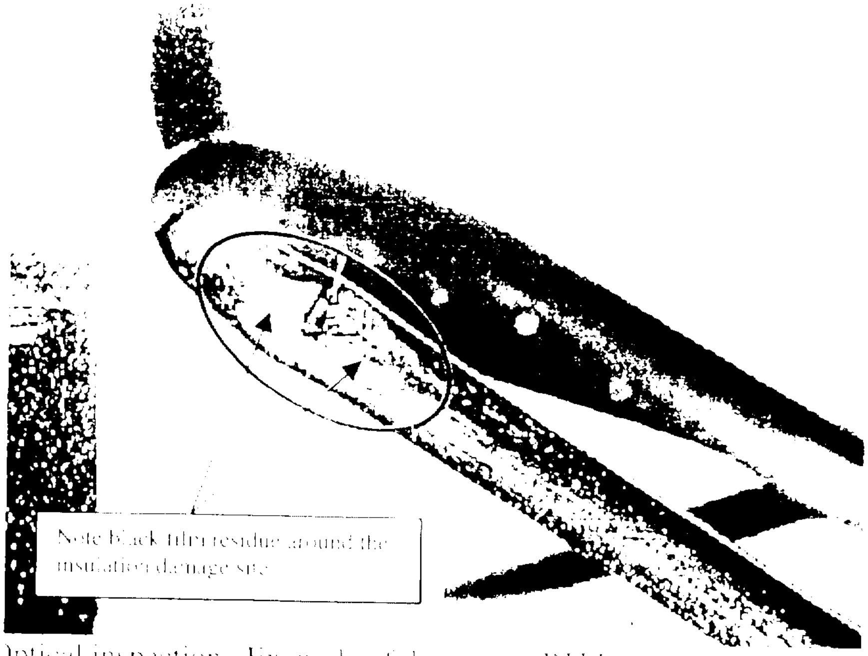

Figure 8. Optical inspection. Example of damage to PTFE wire insulation with black film residue (copper/silver/sulfur) visible around the damage site (fuel probe: Model No. FG420A29, Serial No. A 710 from Boeing 747 N134TW)

Mag: [illegible]X

Figure 9. Optical inspection. Example of damage to PTFE wire insulation (fuel probe Model No. FG420A34, Serial No. A 121 from Boeing 747 N134TW).

Mag. 15.1X

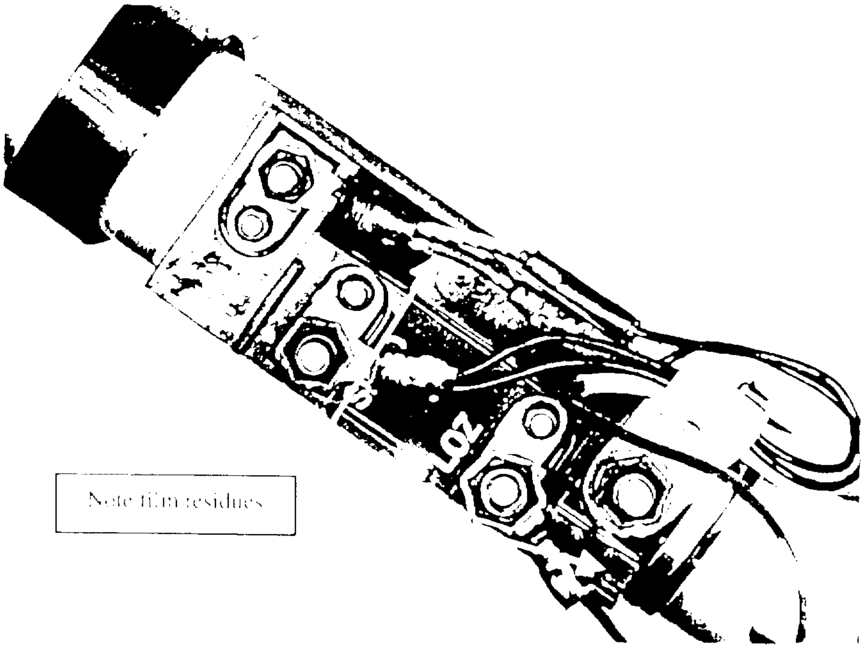

Figure 10. Typical as received condition of fuel probe terminal block from 747-156, number N134TW (FG420A12 Serial No. Z 119)

Mag. 1.6X

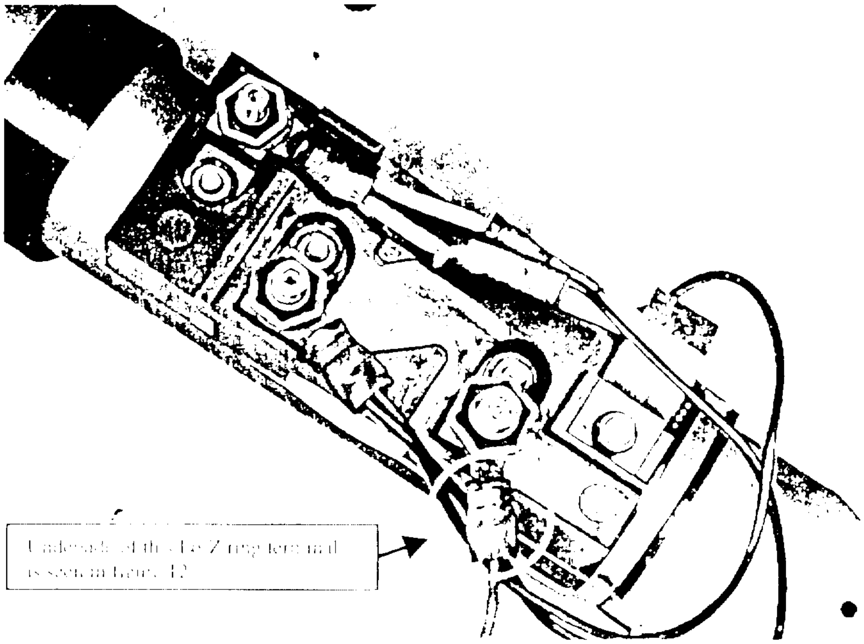

Figure 11. Example of film residues found on 747-156, number N134TW (probe serial number A-118).

Mag: 1.1X

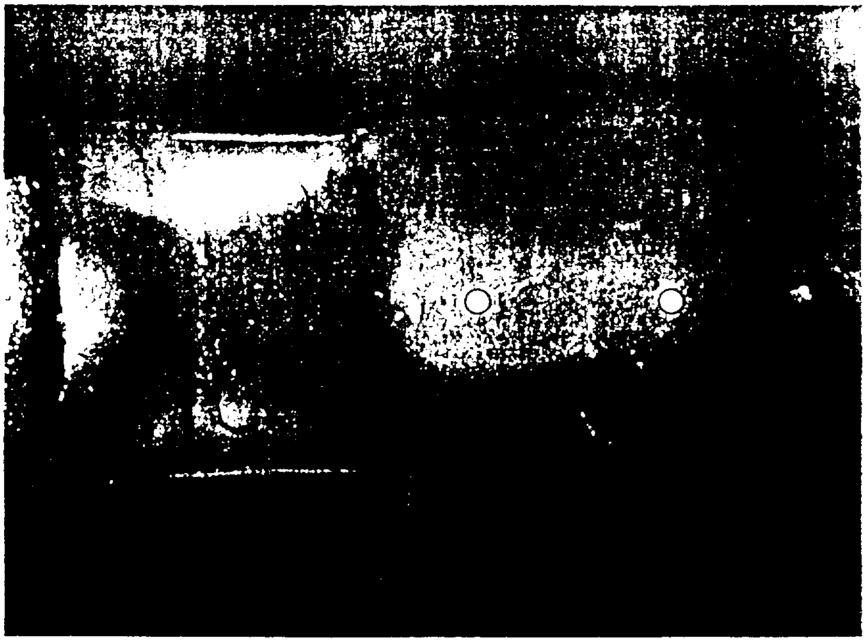

Figure 12. Example of film residues found on Lo-Z wire terminal (same as seen in figure 11) from 747-156, number N134TW. Resistance between two points varied between 1.2K and 2.5K Ω using an ohmmeter.

Mag: 9.5X

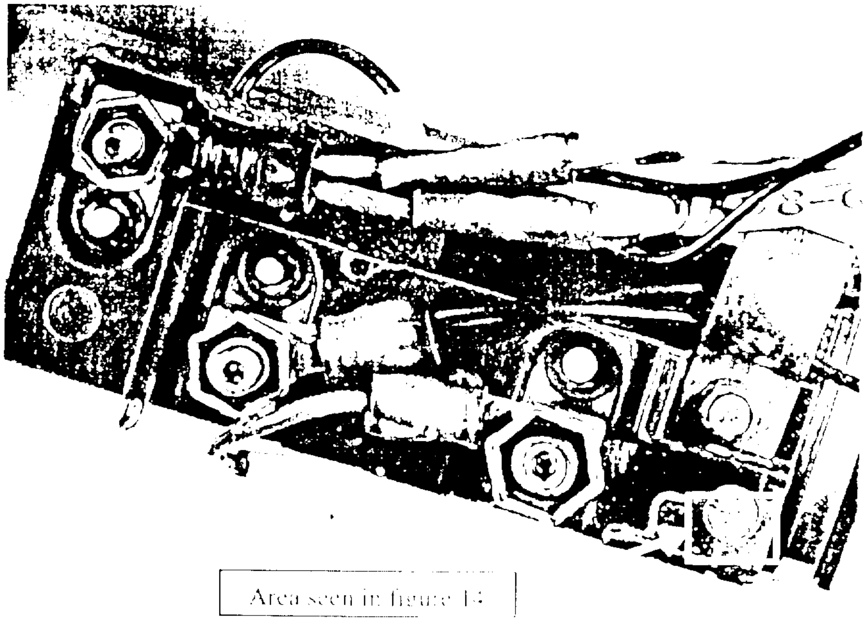

Figure 13. Example of terminal block exhibiting film residues. Red L to Z wire has been rotated 180 degrees out of place to expose residue stain beneath (747-156, number N134TW, probe serial number A-173)

Mag: 1.5X

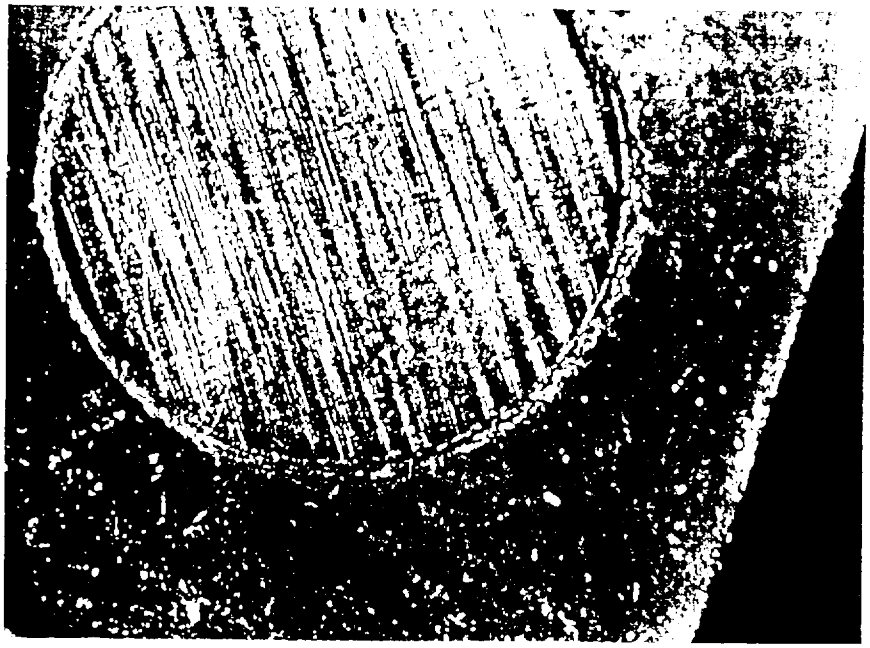

Figure 14. Closer view of film residues seen in figure 13 adjacent to L to Z terminal (747-156, number N134TW, probe serial number A-173)

Mag: 18.9X

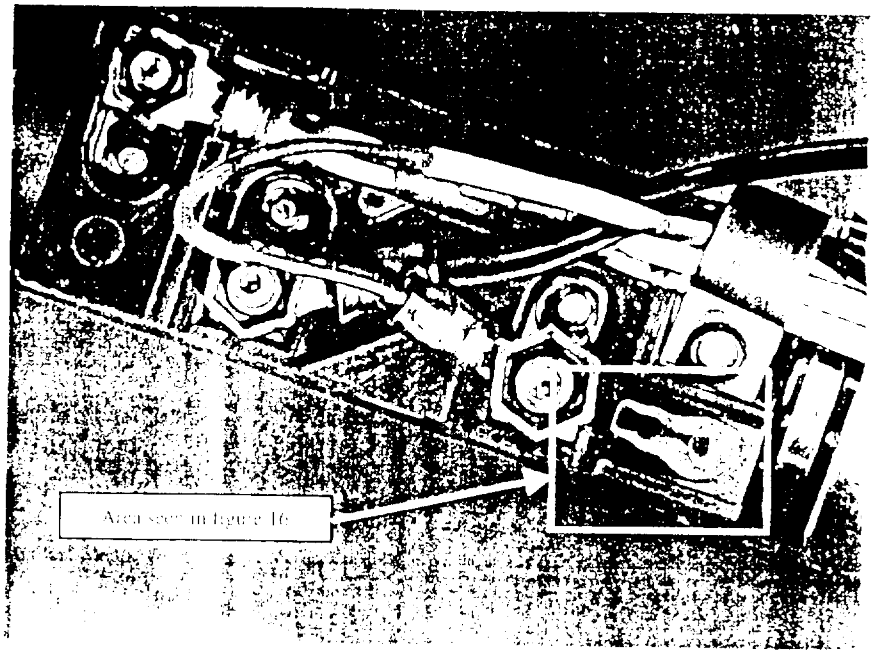

Figure 15. Example of terminal block exhibiting film residues. Red Lo Z wire has been rotated 180 degrees out of place to expose residue stain beneath (747-156, number N134TW, probe serial number A 65).

Mag: 1.4X

Figure 16. Example of terminal block exhibiting film residues (747-156, number N134TW, probe serial number A 65).

Mag: 5.5X

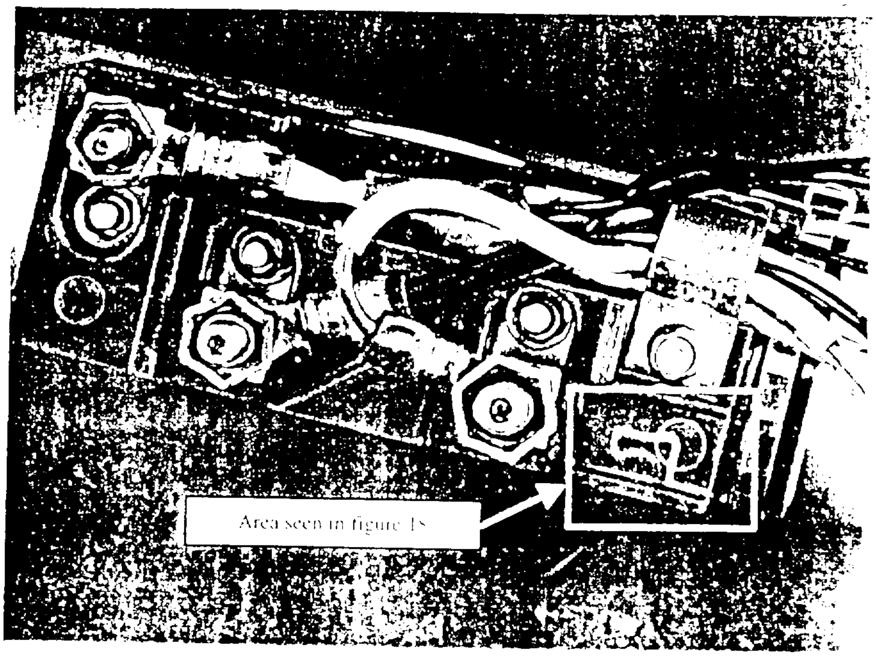

Figure 17. Example of terminal block exhibiting film residues. Red Lo Z wire has been rotated 180 degrees out of place to expose residue stain beneath (747-156, number N134TW, probe serial number A-70).

Mag. 1.4X

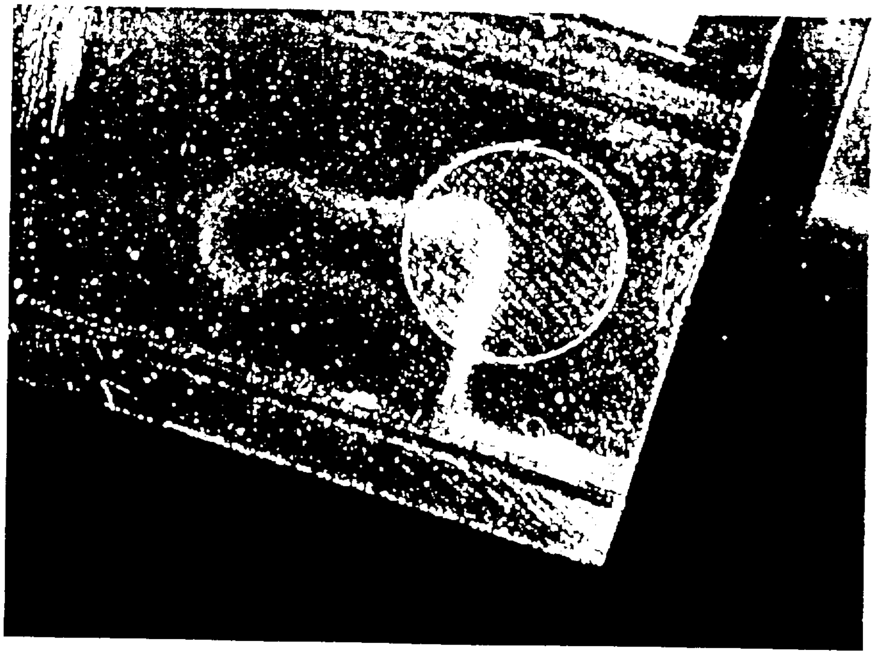

Figure 18. Example of terminal block exhibiting film residues (747-156, number N134TW, probe serial number A-70).

Mag. 8.0X

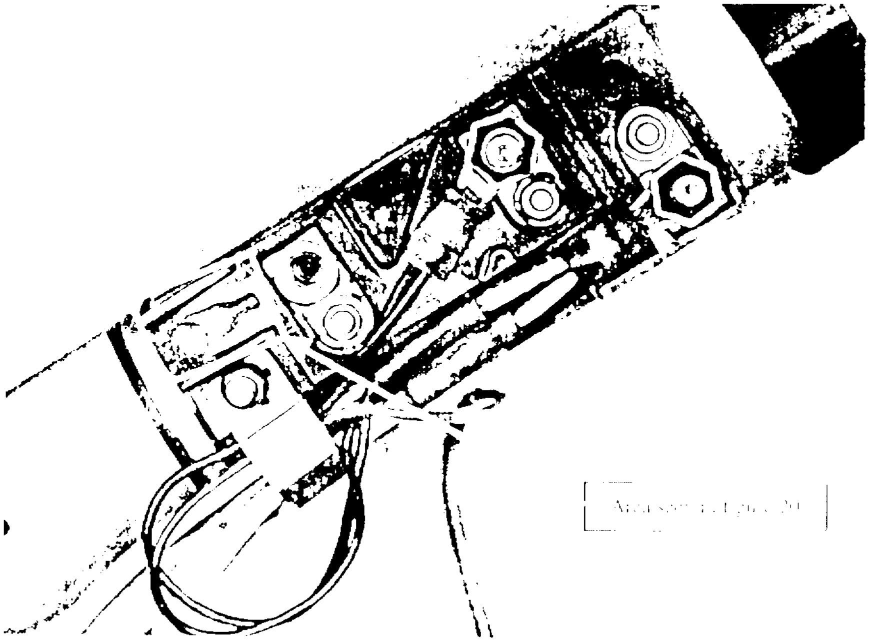

Figure 19. Example of terminal block exhibiting film residues. Red Lo Z wire and screw terminal have been removed to expose residue stain beneath (747-156, number N134TW, probe serial number A-85).

Mag: 1.1X

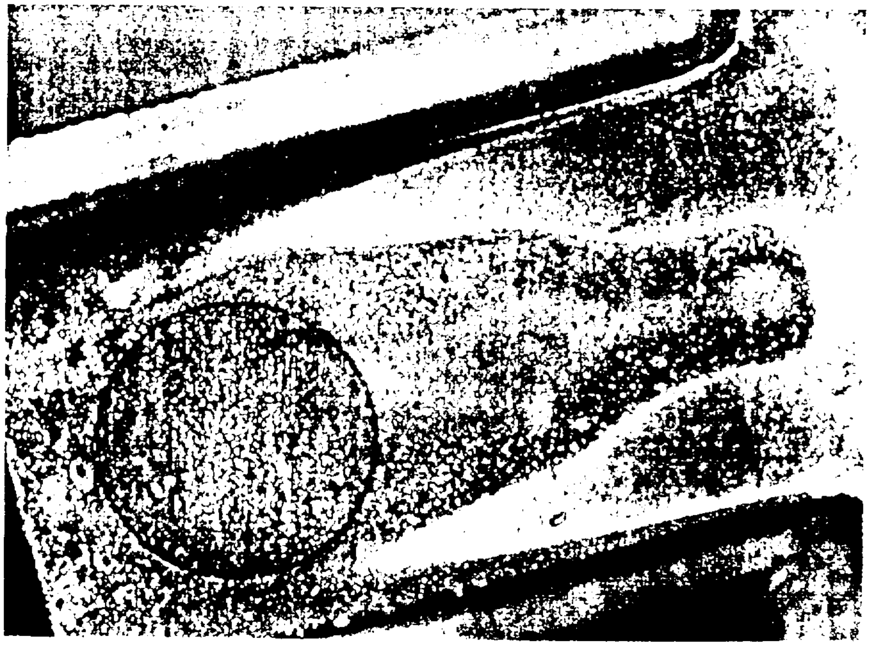

Figure 20. Example of terminal block exhibiting film residues (747-156, number N134TW, probe serial number A-85).

Mag: 7.5X

Figure 21. Insulation sleeve of Lo-Z wire crimp on terminal from assembly seen in figure 19. Insulation is covered with heavy film residues (747-156, number N134TW, probe serial number A-85).

Mag. 10.2X

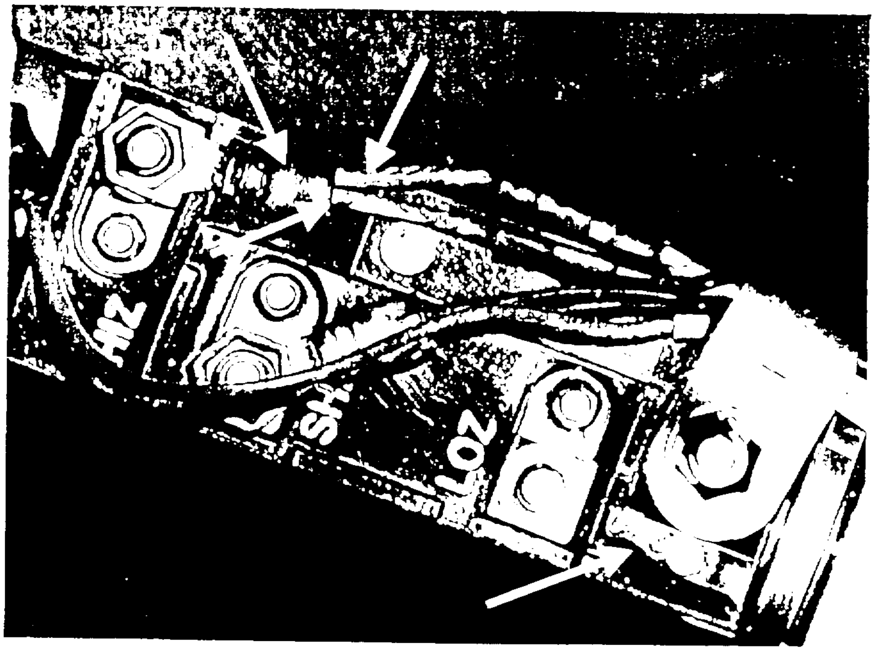

Figure 22. Fuel probe terminal block with Lo Z (red) wire removed from terminal post. Copper/silver/sulphur rich film residues are visible adjacent to Lo Z terminal and deposited on Hi Z (white) wire insulation (model No. FG420A14 Serial No. Z 60 from aircraft N134TW).

Mag. 1.8X

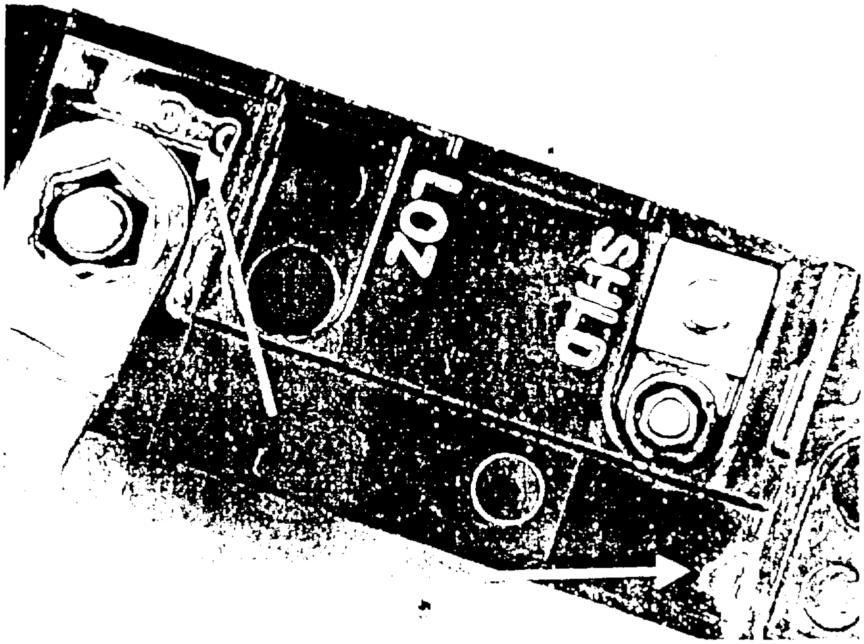

Figure 23. Fuel probe terminal block with FQIS wires removed. Copper/silver/sulphur rich film residues are present adjacent to Hi Z and Lo Z terminals (fuel probe - Model No. FG420A14 Serial No. Z-60 from aircraft N134TW)

Mag. 1.85X

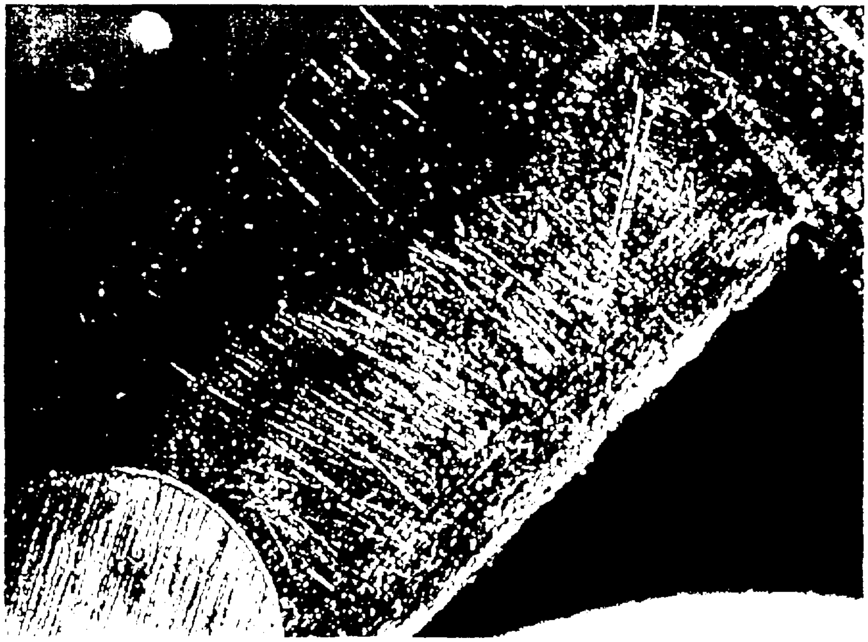

Figure 24. Closer view of Copper/silver/sulphur rich film residue seen in figure 23 adjacent to the Lo Z terminal position (fuel probe: Model No. FG420A14 Serial No. Z-60 from aircraft N134TW)

Mag. 9.3X

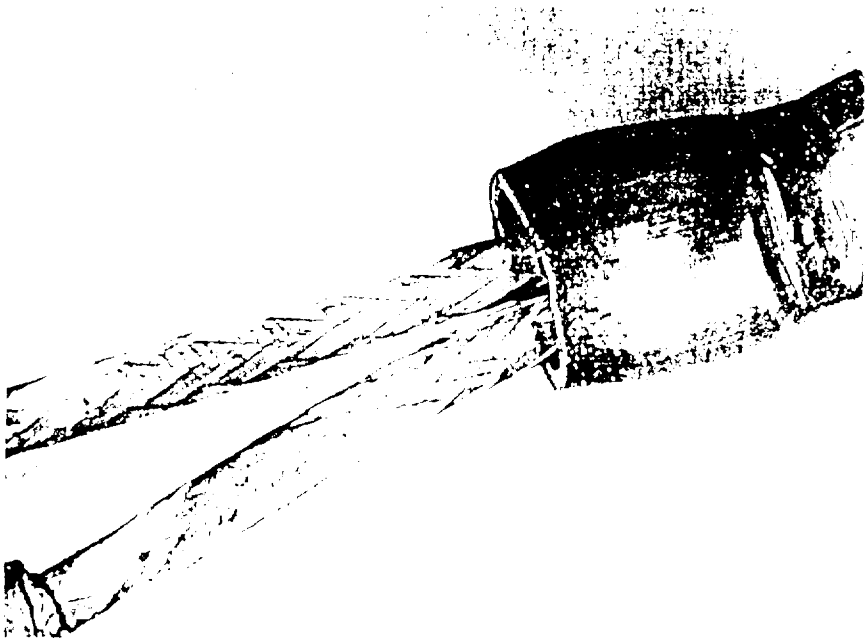

Figure 25. Closer view of copper/silver/sulphur rich film residue seen in figure 22 deposited on Hi Z wire (fuel probe: Model No. FG420A14 Serial No. Z [illegible] from aircraft N134TW).

Mag 4.8X

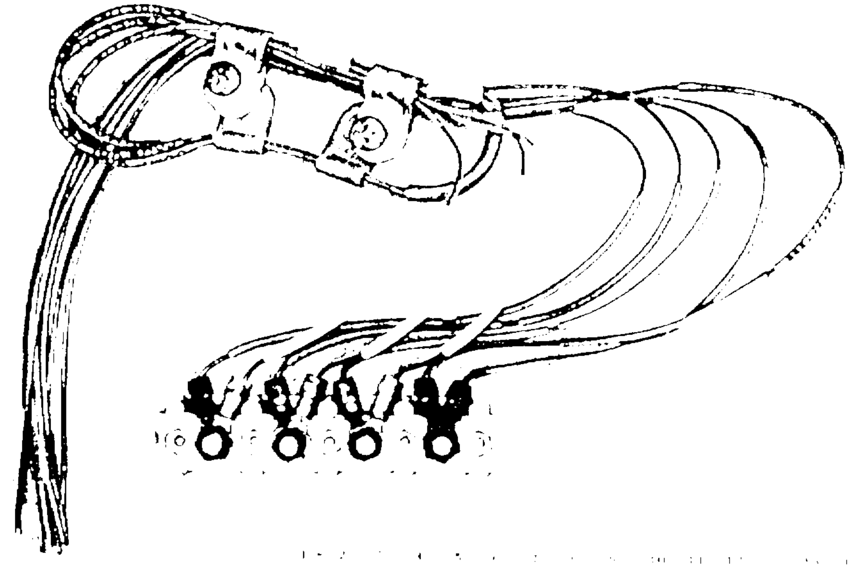

Figure 26. As-received condition of an FQIS terminal block from 747 [illegible] N134TW

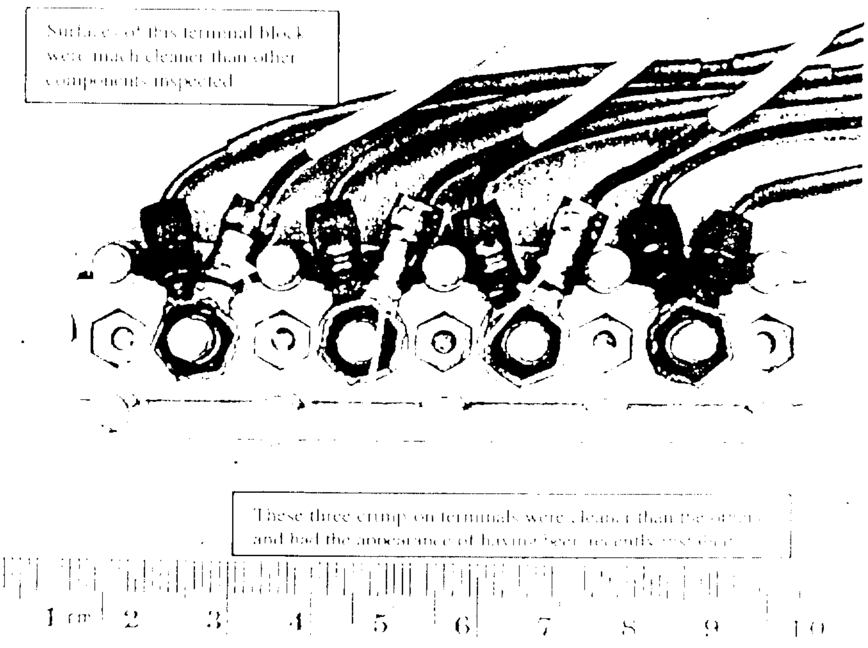

Figure 27. Closer view of an FQIS terminal block seen in figure 26. Clean surfaces and freshly terminated wires gave the appearance of a component having been recently installed (from 747-156, number N134TW).

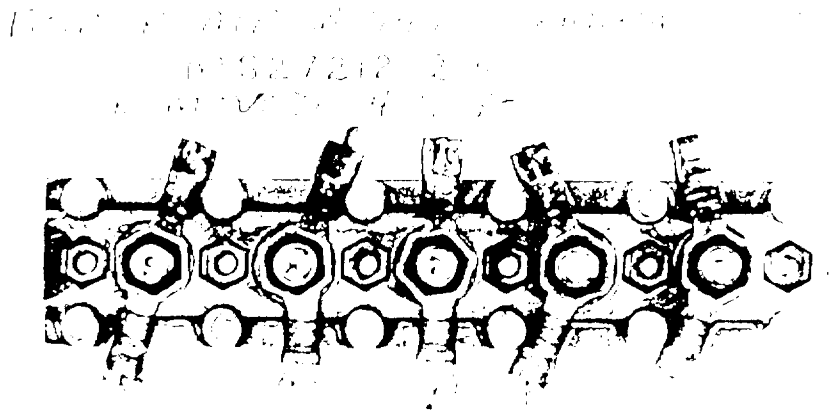

Figure 28. Boeing 747 CWT terminal strip with crimp on ring connector in place. Strip was removed by cutting FQIS wiring at ring connectors. Terminal posts are numbered one to five from right to left. Lower row of crimp on terminal and attached wire were clean and appeared to have been recently installed.

Mag. 1.0X

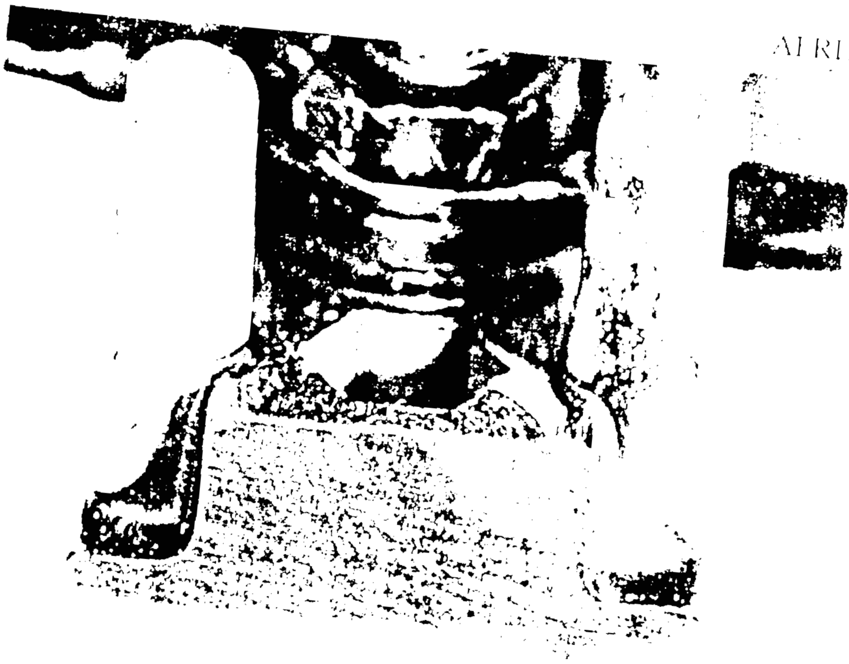

Figure 29. Lower end of terminal strip as mounted in aircraft (same strip seen in figure 28). Note dark residue stain on top, side and end surfaces.

Mag: 3.6X

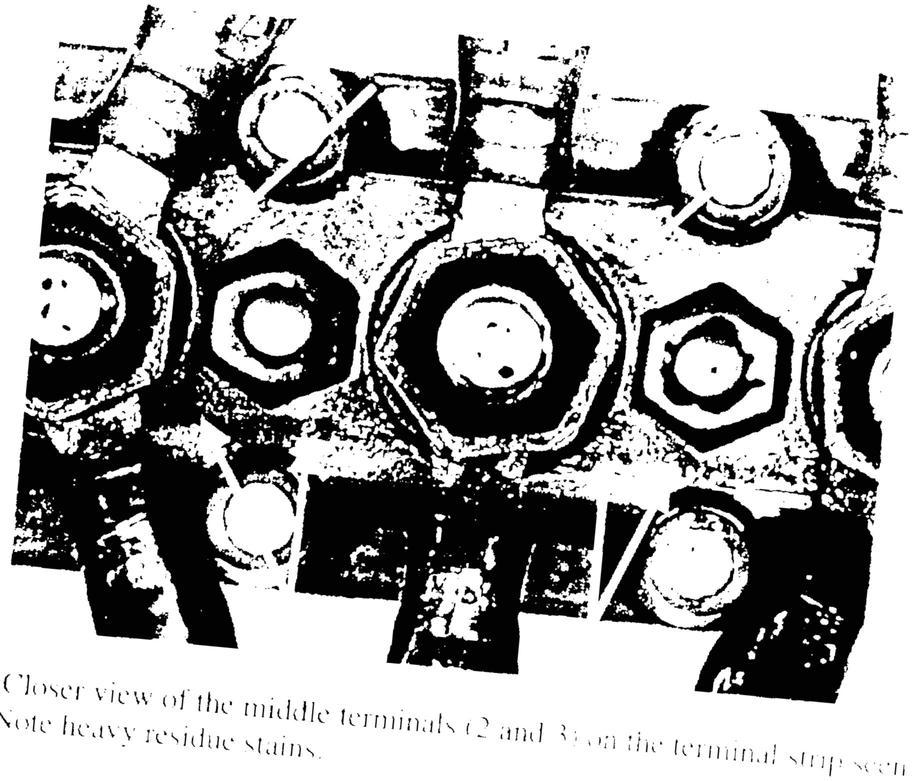

Figure 30. Closer view of the middle terminals (2 and 3) on the terminal strip seen in figure 28. Note heavy residue stains.

Mag: 2.9X

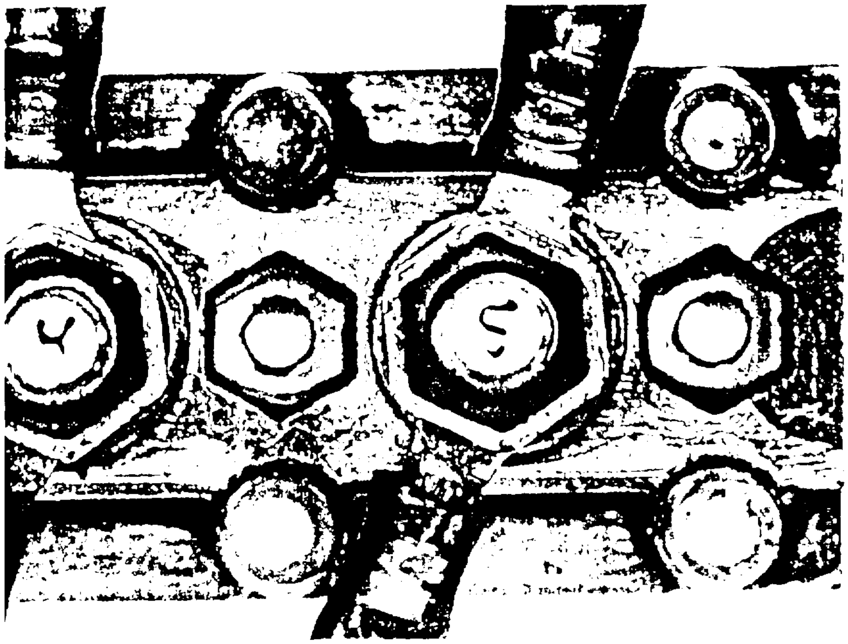

Figure 31. Closer view of end terminals 4 and 5 on the terminal strip seen in figure 28. Note heavy residue stains.

Mag: 2.9X

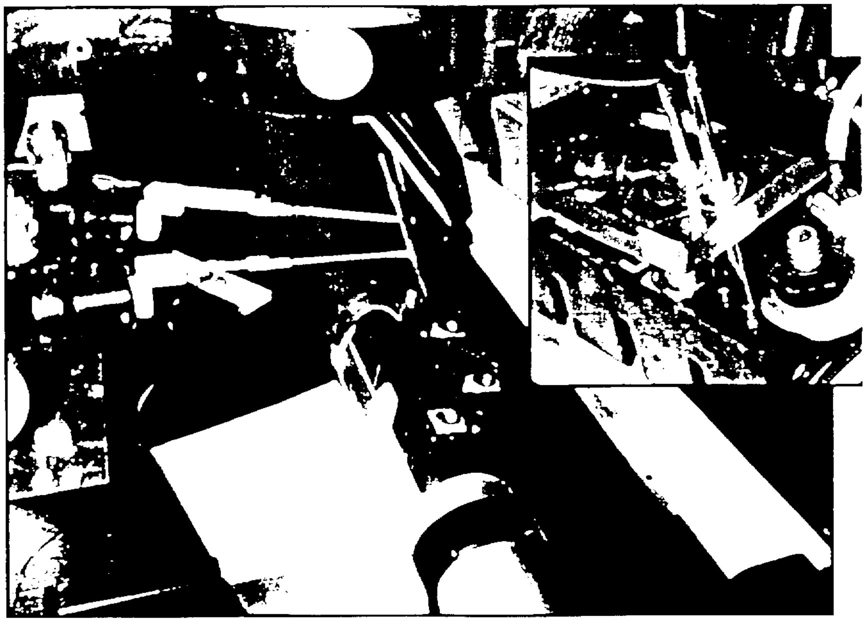

Figure 32. FQIS fuel probe mounted in MLSA custom test fixture. Microprobe manipulators used to bring test probes in contact with terminal block surface for making surface resistance measurements. Insert shows fixture used to make .125 inch distance measurements.

Mag: 0.5X

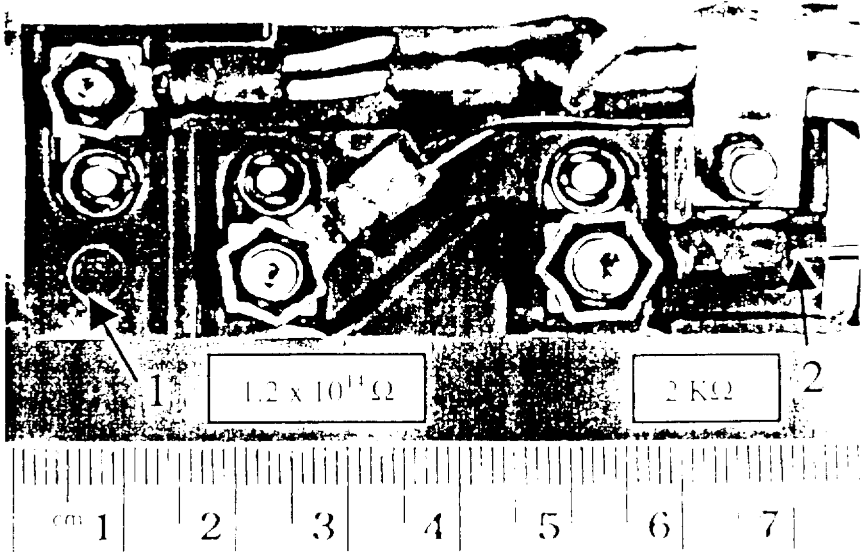

Figure 33. Fuel probe terminal block (Model No. FG420A20, Serial No. A [illegible]). Point-to-point surface resistance measurements were taken at points 1 and 2 (using fixture seen in figure 32 and HP 4329A high resistance meter with probes spaced at approximately 0.1 inch). Note the correlation between low resistance and the presence of film residue.

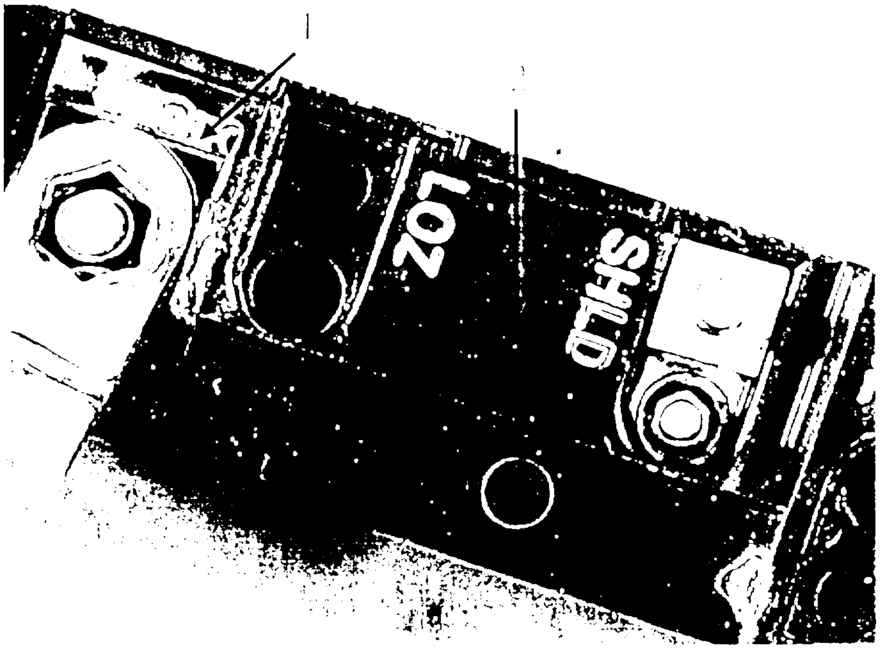

Figure 34. Evergreen fuel probe Model No. 420A14, Serial No. Z 60

Mag: 1.8X

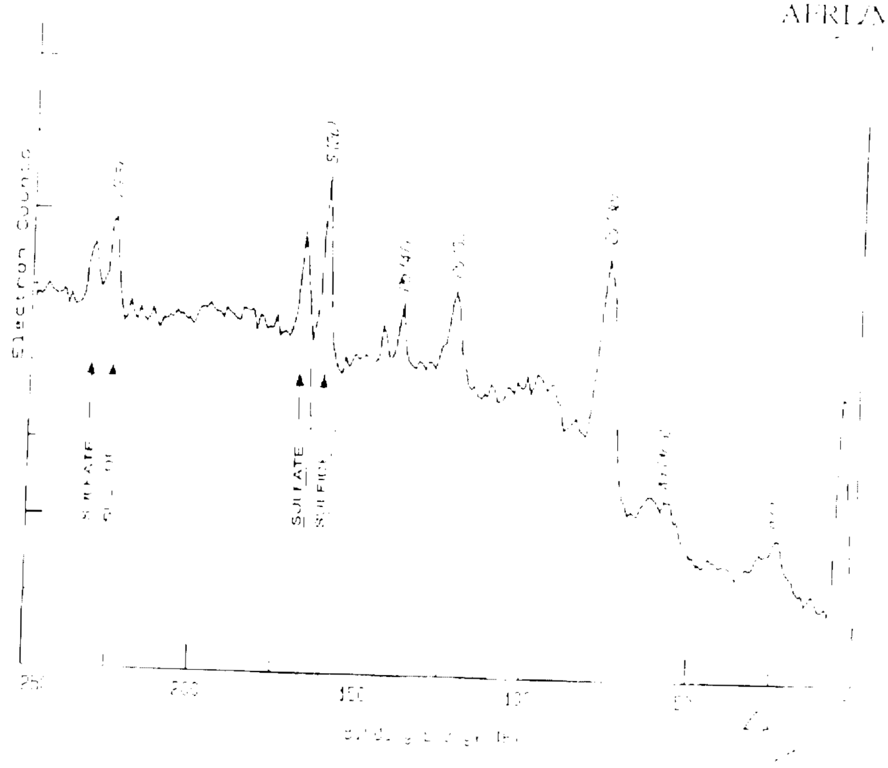

Figure 35. Photoelectron spectroscopy plot of film residue observed in region 1 (as seen in figure 34).

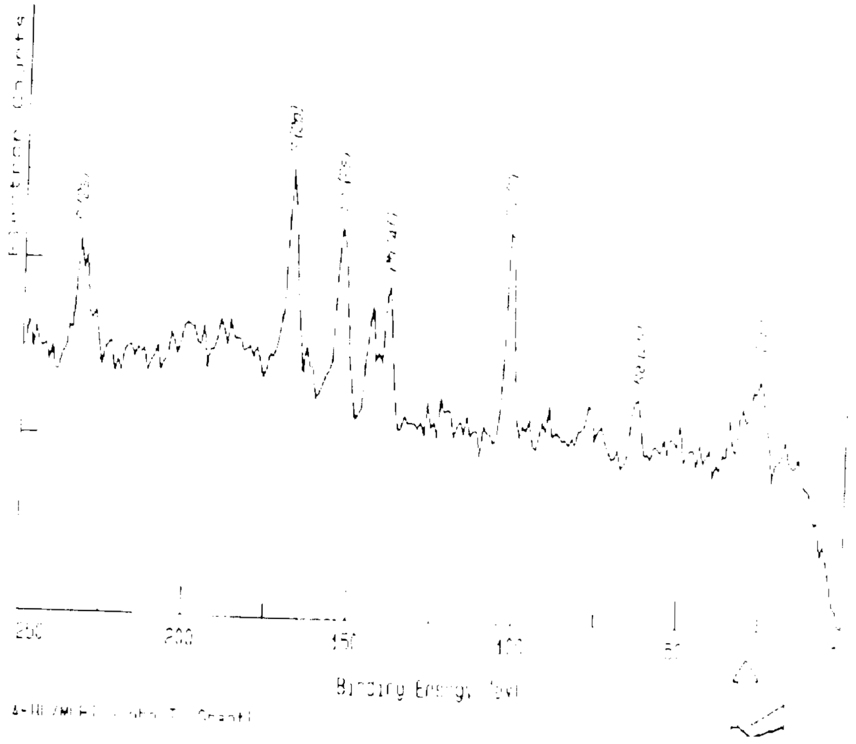

Figure 36. Photoelectron spectroscopy plot taken in region 2 (as seen in figure 34) where no evidence of film residue was observed.

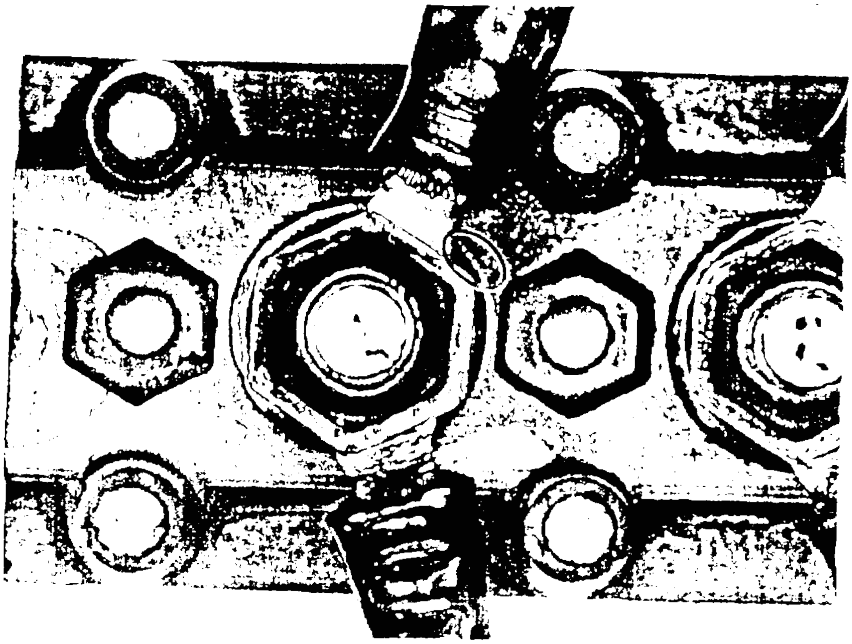

Figure 37. Closer view of the top end of terminal strip (as mounted in CWT) seen in figure 28. Note dark residue stain starting at top most terminal (terminal 1) and "running" down. EDS surface analysis was performed in circled area. The resulting spectral plot is seen in figure 38.

Mag: 2.9X

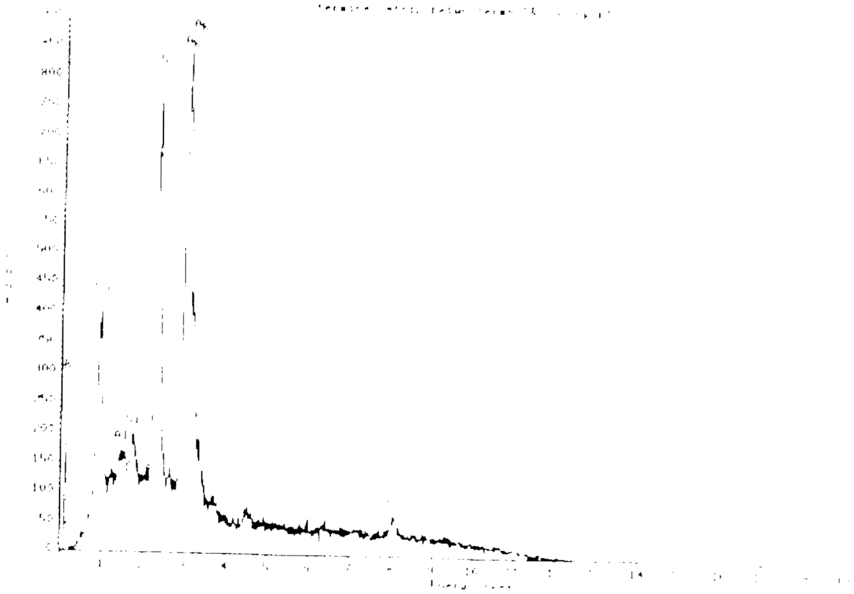

Figure 38. Energy dispersive spectroscopy analysis of surface chemistry in the circled area seen in figure 37. The terminal strip surface in the circled area was covered with a heavy black residue stain containing silver, copper and sulfur as indicated above.

APPENDICES

APPENDIX A

Listing of FQIS Components from 747 Aircraft, S/N 19958, ID N134TW, Built 11/10/70, Hours of Operation: 92,141, Last Flight 1/13/97

EVERGREEN **Table 1** **ACFT SN-19958/N134TW**

PACKING LIST

Nomenclature	Part Number	ALT P/N	SERIAL NO.	QTY
Fuel Qty. Unit RW	FG420A18	60B92010-18	A-88	1
Fuel Qty. Unit RW	FG420A39	60B92010-39	A-158	1
Fuel Compensator RW	FG6C2	60B92010-50	Z-655	1
Fuel Qty. Unit RW	FG420A17	60B92010-17	A-102	1
Fuel Compensator RW	FG6C2	60B92010-7	A-491	1
Fuel Qty. Unit RW	FG420A30	60B92010-30	Z-49	1
Fuel Qty. Unit RW	FG420A31	60B92010-31	Z-121	1
Fuel Qty. Unit RW	FG420A32	60B92010-32	A-117	1
Fuel Qty. Unit LW	FG420A9	60B92010-9	A-171	1
Fuel Compensator LW	FG6C2	60B92010-50	A-656	1
Fuel Qty. Unit RW	FG420A33	60B92010-33	Z-3	1
Fuel Qty. Unit	FG420A37	60B92010-37	Z-26	1
Fuel Compensator LW	FG6C2	60B92010-50	Z-772	1
Fuel Compensator RW	FG6E1	60B92010-63	W-405	1
Fuel Qty. Unit	FG420A29	60B92010-29	A-110	1
Fuel Qty. Unit LW	FG420A10	60B92010-10	Z-73	1
Terminal Block (Fuel Compensator)	MS27212-2-4		NSN	1
Fuel Compensator LW	FG6C2	60B92010-50	Z-795	1
Fuel Qty. Unit LW	FG420A11	60B92010-11	Z-229	1
Fuel Qty. Unit RW	FG420A19	60B92010-19	A-125	1
Fuel Qty. Unit RW	FG420A20	60B92010-20	A-174	1
Fuel Qty. Unit RW	FG420A24	60B92010-24	A-127	1
Fuel Qty. Unit	FG420A34	60B92010-34	A-155	1
Fuel Qty. Unit	FG420A38	60B92010-38	A-109	1
Fuel Qty. Unit	FG420A36	60B92010-36	A-126	1
Fuel Qty. Unit	FG420A35	60B92010-35	A-146	1
Fuel Qty. Unit	FG420A40	60B92010-40	Z-8	1
Fuel Qty. Unit	FG420A35	60B92010-35	A-25	1
Fuel Qty. Unit	FG420A39	60B92010-39	A-106	1
Fuel Qty. Unit	FG420A38	60B92010-38	A-118	1
Fuel Qty. Unit	FG420A36	60B92010-36	A-120	1

Table 1 (continued)

Listing of FQIS Components

Nomenclature	Part Number	Serial Number	Quantity
Fuel Qty. Unit	FG420A18	A-85	1
Fuel Qty. Unit	FG420A33	A-100	1
Fuel Qty. Unit	FG420A19	A-118	1
Fuel Qty. Unit	FG420A32	A-106	1
Fuel Qty. Unit	FG420A31	A-115	1
Fuel Qty. Unit	FG420A34	A-121	1
Fuel Qty. Unit	FG420A30	A-118	1
Fuel Qty. Unit	FG420A17	A-101	1
Fuel Qty. Unit	FG420A20	A-152	1
Fuel Qty. Unit	FG420A21	A-122	1
Fuel Qty. Unit	FG420A23	A-124	1
Fuel Qty. Unit	FG420A26	Z-52	1
Fuel Qty. Unit	FG420A25	A-64	1
Fuel Qty. Unit	FG420A26	Z-40	1
Fuel Qty. Unit	FG420A25	A-133	1
Fuel Qty. Unit	FG420A24	A-123	1
Fuel Qty. Unit	FG420A64	T-133	1
Fuel Qty. Unit	FG420A64	T-127	1
Fuel Qty. Unit	FG420A23	A-199	1
Fuel Qty. Unit	FG420A22	Z-94	1
Fuel Qty. Unit	FG420A22	Z-93	1
Fuel Qty. Unit	FG420A21	A-123	1
Fuel Qty. Unit	FG420A40	Z-9	1
Fuel Qty. Unit	FG420A15	Z-57	1
Fuel Qty. Unit	FG420A13	Z-120	1
Fuel Qty. Unit	FG420A16	Z-54	1
Fuel Qty. Unit	FG420A12	Z-100	1
Fuel Qty. Unit	FG420A12	Z-119	1
Fuel Qty. Unit	FG420A14	Z-60	1
Fuel Qty. Unit	FG420A13	Z-108	1
Fuel Compensator	FG6C2	Z-776	1
Fuel Compensator	FG6C2	Z-612	1
Fuel Compensator	FG6E1	W-402	1
Fuel Compensator	FG6C2	Z-201	1
Fuel Compensator	FG6C2	Z-625	1
Fuel Compensator	FG6E1	W-401	1
Terminal Block (fuel compensator)	MS27212-2-4		2
Terminal Block (fuel compensator)	MS27212-2-4	NSN	1

APPRNDIX B

SORTING OF FQIS COMPONENTS TO IDENTIFY ELECTRICAL BREAKDOWN TEST CANDIDATES

Table 1

Bruntingthorpe England Boeing 747, Tail No. F-BPVE
Measurements performed at NTSB L'Enfant Plaza, Washington, DC Facility
Terminal-to-Terminal Resistance Measurements
(Hewlett Packard HP4339B High Resistance Meter)

Nomenclature	Part No	Serial No	Resistance Hi Z to shield	Resistance Lo Z to shield	Resistance Hi Z to Lo Z	Test Voltage DC
Compensator	EG6C2	Z-108	$1.0x10^{13}$	$1.5x10^{11}$	$2.0x10^{13}$	50
	EG6C2	Z-317	$1.0x10^{13}$	$8.0x10^{11}$	$2.0x10^{13}$	50
Probe	EG420A9	Z-74	$5.0x10^{13}$	$1.0x10^{13}$	$1.0x10^{13}$	50
	EG420A10	Z-132	$9.0x10^{11}$	$1.0x10^{13}$	$1.0x10^{13}$	50
	EG420A8	2-104	$2.0x10^{13}$	$1.0x10^{13}$	$5.0x10^{13}$	50
	EG420A8	2-136	$1.0x10^{13}$	$5.0x10^{13}$	$1.0x10^{13}$	50
	EG420A11	A-132	$4.5x10^{13}$	$2.0x10^{13}$	$3.0x10^{13}$	50
	EG420A9	A-43	$8.0x10^{13}$	$8.0x10^{13}$	$1.0x10^{13}$	50

Table 2

Boeing 747, Tail No. N93117
Measurements performed at NTSB L'Enfant Plaza, Washington, DC facility
Terminal-to-Terminal Resistance Measurements
(Hewlett Packard HP4339B High Resistance Meter)

Nomenclature	Part No	Serial No	Resistance Hi Z to shield	Resistance Lo Z to shield	Resistance Hi Z to Lo Z	Test Voltage (DC)
Compensator	FG6C2	E-36	$4.4x10^{17}$	$5.0x10^{17}$	$4.5x10^{17}$	50
	FG6C4	Q-98	$6.5x10^{17}$	$1.5x10^{17}$	$8.0x10^{17}$	50
Probe	FG420A23	Z-117	$1.0x10^{17}$	$1.0x10^{17}$	$2.0x10^{17}$	50
	FG420A14	Z-61	$2.8x10^{17}$	$4.0x10^{17}$	$1.0x10^{14}$	50
	FG420A27	Z-20	$1.0x10^{17}$	$1.0x10^{13}$	$3.0x10^{17}$	50
	FG420A12	A-65	$5.0x10^{17}$	$5.0x10^{17}$	$5.0x10^{17}$	50
	FG420A24	Z-104	$1.5x10^{17}$	$5.0x10^{17}$	$2.0x10^{17}$	50
	FG420A26	Z-116	$1.0x10^{17}$	$3.0x10^{17}$	$1.0x10^{17}$	50
	FG420A25	Z-124	$5.0x10^{17}$	$3.0x10^{17}$	$4.0x10^{17}$	50
	FG420A28	Z-63	$1.0x10^{17}$	$1.0x10^{17}$	$1.0x10^{17}$	50
	FG420A12	A-173	$5.0x10^{17}$	$1.0x10^{17}$	$1.0x10^{17}$	50
	FG420A16	Z-74	$5.0x10^{17}$	$5.0x10^{17}$	$5.0x10^{17}$	50
	FG420A13	A-86	$3.0x10^{17}$	$5.0x10^{17}$	$1.0x10^{14}$	50
	FG420A13	Z-123	$1.0x10^{17}$	$2.0x10^{17}$	$3.0x10^{17}$	50
	FG420A15	A-70	$5.0x10^{17}$	$1.0x10^{17}$	$3.0x10^{17}$	50

APPRNDIX B (Cont)

TERMINAL-POST-TO-TERMINAL-POST RESISTANCE MEASUREMENTS
TOWER AIR CWT TERMINAL STRIP (MS27212-2-5)

Table 3

Copper/Silver/Sulfur Film Residues Present
Hewlett Packard 4339B High Resistance Meter

Terminal Pair	Resistance (ohms)	Test voltage (volts)	Note
1 - 2	1.30×10^{5}	3.0	
1 - 2	1.52×10^{5}	3.0	
1 - 3	3.40×10^{5}	3.0	
1 - 3	2.70×10^{5}	3.0	
1 - 4	3.25×10^{5}	3.0	
1 - 5	1.30×10^{4}	3.0	
2 - 3	2.25×10^{4}	3.0	
2 - 3	2.05×10^{4}	3.0	
2 - 4	3.80×10^{4}	3.0	
2 - 4	3.73×10^{4}	3.5	
2 - 5	8.20×10^{4}	3.0	
3 - 4	2.06×10^{4}	3.0	
3 - 5	9.4×10^{4}	3.0	
4 - 5	4.0×10^{6}	3.0	
2 - 4	2.75x10[illegible]	0.20	
2 - 4	4.50×10^{7}	0.40	
2 - 4	2.30×10^{7}	0.70	
2 - 4	2.20×10^{6}	0.90	
2 - 4	7.00×10^{4}	1.00	
2 - 4	5.62×10^{4}	2.00	
2 - 4	4.80×10^{4}	3.00	
2 - 4	3.80×10^{4}	3.50	brought down from above
2 - 4	3.73×10^{4}	3.73	brought down from above

APPRNDIX B (Cont)

POINT-TO-POINT SURFACE RESISTANCE MEASUREMENTS ON TERMINAL BLOCK SURFACE WITH FILM RESIDUE PRESENT

TABLE 4

HP E2378A Digital Multimeter, HP 6826A Power Supply, Custom MLSA Test Fixture (figure 32), Flat Tipped Probes, Probe Spacing = 0.125 inch*

Model Num.	Serial Num.	Test Voltage	Measured Value ohms
FG420A23	A-119	1.8	692
FG420A23	A-119	4.4	681
FG420A23	A-119	5.0	675
FG420A23	A-119	10.0	film ruptured
FG420A23	A-119	5.0	9.3K
FG420A23	A-119	10.0	1.96K
FG420A23	A-119	15.0	1.97K

---

* Measurements were taken at various locations on the surface of the terminal block

APPENDIX C

Data on Recently Received FQIS Terminal Strips

APPENDIX C

The termminal strips seen in the figures of this appendix were received just before the final completion of this report and are included here for completeness. They were provided by the NTSB as possible candidates for voltage breakdown testing. One or more sites on the terminal's strip, having a surface resistance measurement of less than 10 kilohms, were the criteria used for selection. All sites tested had surface resistances of greater than 10 megohms when measured with a probe spacing of about 0.1 inch. Therefore, neither of the two terminal strips reported in this appendix were selected for any further testing.

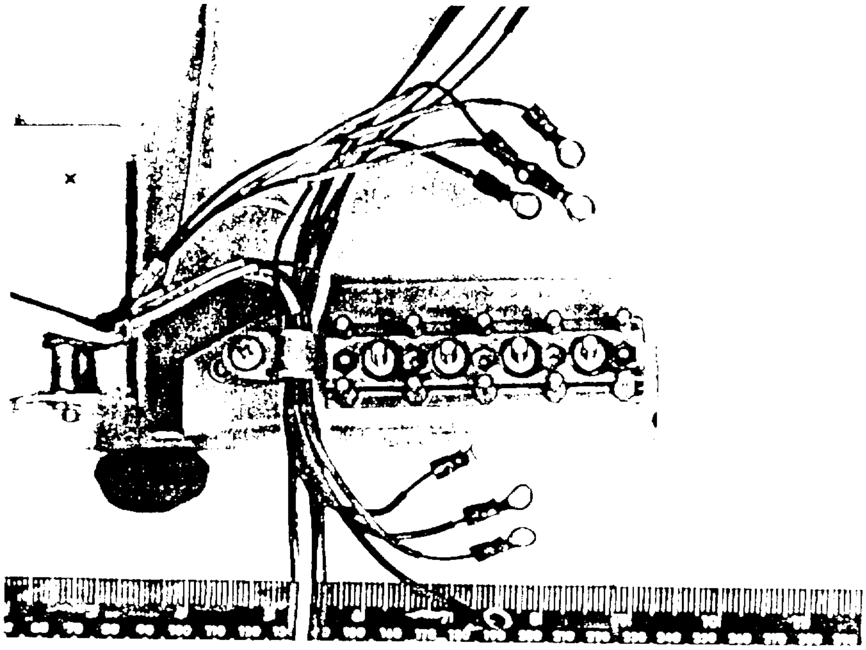

Figure 1C. As received condition of T347 terminal block provided for evaluation by the NTSB after removal from a retired aircraft.

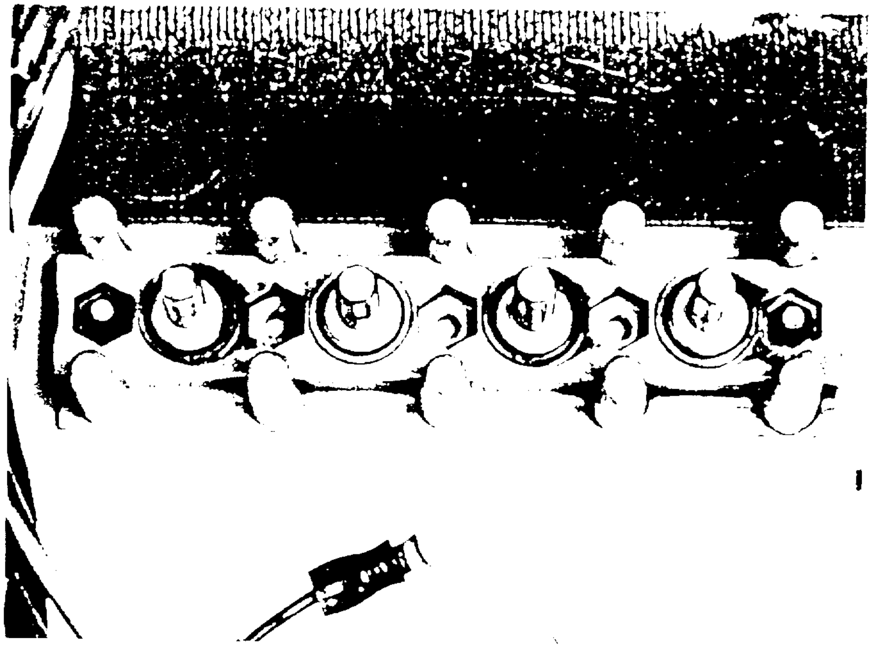

Figure 2C. Closer view of terminal strip seen in figure 1C. Note residue stains on the surface around and beneath threaded terminal posts.

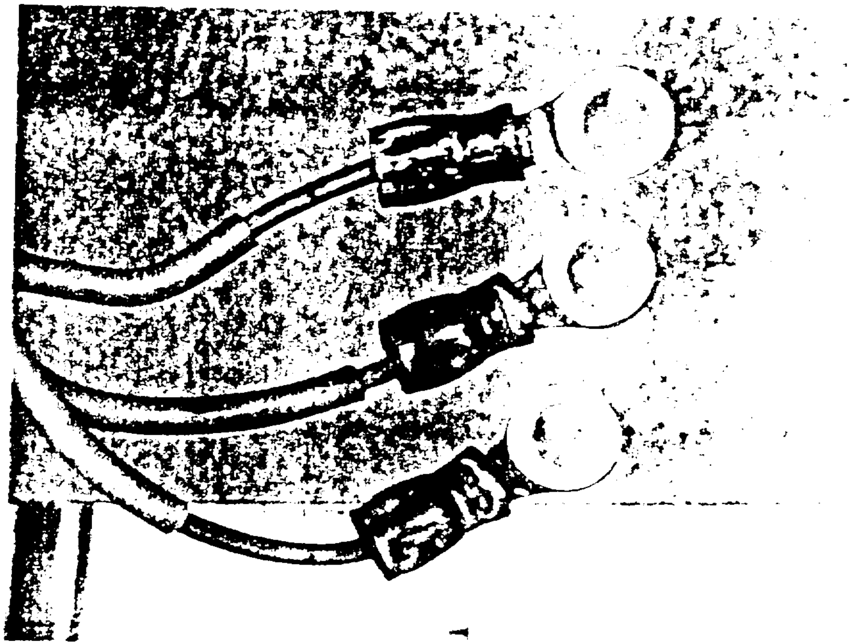

Figure 3C. Closer view of crimp-on wire terminals seen in figure 1C. Note presence of dark residue stains on terminal and wire insulation.

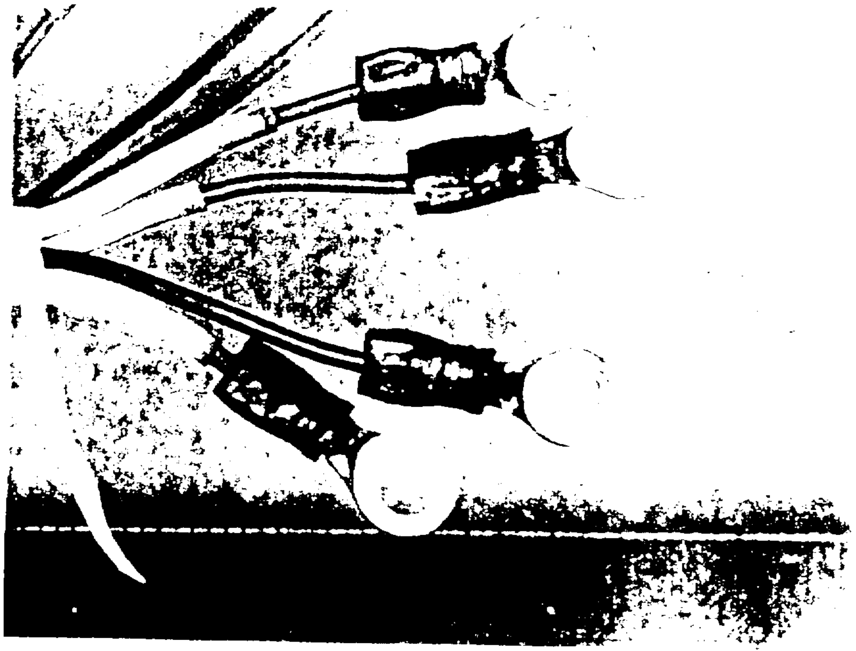

Figure 4C. Closer view of crimp-on wire terminals seen in figure 1C. Note presence of dark residue stains on terminal and wire insulation. (Wires were tied together to facilitate taking this photograph.)

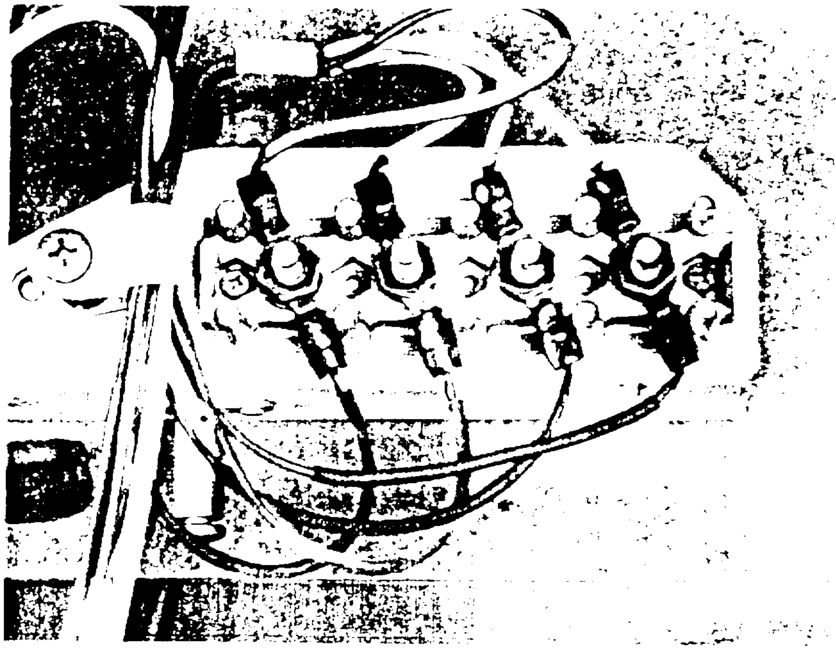

Figure 5C. As received condition of a second T347 terminal block provided by the NTSB for evaluation after removal from a retired aircraft.

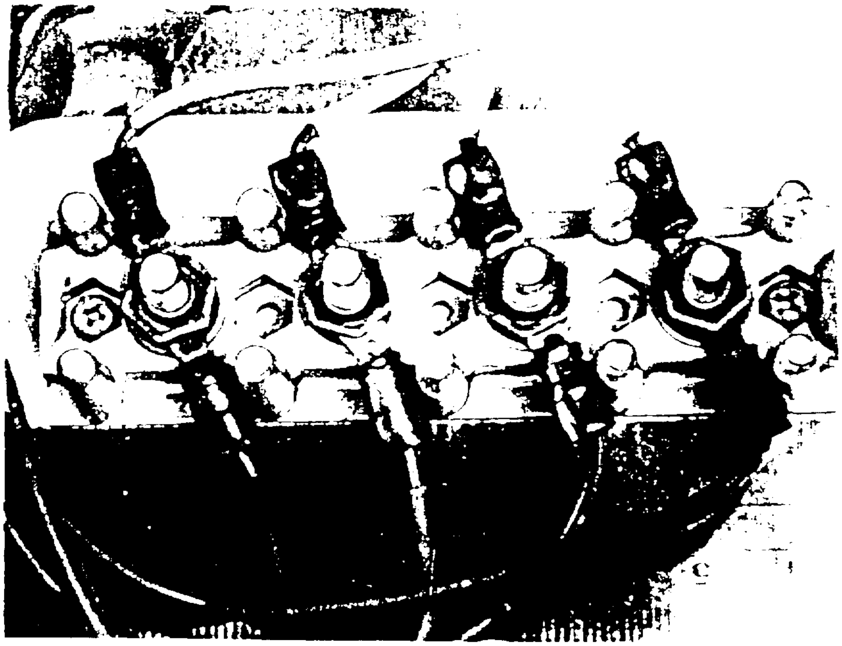

Figure 6C. Closer view of the terminal strip seen in figure 5C. The surface of the terminal strip is relatively free of residue stains and the screws holding the terminal block are reversed, which compared to the other terminal strip (figure 2C). Three of the four crimp-on terminals at the top of the picture, and the middle two at their bottom, appear to be clean and free of residue stains.

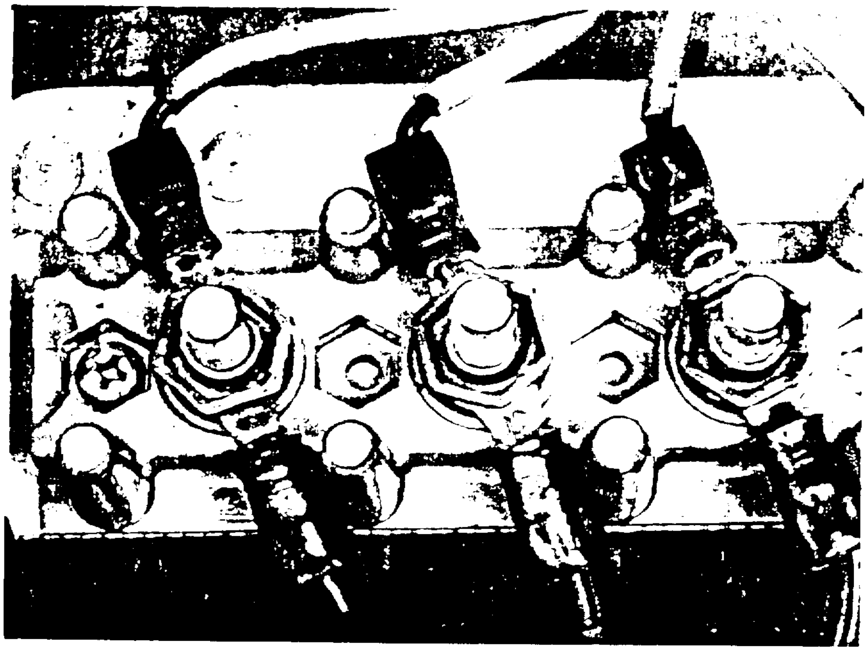

Figure 7C. Closer view of terminal strip seen in figure 5C. Note the stained appearance of the two wire terminals to the left of the picture. This is the top end of the terminal strip as mounted in the aircraft. Terminal strips with heavily stained wire terminals typically exhibit stains on the surface of the terminal block beneath the wire terminals running down across the surface of the terminal block. The absence of such staining suggests this terminal block was in service a shorter time than the stained crimp-on wire terminals.

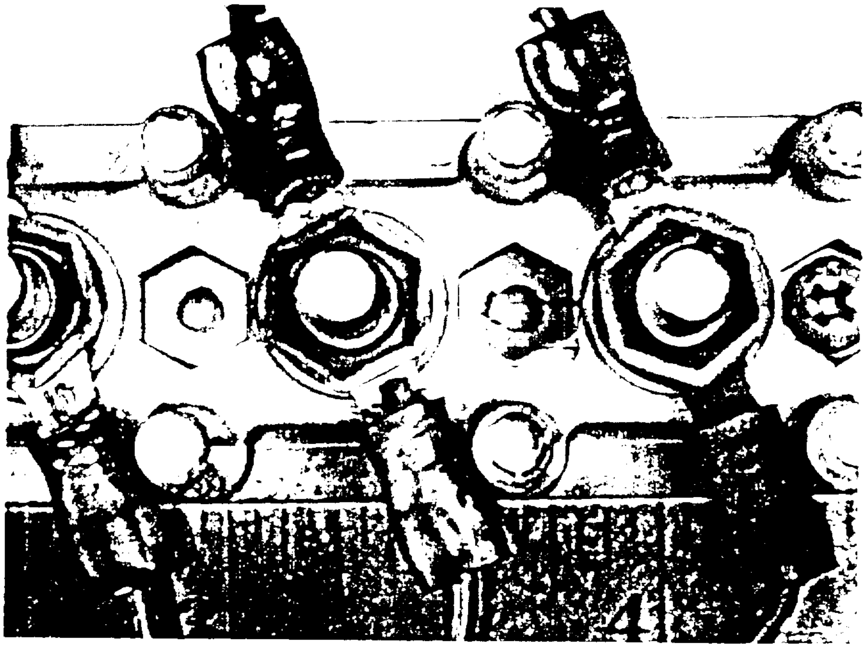

Figure 8C. A closer view of the terminal block shown in figure 5C. Note the very heavily stained wire terminal (far right). A heavily stained wire terminal is typically associated with residue deposits on the surface of the terminal strip.

EVALUATION REPORT FEEDBACK

We are striving to improve our performance in supporting our customers and would appreciate a few moments of your time to complete the brief questionnaire concerning the attached evaluation report. Your input will greatly assist us in judging how effectively we have helped you and how to best improve our support in the future. **Mail** to AFRL/MLSA, 2179 12th Street, Building 652, Room 122, Wright-Patterson Air Force Base, Ohio 45433-7718, or **fax** to 937-656-4600.

Evaluation Report Number: AFRL/MLSA 99-33
Title: Acft Fuel Quantity Indicator System Component Inspection
Author: Johnson

	Yes	Partly (explain)	No (explain)
Did our evaluation report provide the information you requested/needed? If not, what additional information do you require?	☐	☐	☐
Did the report contain sufficient detail and adequate pictorial coverage?	☐	☐	☐
Was adequate testing conducted and were the conclusions fully supported? If not, please explain.	☐	☐	☐
If requested, were adequate updates received during the investigation?	☐	☐	☐
Was the time frame for completion adequate?	☐	☐	☐
Were our analysts responsive? Helpful?	☐	☐	☐
How will our report be of help to you?	☐	☐	☐

What cost benefits are expected as a result of our findings?

Other "nontangible" benefits

Specific actions taken as a result of this report.

Recommendations for improvement

Name of Respondent
Company Name or Symbol/Telephone

Date

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- Failure Analysis/Accident Investigation
  - Structural
  - Electronic
  - Chemical
- Consultations on
  - Materials/Process Specifications
  - Physical and Mechanical Metallurgy
  - Materials and Component Failure Analysis
  - Electronics and Packaging
  - Adhesive Bonding and Nonmetallic Materials
  - Welding and Joining
- Nondestructive Inspection
- Electrostatic Discharge (ESD) Testing
- Air Force Electrostatic Discharge Control Policy OPR
- ESD Material Qualifications/Acceptance Testing
- ESD Material Process Specs/Standards
- Environmental Test and Evaluation

Ignition of Jet-A Fuel Vapor by the Breakdown of Aircraft Fuel Gauge Terminal Strip Deposits

6 January 2000

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INTRODUCTION

In aircraft fuel tanks, fuel vapor and atmospheric oxygen are commonly present. If the fuel vapor and air are mixed in the right proportions they will constitute a combustible mixture within the fuel tank. If this mixture is exposed to a proper source of ignition, combustion will occur. The ignition source can be a spark produced by an electrostatic discharge, a heated surface, mechanical impact, or friction. The ignition source adds enough energy to produce a small self-sustained flame kernel locally within a mixture. This flame kernel will grow provided the rate of heat release by chemical reaction within its volume exceeds the rate of heat loss from its surface. When this enthalpy balance is met, the flame kernel continues to grow and ignites the rest of the mixture and successful combustion ensues. If the rate of heat release by chemical reaction within the flame kernel volume is less than the rate of heat loss from its surface it will not grow, resulting in the flame kernel being extinguished.

To achieve sustained ignition of a combustible mixture, several conditions have to be satisfied. First, the fuel and oxygen should be mixed in the right proportions; that is, there should be a sufficient amount of each present without an excess of either. The range of fuel-air ratio over which successful ignition will occur are called the "ignition limits" of the mixture. If there is not enough fuel (fuel-lean) or excess fuel (fuel-rich) in the mixture, ignition and subsequent combustion cannot be achieved irrespective of how much ignition energy is available to produce the initial flame kernel. This is because as the flame kernel grows it is diluted by excess air or excess fuel and does not produce enough heat release within its volume to meet the rate of heat loss from its surface. Thus, ignition fails to occur.

If the mixture is within the ignition limits, a minimum amount of energy has to be supplied to ignite the mixture successfully. This energy called the minimum ignition energy, depends upon a variety of parameters. These parameters are igniter properties (igniter energy, duration, and igniter size), chemical properties (fuel volatility, latent heat of evaporation, and fuel-air ratio) and physical properties (pressure, temperature, velocity, and turbulence level) of the combustible mixture.

The igniter properties have a strong influence on the way ignition will be initiated. For spark ignition, an arc source (as opposed to a glow discharge) with an optimum duration of 60 to100 microseconds is found to be best from an ignition viewpoint. In general, the shorter the duration of thermal energy input (from heated rod, wire, impact, friction) and shorter the size of the igniter (point source is better than a line source) the more efficient will be the process of ignition. This is because discharging thermal energy in a concentrated source at a rapid rate significantly improves the probability of establishing a self-propagating flame kernel within the combustible mixture. In contrast, spreading the thermal energy over a longer duration and bigger volume results in wasted energy and a less likely chance of ignition.

In an aircraft, liquid fuel is used. The liquid fuel must first be vaporized and then mixed with the surrounding air before it will ignite. The volatility of the liquid fuel, as given by its Reid vapor pressure or flash point, determines how readily the liquid fuel will evaporate. The less volatile the liquid fuel and the higher its flash point temperature, the more energy required to vaporize the fuel before it can be ignited. This additional heat of vaporization supplied increases the minimum ignition energy requirement for the fuel. Also, fuel and air mixed in stoichiometric proportion, or slightly fuel rich, requires the least amount of ignition energy.

The physical properties of the combustible mixture also strongly influence the ignition process. For example, at low (subatmospheric) ambient pressure corresponding to high-altitude aircraft operation, both the chemical reaction rates and density decrease significantly thereby decreasing the rate of heat release. This means that more ignition energy is required at high altitude. A reduced air temperature would result in a lower mixture temperature requiring more energy to vaporize and ignite a mixture. If the mixture is flowing at high velocity and with high turbulence, heat losses from the flame kernel increase substantially. This increases the ignition energy requirement.

Successful ignition occurs when the self-propagating flame kernel grows and continues to maintain the condition of enthalpy balance necessary for its propagation. Extinction occurs when the flame kernel either does not produce enough energy or dissipates the energy to rapidly to maintain the condition of enthalpy balance to sustain flame propagation. The process of ignition is influenced by the nature of the ignition source and also by the chemical and physical properties of the fuel and air mixture.

It is thought that fuel vapors in the center wing tank of a Boeing 747 ignited resulting in the TWA800 mishap. A possible ignition source is from the breakdown of deposits on a fuel gauge terminal strip. An investigation was undertaken to determine if the breakdown of conductive deposits on a representative fuel gauging terminal strip could provide a source of ignition energy for the surrounding Jet A fuel vapor and air mixture. An effort was made to duplicate the fuel conditions that were believed to be present in the center wing tank of the Boeing 747 at the time of the TWA800 accident.

EXPERIMENTAL

Jet fuels have been found to form deposits on surfaces within fuel tanks. Such deposits found on fuel gauge terminal strips have been extensively studied (References 1-4). If these deposits are shorted to 120-volt rms the surrounding conductive films will be exposed to a peak voltage of 177 volts. At these voltages it is possible that a conductive surface deposit will be vaporized and initiate a plasma arc which has very low electrical resistance and will dissipate energy to its surroundings. If the surroundings are a flammable fuel vapor and air mixture the release of energy could ignite the mixture.

The flammability properties of jet fuel vary from batch to batch, thus when conducting a test of this nature it is important to select a fuel that properly suits the test. For these tests a Jet A fuel with a flash point of 118 °F was chosen because it is representative of the flash point of the fuel found at John F. Kennedy International Airport at the time of the TWA800 accident. A complete fuel analysis can be found in Table 1.

Since the flammability limits are dependent upon temperature, the fuel temperature for the tests should be representative of the maximum fuel temperatures encountered in the center wing tank of a Boeing 747. Tests previously performed by the National Transportation Safety Board, NTSB, indicated that this temperature is in the 135 to 145 °F range (Reference 5). The air temperature for the tests was not controlled/measured but would be near the temperature of the fuel, i.e. between 135 and 145 °F. There was a five minute delay before each test to assure that the fuel liquid and vapor mixture had reached thermal and chemical equilibrium and thus a flammable fuel vapor and air mixture was present.

To obtain a fuel air mixture at the conditions described above, a 2.8-liter Pyrex vessel containing 50 ml of fuel was heated on a hot plate (Figure 1). The temperature of the liquid fuel was measured using a thermocouple. The sample being tested was suspended in the center of the vessel above the fuel vapor and air mixture. The Pyrex vessel was covered to contain the flammable mixture. The igniter source was placed in the Pyrex container approximately three centimeters above the liquid fuel surface.

The energy for the ignition source was supplied by a capacitor charged to 177 volts. A power supply was constructed using a half wave rectifier, capacitors and a variable transformer. With no load the capacitor charged to the peak voltage supplied by the transformer. The peak voltage of an alternating 120-volt rms supply is 177 volts. The break down of the sample as a result of the energy released from the capacitor generates the arc for ignition. A toggle switch was thrown to release the stored energy in the capacitor to the ignition source. The energy consumed in the event was determined from the voltage drop of the capacitor as a result of the event and is calculated as $E=1/2CV^2$ were E is energy in Joules, C is capacitance in Farads, and V is potential in volts. An oscilloscope tracked the voltage and was used to determine the voltage just prior to arc formation, V_i, and the voltage remaining in the capacitor after the event, V_f. Using the measurements from the oscilloscope the energy released during the event is calculated as $E=1/2C(V_i-V_f)^2$. The total energy dissipated by the test igniter is comprised of two distinct parts, the energy required to heat the material to vaporization and the energy dissipated by the electrically conductive vapor or plasma. In some cases the discharge voltage record from the oscilloscope was lost while in other cases it was not apparent where the initial vaporization ended and the arc started.

IGNITION SOURCES

The ignition source acts as a fusible link between the power supply and ground. Three types of ignition sources were employed, carbon fibers, conductive films and an aircraft fuel gauge terminal strip. Each type will be described below.

Carbon fibers attached across the screw terminals of a thermocouple plug (Figure 2) were used as the ignition source. The carbon fibers were a reliable ignition source and were used to demonstrate that a flammable mixture was present. Groups of three to seven fibers (Figure 3) were attached to the screw heads with fluid from a Circuitworks ™ conductive pen. The resistance of these fibers ranged from 0.35 to 1.300 kOhms. The thermocouple plug made it possible to quickly replace the spent igniter with a new one for sequential ignitions of the same fuel mixture.

Several laboratory grown conductive films were used as ignition sources. The conductive carbon films were deposited on glass microscope slides (Figures 4 and 5) and connected to the discharge circuit using thin wires and a silver filled epoxy. The resistance of the dry films ranged from 3 to 4 kOhms. The conductive films were on the order of 5 mm long by 0.25 to 1 mm wide and ranged up to 0.01 mm thick. For a more extensive analysis of the conductive films see References 1 to 4.

The fuel gauge terminal strip had smooth deposits of undetermined thickness. NTSB provided the terminal strip (Figure 6). The deposits on the terminal strip have been extensively studied (References 1-4). Wires were attached to the deposits at several locations with silver filled epoxy (Figure 7). Most connection pairs were less than 3 mm apart and no effort was made to limit the width of the conductive path.

RESULTS AND DISCUSSION

The results of 22 ignition tests using carbon fibers at temperatures from 132 to 147 °F with a five-minute equilibrium period showed that a flammable atmosphere could be formed repeatedly. These igniters were capable of dissipating between 2 and 0.013 Joules using charge stored in capacitors of 4.7 μF to 1900 μF. Charging a 4.7 μF capacitor to 177 volts results in a discharge lasting approximately 0.4 ms and dissipating a maximum of 13 mJ. All but one discharge dissipated from 7 to 10 mJ and provided a consistent arc that ignited the flammable mixture.

Figure 8 shows the role temperature plays in establishing an ignitable mixture. Above 135 °F all but two events using the carbon fibers resulted in ignition of the fuel and air mixture. The two failures to ignite at 146 °F occurred using a small 4.7 mF capacitor and higher resistance igniters, 2.9 kOhms. The higher resistance tends to lengthen the discharge time allowing the energy to dissipate before igniting the fuel vapors.

Seven conductive films were tested. One of the seven conductive films, with an initial resistance of 3.25 kOhms, ignited a 140 °F fuel air mixture after five consecutive discharges. Each discharge modified the film slightly until the current density was exceeded and an arc formed. Due to the consecutive discharges the energy release data was lost. The higher resistances, 3 to 4 kOhms, of the other six slides made it impossible to get a breakdown without increasing the voltage.

A total of ten discharges were attempted through conductive deposits on the aircraft terminal strip. In all cases no arcs were observed, no current surges were recorded, and all current paths were 'open' after the test was completed. The conductive paths had resistance in the range of 1 to 4 kOhms prior to the test. In most cases the resistance of the current path increased upon exposure to fuel vapors. It was not clear whether the conductive epoxy used to connect wires to the deposits was causing the increased resistance or if some of the increase was caused by the exposure of the deposits to the fuel. After the ignition attempts with the aircraft terminal strips the fuel vapor and air mixture was ignited using a carbon fiber ignition source.

SUMMARY

This study demonstrated that breakdowns from fibers resulting in energy release of 11 mJ and greater ignited a Jet-A vapor and air mixture using the configuration described above.

Although one ignition from deposits grown on slides was achieved, ignitions from the slides were not repeatable. After the event visual inspection of the deposits showed evidence of a breakdown although the release of energy to the surroundings was not sufficient to ignite the surrounding fuel vapor and air mixtures.

Ignition from the release of energy from the breakdown of deposits on a terminal strip was not demonstrated. Questions remain as to whether or not the epoxy used to fasten the electrode leads was breaking down and shorting the circuit before the deposits had sufficient energy to break down, i.e. epoxy broke down and released a small amount of energy resulting in an open circuit but not enough energy to ignite the fuel vapors. The terminal strips had been extensively handled and the deposits may have been damaged prior to the tests. Due to prior probing and testing the film deposits on the terminal strip had degraded to the point were further testing was not pursued.

While an ignition from the breakdown of deposits on an actual fuel probe was not demonstrated, it was shown that an arc releasing 75 mJ from the breakdown of carbon fibers was sufficient to ignite a Jet-A and air mixture at 135 °F.

ACKNOWLEDGEMENTS

This work was supported by the Air Force Research Laboratory, Propulsion Directorate, Propulsion and Sciences and Advanced Concepts Division, Wright-Patterson Air Force Base, Ohio under Contract No. F33615-97C-2719, Technical Monitor, C. W. Frayne. Dale Hart, David Johnson and George Slenski of the Materials Integrity Branch, Materials Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio provided the laboratory conductive films on slides along with many insightful conversations.

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2. MLS 99-2, 26 Jan 1999
3. MLS 99-33, 21 June 1999
4. MLS 99-68, 18 Oct 1999
5. "Flight Test Results: TWA800 Emulation Flight", Docket #SA-516, Exhibit 23F, NTSB, Washington D. C.

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	PROPERTY	UNITS		ASTM D1655 SPECIFICATION	TEST FUEL
Composition					
	Acidity, Total	mg KOH/g	max	0.1	0
	Aromatics	vol %	max	20	21*
	Doctor Test			negative	negative
Volatility					
	Distillation				
	Temperature 10% Recovered	°C	max	204.4	182
	Temperature 50% Recovered	°C	max	Report	210
	Temperature 90% Recovered	°C	max	Report	253
	Temperature Final Boiling Point	°C	max	300	272
	Residual	vol %	max	1.5	1.1
	Loss	vol %	max	1.5	1
	Flash Point	°C	min	37.8	118
	Gravity API			37-51	42.8
	Relative Density @ 15.5 °C			0.7753-0.8398	0.8105
Fluidity					
	Freezing Point	°C	max	-40	-48.5
	Viscosity @ -20°C	cSt	max	8	5.11
Combustion					
	Net Heat of Combustion	MJ/kg	min	42.8	43.2
	Smoke Point	mm	min	25	20
	Naphthalenes	vol %	max	3	1.3
Corrosion					
	Copper Strip (2 hours at 100°C)		max	1	1A
Stability					
	JFTOT ΔP	mm Hg	max	25	2
	JFTOT Tube Color Code		max	<3	0
Contaminants					
	Existent Gum	mg/100 ml	max	7	0
	Water Reaction Interface		max	1b	1b
	Water Reaction Separation		max	2	2
Other					
	Electrical Conductivity	pS/m		50-450	1**

* Fuels Containing up to 25 vol % aromatics may be shipped if supplier notifies user.

** At time, place, and temperature of delivery into aircraft if antistatic additive is used. Antistatic additive was not used in the test fuel.

Table 1. Jet A specification and test fuel properties

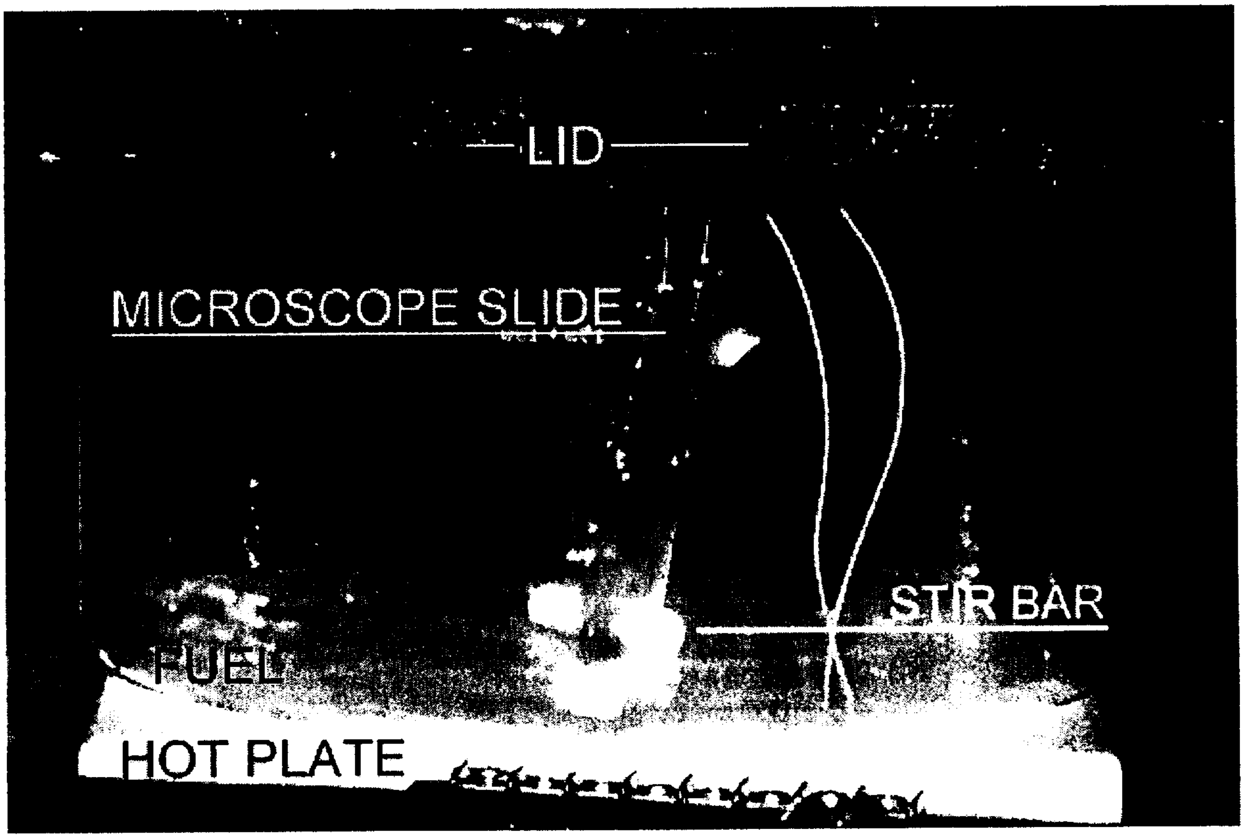

Figure 1. Test container with conductive film igniter installed.

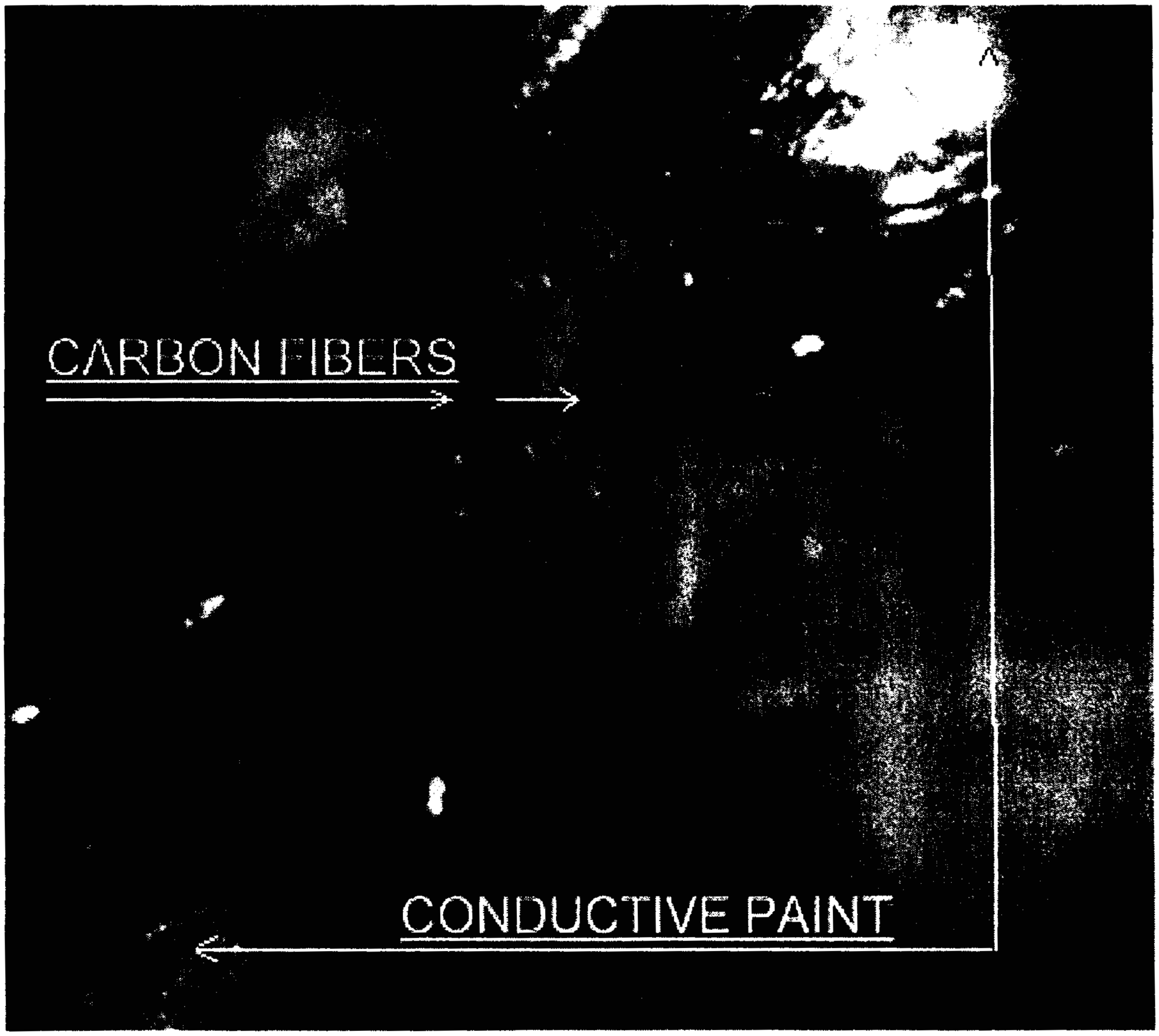

Figure 2. Fibers attached to thermocouple plug.

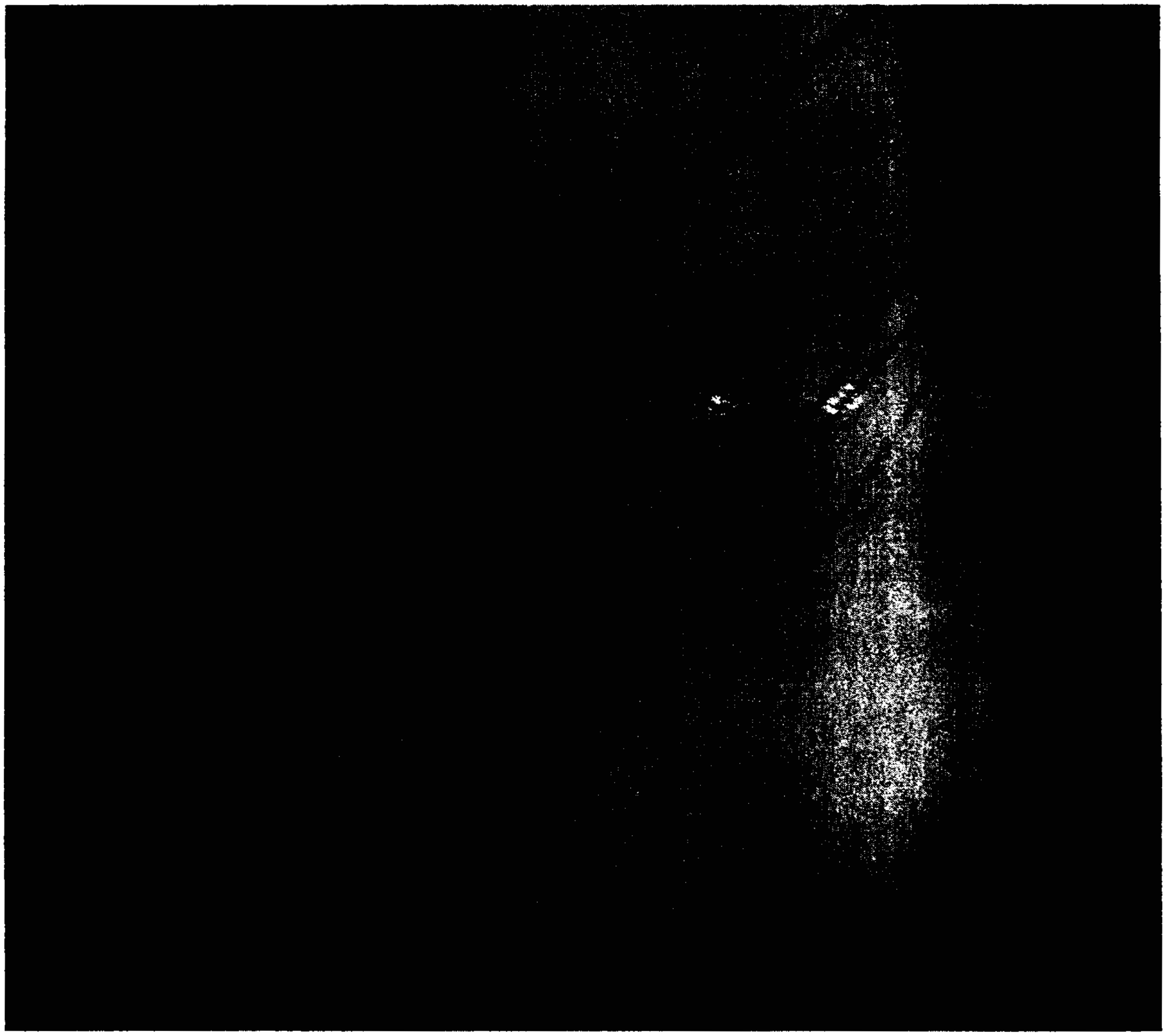

Figure 3. Close up of individual carbon fibers.

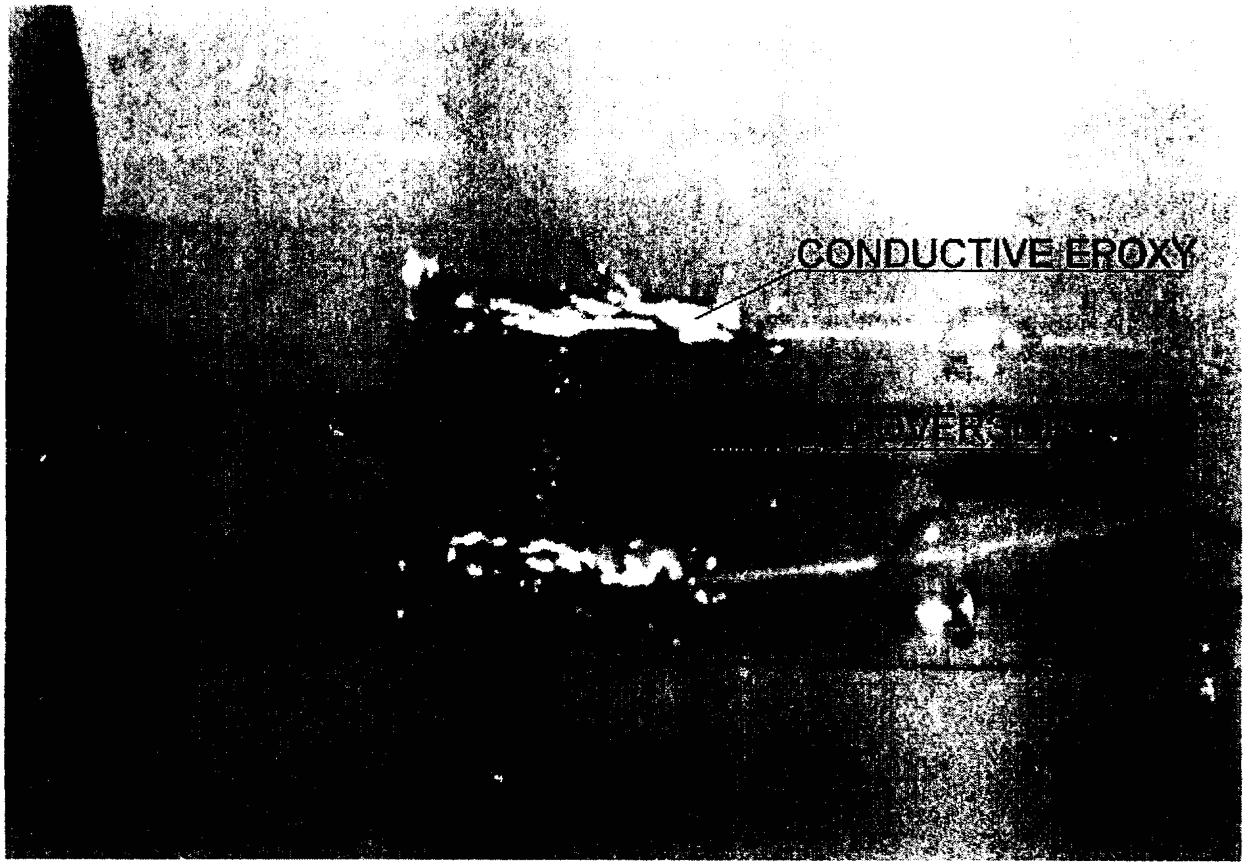

Figure 4. Conductive film on microscope slide.

Figure 5. Carbon deposit on glass cover slip.

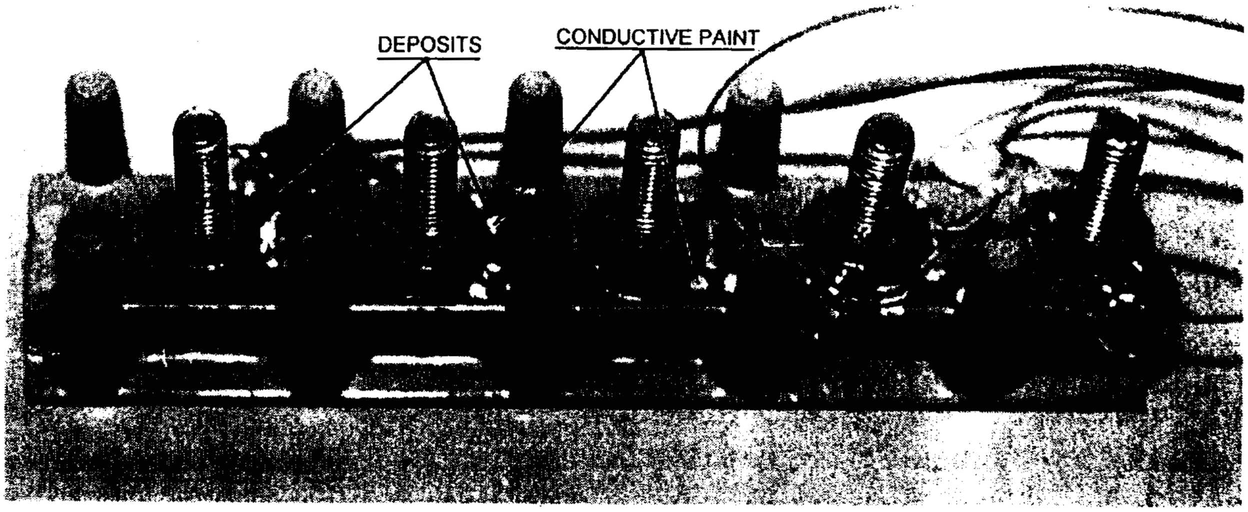

Figure 6. Terminal strip from aircraft fuel tank.

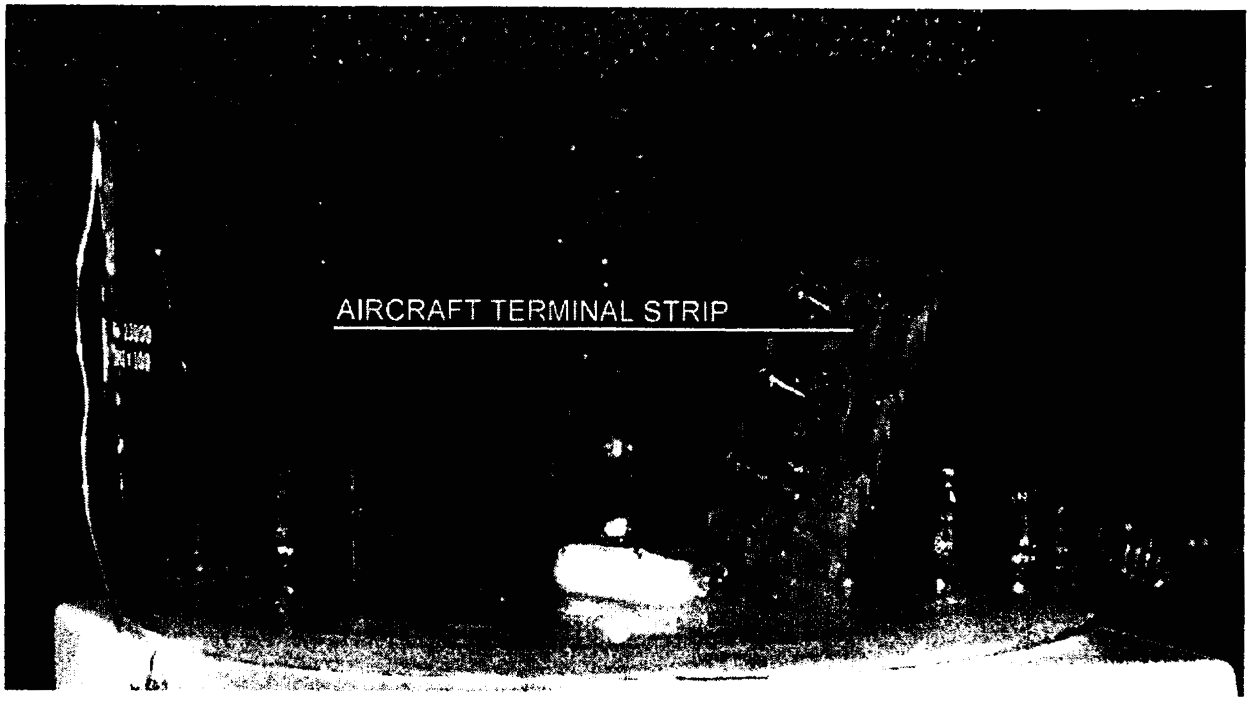

Figure 7. Test container with conductive aircraft terminal strip.

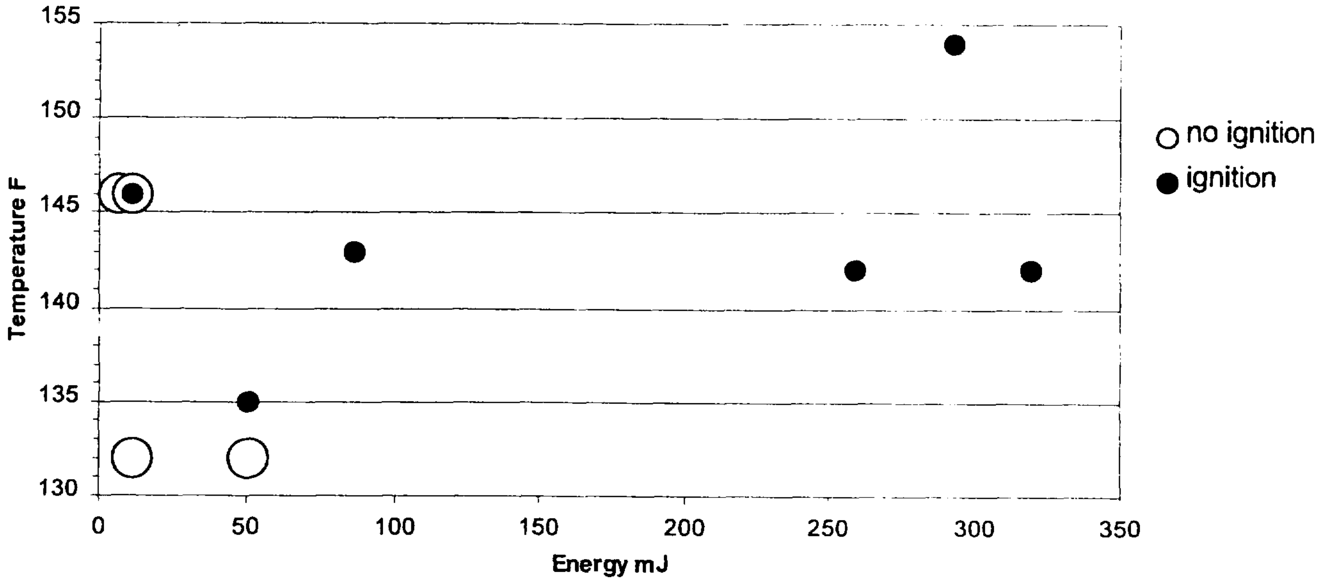

Figure 8. Temperature of fuel vs. energy dissipated using fiber igniters.

Ronald J. Hinderberger
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Airplane Safety
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The Boeing Company
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BOEING

13 December, 1999
B-H200-16843-ASI

Mr. R. Swaim, AS-40
National Transportation Safety Board
490 L'Enfant Plaza East, SW
Washington DC 20594

Subject: Sulfide Contamination, TWA 747-100 N93119, Accident off Long Island, NY – 17 July 1996

Dear Mr. Swaim:

Following is in response to your questions regarding sulfides and coverage of that subject in Service Bulletin 747-28A2208. You also questioned whether wiring terminations were being potted with fuel tank sealant and whether the sealant contains sulfur.

We have completed our EQA of fuel probes and wiring removed from in-service 747 Classics. The applicable reports have been submitted to the NTSB. These analyses have provided information that has significantly modified the content of the SB 747-28A2208. Indirectly, the modifications made to the wire routing on the probe do address some of the issues associated with possible sulfide contamination. SB 747-28A2208 eliminates the Series 1 through 3 terminal blocks, which is a potential source for damage to the wiring. In addition, the wire routing on all probes has been clarified and detailed in the bulletin. This wire routing ensures that damage to the wiring associated with contact between the Hi-Z and Lo-Z wires and various parts of the terminal block are eliminated.

In addition, new wire bundles that are installed due to extensive damage (or airline preference) will have crimped and soldered terminals and ferrules which will be sleeved. This is the standard design for the 747 Classic FQIS in-tank harnesses since about 1995 and was introduced as a standardization of processes from the bundle supplier.

When retermination or splicing of the wiring to the terminal block is required per the instructions in the -2208 SB, the crimped terminals and ferrules are potted with tank sealant. This was done since soldering and shrink sleeving could not be accomplished in a fuel tank. The potting compound used to coat the terminals does contain some sulfur, but due to the insignificant amounts, it does not contribute to the accumulation of sulfides. The fuel potentially provides an unlimited supply of sulfur compounds that represent a much larger source for the initiation of sulfide contamination accumulations. The purpose of the potting compound is to limit the amount of exposure any exposed wire shield or conductor has to the fuel. The potting of the terminals in this fashion was implemented upon the release of SB 747-28A2208.

We are in the process of evaluating whether or not it is practical to "clean" and pot existing terminals and wiring in the tank. This is part of our on-going study of the probes and wiring removed from the in-service 747's. Presently, this has not been added to the -2208 SB, but the process was validated in two center tanks of a customer's airplanes earlier this spring. We are awaiting the results of the FAA study on sulfide contamination to determine what, if any, action should be taken.

So, even though the SB does not appear to directly address the issue of sulfide contamination, there are several means by which it is being eliminated by several actions in SB 747-28A2208.

If you have any questions, please do not hesitate to call.

Very truly yours,

Ronald J. Hinderberger
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U.S. Department
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FACSIMILE COVER PAGE

To: BOB SWAIM
Company: NTSB
Phone: 202 314 6394
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From: Charles Fowler
Company: FAA
Phone: (516) 228-8029 ext 242
Fax: (516) 228-8827

Date: 05/29/98
Pages including this cover page: 4

Comments: BOB THIS IS IN REPLY TO THE 13 QUESTIONS ASKED ABOUT TOWER AIR'S N623FF FUEL QUANTITY PROBLEM.

TowerAir

Hangar 17 JFK International Airport Jamaica, New York 11430

May 28, 1998

Charles Fowler
Federal Aviation Administration
FSDO - 15
990 Stewart Ave., Suite 630
Garden City, New York 11530

Re: Reply to NTSB questions on A/C N623FF Fuel Tank Terminal Strip

Dear Mr. Fowler:

To reply to the NTSB's questions on the fuel tank terminal strip,

<u>1. What is the history of the aircraft ?</u>

This aircraft was operated by Philippines Airline since new:

Registration number:	N744PR / N623FF		
Model:	B747-2F6B	<u>As of 3/13/98</u>	
Delivery date:	December 02, 1980	Total Hours:	65,984
Serial number:	22382	Total Cycles:	13,338
Line number:	498		
Boeing Customer #:	RD414.		

The aircraft was maintained under a approved program by Philippines Airlines.

<u>2. How long had it had refuel / fuel qty problems ?</u>

This aircraft has had fuel quantify problems for quite sometime during the operation by PAL and since it was put into operation by Tower Air. Smith Industries has been involved trouble shooting and repairing the problems, both in and outside of the tanks.

<u>3. Are gauge problems common ?</u>

This aircraft had a Smiths Industries system installed per Boeing S/B 747-28-2116, which is a conversion from analog to digital gauges. This is the only aircraft in the Tower Air fleet that has the Smith's fuel quantify system and the reliability of that system is unacceptable to date.
The analog systems in the other aircraft are in line with industry standards.

4. Problems with refuel system ?

Refueling problems, were directly related to fuel quantify problems, tank shutting off early, or to late. The VTO required calibration to keep the system in trim, with this aircraft because of all the wire harness problems it would impossible to give a accurate answer.

5. How did the mechanics isolate the strip.

Trouble shooting was done using the maintenance manual and wiring diagram (WDM 28-41-11), the indicators in the cockpit were indicating hard failure codes. Measurements were taken using a Barfield 8000 and Gull GTF-2 fuel quantify tester. Compensators on right wing read shorted when wires were removed from T347 terminal strip, indication of the short disappeared. When the terminal were re-installed all wires again showed short, stud to stud.

6. Have the mechanics ever seen similar blackening .

None of the mechanics involved have ever seen a terminal strip with blackening or a short of that nature.

7. How come the gauge errors existed after "D" check

This aircraft was not on the Operation Specifications of Tower Air until the " D " check was completed and the aircraft delivered to Tower Air. The "D" check was performed by SIA in "Singapore" in accordance to Tower Air maintenance program as part of the lease agreement and phase in of the aircraft.
After numerous delays in performing the "D" check a decision to ferry the aircraft to New York was made between Tower Air and GE Capital the owner of the aircraft, at which time Smith Industries could perform the repairs to the fuel quantify system, SIA did not have expertise to accomplish the repairs.

8. What was exactly shorted?

The short was from stud to stud.

9. Type of meter used ?

Equipment used was the Barfield 8000 and Gull GTF - 2 fuel quantify test box's.
No meter was taken directly into the tank.

10. Had they replaced the wiring on the terminal strip?

In trouble shooting the problem the wires were removed from the terminal strip and then reinstalled to check for the short, none of the eyelet's were replaced.

11. Did they check other wiring?

No one can say if the wiring on the all the probes/compensators were inspected closely at that time.

12. What's there individual experience level based on the residues ?

I am not sure how to answer that question. No one has ever seen that kind of residue on a terminal block before.

13. Kind of protection when accomplishing S/M repairs ?

When accomplishing sheetmetal repairs the customary procedure is to place a cloth / fabric " blanket" down to catch all the metal shavings and then vacuum the tank area. Any open lines or cannon plugs are covered with plastic bags before the job is started. part of the inspection process before the closing of the fuel tank is to inspect for cleanliness.

Documentation of this is only found to the closing card for fuel tank entry in which part of the inspection procedure is to check for containment's.

Sincerly;

Paul Marks
Director, Quality Control

NASA TN D-4327

CHEMICALLY INDUCED IGNITION IN AIRCRAFT AND SPACECRAFT ELECTRICAL CIRCUITRY BY GLYCOL/WATER SOLUTIONS

By W. R. Downs

Manned Spacecraft Center
Houston, Texas

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

ABSTRACT

Electrical circuitry of military aircraft and spacecraft consists, in part, of insulated silver-covered copper wires and components. This circuitry creates a potential flammability hazard when solutions of glycol/water come in contact with either a bare or a defectively insulated wire or component carrying direct current. The hazard arises from chemical reactivity of the silver-covered copper anode in contact with glycol/water solutions. Similar reactivity does not occur with pure copper, nickel-covered copper, or tin-plated copper elements in electric circuits. Some chemical and physical properties of glycol/water fluids are presented, and glycol-induced corrosion of metals and corrosion inhibitors are discussed. A tentative chemical mechanism for the reactions of glycol/water solutions with silver wire carrying direct current is proposed. A means of detecting reaction by use of a transistorized amplitude-modulation receiver is reported, and a means of preventing reaction of glycol/water solutions with silver wires carrying direct current by adding a silver chelating agent to the glycol/water fluid is described.

CHEMICALLY INDUCED IGNITION IN AIRCRAFT AND SPACECRAFT ELECTRICAL CIRCUITRY BY GLYCOL/WATER SOLUTIONS

By W. R. Downs
Manned Spacecraft Center

SUMMARY

Work at the NASA Manned Spacecraft Center following the Apollo-Saturn 204 incident in January 1967 demonstrated that bare or defectively insulated silver-covered copper wires carrying a direct-current potential produced ignition when contacted by glycol/water fluids used in the Apollo environmental control system. Mechanisms of inhibiting glycol/water-induced reactions with metals are discussed with particular reference to the Apollo coolant fluids. Measurements of milliampere current flow during the reaction of glycol/water with silver and utilization of a transistorized amplitude-modulation receiver for detecting radiofrequency emissions are described as a means of locating circuitry defects leading to flammability. Since glycol/water coolant fluids cannot easily be removed from contaminated circuitry, use of a silver chelating agent in the glycol/water coolant to arrest chemical reactivity and thereby minimize the hazard of flammability is proposed.

INTRODUCTION

Since World War II, silver-covered copper wires (Military Specifications MIL-W-7139 and MIL-W-8777) have been used in electrical circuits in military aircraft because of the ease and reliability with which silver can be soldered to produce high-quality electric circuits. It was natural, therefore, to specify silver-covered copper wires in spacecraft construction. Use of silver-covered wires, switches, and disconnects seemed sound, not only because of the ease of joining but also for the protection afforded copper by the resistance of silver to oxidation when high-melting polymers for electrical insulation coverings were extruded over the conductor. Because of occasional bleed-through of copper to the surface of the silver, some aerospace designers specify nickel-covered copper wires instead of silver-covered copper wires. Nickel-covered copper wires are used in the Apollo command module (CM), and silver-covered copper wires are used in the lunar module (LM). The ground-support-equipment wiring and auxiliary wiring are usually insulated, and are pure copper or tin-plated copper wires.

Chemical effects of glycol/water solutions on electrical wire circuitry of aircraft or spacecraft have practical importance in the aerospace industry. This was illustrated by the investigations following the Apollo AS-204 incident in January 1967, when it was observed that defectively insulated spacecraft coaxial silver-covered copper cable carrying 28 volts direct current in a 16.7-psia pure oxygen atmosphere caught fire when glycol/water thermal transport fluids dripped over the cables. In the investigations it was noted that the time required to attain ignition after onset of the glycol/water exposure was an inverse function of the drip rate; that is, the slower the drip rate, the more rapidly ignition occurred. Further observation showed that defectively insulated pure copper cables exposed to glycol/water coolant in oxygen did not produce fire.

An examination of the glycol/water-induced corrosion of metals, of mechanisms for inhibiting corrosion, and of the reasons why silver-covered copper wires reacted differently than copper or nickel-covered wires when exposed to glycol/water solutions therefore seemed appropriate. This paper discusses the use of additive reagents to inhibit reactivity of glycol/water solutions on wire circuitry, gives a tentative explanation for the observed reactivity of silver to glycol/water solutions, and proposes a means of detecting some types of ongoing chemical reactions in wire circuitry before fire ensues.

MECHANISMS FOR INHIBITING FLUID-METAL REACTIONS

The inhibitor system found superior for the Apollo CM and LM environmental control units is termed "NAA Type II." It contains a pH buffering agent (triethanolamine phosphate, called TEAP) and a copper chelating agent (sodium mercapto benzothiazole, called NACAP) (refs. 1 and 2). The TEAP in NAA Type II has three functions: (1) to pull copper atoms on the surface of the alloy into solution where the chelating agent (NACAP) can react with the copper ions to form an undissociated copper chelate (organometallic complex); (2) to supply phosphate ions to produce a uniform coating of aluminum phosphate over the metal surfaces, thereby protecting the natural oxide coating; and (3) to serve as a phosphate salt buffer for maintaining the pH of the solution close to 7 and preventing wide local excursions of the hydrogen ion concentration.

Other corrosion inhibitors for spacecraft are available, for example, a potassium phosphate-tetraborate mixture known as NAA Type III, anthranilic acid, or boric acid. The use of selective oxidation agents, such as potassium tetraborate, is employed in NAA Type III. The potassium tetraborate, in conjunction with potassium monoacid phosphate, produces a thin tenacious coating of aluminum oxide borate on the metal surfaces, thus preventing corrosion.

The choice of an inhibitor system for glycol/water solutions depends on the metals used in the coolant loop construction of the spacecraft. The Apollo environmental control system utilizes NAA Type II in a eutectic mixture (a eutectic mixture is one which has the lowest freezing point possible) consisting of 62 percent ethylene glycol and 38 percent water (G/W-1). This mixture carries the trade name of "RS 89-a."[1]

RS 89-a (in bulk quantities) is not a fire hazard in a 15-psia oxygen atmosphere. Its autoignition point has been demonstrated to be somewhere above 450° F in a 15-psia oxygen atmosphere; in air, this point is given at 790° F for RS 89-a and at 750° F for pure ethylene glycol. The flashpoint temperature of RS 89-a is between 230° and 240° F.

LABORATORY DATA

A series of laboratory experiments was performed at the NASA Manned Spacecraft Center (MSC) to determine the physical properties of RS 89-a and its effects on wire circuitry so that a method could be specified for cleaning contaminated circuit elements.

NASA MSC laboratory distilled water at ambient temperature (23.3° C) has an ion concentration of 0.74 ppm. By contrast, RS 89-a fluid at ambient temperature produces an ion concentration of 243.0 ppm because of the phosphate and sodium ions in the inhibitors.

RS 89-a cannot, within practical time limits, be completely evaporated by vacuum techniques because of the presence of the ions and because of the low vapor pressures of the ethylene glycol and undissociated amines. Excess tertiary amine and its phosphate, on evaporation of solvent, remain as hygroscopic material and are deliquescent. They tend to pull water from the surroundings to produce an electrically conductive, corrosive fluid. The sodium ions present will remain as the salt, sodium mercapto benzothiazole. In any case, the sodium ions, the undissociated alkaline amine, and the ethylene glycol remain when RS 89-a is spilled around electrical cables or on electrical connectors, despite efforts to evaporate the spillage by pulling a vacuum.

Because of the hygroscopic nature of the amine residues and the existence of ions, a corrosive, electrically conductive moist locale is produced, commencing with the admission of air or moist oxygen to the RS 89-a-soaked equipment. The pulling of moisture to RS 89-a-stained regions is time dependent and cumulative. The cleansing of wire circuitry contaminated with glycol/water requires adherence to criteria which are based on the physical properties of the mixture. The criteria are as follows:

1. Removal or dilution of pools of glycol/water solution is imperative, since the solution can feed a firesite.

2. Cleaning liquids (for example, alcohols and Freons) which tend to spread contaminants are harmful.

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[1] RS 89-a is compounded to the following proportions: 506 grams of ethylene glycol, 399.5 grams of distilled water, 14.18 grams of TEAP, and 1.41 grams of NACAP (50-percent solution) for a total of 921.09 grams.

3. Evaporation of contaminants is not possible because of the low vapor pressure of ethylene glycol and the presence of ionic species.

Based on the previously discussed criteria, the use of distilled water is specified for repetitive rinsing and drying of contaminated wire circuitry until the rinse water achieves a low ion content arbitrarily selected at a value not to exceed that of twice the ion concentration of the distilled water.

The NASA MSC observations showed that bare or defectively insulated silver-covered copper wires (carrying a direct-current potential) exposed to glycol/water solutions produced smoke and fire in oxygen or in air. Also, it was found that copper wires or nickel-covered copper wires under conditions of electrical potential and oxygen exposure identical to that of silver-covered wires did not exhibit chemical reactivity to glycol/water solutions and did not produce ignition.[2] The experimentation is described in the following paragraph.

Silver-covered copper wire as used on the LM circuitry was completely stripped of its insulation. Two pieces, each about 5 centimeters long, were taped to cardboard so that approximately a 1-millimeter space separated the two wires. A 22.5-volt dry-cell battery supplied direct-current potential, and the wires were attached to the battery terminals with a direct-current milliammeter in series. RS 89-a solution was dripped slowly into the 1-millimeter space between the wires. Electrolysis commenced at once, and in 4 to 5 seconds a black deposit was observed on the silver wire connected to the positive terminal of the battery. The milliampere current flow fluctuated between 10 and 80 milliamperes, and the needle of the meter jumped constantly. In a few minutes, copious white smoke and flame ensued. These phenomena occurred whether the reaction was carried out in air or in 100 percent oxygen at 15 psia.

A transistorized amplitude-modulation (AM) receiver placed near the electrolysis started to click and emit static, which, as the electrolysis proceeded, built up to a constant static noise that drowned out all other reception on the receiver. The radio-frequency (rf) disturbance was observed on the receiver when it was held as far away as 3 feet, and the intensity of the noise increased as the receiver was moved toward the reaction site. The application of the AM receiver to detect a reaction between the glycol/water solution and the silver wiring was found to be more convenient than using a milliampere meter in the circuit. The slower the application of glycol/water solution after the first drop or two, the louder the rf disturbance over the receiver became. Finally, the chemical reactions detected by the AM receiver produced smoke and flame.

Nickel-covered copper wires, pure copper wires, and tin-plated copper wires did not show evidence of chemical reactivity when subjected to a direct-current potential

---

[2] D. K. Elliot (ref. 3) reports on so-called wet-wire fires produced from insulated wires of various metal compositions when the wires are exposed to direct current and to aqueous conducting solutions. The work of Elliot discusses a different sort of phenomenon, namely, the formation of metallic dendrites leading to an electrical short, followed by ignition and burning of the wire insulation.

and exposed to the glycol/water solution. In such instances, the solution simply electrolyzed away with mild generation of heat, with no rf radiation emission, and with no tendency to flammability.

To illustrate the previously described phenomena and to compare the reactions of silver-covered and nickel-covered copper wires with the glycol/water solution, two bare wires separated by a sheet of filter paper were connected to a 22.5-volt battery, with a milliampere chart recorder in series in the circuit. When the first drop of glycol/water solution was placed on the filter paper, a current measured in milliamperes was established. Four experiments were performed in air.

The first experiment showed the effect of glycol/water (RS 89-a) solution on nickel-covered copper wires. Current flow was observed for the first few seconds following each drop of glycol because the glycol/water solution was evaporating because of electrolysis during this time. Thereafter, no current flowed until the next drop was made. Six droppings were made over a 45-minute interval; the experiment was then discontinued. There was no smoke, and no ignition resulted.

The second experiment showed the effect of uninhibited glycol/water solution on silver-covered copper wires. Two drops of solution produced ignition in slightly over 7 minutes, with a current flow sustained after the first half minute.

The third experiment showed the effect of NAA Type III inhibited glycol/water solution and of RS 89-a glycol/water fluid on silver-covered copper wires. The first drop of solution in both instances produced ignition in less than 1 minute, with a sustained current flow.

The fourth experiment showed the effect of a low-ion inhibitor (anthranilic acid) in glycol/water solution (G/W-1) on silver-covered copper wires. Current flow started on the first drop and terminated with ignition when the second drop was made at 7 minutes; the behavior was similar to that of the uninhibited glycol/water solution.

The foregoing experimental results were independently confirmed by Boies and Northan (ref. 2). In the current investigation, further laboratory verification was obtained by dripping RS 89-a fluid on defectively insulated coaxial silver-covered copper cable and on nickel-covered copper cable in a 100 percent pure oxygen atmosphere at 15 psia. The chemical reactivity of silver-clad wires was measured by recording the current flow until ignition and subsequent burning of the glycol occurred. Nickel-covered copper wires did not produce heavy current flow between the conductors, and ignition did not ensue.

It makes little difference in reactivity whether the glycol/water fluid is simply ethylene glycol solution in water or if the fluid contains inhibitors such as NAA Type II or Type III. Chemical reaction of silver with glycol/water solution occurs only when the silver is the positive terminal. This signifies that the silver undergoes anodic oxidation, which occurs readily at a 6-volt potential but is barely apparent at a 1.55-volt potential. The latter, therefore, is considered to be the minimum potential at which reactivity commences.

Reaction occurs as soon as glycol/water contacts the current-carrying silver-covered wires, evidencing itself initially by electrolysis between the wires and by the formation of a black deposit. Steps in the chemical mechanism leading to ignition are shown in figures 1 to 5. These figures are stereoscopic photomicrographs produced from frames of a movie film taken of the reaction resulting when RS 89-a fluid was placed between two silver-covered wires separated by a distance of 1 millimeter and impressed with 22.5 volts of direct current. The action occurred over a span of approximately 1 minute, during which time the current did not exceed 80 milliamperes and the average current was 50 milliamperes. In the figures the upper wire is negative and the lower wire is positive.

Figure 1 shows hydrogen bubbles forming at the negative pole and streamers of brown silver hydroxide issuing from the positive pole. This happened as soon as the current was impressed.

As seen in figure 2, within a few seconds the silver hydroxide conglomerated to black silver oxide. Centers of explosive energy releases are visible in the mass of silver oxide as ethylene glycol commenced to dehydrate.

Figure 3, a view several seconds later than the view in figure 2, shows an extensive region of glycol oxidation (indicated by the intense blue light) accompanying the decomposition of the ethylene glycol, the rearrangement to form ethylene oxide, and the formation of ethylene. Steam and smoke are observed rising from the negative-pole regions.

Figure 4 shows generalized reaction all along the wire surfaces and copious liberation of smoke and steam, indicative of energy releases in excess of the energy drain from the battery. The total power from the battery, if the maximum current rate were maintained for 1 minute, would be 108 joules (approximately 25 gram-calories), most of which would produce silver oxide and hydrogen, as noted in figures 1 and 2.

In figure 5, a burst of flame, caused by the reactions of ethylene oxide with hydrogen and of ethylene with air, is visible in the negative-pole region. Another burst is seen on the right side. Analysis showed that the washed-and-dried black deposit contained silver, carbon, oxygen, and nitrogen (ref. 4).

Pure copper wires or nickel-covered copper wires, in contrast to the reaction of the silver-covered copper wires, do not react when exposed to glycol/water solutions, either in air or in pure oxygen atmospheres. On these types of wires, the glycol/water solution evaporates (from the heat of electrolysis) without producing incandescence or sparks. It has been found impossible, even in a 100 percent pure oxygen atmosphere at 15 psia, to produce ignition from nickel-covered or pure copper wires carrying direct-current voltage upon exposure to glycol/water solutions.

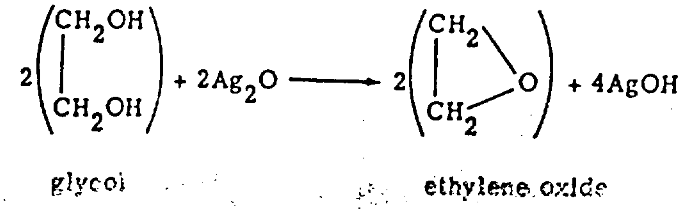
CHEMISTRY OF OBSERVED PHENOMENA

Laboratory results indicate that silver-covered copper wires impressed with a direct-current potential react chemically with glycol/water solutions. Pure copper or nickel-covered copper wires similarly treated do not react with glycol/water solutions; instead, the solution boils away with some dissolving and plating of the copper. These observations can be explained chemically as follows.

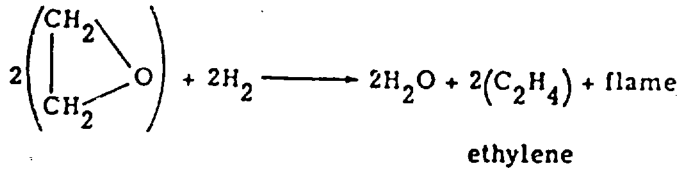
Silver is anodically oxidized to silver oxide (Ag_2O), which dehydrates glycol to ethylene oxide, which in turn reacts with hydrogen from the electrolysis. These reactions are represented by the following equations:

$$4Ag \longrightarrow 4Ag^+ \qquad (1)$$

$$4Ag^+ + 4OH^- \longrightarrow 2Ag_2O \text{ (anodic oxidation)} + 2H_2O \qquad (2)$$



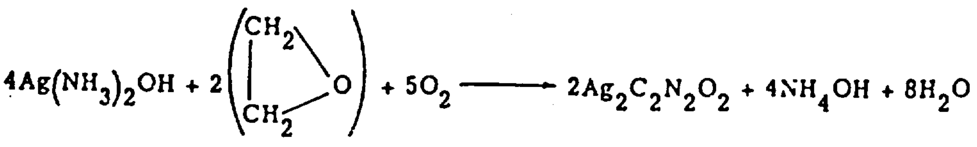
(3)



(4)

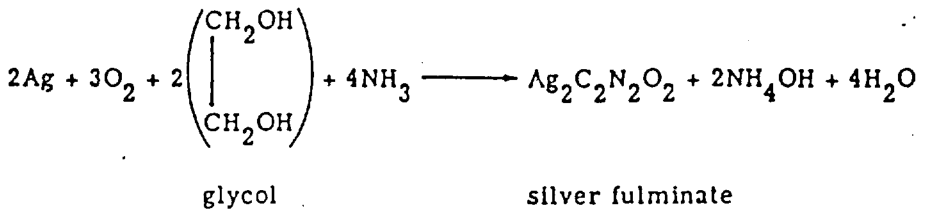
If amines are present (for example, TEAP in RS 89-a), the triethanolamine reacts with silver hydroxide (AgOH) to form silver ammonia hydroxide ($Ag(NH_3)_2OH$), which in turn is oxidized by ethylene oxide and oxygen to yield silver fulminate which is a sensitive detonator. The reactions are as follows:

$$\left.\begin{aligned} 4AgOH + 8N(CH_2CH_2OH)_3 &\longrightarrow 4Ag\left[N(CH_2CH_2OH)_3\right]_2OH \\ 4Ag\left[N(CH_2CH_2OH)_3\right]_2OH &\longrightarrow 24C_2H_4O + 4Ag(NH_3)_2OH \end{aligned}\right\} \qquad (5)$$



(6)

A complete chemical equation is obtained by adding equations (1) to (6) to yield



$$2Ag + 3O_2 + 2\underset{\text{glycol}}{\left(\begin{array}{c} CH_2OH \\ | \\ CH_2OH \end{array}\right)} + 4NH_3 \longrightarrow \underset{\text{silver fulminate}}{Ag_2C_2N_2O_2} + 2NH_4OH + 4H_2O \qquad (7)$$

The chain-reaction mechanism involving the action of glycol/water solution on silver wire begins with the anodic reactions

$$2Ag \longrightarrow 2Ag^+ \qquad (8)$$

$$2Ag^+ + 2OH^- \longrightarrow 2AgOH \qquad (9)$$

$$2AgOH \longrightarrow Ag_2O + HOH \qquad (10)$$

The chain-reaction mechanism may be prevented if a silver chelating agent exists in the solution to tie down the Ag^+ ion before it can form silver oxide. Such a chelating agent is benzotriazole, suggested in reference 2. It has been confirmed experimentally that benzotriazole in concentrations of from 2000 to 5000 ppm in glycol/water solutions inhibits the chemical reactions of silver and glycol under an impressed direct-current potential. No black deposits form on the silver electrode, no rf radiation is detectable on an AM receiver near the reaction site, the reactants do not tend to flame, and the current flow is steady and time decreasing. The interaction of benzotriazole decreases the activity of silver towards glycol/water solutions to a point where the silver-covered copper wires behave similarly to nickel-covered or pure copper wires; namely, a simple electrolysis occurs between the shorted wires which gradually ceases as the solution evaporates. The benzotriazole interaction produces a greenish-white gelatinous precipitate around the silver conductors. This precipitate presumably is an organo-silver chelate hydroxide which removes the silver ion and thereby prevents formation of silver oxide. The current flow between the wires is impeded by the precipitate, and the reaction rates are noticeably slowed. The chain-reaction mechanism leading to flammability is interrupted and prevented.

CONCLUSIONS

Work at the NASA Manned Spacecraft Center following the Apollo-Saturn 204 incident in January 1967 demonstrated that bare or defectively insulated silver-covered copper wires carrying a direct-current potential produced ignition when contacted by glycol/water fluids used in the Apollo environmental control system. Copper, nickel-covered copper, and tin-plated copper wires showed no detectable chemical reactivity and, therefore, no ignition when similarly treated and exposed to glycol/water coolant solutions. Mechanisms of inhibiting glycol/water-induced reactions with metals are discussed with particular reference to the Apollo coolant fluids. Laboratory results indicated that glycol/water fluids, particularly those containing corrosion inhibitors, were extremely difficult to clean from surfaces of wire bundles which had been contaminated by spillages and leakages.

A chemical-reaction mechanism which explains why flammability hazards exist when glycol/water solutions contact silver-wire circuitry carrying direct current is proposed. Measurements of milliampere current flow during the reaction of glycol/water with silver and utilization of a transistorized amplitude-modulation receiver for detecting radiofrequency emissions are described as a means of locating circuitry defects leading to flammability. Since glycol/water coolant fluids cannot easily be removed from contaminated circuitry, use of a silver chelating agent, benzotriazole, in the glycol/water coolant to arrest chemical reactivity and thereby minimize the hazard of flammability is proposed.

The following conclusions are drawn from this study:

1. Glycol/water solutions cannot effectively be evaporated from a region on which spillage has occurred because the ions contained in the corrosion inhibitors of the fluid remain after evaporation of the low-vapor-pressure-producing glycol.

2. The ionizable amine-containing materials remaining after evaporation of glycol/water coolant fluid from equipment surfaces will absorb moisture from the surroundings, becoming progressively more alkaline as the amines are hydrolyzed by the absorbed moisture.

3. Glycol/water solutions with or without inhibitor additions (except for the addition of benzotriazole) produce flammable reactions accompanied by easily detectable radiofrequency radiation upon contacting silver-covered copper wires on which a direct-current potential is impressed.

4. Pure copper, nickel-covered copper, or tin-plated wires do not show evidence of chemical reactivity towards glycol/water solutions.

5. Silver-covered copper wires in spacecraft circuitry exposed to glycol/water coolant, or likely to be so exposed, should be recognized as a potentially dangerous ignition source in air or in an oxygen atmosphere.

6. If contamination of silver-wire circuitry occurs, rinsing with distilled water until only a nominal ion pickup is indicated in the rinse water constitutes the recommended decontamination procedure for spacecraft.

7. A silver chelating agent, benzotriazole, when added to glycol/water coolant fluids in concentrations from 2000 to 5000 ppm, completely inhibits reactivity of glycol/water solutions to silver wires.

8. A transistorized amplitude-modulation receiver will pick up a constant radio-frequency static noise as the chemical reaction of glycol with silver wire progresses. Such a receiver, therefore, should serve as a ready detector of incipient trouble in wire circuitry during spacecraft tests and checkout.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, November 20, 1967
914-50-20-21-72

REFERENCES

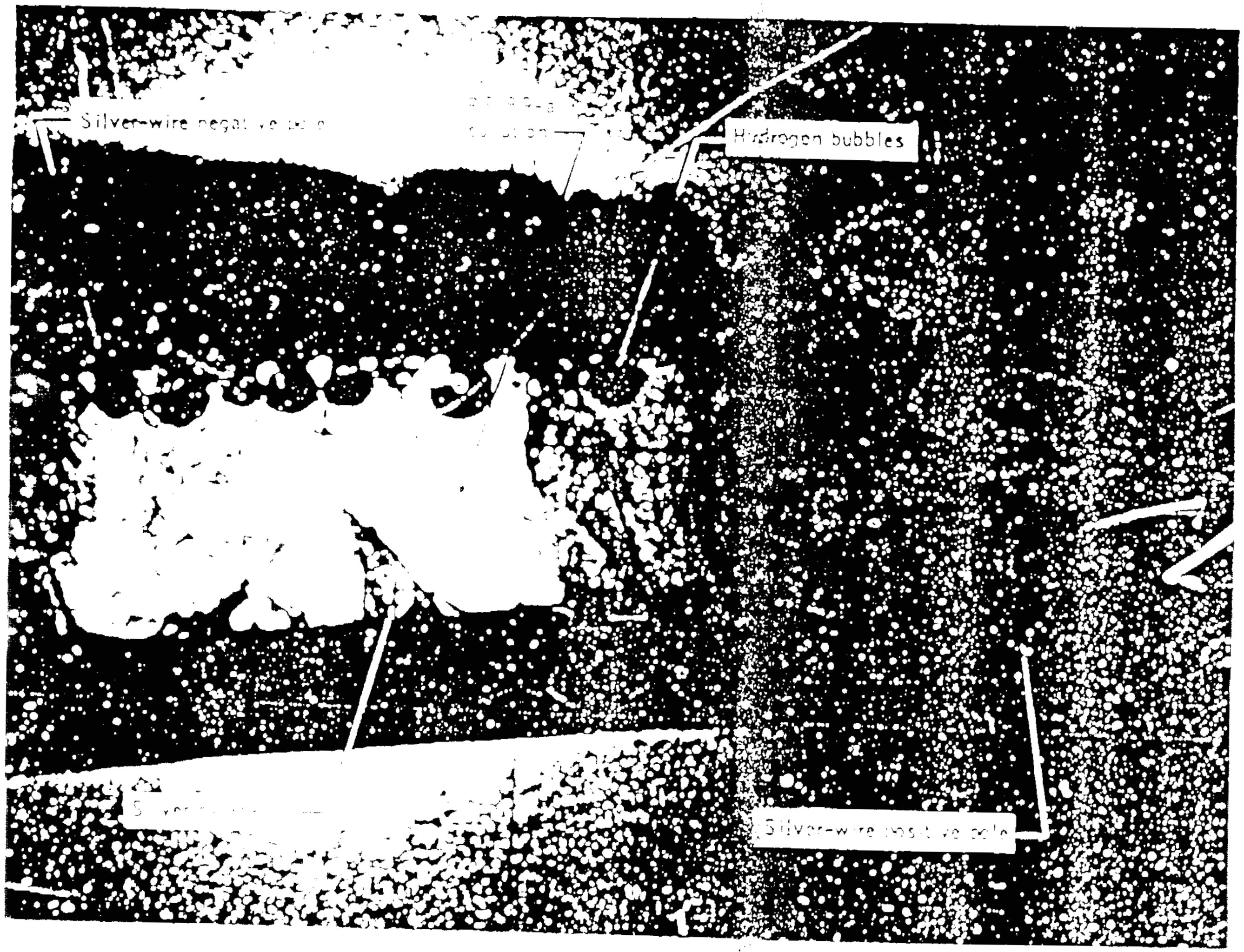
1. Boles, David B.; and Northan, Barbara J.: Development of a Corrosion-Inhibited Heat Transfer Fluid for ECS Systems. NASA CR-[illegible]

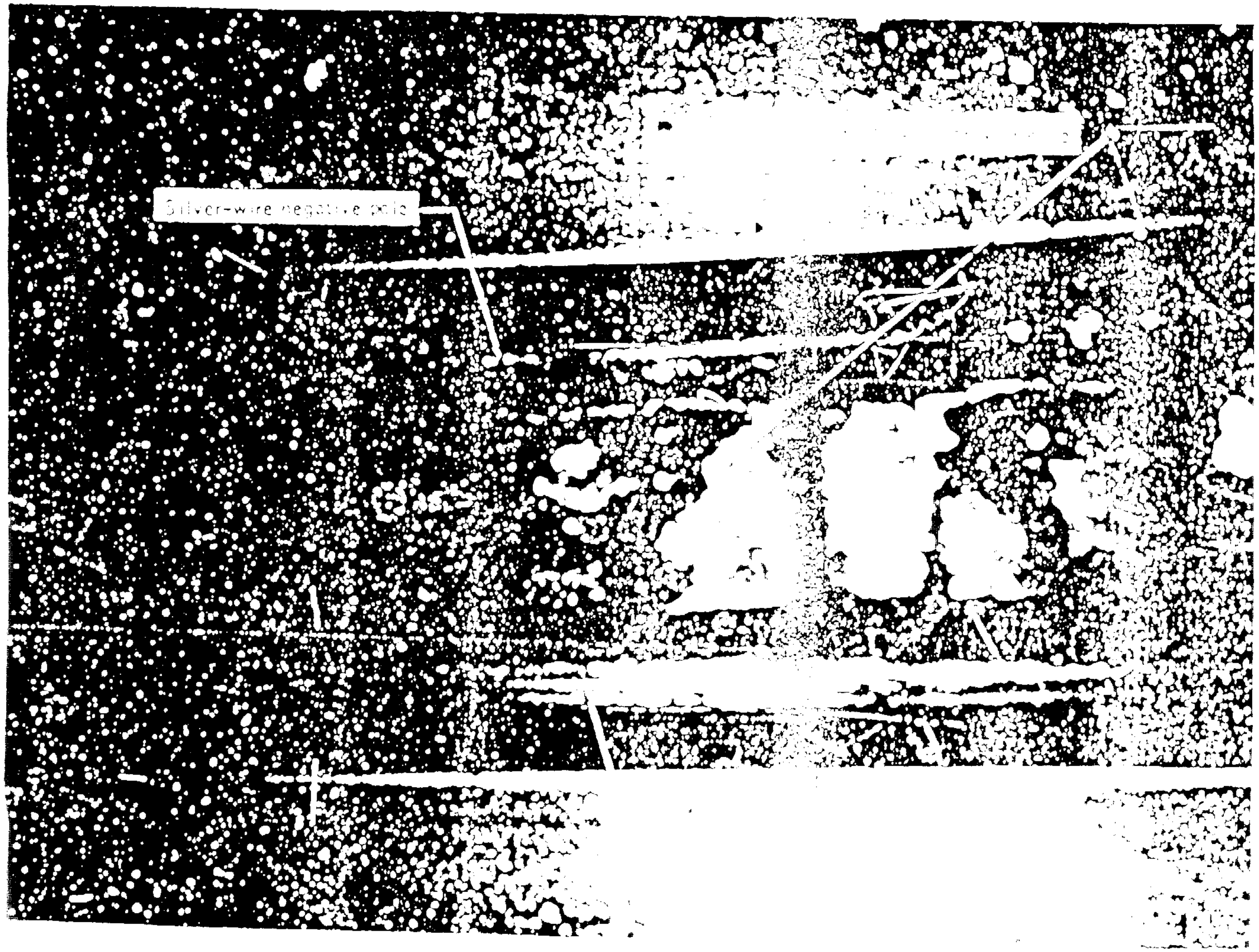
2. Boles, David B.; and Northan, Barbara J.: Study of Corrosion Inhibitors for Apollo Thermal Transport Fluids. NASA CR-65775, 1967.

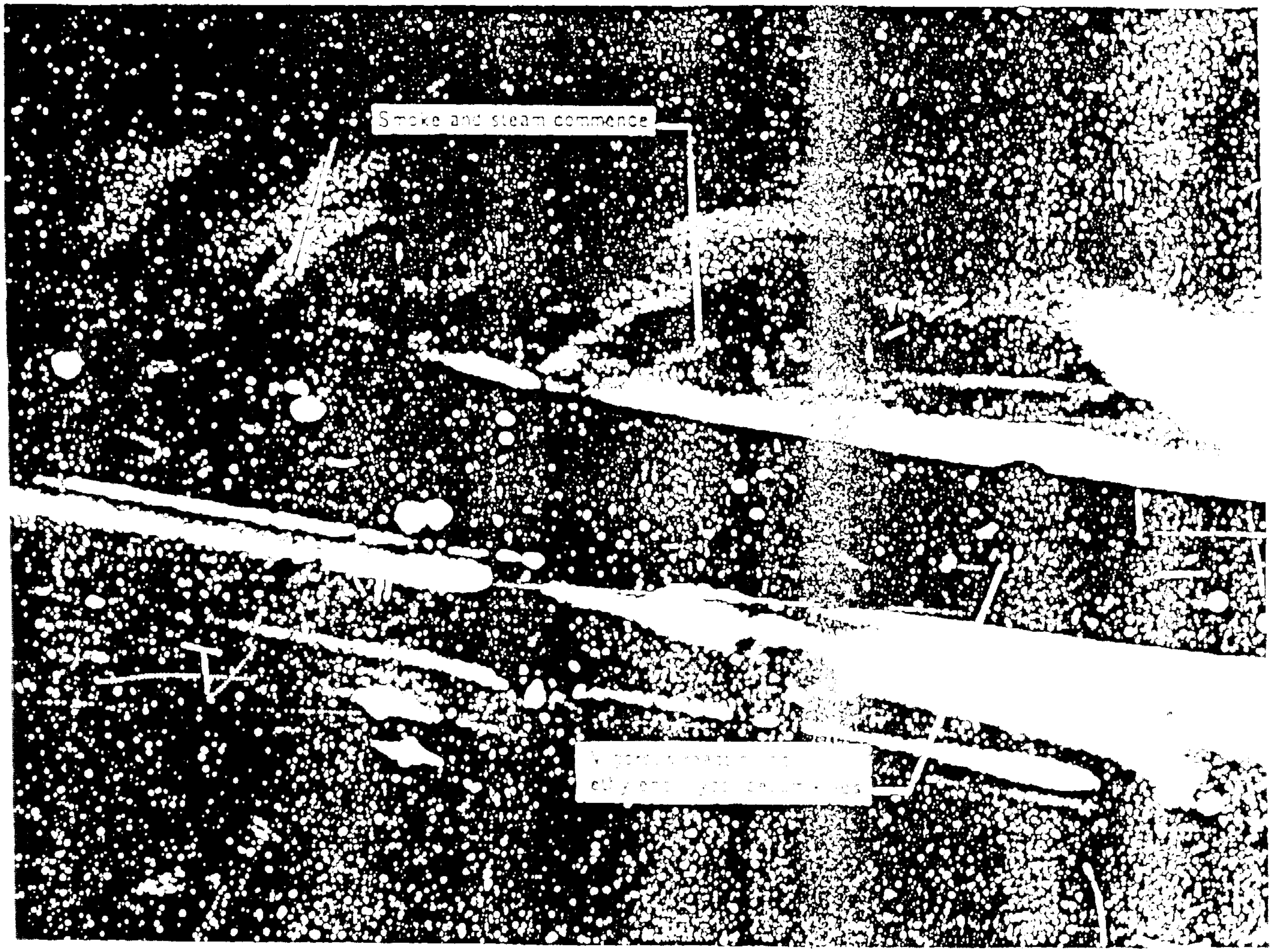
3. Elliot, D. K.: Wet-Wire Fires. Natl. Res. Council Publ. 1141, 1964, pp. 124-127.

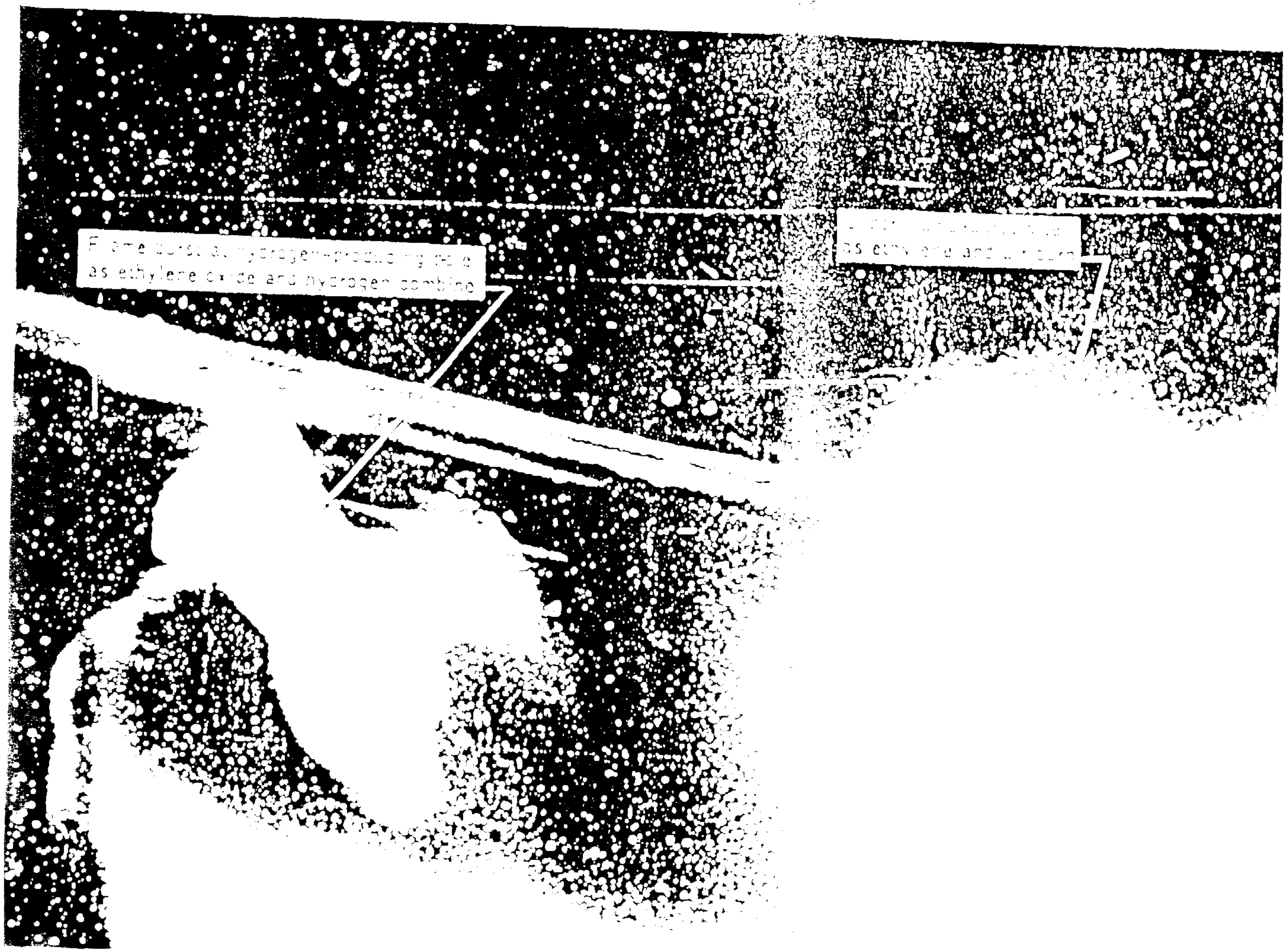
4. Setty, H. S. N.: Examination of the Chemistry Involved in Anodic Oxidation of Silver in the System - Silver: Oxygen: Inhibited Glycol/Water Solution. NASA CR-65681, 1967.

Lockheed Report


Silver-wire negative pole
Hydrogen bubbles
Silver-wire positive pole


Silver-wire negative pole


Smoke and steam commence
[illegible]
ethylene glycol commences



Flame burst at hydrogen-producing pipe as ethylene oxide and hydrogen combine

[illegible]
as ethylene and [illegible]

EVANS EAST
SPECIALISTS IN MATERIALS CHARACTERIZATION

April 24, 1998

Dr. Merritt M. Birky
United States of America
National Transportation Safety Board
490 L'Enfant Plaza East, S.W.
Washington, D.C. 20594

Tel:	(202) 314-6503	Invoice #:	98-966
Fax:	(202) 314-6599	Problem #:	21-2616
email:	birkym@ntsb.gov	PO #:	12-98-SP0249

Dear Merritt,

Enclosed are the results of the XPS analysis of seven (7) sections of one (1) wire bus bar which we analyzed during your visit on 4/20/98. This analysis will be billed at the visit rate of $450 per hour for which your purchase order will be billed a total of $2,700 (6 hrs). Please inform your accounting/receiving department that you have received your data.

We hope these results are of use to you. If you have any questions about them, please do not hesitate to contact me or Dave Cole. Please let us know if we may be of service to you again concerning your surface characterization needs.

Sincerely,

Jeff Shallenberger
Senior XPS Analyst

Enclosures

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X-RAY PHOTOELECTRON SPECTROSCOPY ANALYTICAL REPORT

April 24, 1998

PREPARED FOR:

Dr. Merritt M. Birky
United States of America
National Transportation Safety Board

PREPARED BY:

Jeffrey R. Shallenberger
Senior Analyst
X-ray Photoelectron Spectroscopy

REVIEWED BY:

David A. Cole
Manager
X-ray Photoelectron Spectroscopy

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Fax: (609) 799-8691 • E-mail: staff@evanseast.com • Web site: http://www.evanseast.com

X-RAY PHOTOELECTRON SPECTROSCOPY ANALYTICAL REPORT

April 24, 1998

RE: Invoice #: 98-966
Problem #: 21-2616
PO #: 12-98-SP0249

Purpose: To characterize the surface of seven (7) sections of one (1) wire bus bar by determining the concentration of all detected elements and oxidation state of selected elements.

Analytical conditions:

Instrument	Physical Electronics Model 5701 LSci
X-ray source	Monochromatic aluminum
Source power	350 watts
Analysis region	2 mm X 0.8 mm
Electron exit angle*	65°
Electron acceptance angle	±7°
Charge neutralization	electron flood gun
Charge correction	C-C in C 1s spectra at 284.6 eV

* Exit angle is defined as the angle between the sample plane and the electron analyzer lens.

Experimental:

The areas were examined initially with low resolution survey spectra to determine the concentration of elements present. High resolution spectra were acquired to determine the oxidation state of selected elements observed in the survey spectra. The quantification of the elements was accomplished by using the atomic sensitivity factors for a Physical Electronics Model 5701 LSci ESCA spectrometer. The approximate sampling depth ($3\lambda \sin\theta$) for these experiments was 80 Å, relative to carbon electrons.

Results:

The results of the analysis are summarized in Table I below. Many of the stained areas on the polymer contained the same elements including: Na, Zn, Cu, Ag, O, N, C, S and Si. The nut sample contained a small quantity of Cd. Species observed in the high resolution spectra included: Cu^{o} (or Cu^{+}), C-(C,H), C-O, C=O, O-C=O, metal sulfides and oxidized S (sulfates and/or sulfonates). The C 1s spectra were somewhat consistent with organic acids as opposed to esters (i.e., they contained relatively low C-O concentrations). Silicon was observed on all surfaces although the exact chemical state could not be determined: silicones and/or silicates are possibilities.

The concentration of sulfur species is summarized in Table II. Unfortunately, XPS is not very good at distinguishing different chemical states of silver: Ag°, AgO, Ag_2O, silver halides and Ag_2S all fall within 0.3 eV of 368.0 eV. At least one sample (#6L stained post) likely contained Ag_2S species based on the total amount of metal sulfides and relatively low Cu concentration. The other samples contain Cu and sulfide species in roughly the same concentration leaving open the possibility that copper sulfides are present instead of Ag_2S. The nut edge has a significant quantity of Cd, which could conceivably be present as a sulfide.

The fractured polymer edge contained large quantities of C-(C,H), C-O, O-C=O, silicates and other elements consistent with fiberglass. What's more, tiny (presumably glass) fibers were visible when the sample was fractured.

In summary, the majority of the species present on the stained surfaces was organic in nature and, therefore, probably insulating. Moderate quantities of Ag and Cu species were observed on all surfaces. These elements or their sulfides are conductors or semiconductors. The XPS results agree well with the TOF-SIMS results which found Cu, Ag, metal sulfides, silicones and various organic species present on the surfaces.

If you have any questions or comments feel free to call me or Dave Cole at any time. Thank you for choosing Evans East.

Table I

Concentration of Elements Detected (in Atom%)

Sample	Filename	Na	Zn	Cu	O	N	Ag	C	Cl	S	Si	Cd
Bottom surface (left, as installed) of terminal strip	b0420100	0.6	1.0	0.2	14.9	0.8	0.7	80.5	0.1	0.4	0.8	-
#6L post (cylindrical surface), stained	b0420110	0.3	0.4	0.6	20.2	1.5	3.9	67.3	0.0	4.0	1.9	-
Near post 6R, forward surface, dark stain	b0420120	0.2	1.6	0.1	13.2	0.3	0.3	82.4	0.0	0.5	1.4	-
Near post 6R, forward surface, tan stain	b0420130	0.0	2.0	0.1	12.4	0.2	0.3	83.6	0.0	0.6	0.8	-
#4R connector, dark stain	b0420140	0.5	0.2	0.7	12.0	0.8	0.0	83.4	0.0	0.1	2.3	-
#4 nut edge, dark stain	b0420150	0.5	0.3	0.4	19.8	0.6	4.5	67.4	0.3	3.0	2.0	1.3
Fractured polymer	b0420170*	-	0.2	-	32.0	0.4	-	59.0	0.8	-	4.8	-

* Sample also contained 1.2% Al.

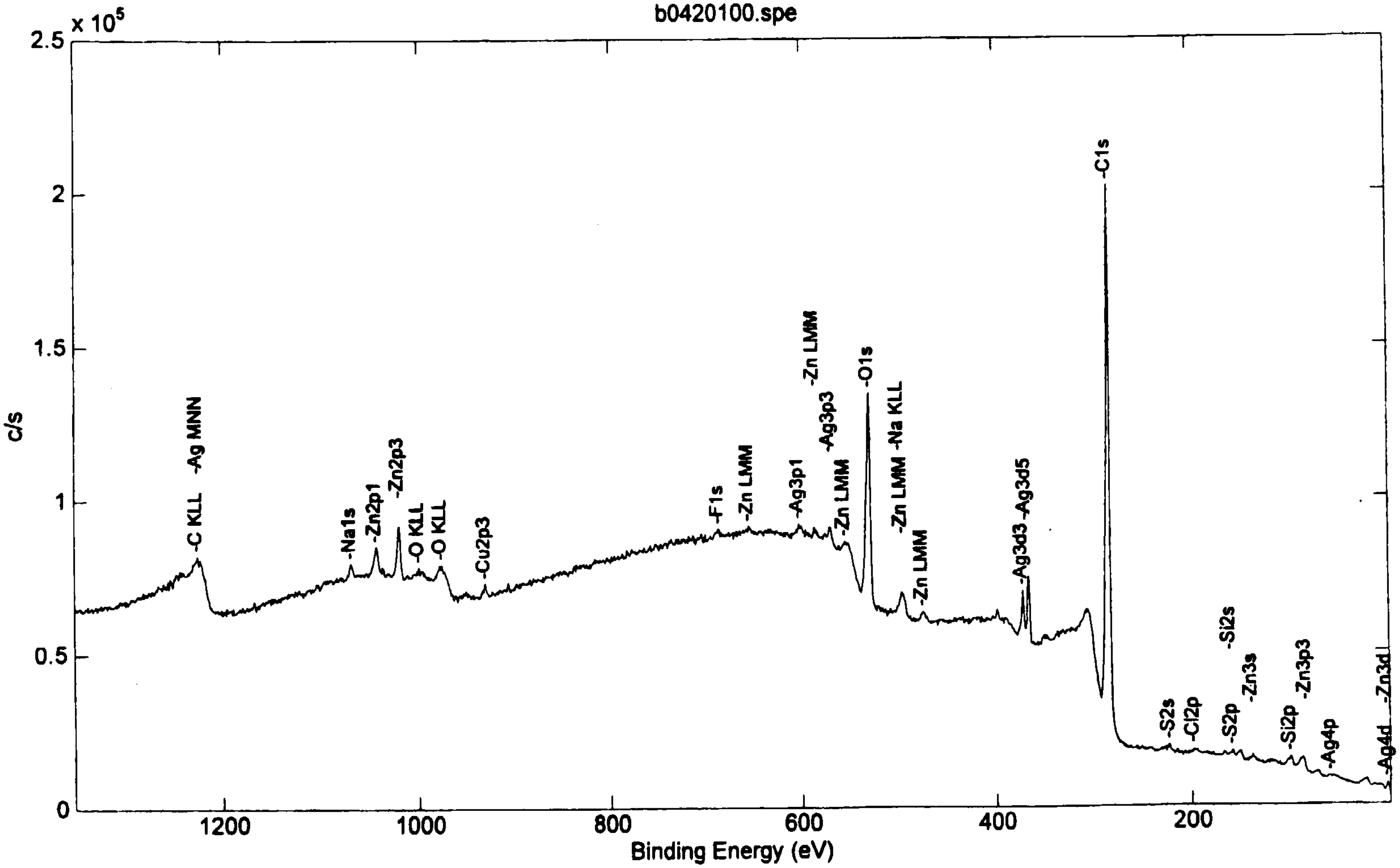
Table II

Concentration of Sulfur Species Detected (in Atom% of S)

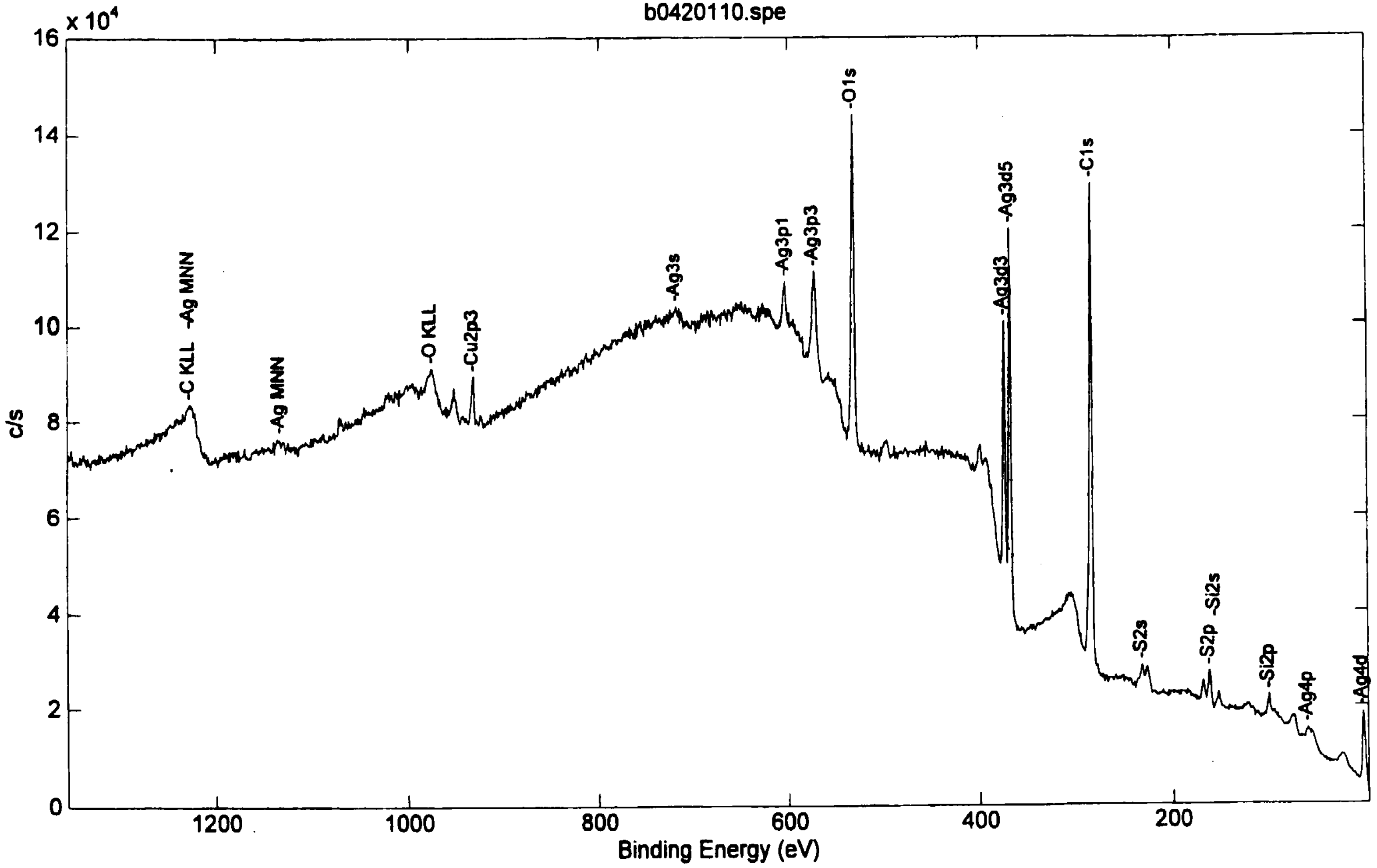
Sample	Sulfide	SOx
Bottom surface (left, as installed) of terminal strip	0.3	0.1
#6L post (cylindrical surface), stained	2.4	1.6
Near post 6R, forward surface, dark stain	0.3	0.2
Near post 6R, forward surface, tan stain	0.3	0.3
#4R connector, dark stain	-	0.1
#4 nut edge, dark stain	2.4	0.6

```
                                                              dir34.tmp
                                        DIRECTORY:  DATA

Filename       Technique Analysis  Date      Comment
============== ========= ========= ========= ===============

b0420100       ESCA      Survey    Apr 20 98 Bottom surface (left, as installed) of
b0420101       ESCA      Multiplex Apr 20 98 Bottom surface (left, as installed) of
b0420110       ESCA      Survey    Apr 20 98 #6L post (cylindrical surface), stained
b0420111       ESCA      Multiplex Apr 20 98 #6L post (cylindrical surface), stained
b0420120       ESCA      Survey    Apr 20 98 Near post 6R, forward surface, dark sta
b0420121       ESCA      Multiplex Apr 20 98 Near post 6R, forward surface, dark sta
b0420130       ESCA      Survey    Apr 20 98 Near post 6R, forward surface, tan stai
b0420131       ESCA      Multiplex Apr 20 98 Near post 6R, forward surface, tan stai
b0420140       ESCA      Survey    Apr 20 98 #4R connector, dark stain
b0420141       ESCA      Multiplex Apr 20 98 #4R connector, dark stain
b0420150       ESCA      Survey    Apr 20 98 #4 nut edge, dark stain
b0420151       ESCA      Multiplex Apr 20 98 #4 nut edge, dark stain
b0420160       ESCA      Survey    Apr 20 98 Fractured post, bulk polymer
b0420161       ESCA      Multiplex Apr 20 98 Fractured post, bulk polymer
b0420170       ESCA      Survey    Apr 21 98 fractured NTSB polymer
b0420171       ESCA      Multiplex Apr 21 98 fractured NTSB polymer
```

b0420100.spe: Bottom surface (left, as installed) of terminal strip | Evans East
98 Apr 20 Al mono 350.0 W 0.0 65.0° 187.85 eV | 2.0195e+005 max | 4.50 min
Sur1/Full/1



b0420110.spe: #6L post (cylindrical surface), stained area **Evans East**
98 Apr 20 Al mono 350.0 W 0.0 65.0° 187.85 eV 1.4418e+005 max 4.50 min
Sur1/Full/1



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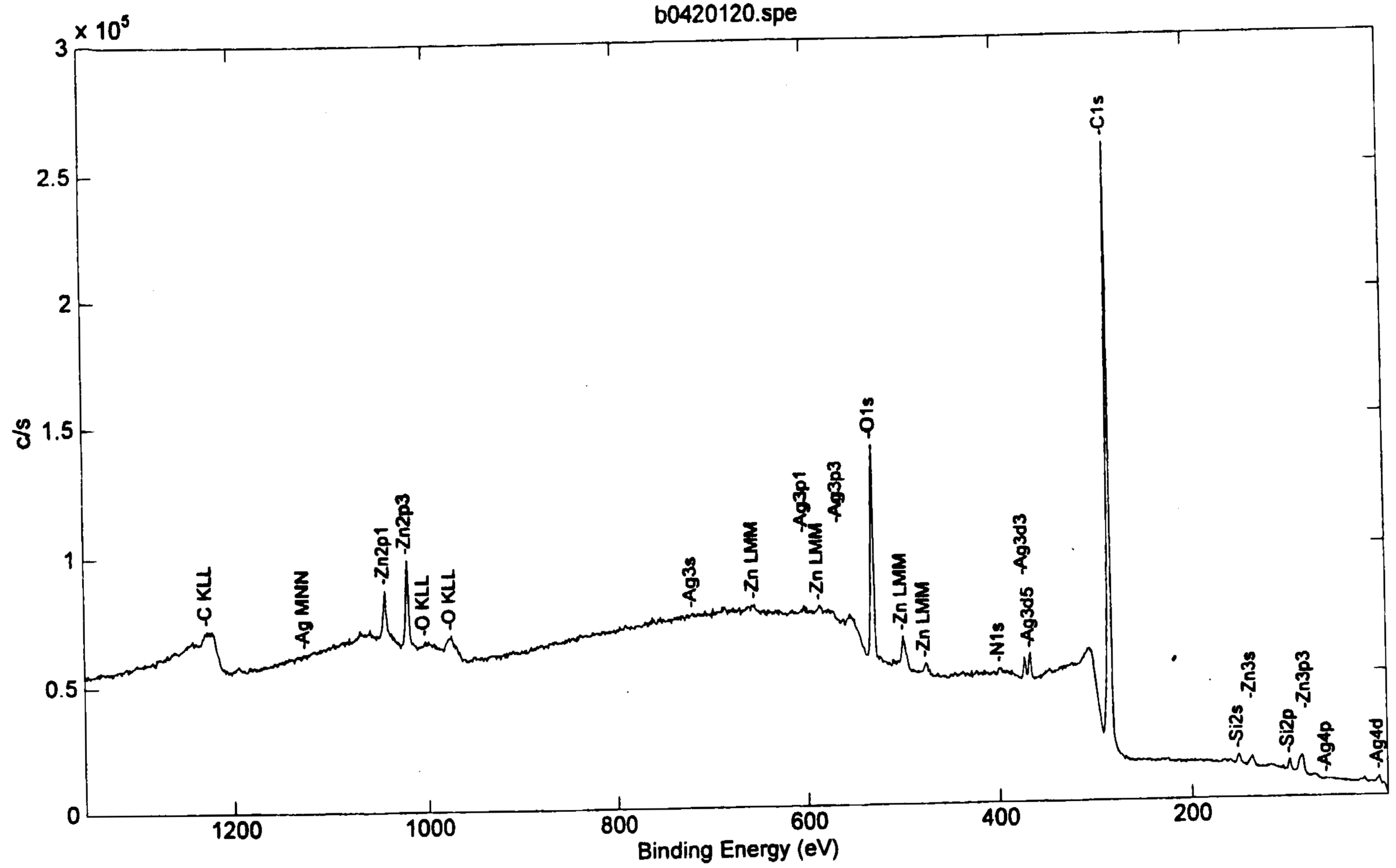
b0420120.spe: Near post 6R, forward surface, dark stain
98 Apr 20 Al mono 350.0 W 0.0 65.0° 187.85 eV
Sur1/Full/1

2.5862e+005 max

Evans East
4.50 min

b0420120.spe



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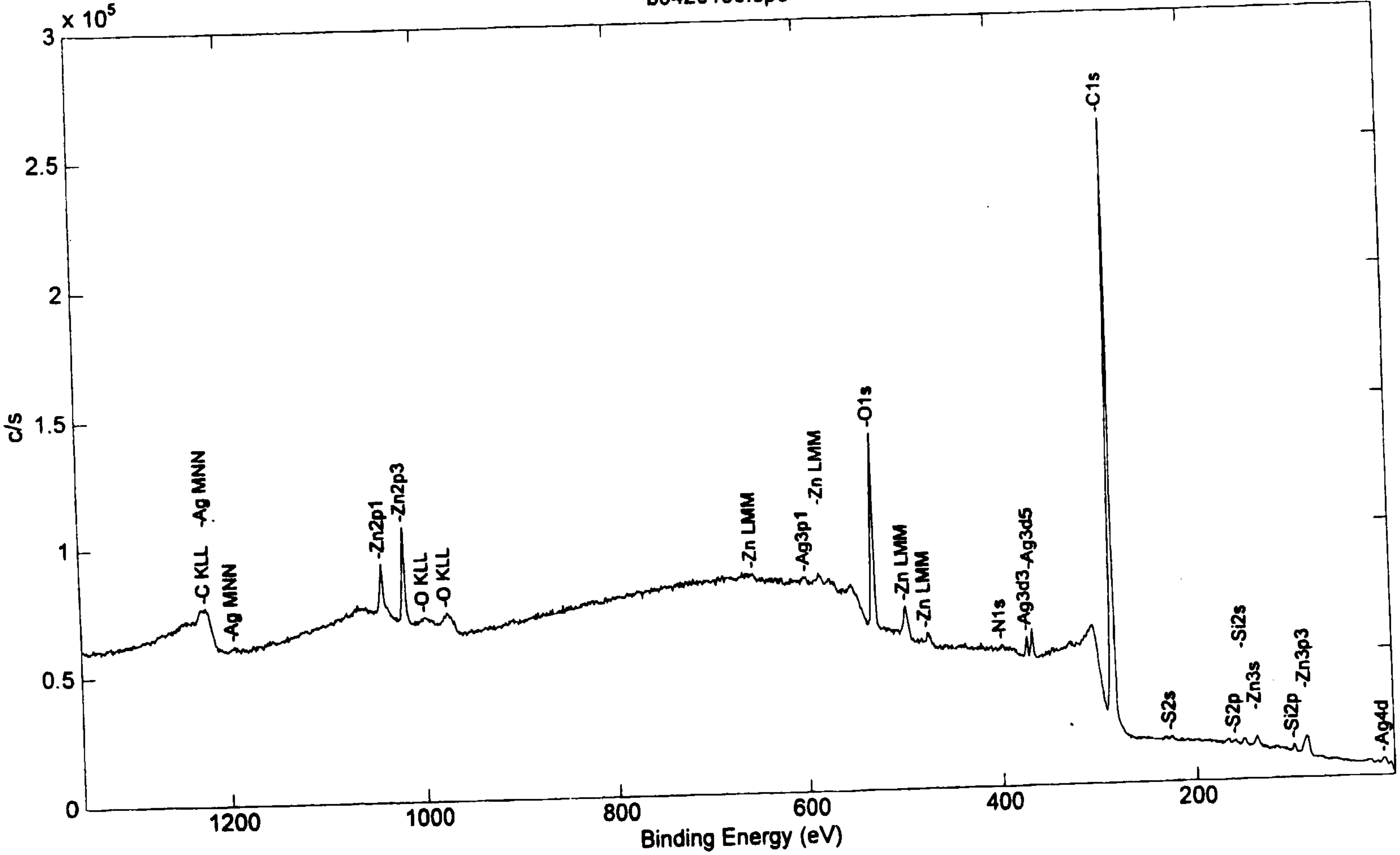
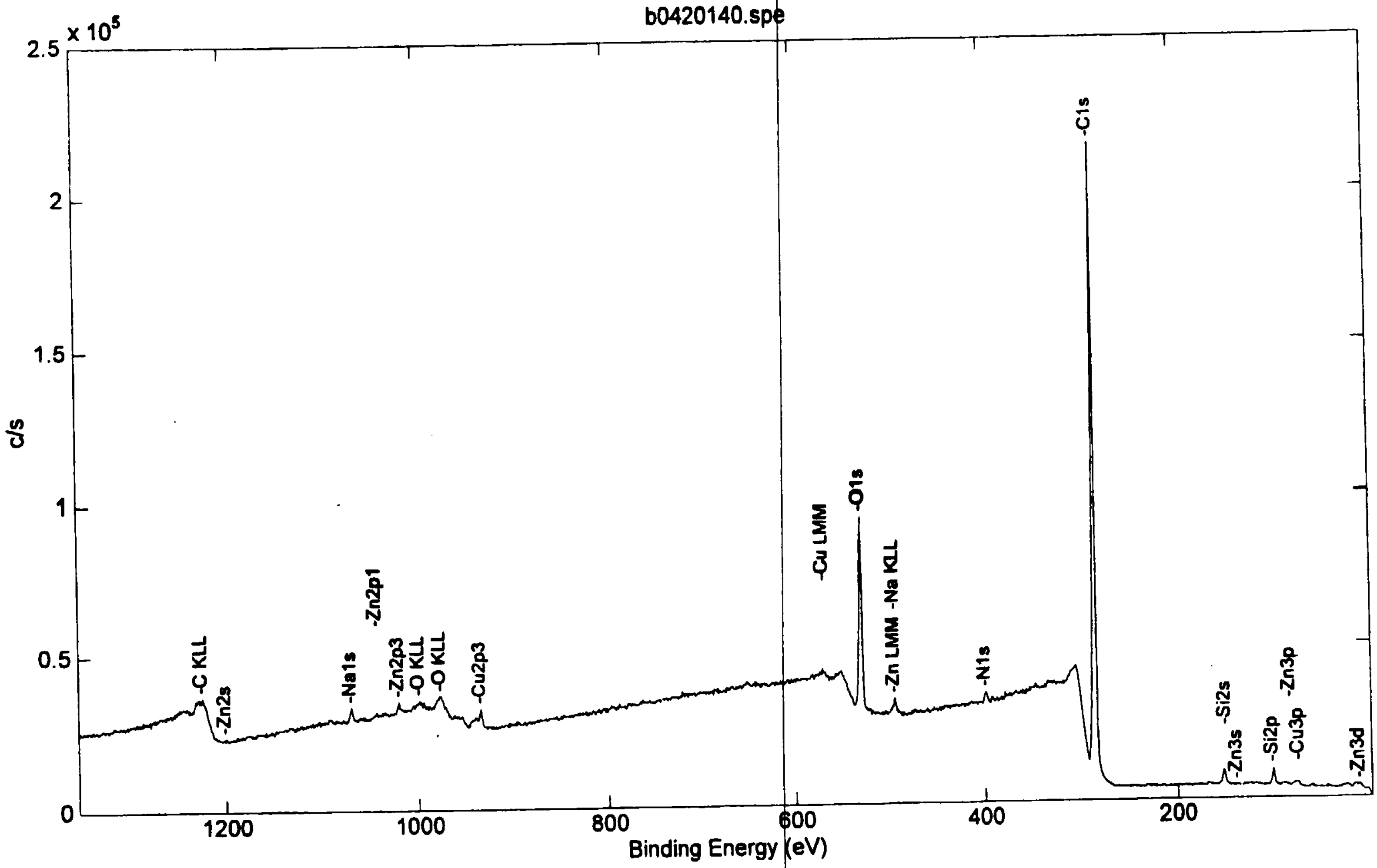
Tel: (609) 799-1904 • Fax: (609) 799-8691

b0420130.spe: Near post 6R, forward surface, tan stain | 2.5815e+005 max | Evans East
98 Apr 20 Al mono 350.0 W 0.0 65.0° 187.85 eV | | 4.50 min
Sur1/Full/1


b0420130.spe

b0420140.spe: #4R connector, dark stain
98 Apr 20 Al mono 350.0 W 0.0 65.0° 187.85 eV
Sur1/Full/1

Evans East
2.1478e+005 max
4.50 min



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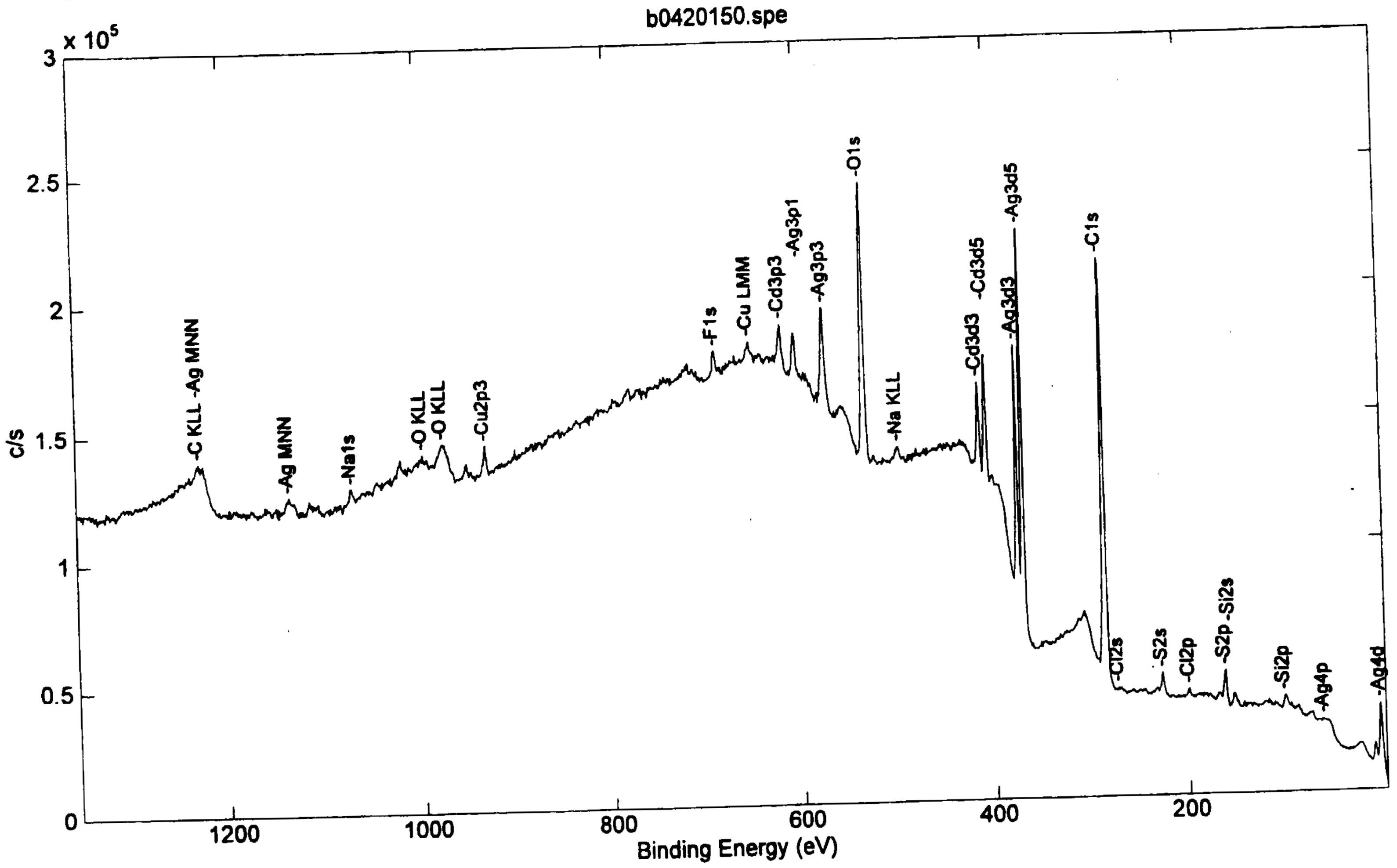
b0420150.spe: #4 nut edge, dark stain
98 Apr 20 Al mono 350.0 W 0.0 65.0° 187.85 eV
Sur1/Full/1

2.4309e+005 max

Evans East
4.50 min



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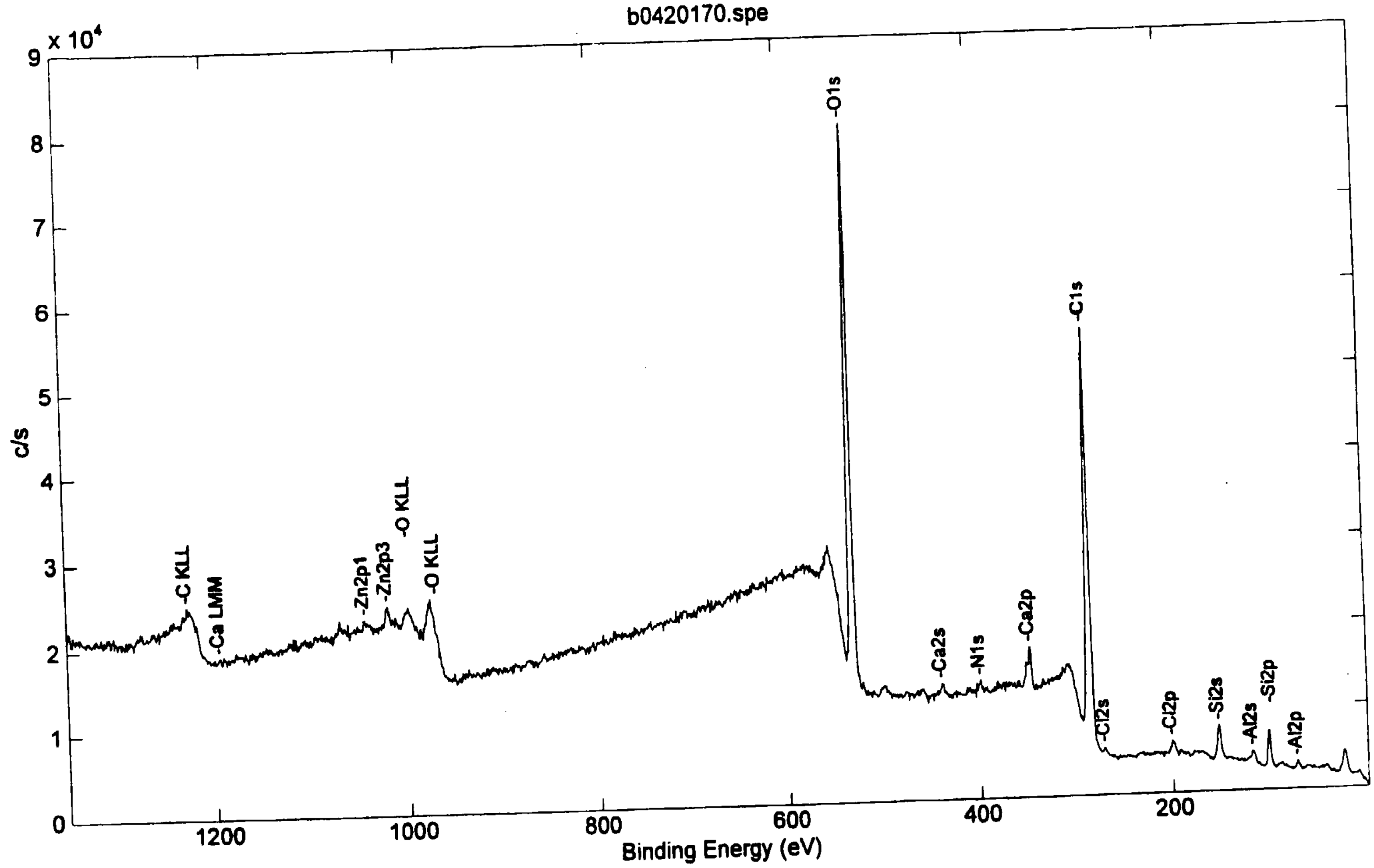
b0420170.spe: fractured NTSB polymer
98 Apr 21 Al mono 350.0 W 0.0 65.0° 187.85 eV
Sur1/Full/1

7.9994e+004 max

Evans East
4.50 min



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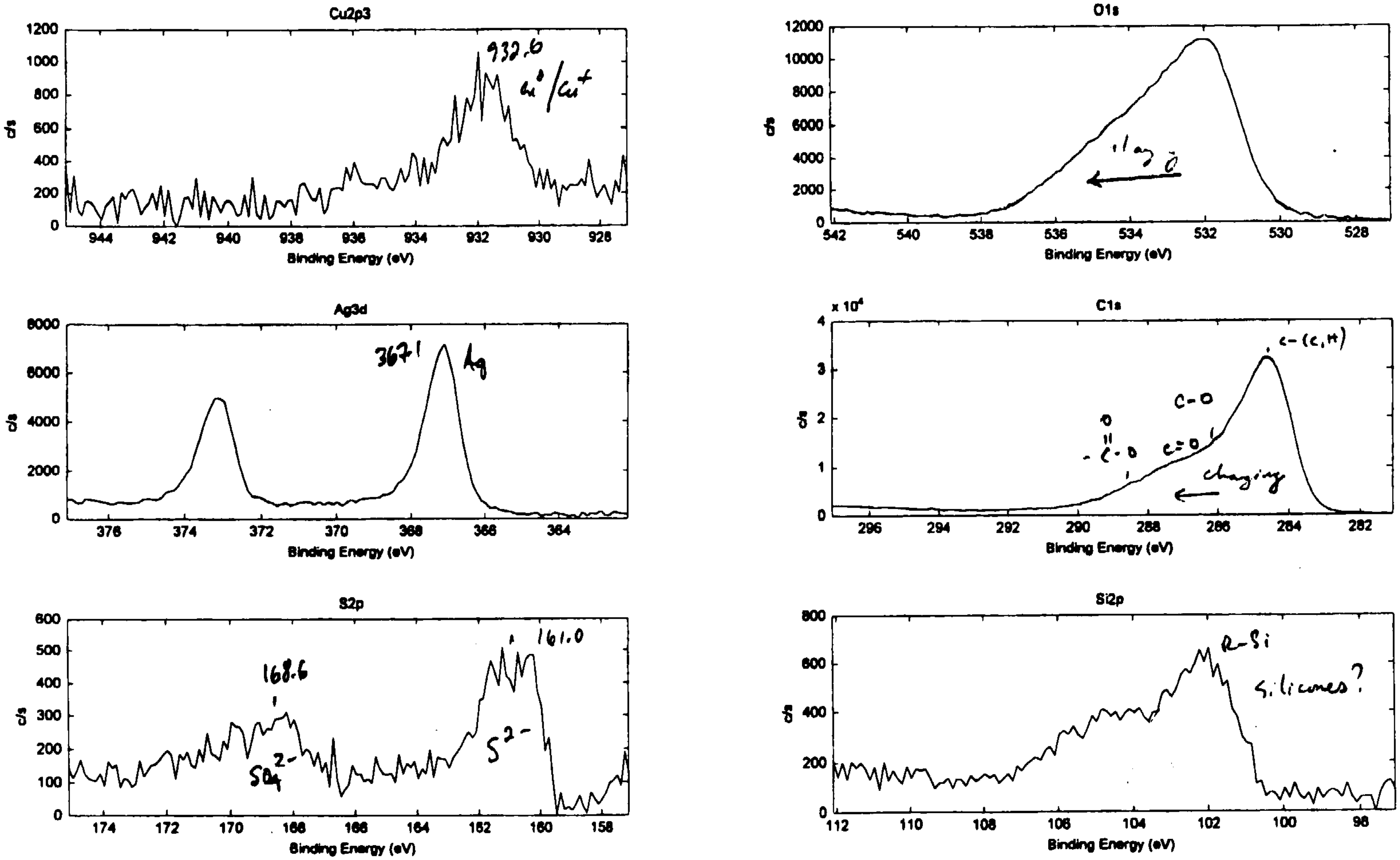
b0420101.spe: Bottom surface (left, as installed) of terminal strip | Evans East
98 Apr 20 Al mono 350.0 W 0.0 65.0° 29.35 eV | 3.4294e+004 max | 1.08 min
C1s/Full/1 (Shft)

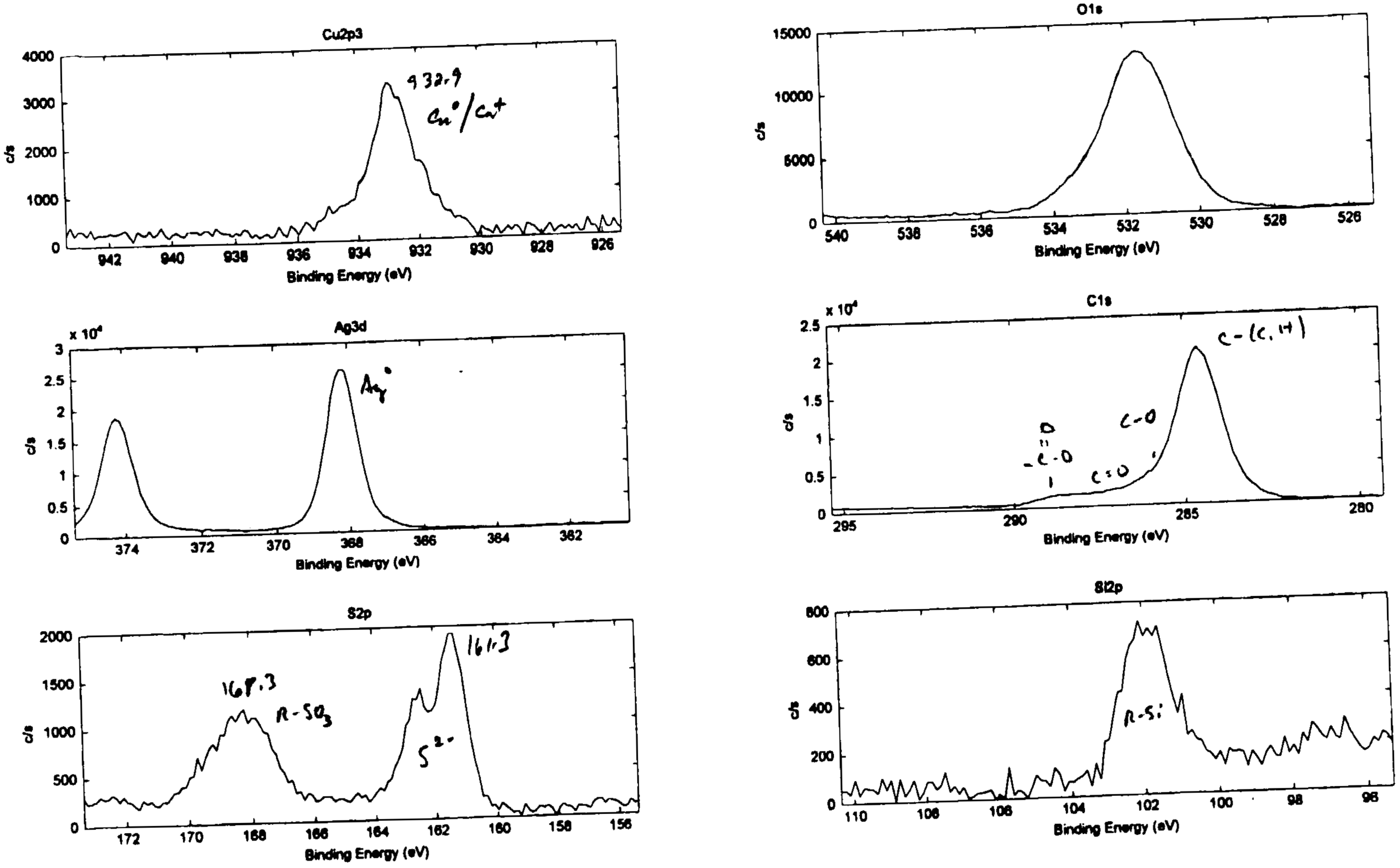


EVANS EAST
SPECIALISTS IN MATERIALS CHARACTERIZATION
Tel: (609) 799-1904 • Fax: (609) 799-8691

b0420111.spe: #6L post (cylindrical surface), stained area
98 Apr 20 Al mono 350.0 W 0.0 65.0° 29.35 eV
C1s/Full/1 (Shft)

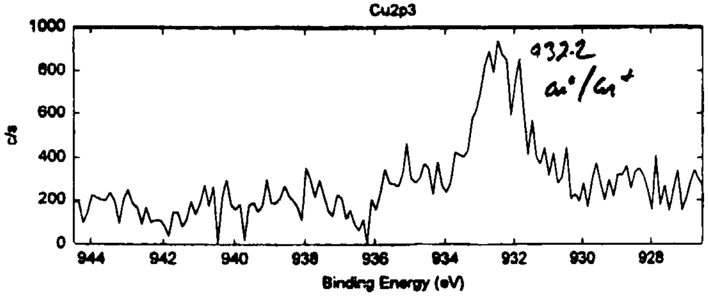
2.3167e+004 max

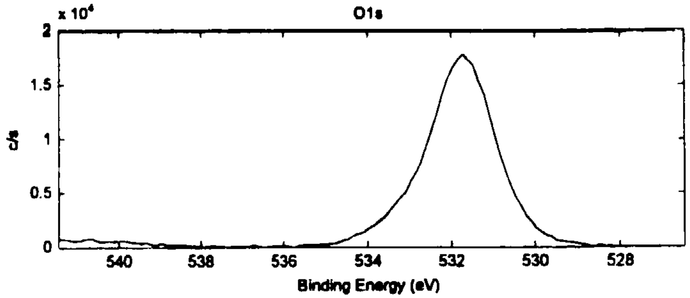
Evans East
1.61 min

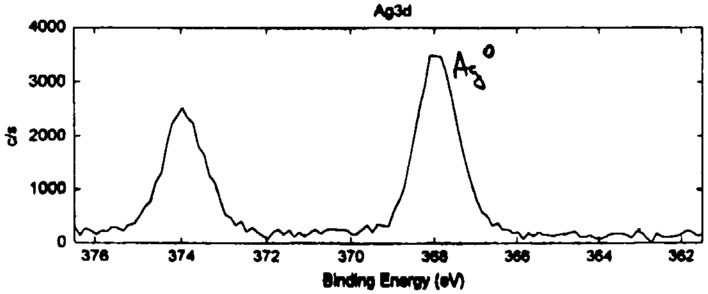


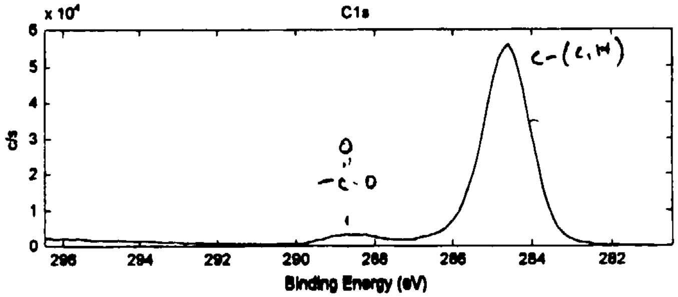
EVANS EAST
SPECIALISTS IN MATERIALS CHARACTERIZATION
Tel: (609) 799-1904 • Fax: (609) 799-8691

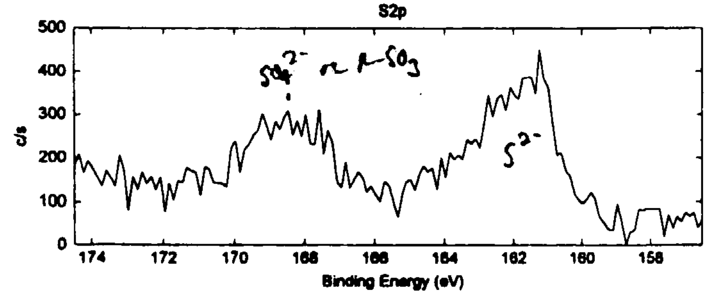
b0420121.spe: Near post 6R, forward surface, dark stain Evans East
98 Apr 20 Al mono 350.0 W 0.0 65.0° 29.35 eV 5.7652e+004 max 32.25 s
C1s/Full/1 (Shft)

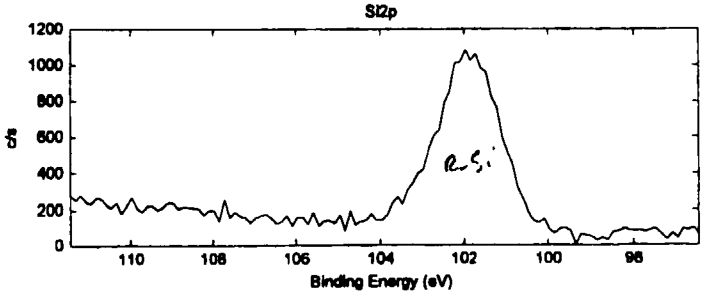












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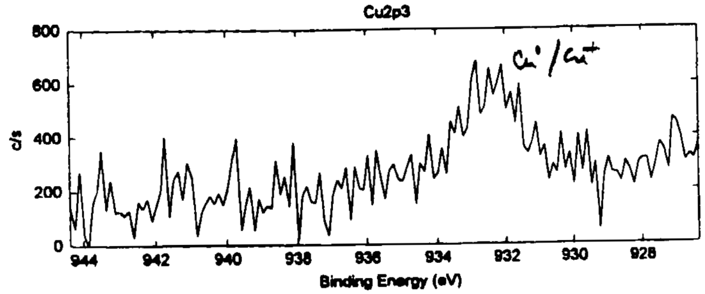
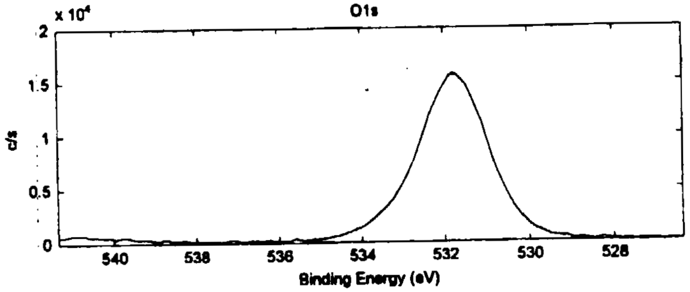
Tel: (609) 799-1904 • Fax: (609) 799-8691

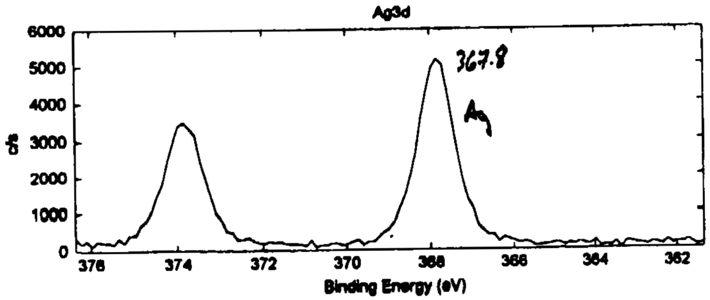
b0420131.spe: Near post 6R, forward surface, tan stain
98 Apr 20 Al mono 350.0 W 0.0 65.0° 29.35 eV
C1s/Full/1 (Shft)

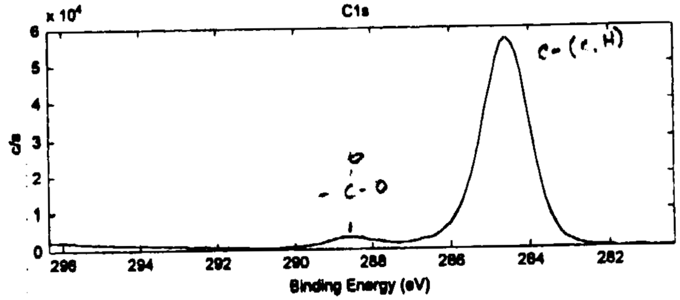
5.8892e+004 max

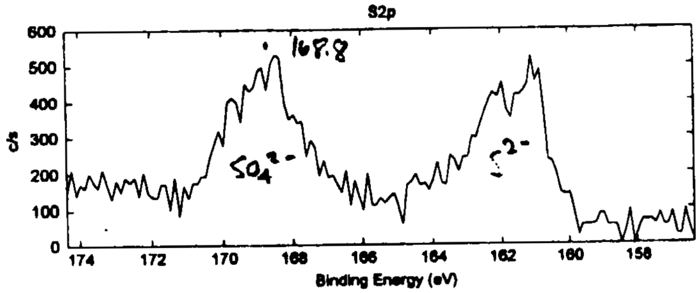
Evans East
32.25 s

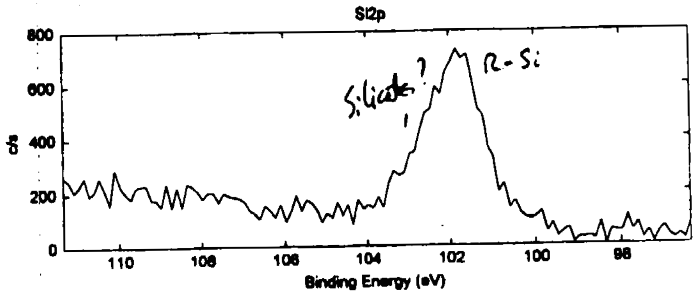












EVANS EAST
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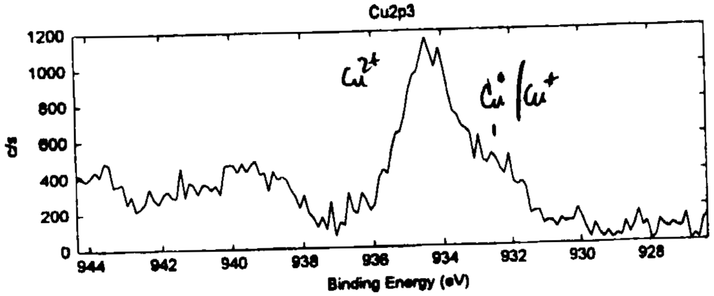
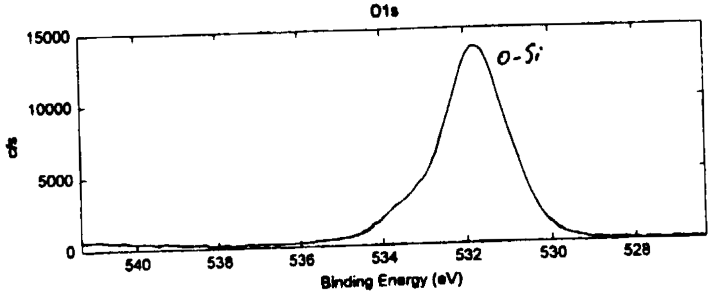
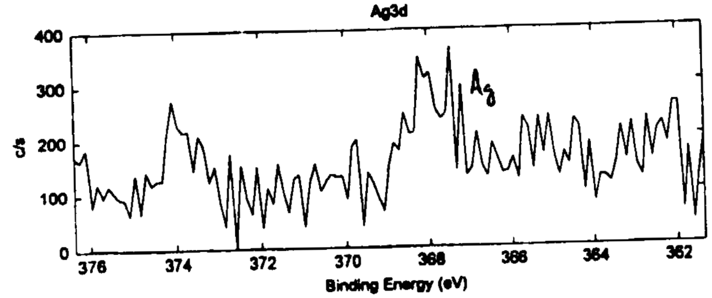
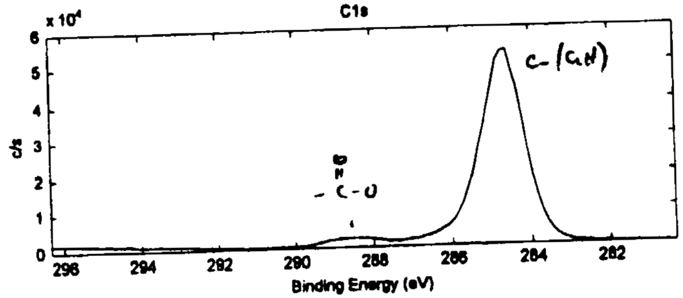
Tel: (609) 799-1904 • Fax: (609) 799-8691

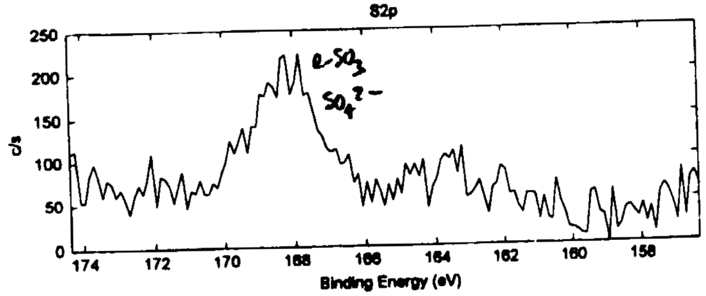
b0420141.spe: #4R connector, dark stain 5.3804e+004 max Evans East
98 Apr 20 Al mono 350.0 W 0.0 65.0° 29.35 eV 32.25 s
C1s/Full/1 (Shft)

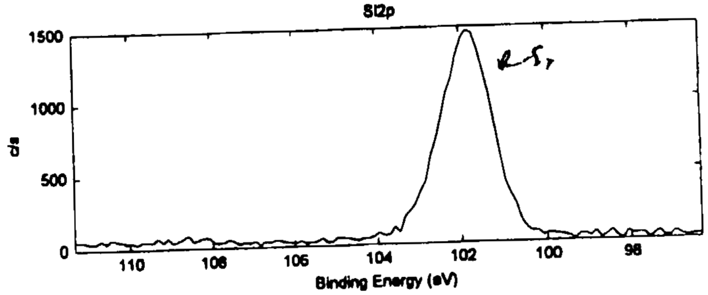












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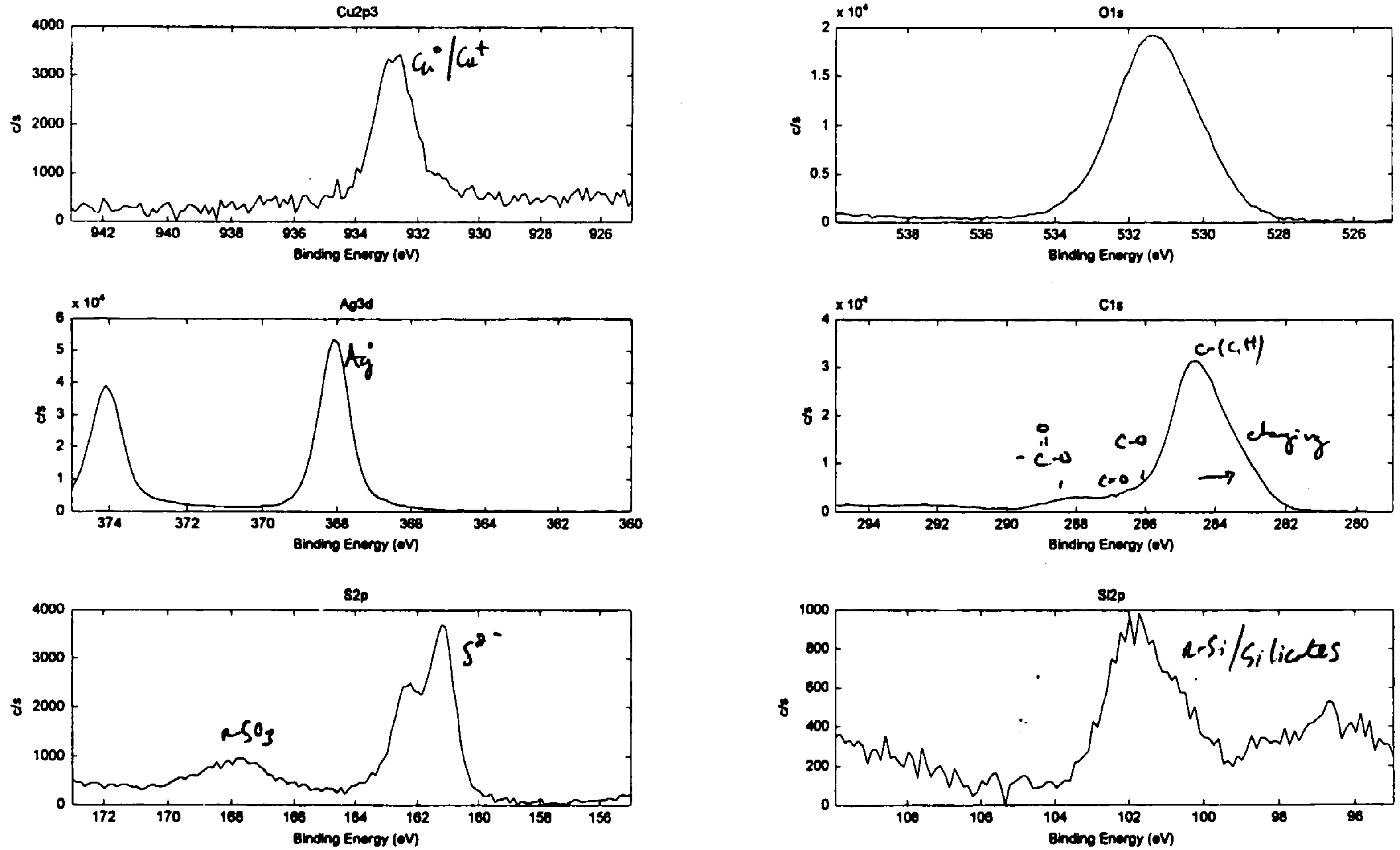
Tel: (609) 799-1904 • Fax: (609) 799-8691

b0420151.spe: #4 nut edge, dark stain — Evans East
98 Apr 20 Al mono 350.0 W 0.0 65.0° 29.35 eV — 4.3960e+003 max — 0.50 s
C1s/Full/1 (Shft)



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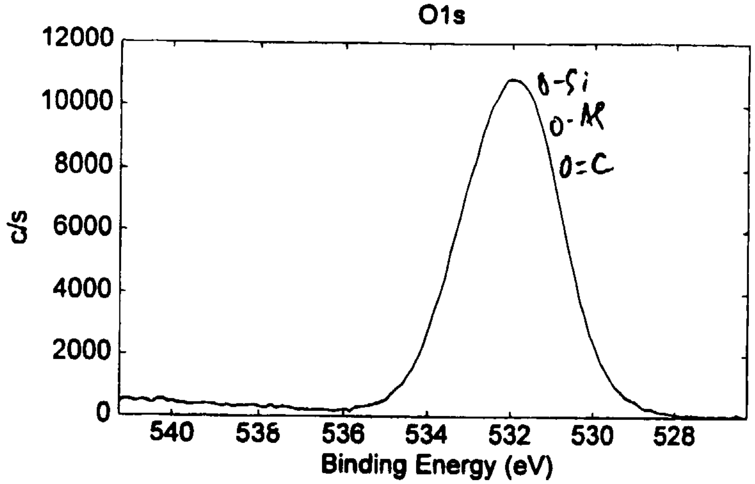
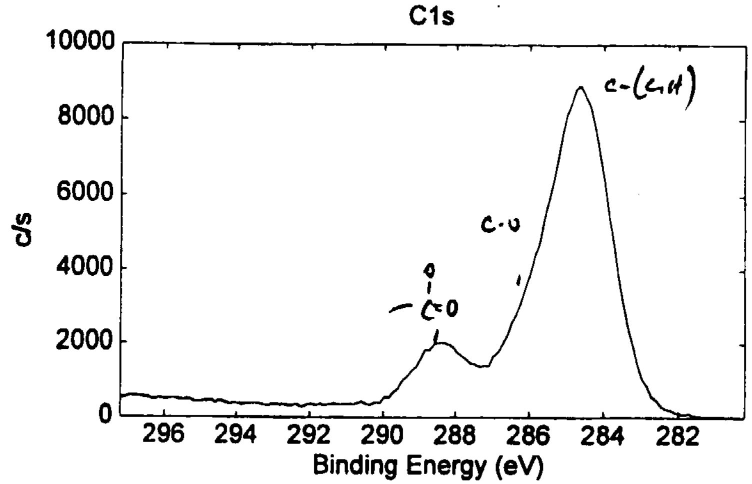
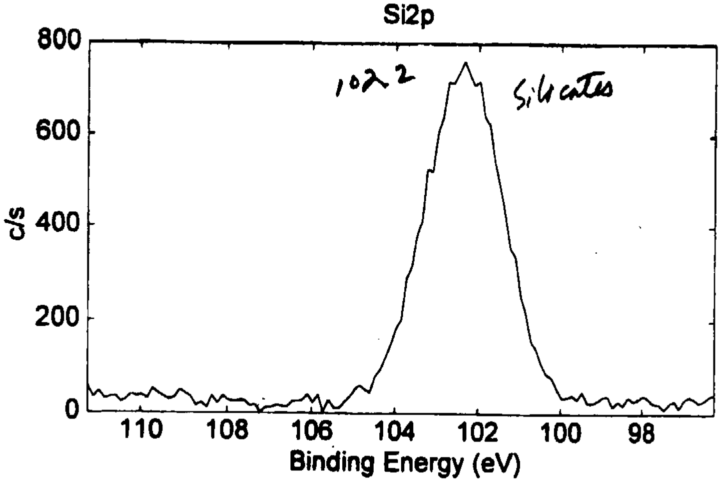
Tel: (609) 799-1904 • Fax: (609) 799-8691

b0420171.spe: fractured NTSB polymer **Evans East**
98 Apr 21 Al mono 350.0 W 0.0 65.0° 29.35 eV 9.3350e+003 max 2.28 min
C1s/Full/1 (Shft)







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EVANS EAST
SPECIALISTS IN MATERIALS CHARACTERIZATION

April 22, 1998

Dr. Merritt M. Birky
United States of America
National Transportation Safety Board
490 L'Enfant Plaza East, S.W.
Washington, D.C. 20594

Tel: (202) 314) 6503
Fax: (202) 314-6599
email: birkym@ntsb.gov

Invoice #: 98-967
Problem #: 24-438
PO #: 12-98-SP0249

Dear Merritt,

Enclosed are the results of the positive and negative ion TOF-SIMS analysis of three (3) sections of one (1) wire bus bar which we analyzed during your visit on 4/20/98. This analysis will be billed at the visit rate of $562.50 per hour for which your purchase order will be billed a total of $1,687.50 (3 hrs). Please inform your accounting/receiving department that you have received your data.

We hope these results are of use to you. If you have any questions about them, please do not hesitate to contact me or Jeff Shallenberger. Please let us know if we may be of service to you again concerning your surface characterization needs.

Sincerely,

Dave Cole
Manager, AES/SEM/TOF-SIMS/XPS

Enclosures

666 Plainsboro Road • Suite 1236 • Plainsboro • New Jersey • 08536 • Tel: (609) 799-1904
Fax: (609) 799-8691 • E-mail: staff@evanseast.com • Web site: http://www.evanseast.com

EVANS EAST
SPECIALISTS IN MATERIALS CHARACTERIZATION

TIME-OF-FLIGHT SECONDARY ION MASS SPECTROMETRY ANALYTICAL REPORT

April 22, 1998

PREPARED FOR:

Dr. Merritt M. Birky
United States of America
National Transportation Safety Board

PREPARED BY:

David A. Cole
Manager
Time-of-Flight Secondary Ion Mass Spectrometry

REVIEWED BY:

Jeffrey R. Shallenberger
Senior Analyst
X-ray Photoelectron Spectroscopy

666 Plainsboro Road • Suite 1236 • Plainsboro • New Jersey • 08536 • Tel: (609) 799-1904

TIME-OF-FLIGHT SECONDARY ION MASS SPECTROMETRY ANALYTICAL REPORT

April 22, 1998

RE: Invoice #: 98-967
Problem #: 24-438
PO #: 12-98-SP0249

Purpose: To characterize the surface of three (3) sections of one (1) wire bus bar by obtaining positive and negative static SIMS spectra.

Analytical conditions:

Instrument	Physical Electronics, PHI-Evans TFS-2000
Primary ion beam	$^{69}Ga^+$ liquid metal ion gun
Primary beam voltage	15 kV
Nominal analysis region	$(120\ \mu m)^2$
Gun aperture	3
Charge neutralization	no
Post acceleration	8000 V
Contrast diaphragm	0
Energy slit	yes

Experimental:

The samples were cut to appropriate size with either a saw or a razor blade to facilitate sample mounting. Positive and negative TOF-SIMS spectra were obtained for each sample. Typical primary ion doses were less than 10^{12} ions/cm^2 for the analysis. This assures that the data were collected within the static limit, i. e., less than 1% of a monolayer was sputtered. Thus, all molecular fragments are indicative of species existing on the surfaces prior to analysis. Under these conditions, the sampling depth of TOF-SIMS is 1 monolayer for molecular fragment ions and 1-3 monolayers for atomic species. Mass spectra are plotted as the number of secondary ions detected (Y-axis) versus the mass-to-charge ratio of the ions (X-axis).

Results:

All three surfaces are quite similar as expected based on the XPS results. Intense inorganic species detected were: Na^+, Si^+, Cu^+, Ag^+, F^-, Cl^-, Br^-, S^-, SO_x^-, and ion characteristic of polydimethyl siloxane (see Table 1). Minor inorganic species detected were: Li^+, B^+, Al^+, K^+, Ca^+, Cr^+, Fe^+, and Zn^+. The positive spectra contain a series of nitrogen-containing ions separated by 28 m/z (C_2H_4) starting around 300 m/z and going through 600 m/z. The best assignments for these are saturated aliphatic amides $(CH_2)_nH_2NO^+$. Two other series of positive ions were observed at higher masses. The first is between 600 and 700 m/z and the second is between 850 and 950 m/z. These ions are most likely metal (Cu or Ag) cationized aliphatic compounds given the low fractional masses (e.g. 641.3 m/z). Unfortunately exact structures could not be determined. My best guess is that the actual aliphatic compounds have a molecular weight distribution around 420 m/z and are unlikely to contain nitrogen. The negative spectra contain a series of aliphatic acid between 200 and 300 m/z. Most of these are fully saturated fatty acids $(CH_2)_nCO_2^-$. However mono-unsaturated fatty acids such as oleic acid $C_{18}H_{33}O_2^-$ (281 m/z) were also detected. Two other high mass negative ions were observed at 459.3 and 585.4 m/z. Likely formula for these are $C_{28}H_{43}SO_3^-$ and $C_{37}H_{61}SO_3^-$ suggesting that they are aliphatic naphthalene sulfonates a class of compounds which are used as rust or corrosion inhibitors.

Although the intense S^- and SH^- ions are strong indicators of metal sulfides, the spectra are rather inconclusive as to whether Cu or Ag sulfides are present. Most of the identifiable clusters are $CuO_xH_y^-$ and $CuSO_xH_y^-$ or $AgO_xH_y^-$ and $AgSO_xH_y^-$.

Conclusions:

All of the polymer surfaces were nearly the same. Species identified were: Cu, Ag, metal sulfides, aliphatic amides and acids, aliphatic naphthalene sulfonates, and polydimethyl siloxane. Two series of positive ions above 550 m/z are likely to be metal adducts of aliphatic compounds which could not be identified. The surfaces might also contain aliphatic hydrocarbons however the low ion yields for this class of compounds makes them very difficult to detected.

If you have any questions after you have examined the data, please feel free to contact me or Jeff Shallenberger at (609) 799-1904. Thank you for choosing Evans East.

Table 1

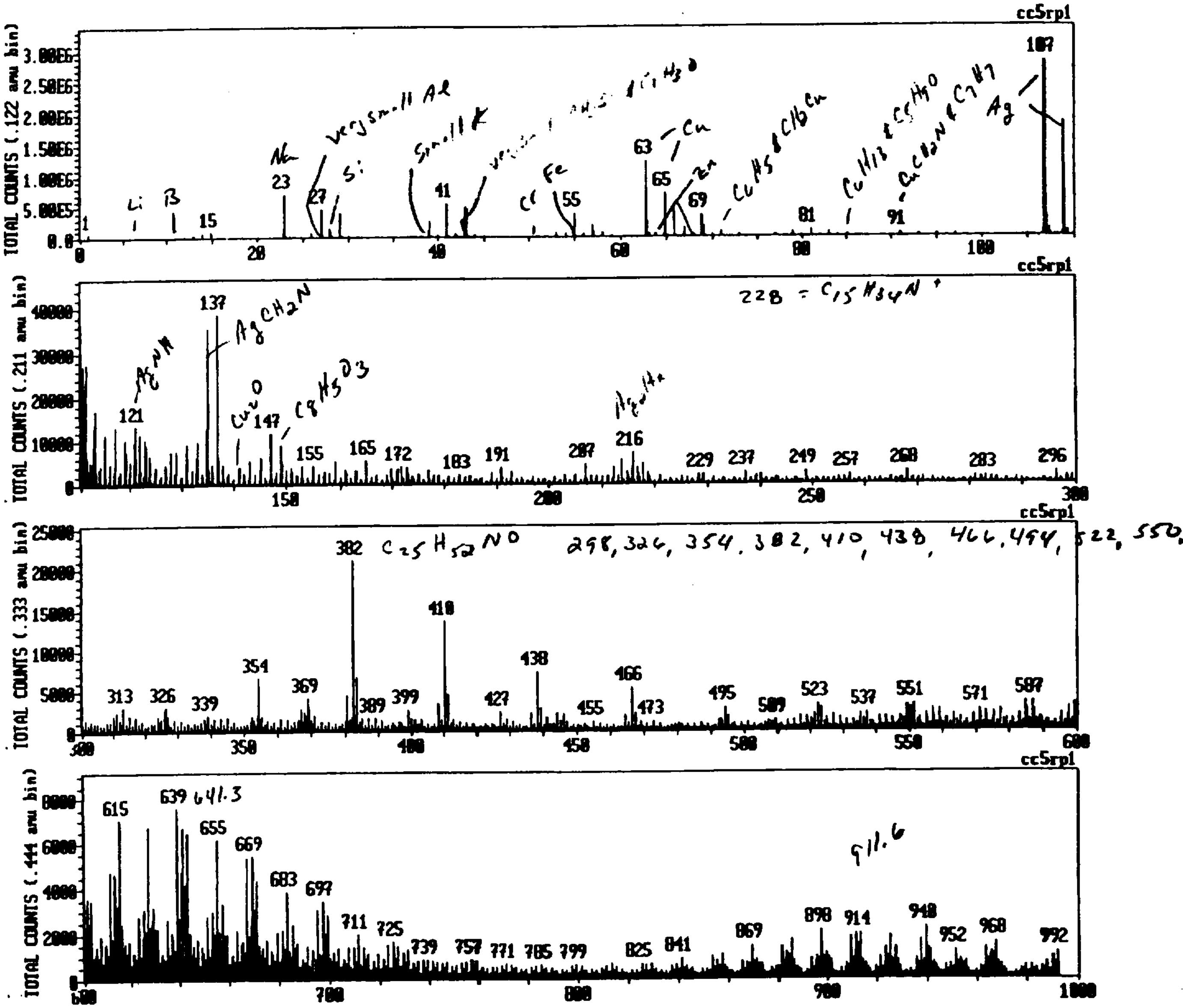
Summary of PDMS Ions

Mass	Species
28	Si^+
45	$SiOH^+$
29, 103, 177, 251, 325, 399, 473, 547, 621, 695,...	$SiH(C_2H_6SiO)_x^+$
43, 117, 191, 265, 339, 413, 487, 561, 635,...	$CH_3Si(C_2H_6SiO)_x^+$
59, 133, 207, 281, 355, 429, 503, 577, 651,...	***$CH_3SiO(C_2H_6SiO)_x^+$***
73, 147, 221, 295, 369, 443, 517, 591, 665,...	***$C_3H_9Si(C_2H_6SiO)_x^+$***
87, 161, 235, 309, 383, 457, 531, 605, 679,...	$CH_3Si_2O(C_2H_6SiO)_x^+$
28	Si^-
60	SiO_2^-
29, 103, 177, 251, 325, 399, 473, 547, 621,...	$SiH(C_2H_6SiO)_x^-$
45, 119, 193, 267, 341, 415, 489, 563, 637,...	$SiOH(C_2H_6SiO)_x^-$
59, 133, 207, 281, 355, 429, 503, 577, 651,...	$CH_3Si(C_2H_6SiO)_x^-$
75, 149, 223, 297, 371, 445, 519, 593, 667,...	***$CH_3SiO_2(C_2H_6SiO)_x^-$***
89, 163, 237, 311, 385, 459, 533, 607, 681,...	$C_3H_9SiO(C_2H_6SiO)_x^-$

Most intense ions are in ***bold - italic***

Table of Contents

Evans East
666 Plainsboro Road, Suite 1236
Plainsboro, NJ USA
Phone: (609) 799-1904   FAX: (609) 799 8691



FILE NAME: cc5rpl   DATE : 20 Apr 98 14:30   ACQUISITION TIME: 15.0 MIN.   SPECTRUM INTEGRAL : 19204632
Inside surface of plastic sleeve from crimp connect 5R;   15 kV bunched, cd0, ga3 aw4, pa8K dv1700, noes, cc10
+ IONS   PRIMARY GUN: LMIG   TIME RECORDER: Multi-Stop TDC   X-Y SOURCE: Raster   TIME PER CHANNEL: 130 ps
DATA SET: 1 Spectra; 3 Image(s)   RASTER SIZE: 121µm   RASTER TYPE: 121

FIGURE 1

PDMS ions
28, 73, 147, 207, 221, 281

Evans East
666 Plainsboro Road, Suite 1236
Plainsboro, NJ USA
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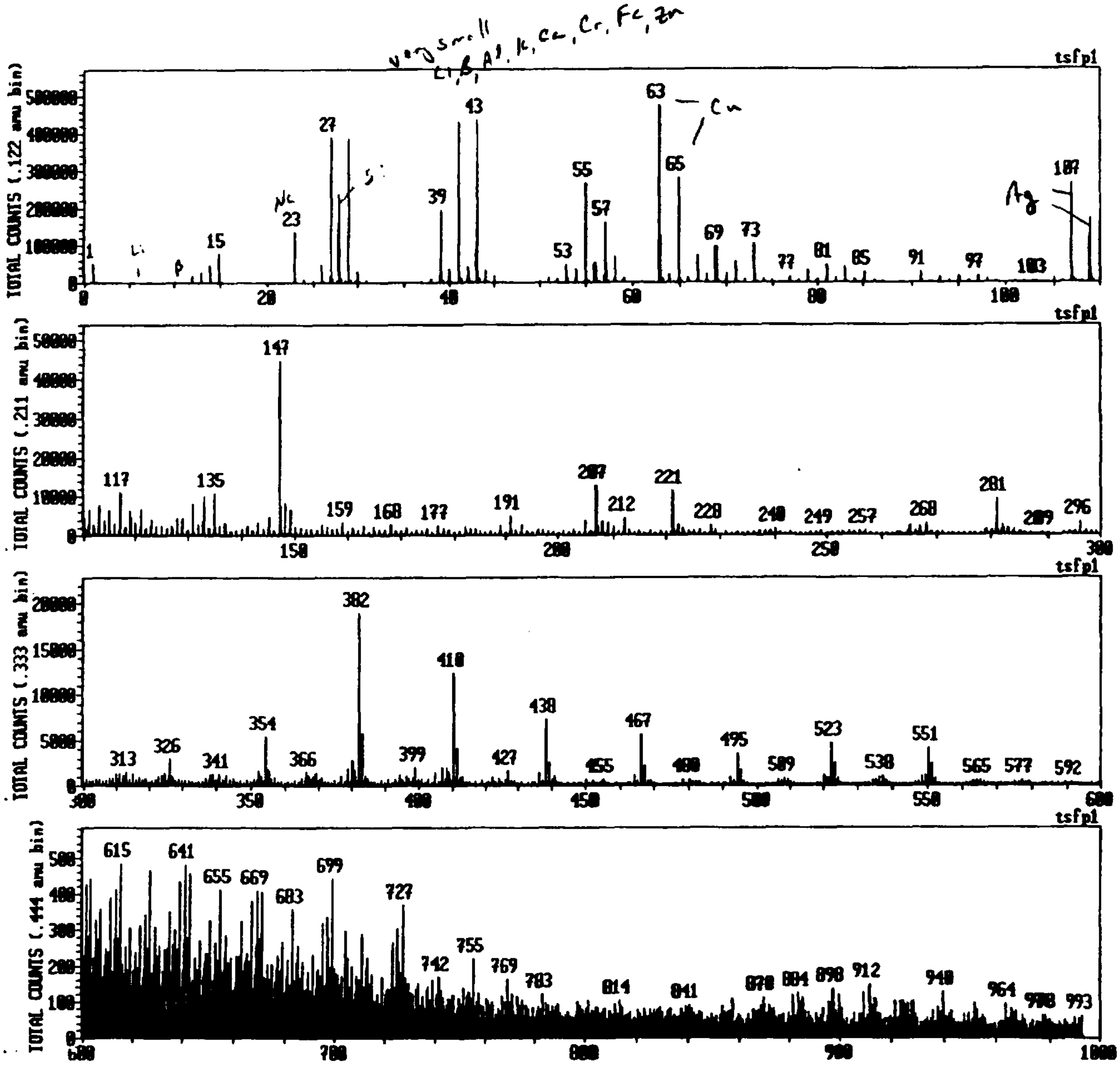
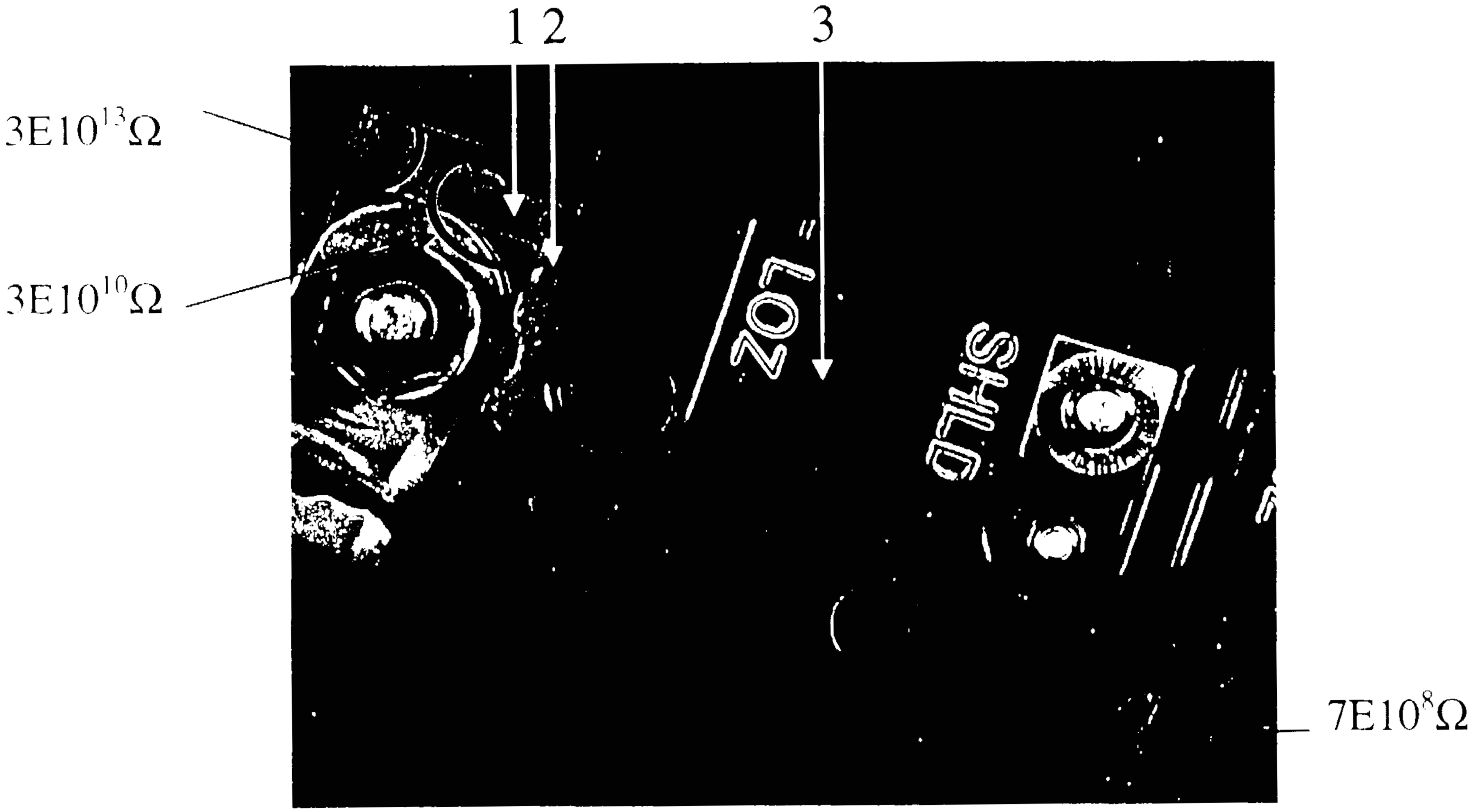


FILE NAME: tsfp1   DATE : 20 Apr 98 14:15   ACQUISITION TIME: 15.0 MIN.   SPECTRUM INTEGRAL : 7320953
Terminal strip flange between 5L and 6L; 15 kV bunched, cd0, ga3 aw4, pa8K dv1700, noes, cc10
+ IONS   PRIMARY GUN: LMIG   TIME RECORDER: Multi-Stop TDC   X-Y SOURCE: Raster   TIME PER CHANNEL: 138 ps
DATA SET: 1 Spectra; 3 Image(s)   RASTER SIZE: 121µm   RASTER TYPE: 121

FIGURE 2



Evergreen Fuel Probe 420A14 SN Z-60
Surface resistance measurements taken in circled areas
XPS measurements were taken at points 1, 2, and 3
Figure 1

AFRL/MLSA
David Johnson
6-9163

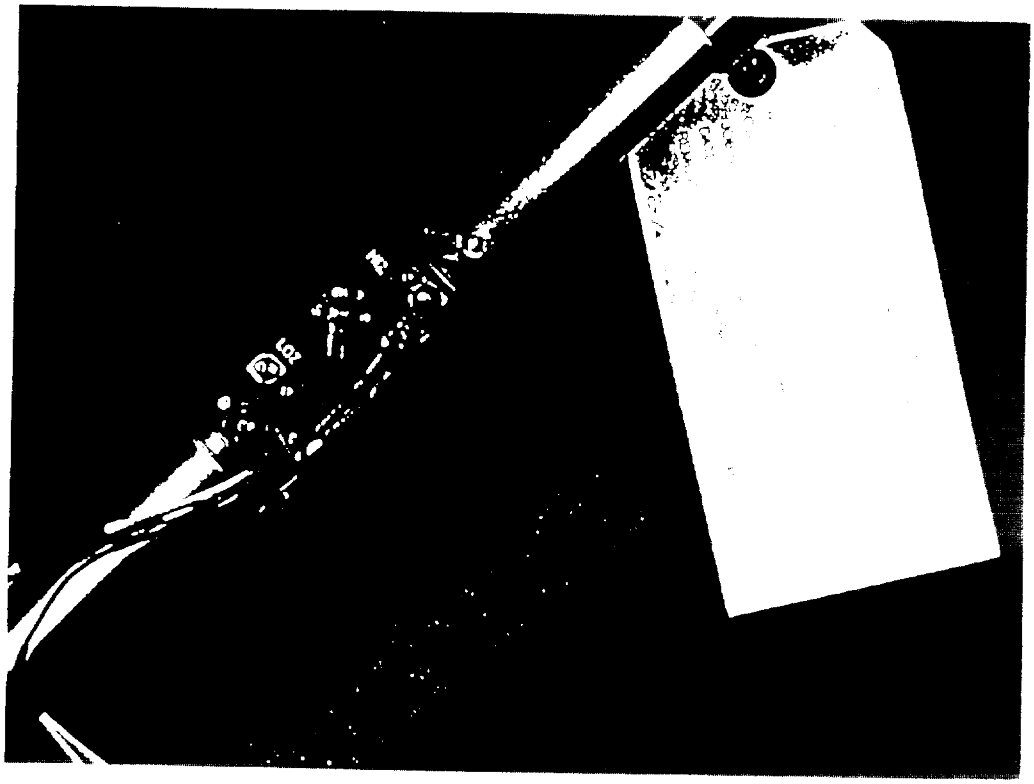


Figure 1. Extension fuel "as received" (identified as 120A[illegible]

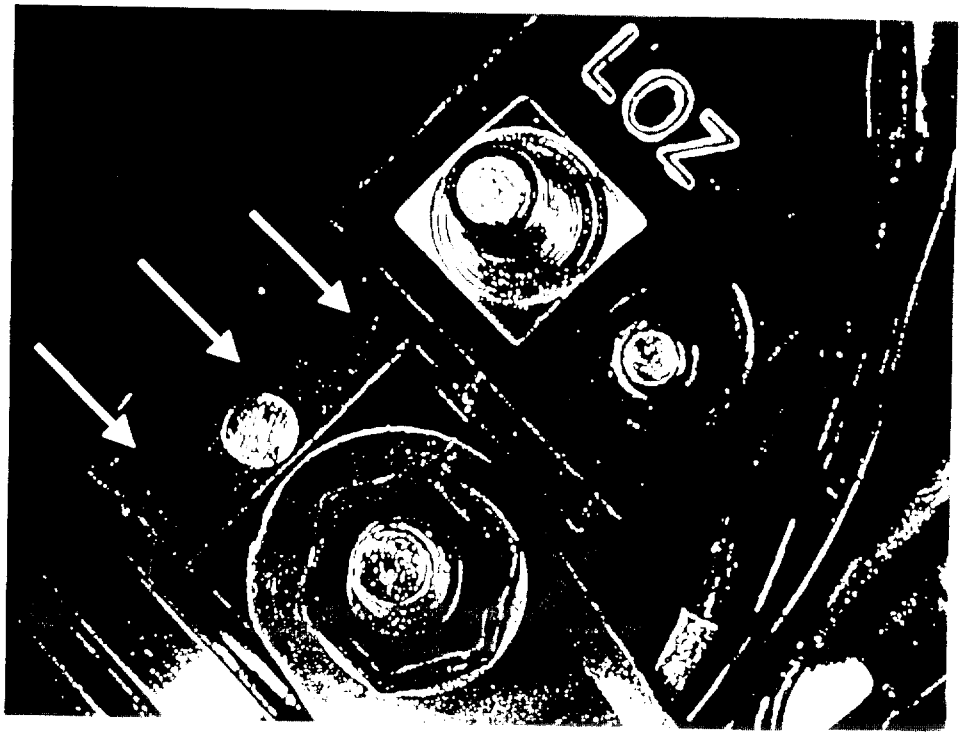


Figure 2. Close-up [illegible] noted near the LOZ [illegible]

Appendix D

Materials Analysis of Residue Test Samples

A JEOL JSM-5800 low-vacuum scanning electron microscope (SEM) with X-ray energy dispersive spectroscopy (EDS) was used to determine if silver paint contaminated the region between the silver dots on the residue surface. The EDS unit consisted of a NORAN Instruments VOYAGER X-ray Microanalysis and Digital Imaging System. A Pioneer Zmax30 detector was used with a SiLi crystal and thin film window for light element detection. The SEM was operated in low vacuum and backscatter mode to reduce charging effects. Imaging and EDS was conducted at 20KV. Silver dots were placed approximately 1.2 millimeters apart on a new high purity carbon stub, as a control. A digital multimeter with probes was used to measure the resistance between the silver dots. The resistance was found to vary between 1.9 and 3.8 ohms between the dots 1.2 mm apart, and 1.3 to 2.7 ohms between the dots 2mm apart.

EDS linescans were used to determine elemental composition along a line between two designated points. The analysis area is represented by the line that appears in the micrograph image. The line started at one silver dot and ended at the other dot. In this way, the elemental composition could be determined in a line connecting the two dots, which included the carbon stub surface in between the two dots. The linescan found primarily carbon between the two silver dots (figure 1). The dots themselves contained silicon as well as silver.

A section of the terminal strip without any visible deposit or residue was examined with EDS. A comparison of a nonresidue and residue area is shown in figure 2. Note the absence of silver (Ag), copper (Cu), and sulfur (S) peaks in the nonresidue area. A linescan was generated on the untested residue film on the terminal strip between terminals 3 and 4 (figure 3). Two silver dots had been applied to the residue. The linescan predictably showed silver primarily in the two dots of paint. Copper, sulfur and silicon were found in the residue between the dots. An EDS X-ray elemental map of the area between the two silver dots shows the distribution of selected elements between the silver dots (figure 4). Note silver is the primary element found in the silver dot area. Silver (a lower concentration), copper and sulfur were found between the silver dots.

EDS X-ray linescan analyses were conducted across a discharge arc between terminals 3 and 4 connecting silver spots labeled 1 and 2 (figure 13 in main report). The first linescan intersected the arc damage to detect any differences in composition of the surface between the arc site and the unaffected areas of the surface on either side (figure 5). At the magnification selected, only the linescan selected to detect silver showed significant changes in concentration across the scan. This is primarily due to the silver dots that were added before the test. A higher magnification X-ray linescan is shown in figure 6. Only slight changes are registered as the scan intersected the arc site.

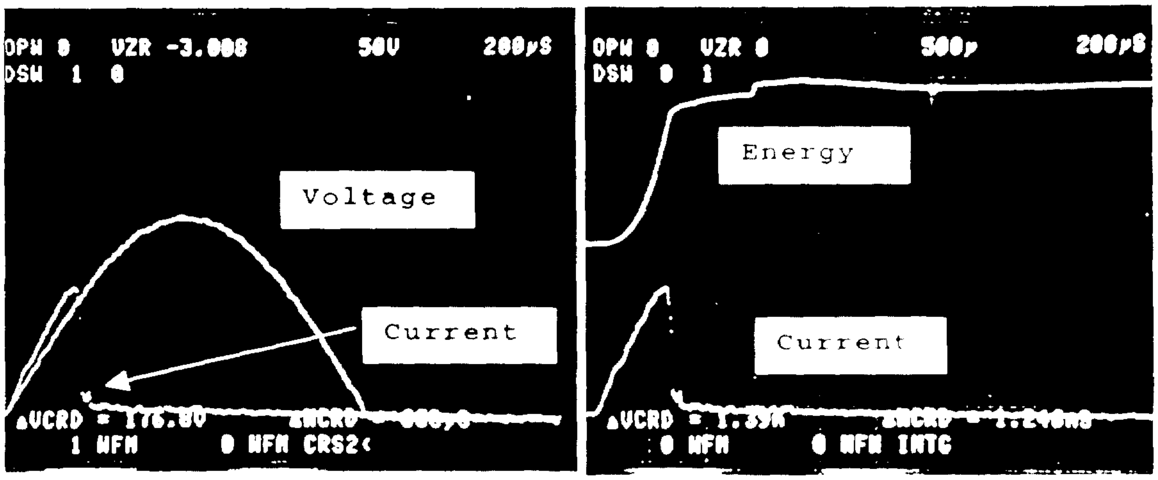


Figure 11. Voltage breakdown on terminal block under Low Z insulated terminal lug from fuel probe 93117 F40 S/N Z-116. Peak breakdown values (red arrows) were 90V and 11mA (left) and calculated energy was 0.14 mJ (right, conversion factor 0.1X)

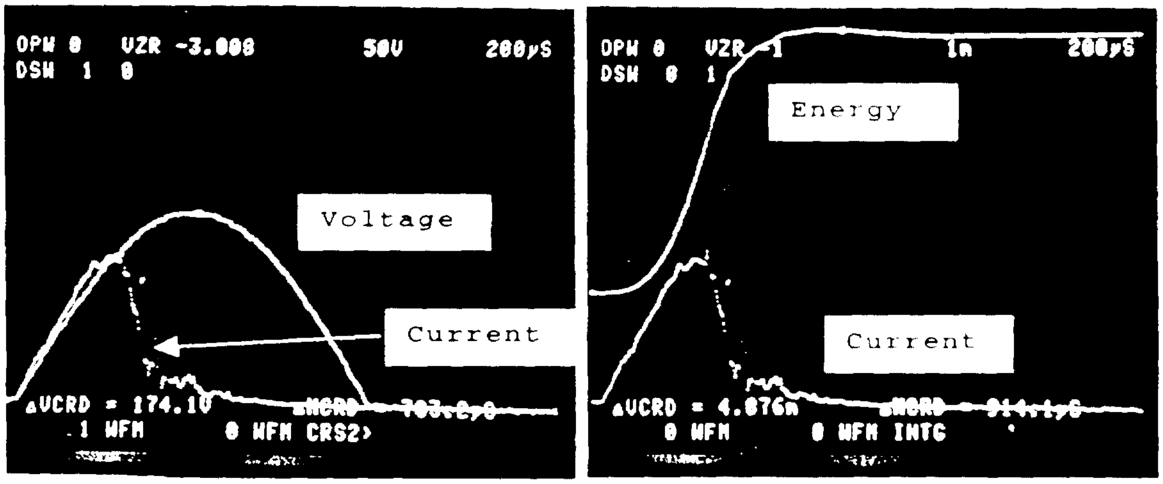


Figure 12. Voltage breakdown on terminal block under Low-Z insulated terminal lug from fuel probe 93117 F40 S/N Z-116. Peak breakdown values (red arrow) were 135V and 13.5mA (left) and calculated energy was 0.49 mJ (right, conversion factor 0.1X)

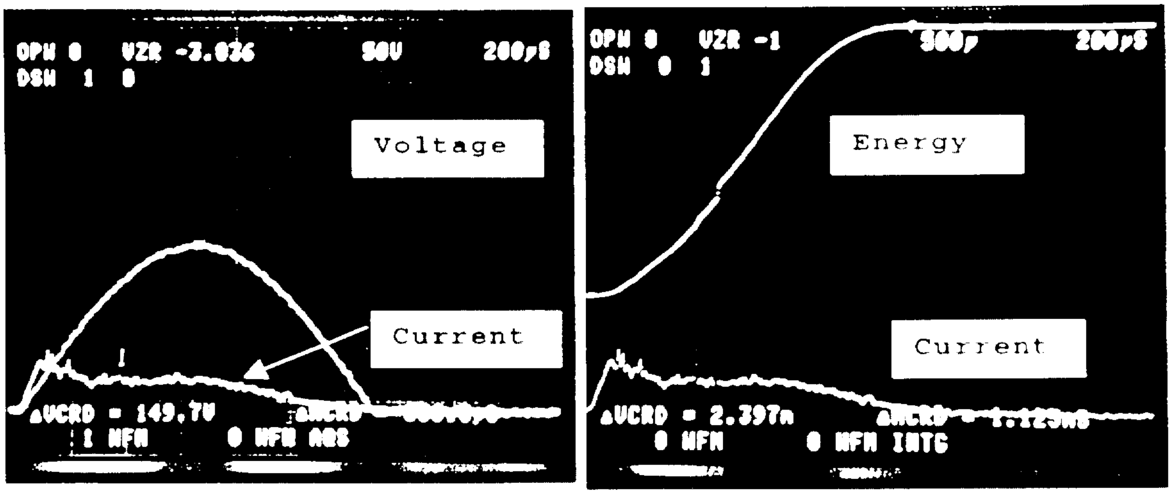


Figure 7. Voltage breakdown on Low-Z insulated terminal lug from fuel probe P/N FG420A23, S/N A-119. Peak breakdown values (red arrow) were at 140V and 5.2mA (left) and calculated energy was 0.24mJ (right, conversion factor = 0.1V)

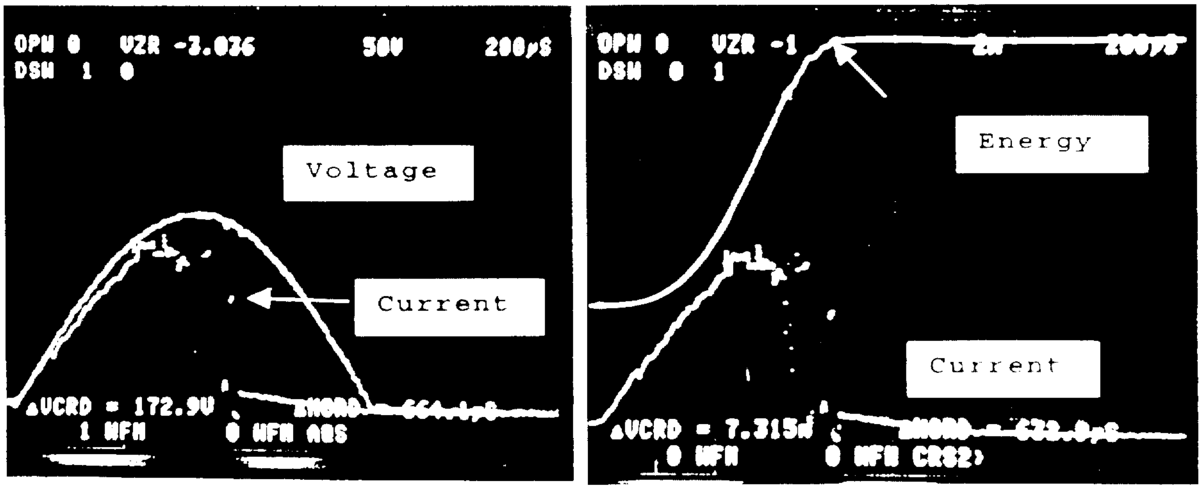


Figure 8. Voltage breakdown on Low-Z insulated terminal lug from fuel probe P/N FG420A23, S/N A-119. Peak breakdown values (red arrow) were 172.9V and 17 mA (left) and calculated energy was 1.1mJ (right, conversion factor = 0.1V)

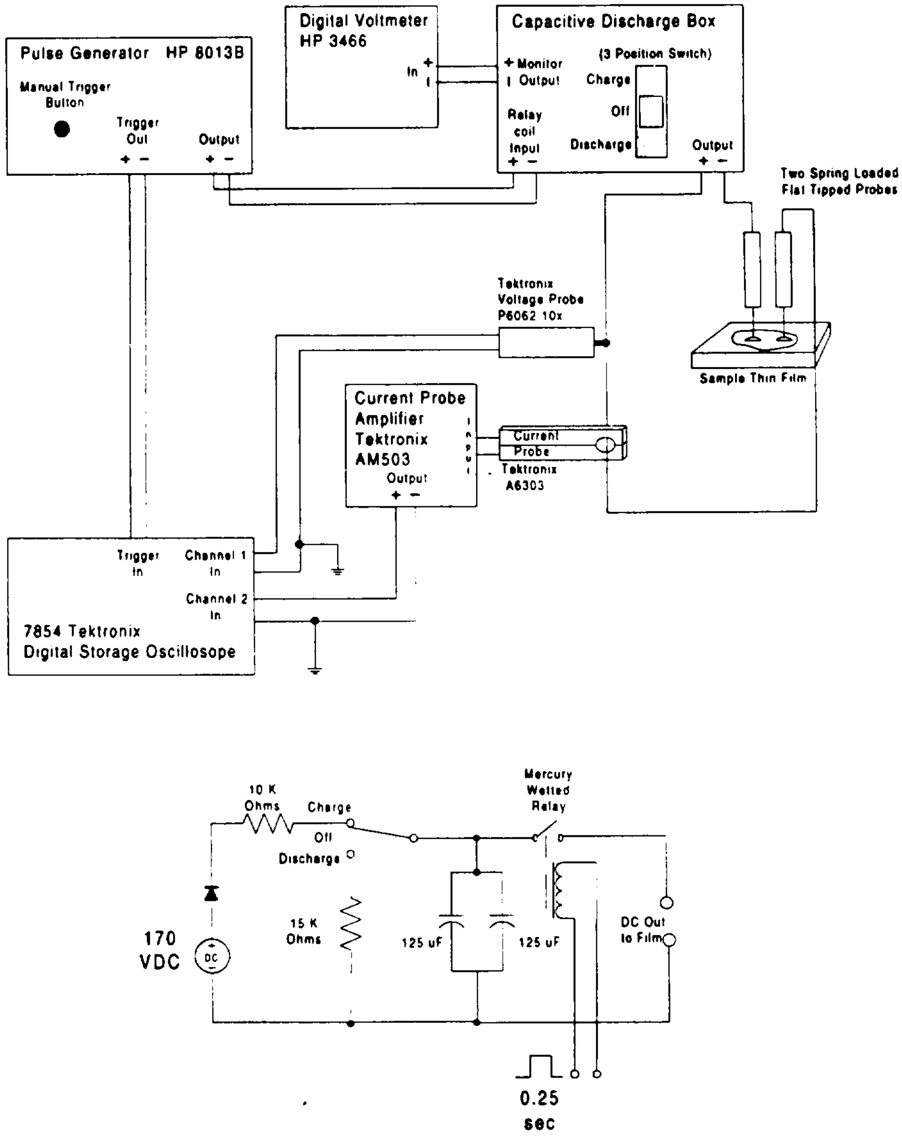


Figure 12. Test circuit used to impress voltage onto residues found on the submitted terminal strip.

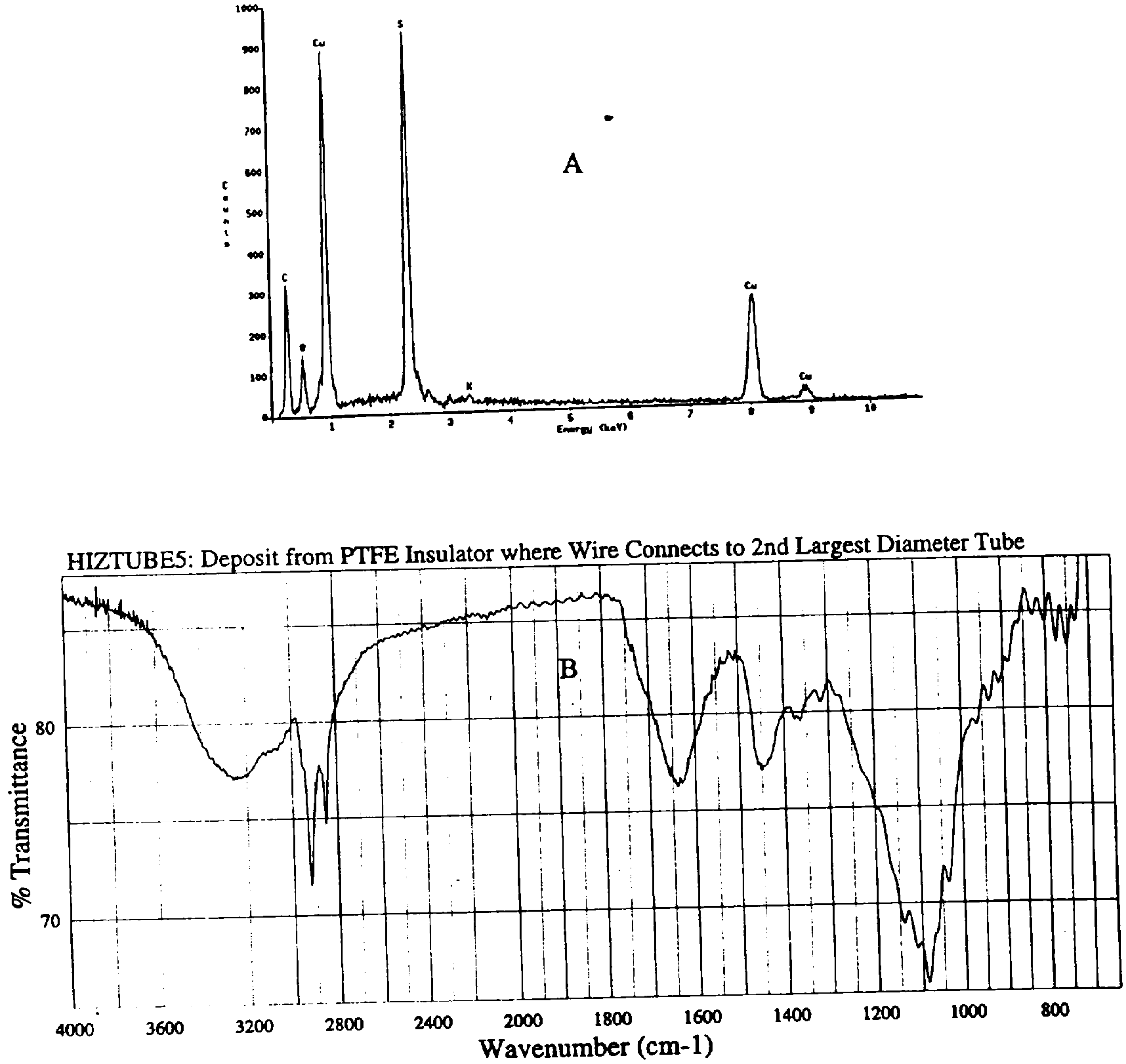
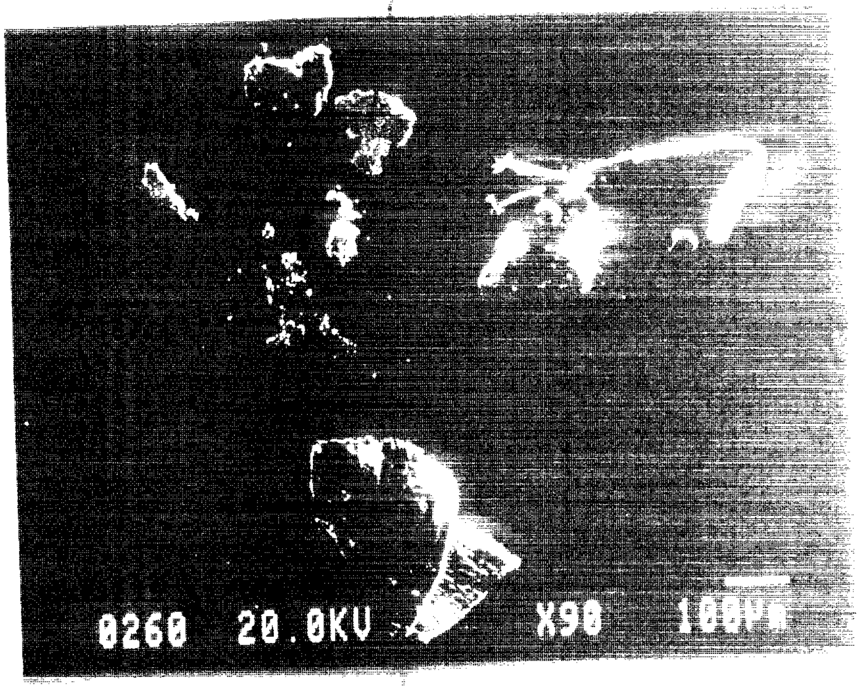


Figure 9. (A) An electron microprobe elemental survey and (B) infrared spectrum of the gray deposits shown in Figure 8. The electron microprobe survey represents deposit from the sleeve on the Hi-Z crimp terminal, while the infrared spectrum corresponds to a sampling from the PTFE insulator for the Hi-Z connection.


0260 20.0KV X90 100µm