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Space Shuttle Columbia Aging Wiring Failure Analysis

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ABSTRACT

A Space Shuttle Columbia main engine controller 14 AWG wire short circuited during the launch of STS-93. Post-flight examination divulged that the wire had electrically arced against the head of a nearby bolt. More extensive inspection revealed additional damage to the subject wire, and to other wires as well from the mid-body of Columbia. The shorted wire was to have been constructed from nickel-plated copper conductors surrounded by the polyimide insulation Kapton®, topcoated with an aromatic polyimide resin. The wires were analyzed via scanning electron microscope (SEM), energy dispersive X-Ray spectroscopy (EDX), and electron spectroscopy for chemical analysis (ESCA); differential scanning calorimetry (DSC) and thermal gravimetric analysis (TGA) were performed on the polyimide. Exemplar testing under laboratory conditions was performed to replicate the mechanical damage characteristics evident on the failed wires. The exemplar testing included a step test, where, as the name implies, a person stepped on a simulated wire bundle that rested upon a bolt head. Likewise, a shear test that forced a bolt head and a torque tip against a wire was performed to attempt to damage the insulation and conductor. Additionally, a vibration test was performed to determine if a wire bundle would abrade when vibrated against the head of a bolt. Also, an abrasion test was undertaken to determine if the polyimide of the wire could be damaged by rubbing against convoluted helical tubing. Finally, an impact test was performed to ascertain if the use of the tubing would protect the wire from the strike of a foreign object.

KEYWORDS Failure analysis, wiring, damage, SEM, EDS, ESCA

Approximately five seconds after the liftoff of the space shuttle Columbia on STS-93, a main engine controller wire short circuited, resulting in a potential single point failure for two main engine power controllers. Post-flight inspection of the Orbiter divulged arcing damage to a wire in a lower wire tray in the midbody port side of the Space Shuttle Columbia, Figure 1.

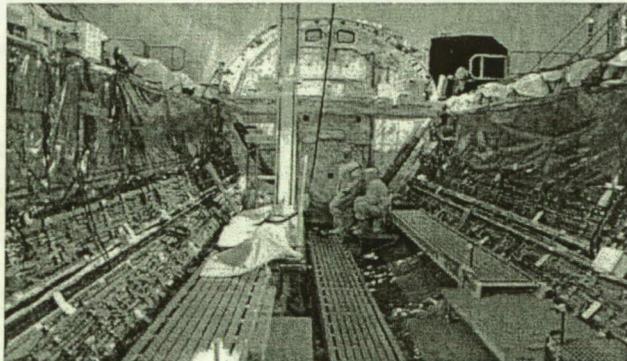


Figure 1
Cargo Bay of OV-102.

The damaged wire was immediately adjacent to a charred bolt head. Similarly, an additional region of damage, in this case an area of exposed conductor, was observed on the same wire approximately 2 inches away from the arced region. It was noted that another bolt head was adjacent to this damaged region as well. Each of the bolts corresponding to the regions of damaged wire had plastically deformed slots with exposed base metal where the bolt head slots had been deformed; the wiring opposite the damaged areas did not display any damage. The subject bolts and damaged wiring was harvested for failure analysis, Figure 2.

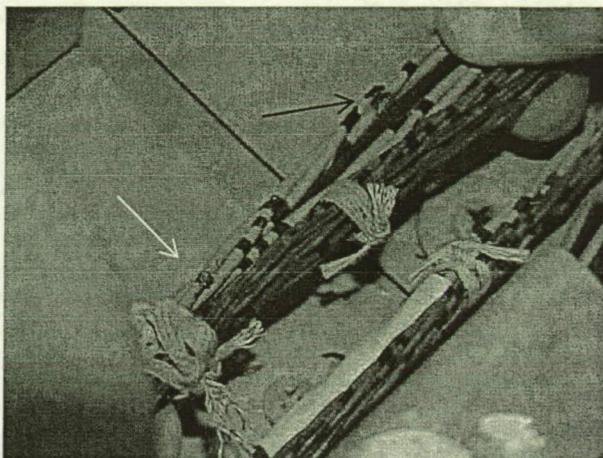


Figure 2

Black arrow indicates arcing location, with the corresponding bolt immediately beneath it. White arrow indicates a second area of damage.

The subject wiring was examined macroscopically. Regions of mechanical damage were observed, with the damage mainly transverse and slightly off-centerline. A melted region was evident adjacent to the mechanically-damaged area. Deposits of dark, charred material were noted. Similarly, the topcoat of the wiring on each side of the arced region were also deformed, Figure 3.

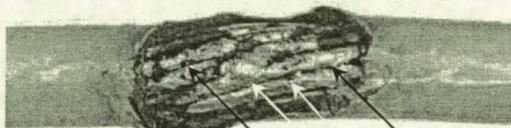


Figure 3

Areas of mechanical damage are indicated by black arrows, shorted regions by white arrows.

A charred area on the bolt head was observed, Figure 4, in the region which was located next to the charred region of the wire. Areas of raised, shiny base metal were present on the edges of the bolt head slots. No paint was evident on the raised areas.

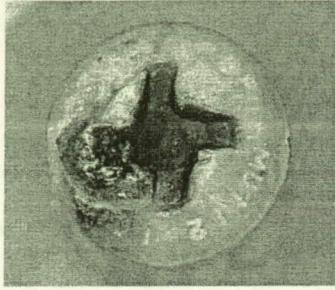


Figure 4
Deformed, charred bolt head.

The second area of damage on the subject wire had its insulation pushed up in a transverse direction, Figure 5. The conductor in this area displayed mechanical gouging.

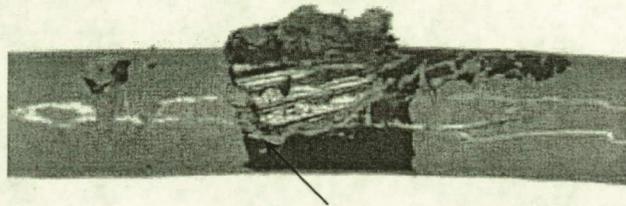


Figure 5
Second damaged area, with mechanical damage to the conductors denoted by the black arrow. Deformation was evident on the topcoat and conductors.

Both damaged regions of wiring were examined with a scanning electron microscope (SEM) equipped with energy dispersive X-Ray spectroscopy (EDX). Electron spectroscopy for chemical analysis (ESCA) was also employed. The polyimide insulation was absent in the charred regions. The damaged insulation did not appear serrated; rather it appeared smooth and even. Three zones of distinctive topographical characteristics were observed: a melted region, a zone displaying microvoid coalescence (MVC), and a mechanically damaged area, Figure 6.

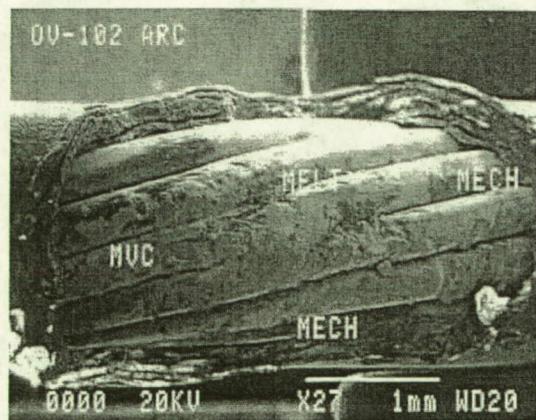


Figure 6
Micrograph of arced area. The melted region is between the "MELT" and "MVC" zones, with mechanical damage evident in the areas denoted "MECH." Magnification: 27X

A mixture of melting and mechanical damage was evident on the central region of the charred area, Figure 7. Directional gouges were observed in the areas of the conductor displaying mechanical damage, Figure 8. MVC, indicative of ductile overload, was evident in the final zone of the exposed area, Figure 9. The MVC correlates to an area where the wire melted and bonded to the bolt head, Figure 10. Charring and melting appeared to be restricted to the outermost strands of the wire. The inner strands appeared intact. The bolt head was examined via EDX and ESCA; copper and nickel were present. An oxide layer was detected via ESCA on the shorted wire. The oxide layer depth of the subject wire was contrasted to oxide layer depths of exemplars of newly nicked copper wire and specimens nicked two years previously; the oxide layer depth of the subject wire was significantly deeper than the oxide layer depths of the exemplars.

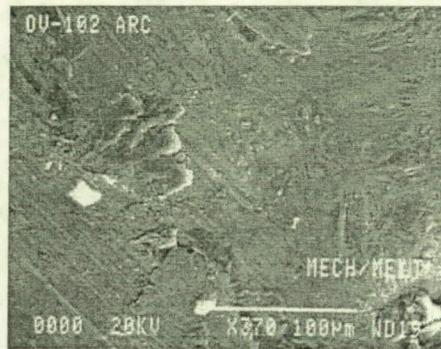


Figure 7

Micrograph of the transition from heat to mechanical damage. Magnification: 370X

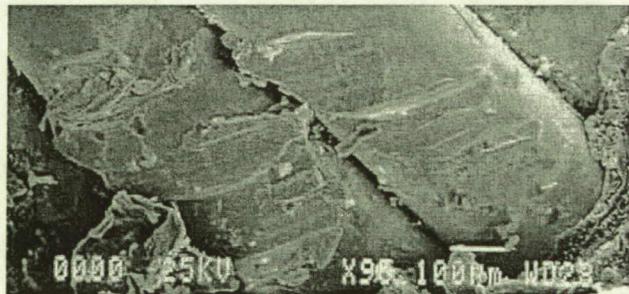


Figure 8

Micrograph of mechanically damaged region of the conductors. Magnification: 90X

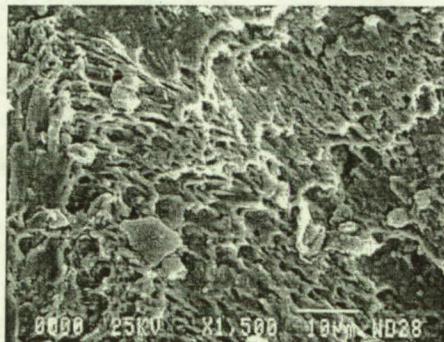


Figure 9

Micrograph displaying MVC. Magnification: 1,500X

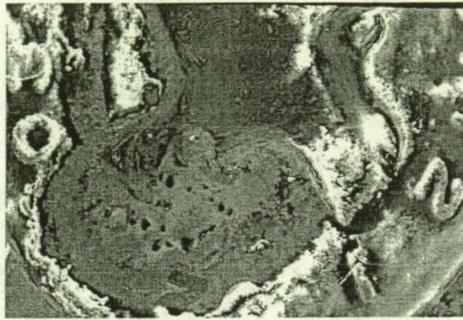


Figure 10

Micrograph of melted metal on the bolt head. Magnification: 16X

Mechanical damage was observed via SEM on the second damaged portion observed aft of the charred area. Gouging, predominantly transverse to the length of the wire, Figure 11, was evident. Additional ESCA evaluation indicated that the oxide layer on this portion was also thicker than the laboratory-induced exemplars.

Various additional analyses, including infrared (IR), thermal gravimetric analysis (TGA), and differential scanning calorimetry (DSC) of new polyimide insulation, as well as the subject wire's insulation, was performed; no significant differences were observed.

Laboratory-controlled mechanical testing was performed in an attempt to replicate the features and characteristics observed on the failed conductors and insulators. Vibrational testing was performed to simulate the service environment encountered by similar wiring in the Orbiter's mid body. No damage was produced via vibration until an additional load of 2100 grams was added to the test wire bundle, which forced the bundle against a bolt head. Although this is not actually encountered during service, it proved necessary in generating vibrationally-induced damage.

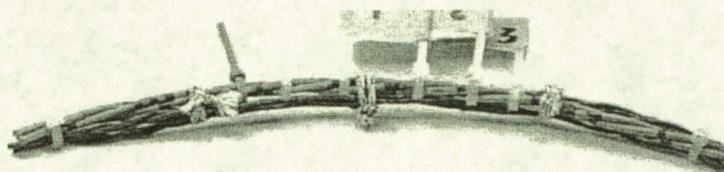


Figure 11

Vibration test specimen.

Shear testing did not damage the test bundles. Only the addition of 42 pounds of force caused any damage to the bundle, Figure 12.

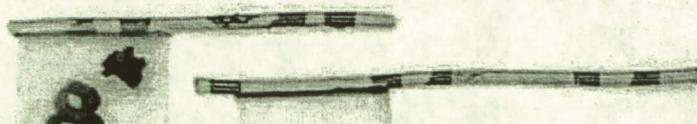


Figure 12

42 pound shear test specimen.

Step testing was performed. Increasing levels of effort and force were utilized, but did not damage the conductor, Figure 13.

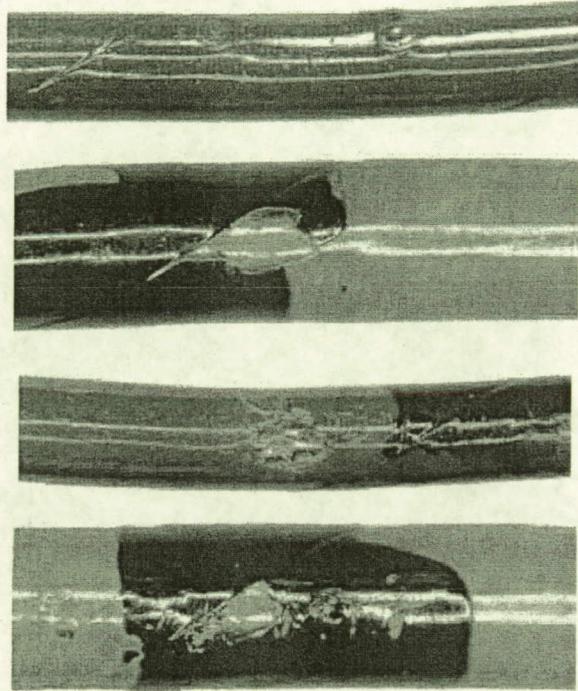


Figure 13
Macrographs of step test specimens, with increasing force.

SEM examination of the step test specimens showed only topcoat/insulator damage. No conductor damage was observed. The drop test as well as the abrasion test, Figure 14, indicated that the convolex tubing experienced damage prior to any damage to the conductor.



Figure 14
Convolex tubing with associated test specimen.

The subject controller wire exhibited mechanical damage in several locations; the mechanical damage was likely extant prior to the arcing event. The mechanical damage tore the insulator and damaged the underlying conductor, eventually resulting in a short when the conductor contacted the adjacent bolt head. The bolt head's base metal, exposed as a result of plastic deformation likely induced during loosening, contacted the conductor while the wires were energized. The resultant absence of a protective coating predisposed system to a short. The presence of nickel and copper, verified via chemical analyses, in the melt zone on the iron-based bolt head, indicated that the conductor had fused with the bolt head. Eventually an applied mechanical force separated the conductor and wire, resulting in MVC on the fused zone. The uniformity of the MVC, with no evidence of a progressive, cyclic separation, tends to indicate that the separation was a single event.

The shorted wire displayed damage in two locations; each location was above the head of an associated bolt. This signified that comparable occurrences likely damaged each area. The exemplar testing indicated that stepping on or vibration of the wire bundles likely would not induce the observed damage. After consulting with personnel working in the midbody of the Orbiter, it appeared probable that there were two likely scenarios for deformation of the bundles: either an impact, such as by a work platform, pliers, or torque tip; or an object being dropped onto or placed upon a bundle, thereby damaging the wires by forcing them against the heads of adjacent bolts.

The oxide layers on both damaged areas of the subject conductor were significantly deeper than those layers of the exemplars, indicating that the mechanical damage of the shorted wire predated the short. Based upon the exemplar evidence, and additional ESCA testing, the age of the oxide layer on the failed wire was estimated to be between five and ten years old.

Based upon the results of the failure analysis, recommendations were issued to ensure that bolts would be examined to verify that no raised or bare areas of metal were present on the heads of similar bolts. Any bolt with raised or exposed metal was to be smoothed and/or repainted as necessary. Likewise, an intensive inspection of wiring from each Orbiter in the fleet was undertaken to mitigate the likelihood of additional wiring failures. During the inspection, any wires found to be damaged or bolts discovered to be deformed or with bare metal present were replaced. Likewise, installation of convoluted tubing to protect the wire bundles was performed at this point.

The combination of inspection, replacement, and protective sheathing have all helped to successfully preclude any such similar failure to date.

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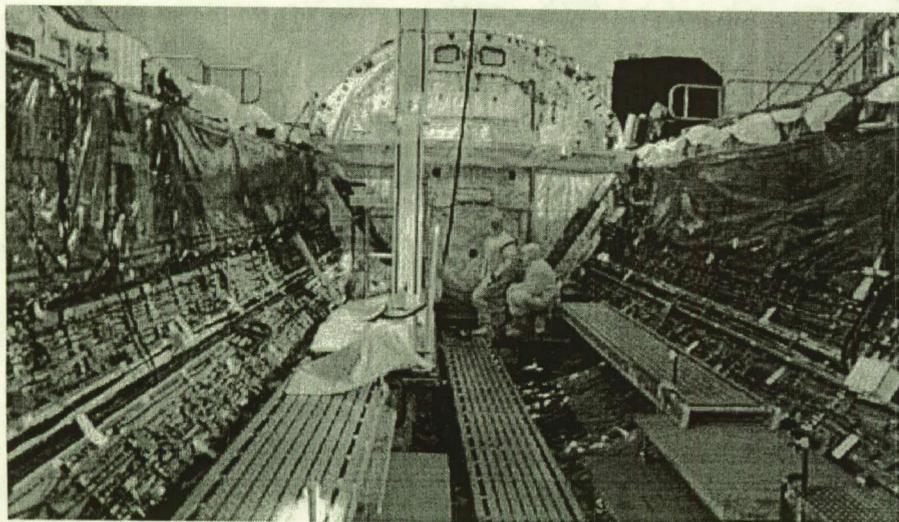
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8th Joint NASA/FAA/DoD Conference on Aging Aircraft

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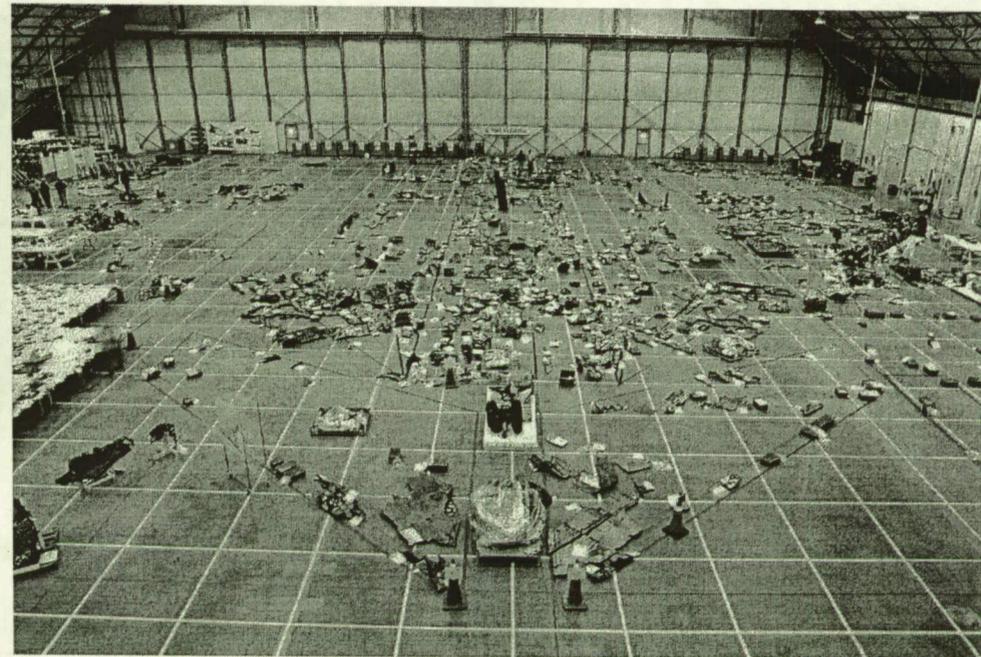


Columbia: 1999 vs. 2003



1999

2003





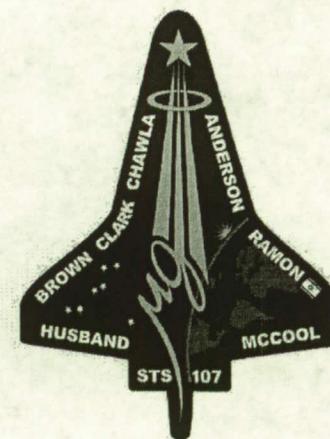
Space Shuttle Columbia



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4-12-81



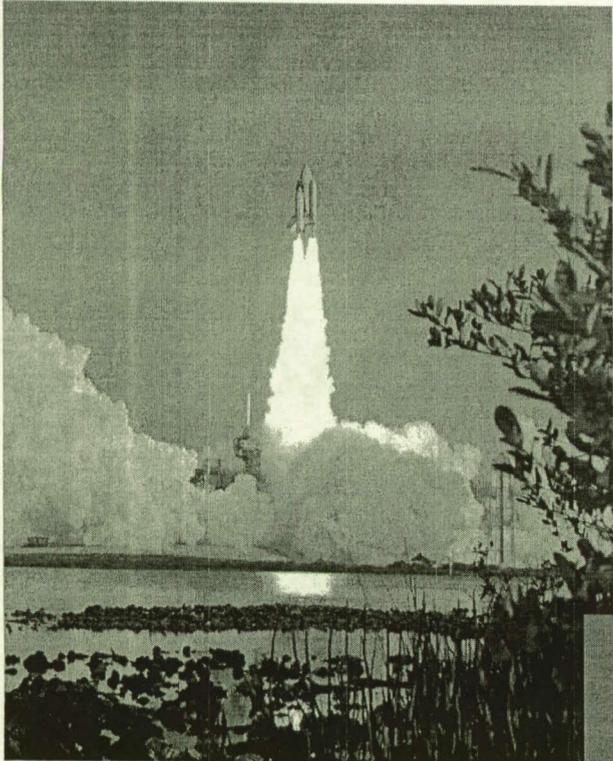
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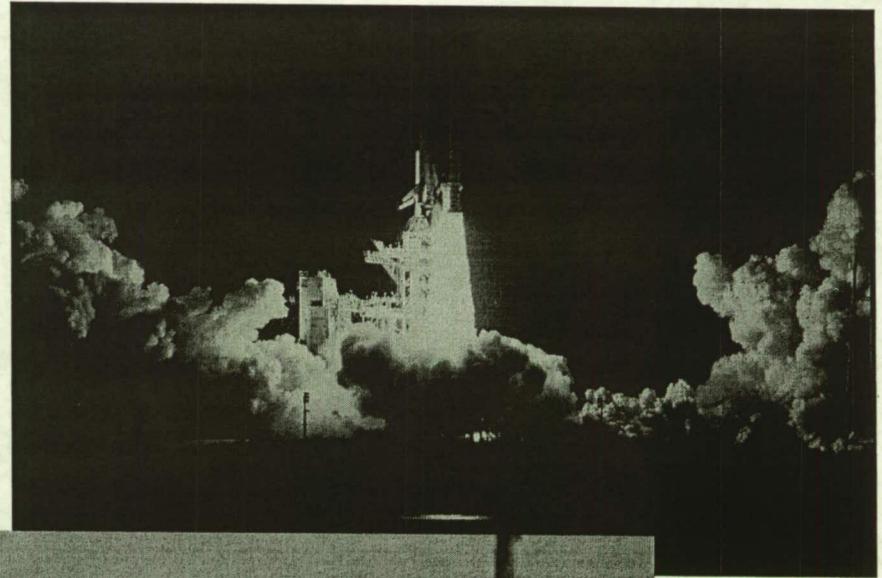
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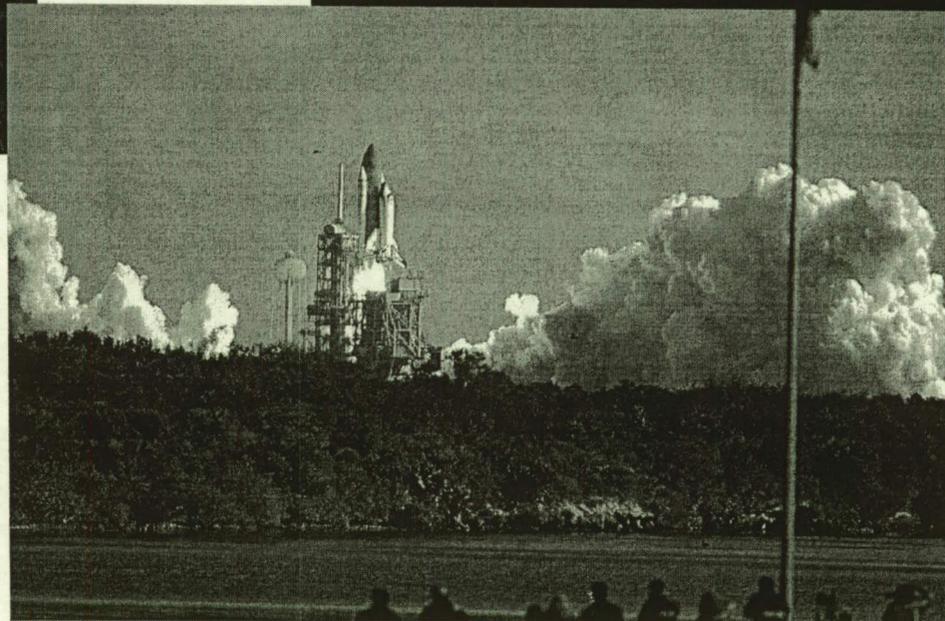
Columbia



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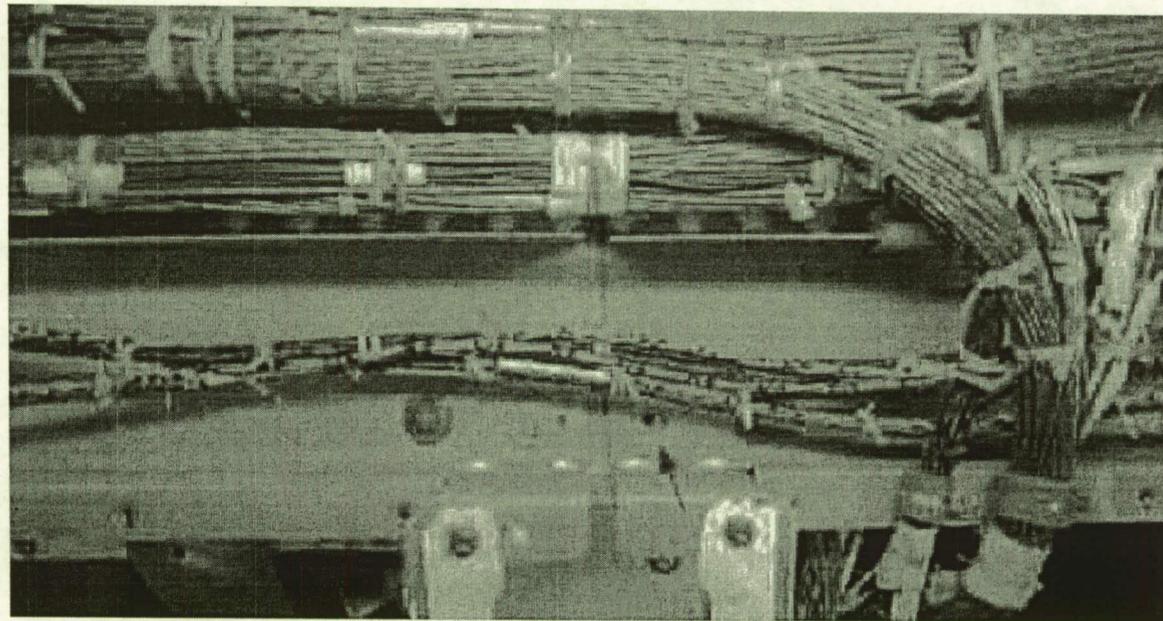
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STS-107



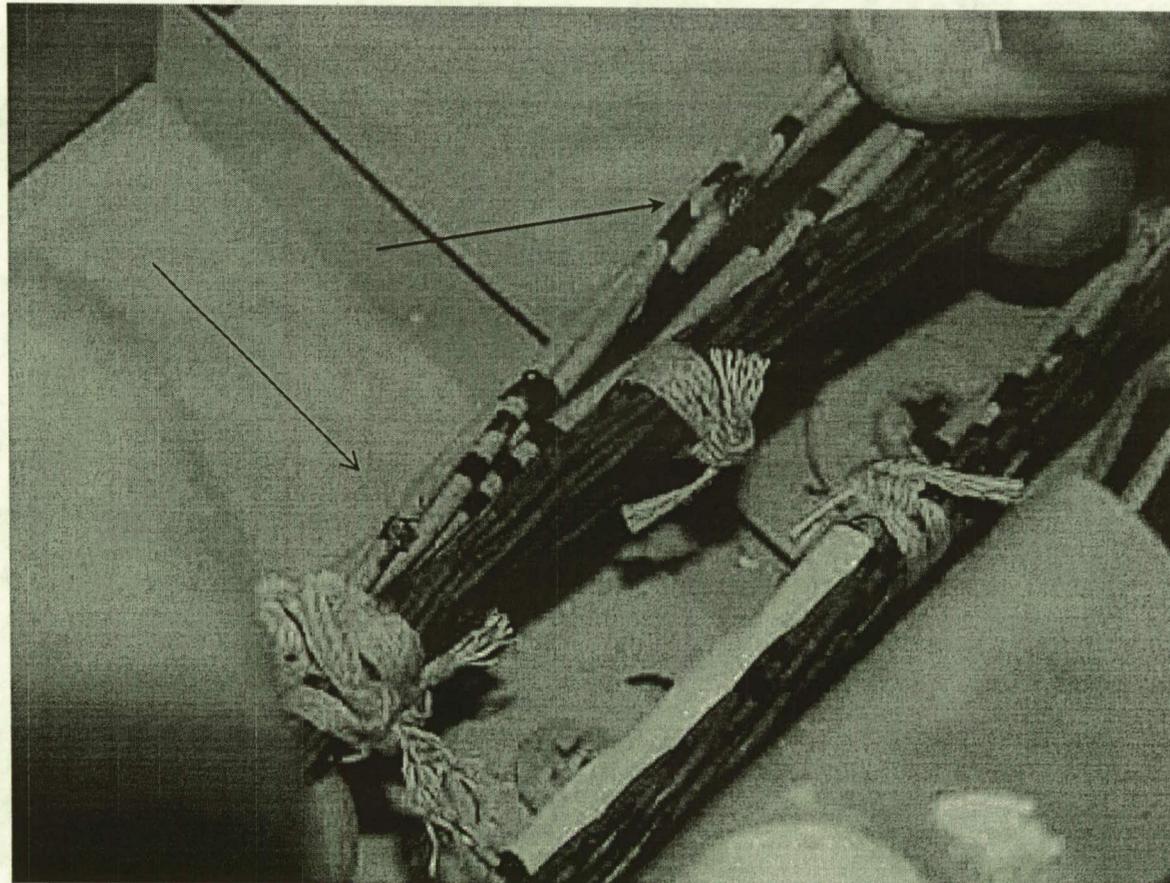
- During the launch of STS-93 a main engine controller wire short circuited
- Subsequent inspection revealed that the wire had arced against an adjacent bolt head.
- Further inspection revealed more damage to the subject wire, as well as other wires from the midbody of OV-102.
- The shorted wire was 14 AWG, with the polyimide insulation Kapton® surrounding nickel-plated copper conductors.
- The insulation was to be topcoated with an aromatic polyimide resin.



Midbody port side lower wire tray of OV-102

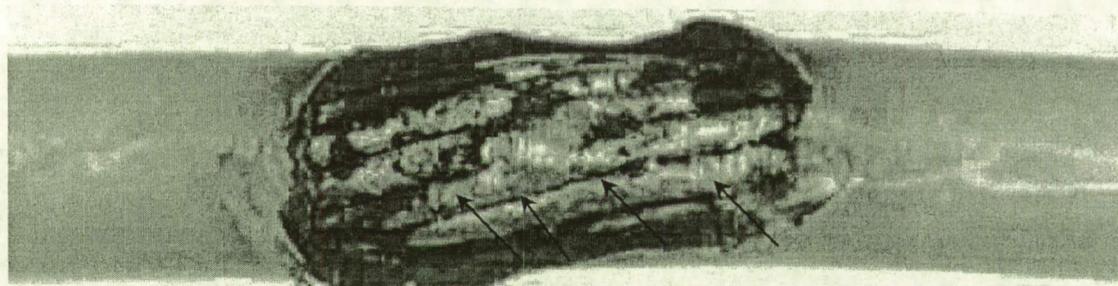


- Arced location (black arrow) with associated bolt head below.
- Bolt heads have exposed base metal.
- A second damaged area is also shown (white arrow).

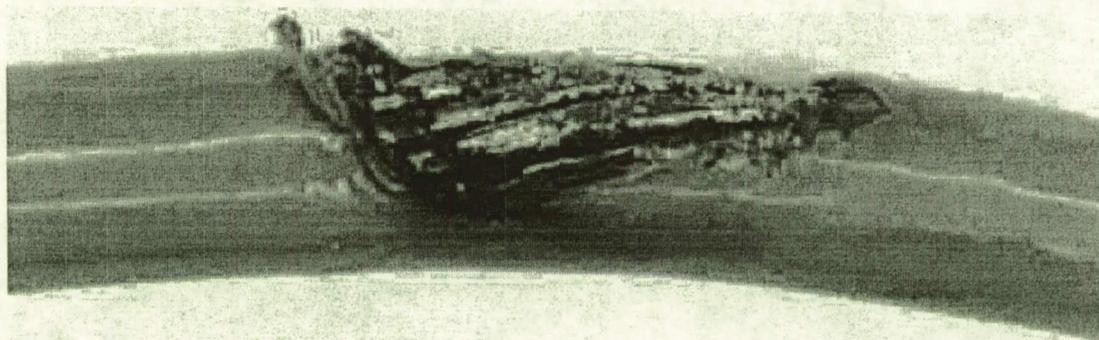




Macroscopic examination:



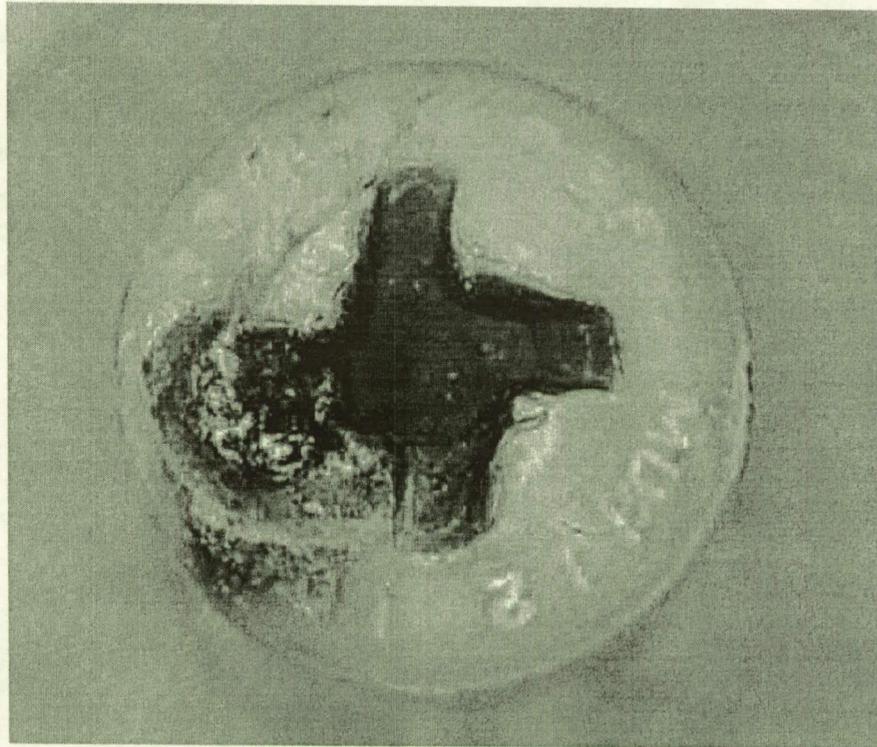
White arrows indicate shorted area;
black arrows indicate areas of mechanical damage.



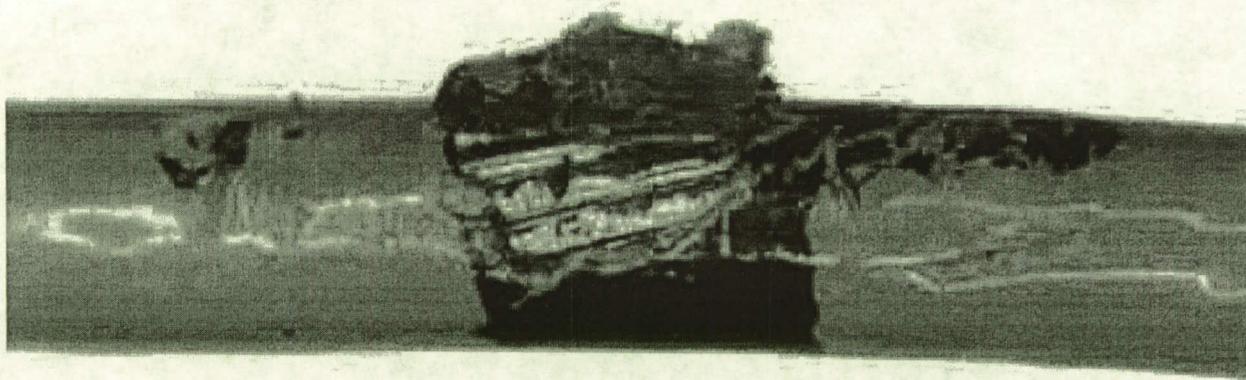
Side view of wire. Note how the topcoat is pushed to the left.



Bolt head that the conductor arced against to cause the short



Raised areas of bare base metal were evident on the sides of the slots in the bolt head; these raised areas were devoid of paint.



Mechanically damaged area approximately two inches from the shorted region.
Note deformation of the conductors and topcoat.

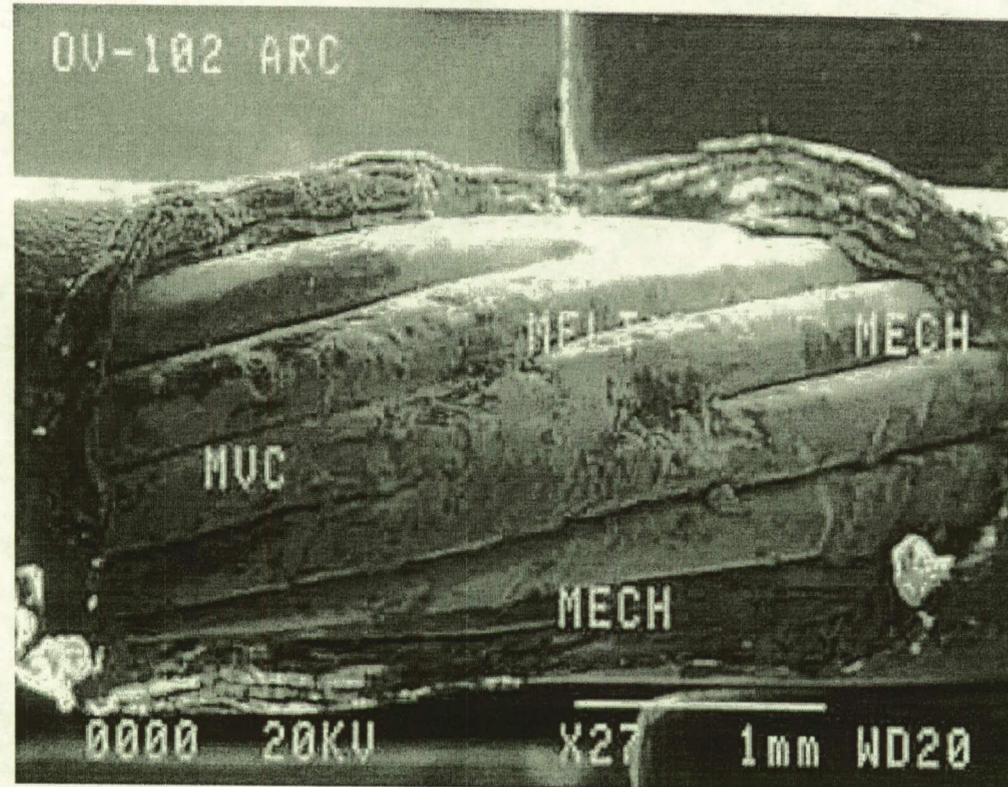


Scanning Electron Microscopy and Energy Dispersive X-Ray Spectroscopy (SEM/EDS)

- SEM utilizes a narrowly-focused high-energy electron beam impinging upon a specimen. The incident beam excites and liberates lower energy secondary electrons, which are detected and analyzed, providing a visual representation of the sample's surface topography.
- EDS also relies on an incident electron beam, except an EDS unit measures X-ray energies generated by the impinging beam. Each element generates a unique X-ray signature; the EDS detector measures these discrete energies. EDS actually penetrates approximately 2 microns into the bulk of the sample.



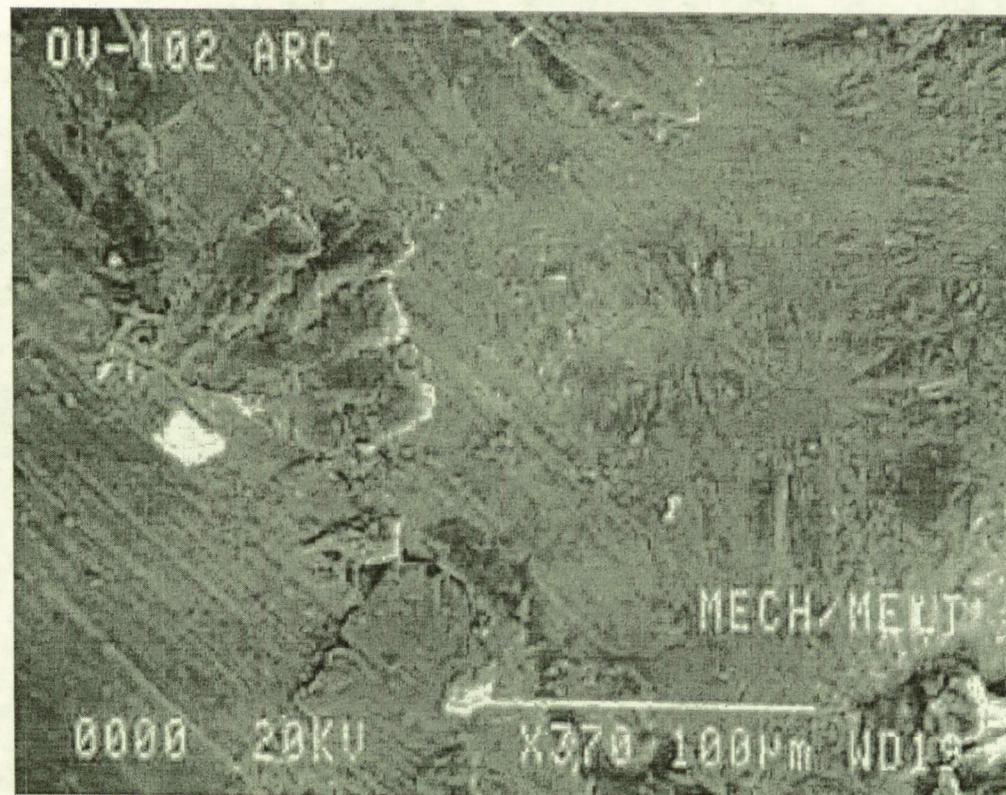
SEM micrograph of shorted region.



- Mechanical damage is evident on the conductors (denoted “MECH”).
- The melted region is between the “MELT” and “MVC” zones.
- Magnification: 27X



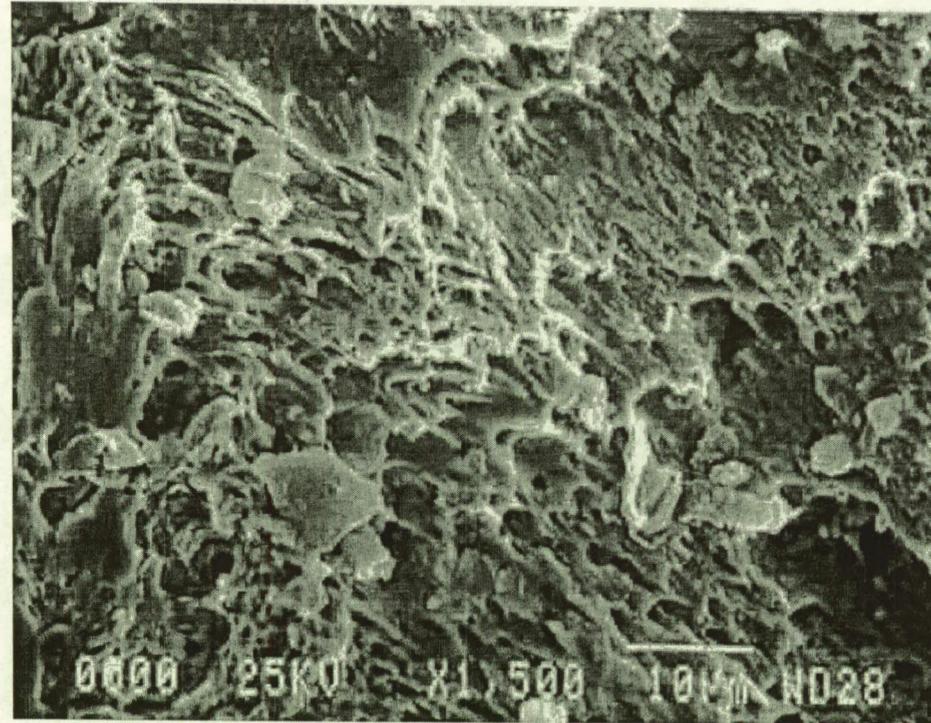
SEM micrograph of shorted region.



- SEM micrograph showing a transition from mechanical damage (left side) to heat damage (right side)
- Magnification: 370X



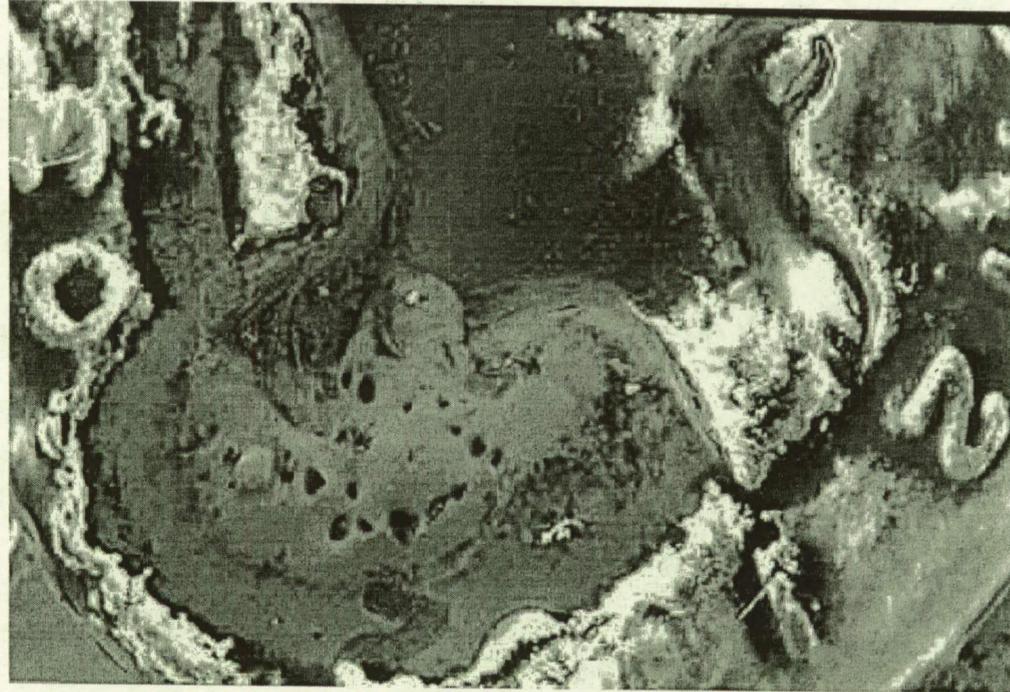
SEM micrograph of shorted region.



- SEM micrograph displaying MVC, typical of ductile overload.
- Magnification: 1,500X



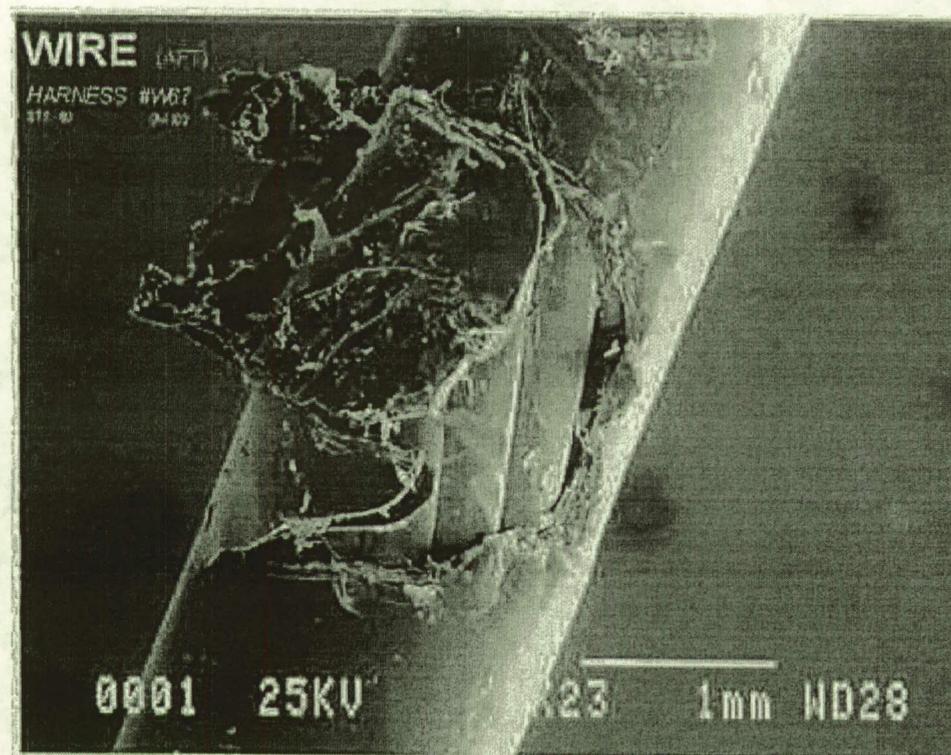
SEM micrograph of bolt head.



- SEM micrograph of the shorted bolt head, with melted metal apparent.
- Magnification: 16X



SEM micrograph of bolt head.



- SEM micrograph of a second damaged area of the wire. The conductors appear mechanically damaged, with the topcoat pushed back.
- Magnification: 23X

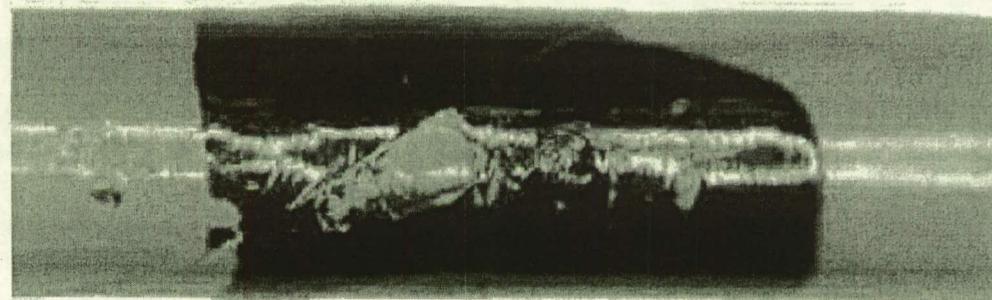
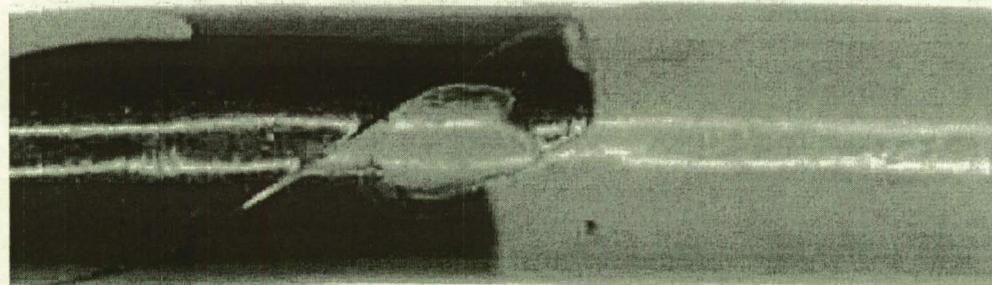
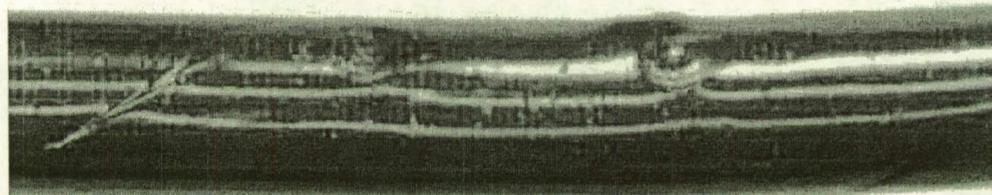


Electron Spectroscopy for Chemical Analysis/X-ray Photoelectron Spectroscopy (ESCA/XPS)

- ESCA/XPS analysis allowed the analyst to “sputter” into the sample with an electron gun, aiding in the identification of the layering sequence.
- Instead of an electron beam, XPS uses photons, which impinge upon the surface of the sample. XPS measures the electrons emitted from within the first 5 nm of the sample’s surface.
- EDX analysis and ESCA revealed the presence of nickel and copper on the bolt head.
- ESCA revealed the presence of an oxide layer on the shorted wire; the depth of this layer was compared to that of laboratory exemplars of varying age ranging from a freshly nicked portion of virgin copper wire to a two-year-old specimen of exposed copper. The depth of the oxide layer on the shorted wire was substantially greater than that of the exemplars.

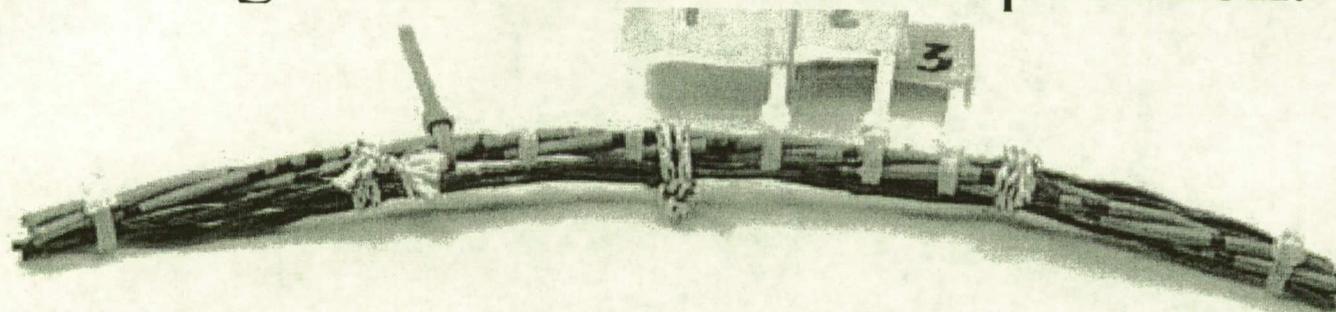


Step test specimens, with increasing force.

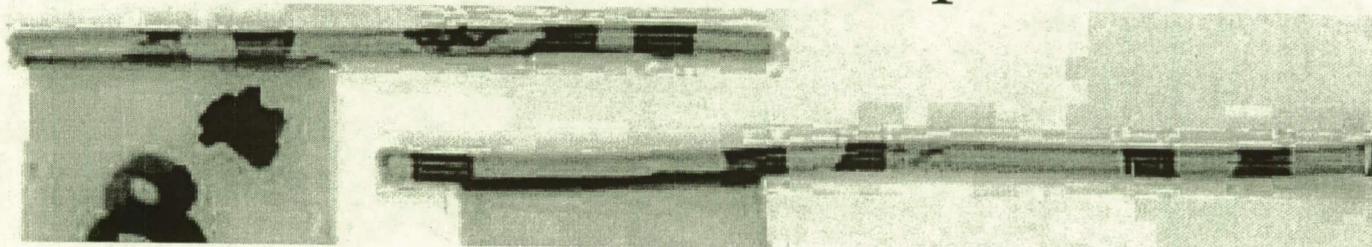




2100 gram vibrational test specimen.



42 pound load test specimen.



Drop test specimen with convoluted tubing.





Conclusions:

- The subject controller wire exhibited mechanical damage in several locations.
- The mechanical damage was likely extant prior to the arcing event.
- The mechanical damage tore the insulator and damaged the underlying conductor, eventually resulting in a short when the conductor contacted the adjacent bolt head
- The bolt head's base metal, exposed as a result of plastic deformation likely induced during loosening, contacted the conductor while the wires were energized.
- The resultant absence of a protective coating predisposed the system to a short.
- The presence of nickel and copper, verified via chemical analyses, in the melt zone on the iron-based bolt head, indicated that the conductor had fused with the bolt head.
- Eventually an applied mechanical force separated the conductor and wire, resulting in MVC on the fused zone.
- The uniformity of the MVC, with no evidence of a progressive, cyclic separation, tends to indicate that the separation was a single event.



Conclusions:

- The shorted wire displayed damage in two locations.
- This signified that comparable occurrences likely damaged each area.
- The exemplar testing indicated that stepping on or vibrating the wire bundles likely would not induce the observed damage.
- It appeared probable that there were two likely scenarios for deformation of the bundles:
 - either an impact, such as by a work platform, pliers, or torque tip;
 - an object being dropped onto or placed upon a bundle
- The oxide layers on both damaged areas were significantly deeper than those layers of the exemplars, indicating that the mechanical damage of the shorted wire predated the short.
- Based upon the exemplar evidence, and additional ESCA testing, the age of the oxide layer on the failed wire was estimated to be between five and ten years old.

Recommendations:



- It was recommended that similar bolts be examined to ensure no metal was raised on the bolt heads.
- Also to ensure that no bolts had bare metal exposed.
- If any were found, the raised areas were to be smoothed and the bolts repainted, as needed.
- A careful inspection of the wiring in the orbiter fleet was also deemed prudent to help preclude similar failures in the future.

Follow up:

- An intense and exhaustive inspection was conducted.
- Damaged wiring and bolts were replaced.
- Convolutted tubing was installed.
- No similar failures from the fleet have been reported.



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- **Peter Marciniak**
- **Dennis Peterson**
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- **Kirk Scammon**
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