

NONDESTRUCTIVE EVALUATION OF AROMATIC POLYIMIDE INSULATED AIRCRAFT AND SPACECRAFT WIRING

E. J. Tucholski, Physics Department, U. S. Naval Academy, Annapolis, MD, USA

Abstract: Spacecraft, and especially aircraft, often fly well past their original design lives and, therefore, the need to develop nondestructive evaluation procedures for inspection of vital structures in these craft is extremely important. One of the more recent problems is the degradation of wiring and wiring insulation. This paper describes three nondestructive characterization methods which afford the possibility to detect wiring and insulation degradation in-situ prior to major problems with the safety of aircraft and spacecraft

Introduction: Civilian and military aircraft, as well as spacecraft, often fly well past their original design lives. A major problem that ensues is the aging of the wiring and associated electrical components. Destructive testing of the wiring systems is both highly expensive and labor intensive since it involves removing the wiring from the craft, determining the serviceability, and then either reinstalling or replacing with new wiring. It is essential that a less invasive, relatively simple nondestructive method be developed to evaluate the status of the wiring bundles and individual wires in situ. There are significant electrical and fire hazards associated with aging and deteriorating wire insulation. Moreover, there are hundreds of miles of electrical wiring on typical commercial jet aircraft. Currently, the wires are inspected visually and only when there is an existent fault in the wiring or when modifications are made.

Over the last 10 years, several aviation accidents have been related to faulty wiring insulation.¹ A study conducted at the behest of the Federal Aviation Administration (FAA) to analyze aging wire insulation concluded that the most common wire condition irregularities involved heat damaged and burnt wire insulation, chafed or frayed wiring caused by vibration or excessive stresses, and cracked and delaminated insulation.²

Arcing was found to be a major contributor in electrical fires involving degraded polymer insulated aviation wiring. Arcing involves luminous discharge of electricity across the polymer insulation. The electrical discharge of an arc can have a temperature of several thousand degrees Celsius. Breaches in wire insulation can lead to a situation in which the conductor is exposed and results in arcing and short circuits. Scintillations, flashing and strong arcing have been observed.³ Scintillations and flashing (400 mJ to 8.25 J) caused substantial charring, discoloration, and erosion of wire insulation and conductors, but rarely did circuit breakers trip. Strong arcing (~5 kJ) occurred in tests involving aromatic polyimide (Kapton®) wiring. Non-contact arcing between conductors separated by insulation may require several kilovolts to initiate, but if separated by carbonized insulation, arcing can occur at normal operating voltages. A fault-current causes the carbon path to open and arcing is established.

The most common aircraft wire insulation flaws are chafes, cracks, cuts, delaminations, and embrittlement. The factors contributing to the insulation deterioration are mechanical vibrations, mechanical stress, moisture, elevated temperatures, repeated temperature variations and exposure to chemicals. There are three major problems common to in service aircraft wiring: chafed or frayed wires damaged mechanically during repairs or replacement of other aircraft components or by traumatic stresses encountered in housing conduits; wiring damaged by exposure to nearby heat sources; and delaminated wiring insulation that has become brittle and cracked due to aging. The principal technique for inspecting aviation and spacecraft wiring components used to date remains visual inspection. These inspections are unable to detect all extant flaws and are subject to discrepancies and errors. Moreover, these tests are also intrusive, since brittle wire bundles are frequently moved to access more remote wiring components and can result in further damage to already cracked insulation. It is imperative that an alternative method be developed to reliably detect the status of wiring insulation without removing it from the plane. In this paper, three methods are described which have been assessed to determine their suitability for determining the status of wiring in situ. In approaching this effort, it was decided to focus on two approaches that

would provide a more global imaging response and one technique that would yield a more detailed portrait of the indicated damage location. To place things in perspective, it is highly unrealistic using current technologies to analyze wires in situ in the middle of a typical aircraft wire bundle. Given this constraint, it was decided to concentrate on developing a global imaging approach to appraise the condition of as many of the wires in a bundle as possible at one time. Once a global technique indicated the presence of a possible damaged area on a given wire, a higher resolution technique was used to obtain a permanent image of that local area. The primary techniques described in this paper are electrical time domain reflectivity, infrared thermographic imaging and pulsed x-radiography

Results:

Wire test specimens were cut from wire bundles removed from a retired Boeing 707 aircraft, provided by NASA Langley Research Center. Several types of wire were contained in the bundles which enabled experiments to be conducted. The main type of insulation on the individual wires was Kapton® (aromatic polyimide). These samples included braided 16, 18, and 20 AWG with nominal bare wire diameters of 1.29 mm, 1.02 mm and 0.813 mm, respectively. The maximum outer diameter with insulation was approximately twice the nominal diameter, consisting of two or three distinct layers. Kapton® experiences an 80% loss of tensile strength and degradation of dielectric properties at elevated temperatures (above 325 °C) for extended periods of time (550 hours). The coefficient of thermal conductivity of Kapton® is 0.12 W/m-K at 23 °C.⁴ For the present investigation, chafed and frayed wires were simulated by stripping or scraping insulation with a knife. The heat damaged wires were prepared by placing the wires in close proximity to a hot object, such as a soldering iron, or exposing them to an open flame. The aged wires were simulated by either dipping the wires in liquid nitrogen or by continuously bending the wire back and forth.

Infrared thermographic imaging of heat generation or infrared thermography portends to be an excellent technique for rapid inspection of aircraft wiring. The major benefits of this technique reside in the portability of infrared cameras and the ability to examine large areas of wiring rapidly. It can provide a global method of testing aircraft wiring for heat generated by shorts in the wiring bundle and problems with wiring insulation. It can also be employed in such a manner to examine numerous wires at the same time and permits non-contact rapid inspection of large sections of wiring in situ. It provides the added convenience of real-time imaging, thus reducing the time necessary for information retrieval or film development. An infrared test would allow inspectors to positively identify a wide array of commonly occurring insulation defects, including chafing, burn and heat damage, cuts, delaminations, frays, nicks, and bent wiring. It is conceivable that such a method would allow technicians to determine the viability of aircraft wiring without significant training. While infrared thermography is unable to identify damaged wires on the interior of a bundle, it can easily find damage on the outside where it is most likely to occur and most likely to result in catastrophic failure.

In the current research, a standard handheld heat gun was utilized to distribute heat over various lengths of single wires, multiple wires and wire bundles. The infrared systems used during this phase of the experimentation were an Inframetrics® Model 600 and a newer higher resolution Raytheon Amber AE173 InSb Galileo® system. The testing was conducted on wires approximately 30 cm long which were affixed across the opening of an insulated styrofoam box with an open face of 23 by 30 cm. A schematic of the infrared thermography system used is shown in Figure 1.

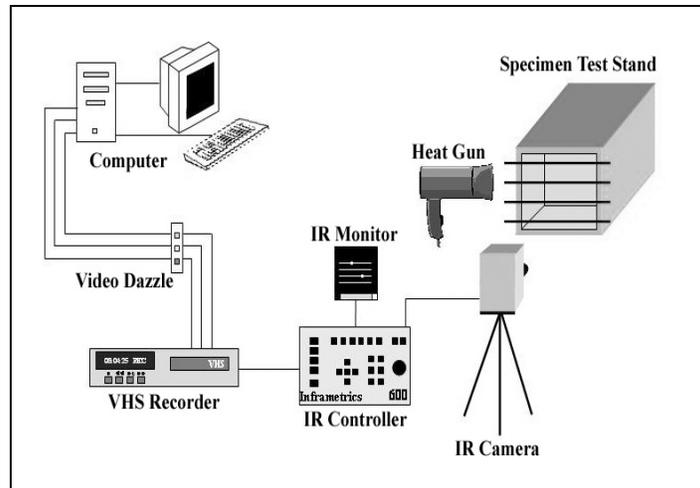


Figure 1. Schematic of the infrared thermography system.

The infrared camera was placed at a standoff distance of approximately 0.6 m. The wires were then heated with hot air from a heat gun possessing a wide nozzle attachment to distribute an even heat flux across the surface of the wires while passing the hot air across the face of the box along the length of the wire samples. The advantage of this procedure was to ensure that all of the wires could be heated concurrently. At a minimum temperature sensitivity span of approximately 10 °C, the baseline image with no heat applied yielded an image of light gray wires against a dark gray background. However, upon a single sweep of the heat gun, set at 320 °C, the radiant intensity of the wires was raised dramatically. At this same sensitivity, the heat being transferred through the wire insulation makes the wire appear as a white line against a gray background. Additionally, defects in the wire insulation have significantly different absorbtivity and emissivity resulting in temperatures well above the bulk of the wire. This allows the defects to stand out prominently in the display.

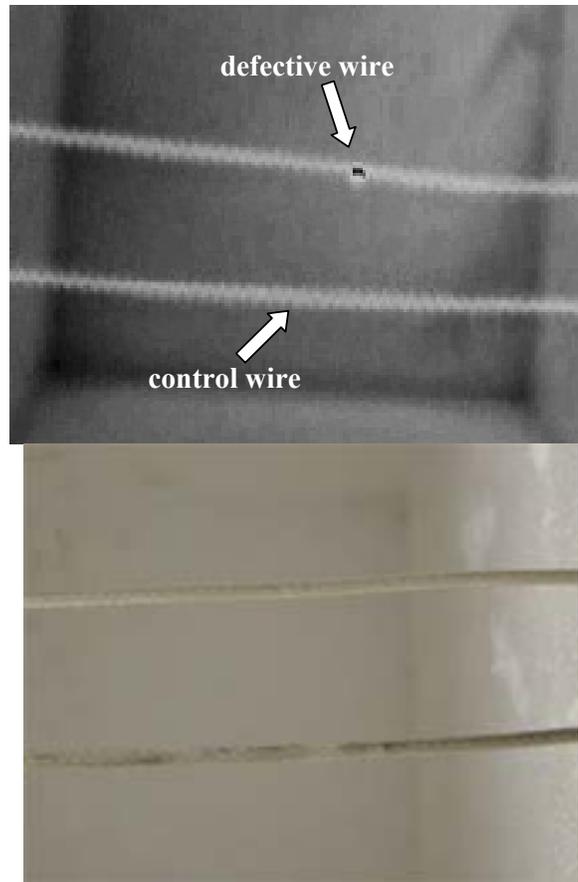


Figure 2. Single wire test: Infrared thermography (left). Photograph of same wires (right)

Initially, to determine the effectiveness of the infrared thermography technique an 18 AWG wire with a minor fray was taped to the open face of the test box. Approximately 25 mm below, a second undamaged control 18 AWG wire was affixed to the box, as shown in Figure 2. While heating with a hot gun, both wires became easily visible when viewed with the infrared camera system (Inframetrics® 600). Most importantly, the region in the vicinity of the fray turned a different color (or different shade of gray) representing a higher temperature making it much more visible than when inspected visually. The control wire, having no such defects, remained uniform in temperature. A black and white photograph on the right of Figure 2 shows the same two wires from a slightly different camera angle. This photograph does not reveal the damage as easily as the infrared thermograph. The discoloration on the lower control wire is not seen on the infrared image. The zigzag pattern on the infrared image shows the braided insulation clearly.

A six wire test was performed to determine the relative sensitivity of this test to wires in close proximity containing various defects. In this test, five 18 AWG wires differing only in the magnitude, type, and location of defect were taped horizontally across the test box. A sixth wire was added as an experimental control. In Figure 3, the top wire was chafed with a knife, the second wire from the top was stripped of its outermost layer of insulation, the third wire suffered a subtle cut, the fourth wire was undamaged, the fifth wire had been crimped and suffered from resulting bend damage, and the sixth wire was significantly frayed.

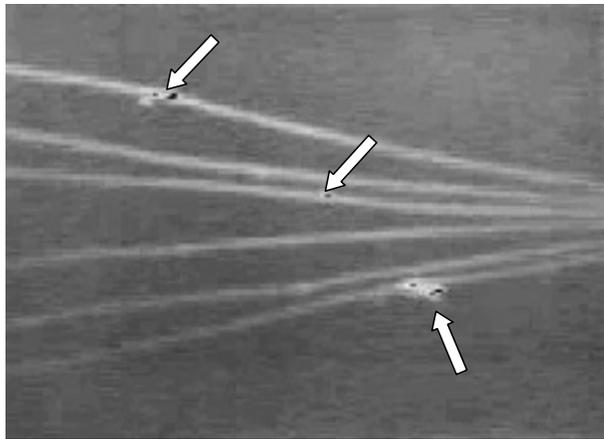


Figure 3. Infrared thermography: multiple wire test

A 0.3 m segment of a wire bundle containing 18 AWG wires was removed from a larger aviation bundle specimen. Two separate wires of the 32 wire bundle were deliberately inflicted with flaws. A superficial nick was placed on the insulation of one wire, while a fray of the outer insulation was imposed upon a second wire. The frayed insulation was readily apparent using both camera systems and also when the bundle was inspected visually. As shown in Figure 4 (left and center), the damaged wire is fairly small but causes the entire wire to stand out in the infrared thermograph. The more sensitive Galileo system was able to detect this defect at ambient temperatures without the benefit of a hot gun. The slight nick was also observed by both IR systems. In Figure 4 (right), a brilliant white orb radiates from the vicinity of the superficial nick using the Galileo system, whereas the other defect-free regions of the wire retain a grayer hue under heating. The horizontal striation in this figure results from the infrared imaging of the outer wires in the bundle.

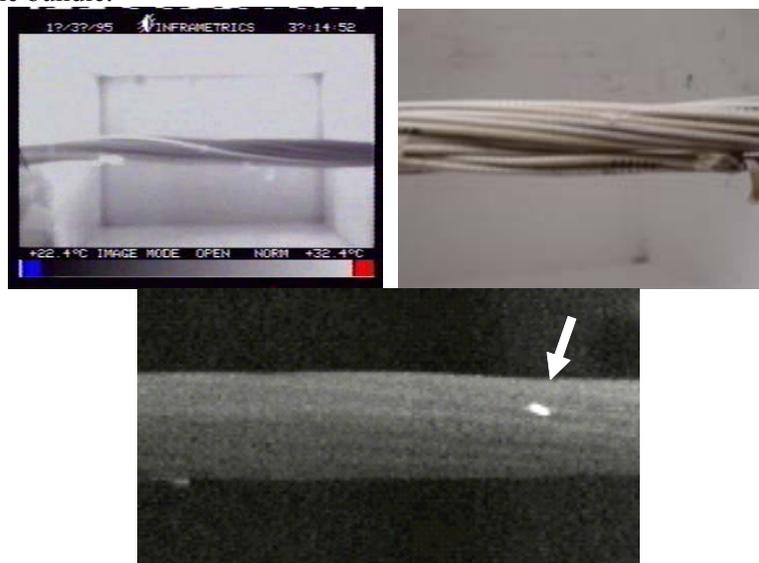


Figure 4. Wire bundle test: Infrared thermography of fray of outer insulation (left), photograph of fray of outer insulation (center), Infrared thermography of superficial nick (right)

Another primary focus of the present research was to nondestructively evaluate the status of the metallic wires or cables inside the insulating cladding as well as to detect degradation of the polymeric cladding itself. The primary method chosen for this aspect of the research was time domain reflectometry (TDR). TDR permits identification of conductor discontinuities and

insulation degradation in long runs of wire and cable which electrically appear to bear at least some semblance to transmission lines. Although the theory of the method is based on an ideal electric transmission line, in practice it can be useful for applications other than ideal transmission lines.

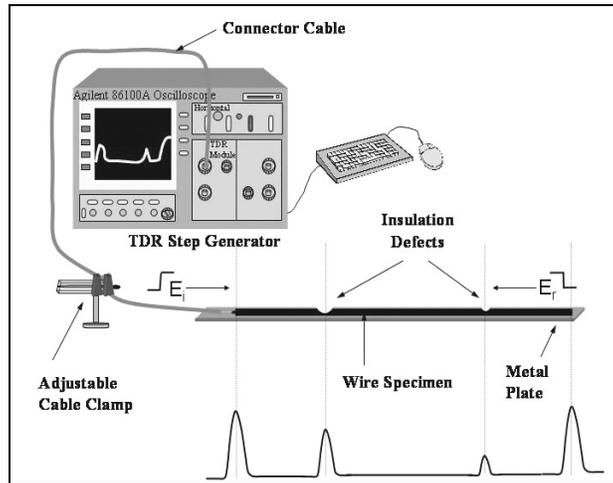


Figure 5. Schematic of time domain reflectivity (TDR) system

As shown in Figure 5, an electrical pulse is launched by the step generator at one end of the wire or cable and reflected from the opposite end. The time of propagation of the pulse from the propagation end and back from the opposite end is determined by the length of the wire or cable and the speed of the signal traveling through the wire. If a flaw exists at an intermediate location, such as a break in the conductor or a significant change in dielectric "loading" of the insulation coating, which would cause a perturbation in electrical impedance, a reflection comes back to the oscilloscope before it should. Its arrival time tells the distance to the flaw and the magnitude of the returning pulse is related to the size of the flaw. When connecting the test wire, the inner conductor of the coaxial connector cable is attached to the conductor of the wire under test and the outer conductor is attached to the metal plate test stand to create a capacitive cell.

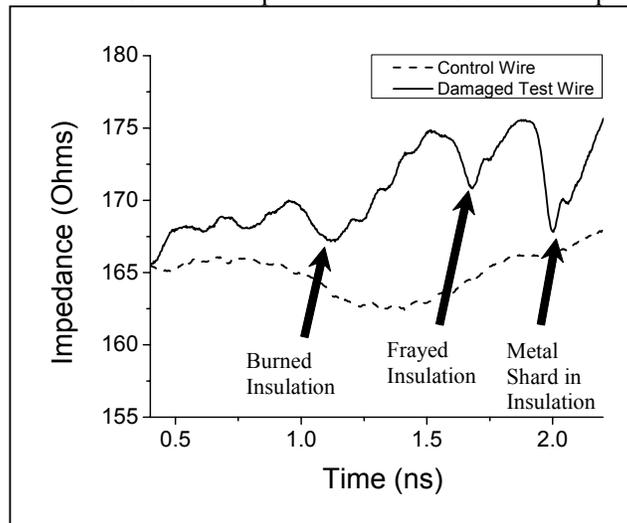


Figure 6. TDR results of metal object in wire insulation

In Figure 5, the connection to the test wire, the defects in the insulation and the end of the wire were described schematically as positive changes in impedance. In fact, the change in impedance is very likely to be negative if the defect in the wire lowers its overall capacitance. As an example, Figure 6 shows the results of a metal shard imbedded in the Kapton® insulation of a

braided conductor wire. The wire specimen is a 25 cm section of 18 AWG wire. The metal does not penetrate through to the conductor, but its presence is easily detected on the time domain reflectometer as a reduction in impedance.

Other damage to the insulation can be detected due to the difference between the relative dielectric constant of air and the insulation. Nicks, scrapes, cuts, chafes and frays are then detectable by a trained operator using this technique. Figure 6 also demonstrates a noticeable change in the impedance in an area where the insulation was stuck with a pin multiple times until frayed. Also visible is a decrease in impedance where the wire insulation was burned with a soldering iron over an area of about one cm in length along the wire insulation surface.

Unfortunately, the time domain reflectometer is extremely sensitive and dirt and moisture on the outer surface of the wire will affect the results. This will require some preparation of the wires prior to testing. Additionally, the connection of the wire to the time domain reflectometer will need to be carefully made each time a wire is tested.

On the other hand, the defects in Figure 6 are worst case attempts to find the most subtle damage to the wire. Obtaining a baseline on new wire and watching for changes over time can reveal significant information on the health of the wire. Additionally, when the damage to the wire insulation is such that the conductor is very close to or almost touching a metal ground, the time domain reflectometer will show a dramatic change in impedance. The same is true when embedded metal shards touch a ground. In both cases, the speed of the signal moving through the wire is known allowing the exact location of the problem area to be determined. This is exceptionally useful for locations within the aircraft where wiring is inaccessible to visual inspection or an infrared camera.

Once a more global technique, such as infrared imaging of heat generation or time domain reflectometry, indicated that a flaw exists in a run of wire or cable, a portable pulsed x-ray system was used to obtain a radiographic image of the portion of the wire or cable. The generator used was a small battery operated Golden Engineering pulsed x-ray source. Either a Polaroid film cassette or a Schick CCD flat panel, solid state array sensor (active area: 36 mm by 26 mm) coupled to a laptop computer was used for data acquisition and image display as illustrated in Figure 7. Use of the CCD array method, however, enabled instantaneous imaging feedback and eliminated the costs and processing time associated with film development. The pulsed x-ray source had a fixed nominal energy of 150 keV, yet other pulsed x-ray sources are available ranging from 100 keV up to 2 MeV. High-speed flash x-radiography can be performed using x-ray pulses having duration of less than 100 ns. The spectrum from molybdenum or tungsten targets consists of a short wavelength component having substantial penetration and additionally a longer wavelength component, which permits enhancement of the image contrast. The pulsed x-rays were controlled by means of a remote electrical switch. The Golden Engineering x-ray source is a pointed anode with an array of cathode wires arranged both circumferentially and longitudinally along its length.

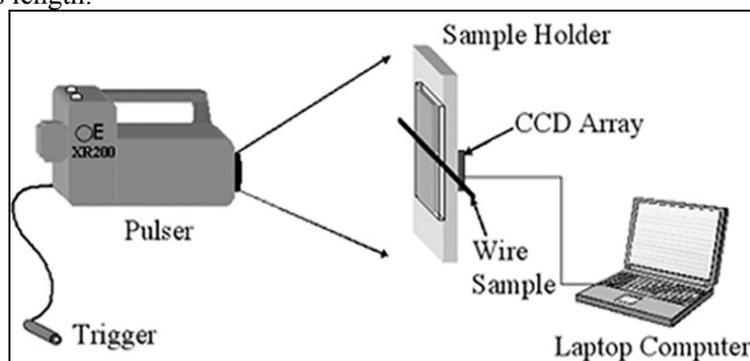


Figure 7. Schematic of pulsed x-radiography system (CCD detection)

Using commercially available software, digital images can be enhanced to improve their resolution in a number of ways. For example, the image of a wire specimen can be repetitively captured and then averaged to improve the signal-to-noise ratio of the resulting picture. Image brightness and contrast can be adjusted to emphasize features of interest. The normally gray scale can be replaced with a nonlinear one customized to make optimum use of the dynamic range of each pixel in the image, which results in a better distribution of grayscale shading. Feature edges can be enhanced using any one of a number of spatial filtering algorithms. Systematic noise can be removed by altering the Fourier transform of the image and then conducting an inverse transform. All of these operations can be readily and efficiently accomplished and the resulting images can then be digitally archived for additional review and/or processing at some later time. This system can be used to locate defects in the polymeric insulation of wiring by using x-rays of relatively low energies compared with those used to examine the metallic and alloy conductors within the identical wiring. The major difference merely involves a change in the x-ray pulser operating voltage.

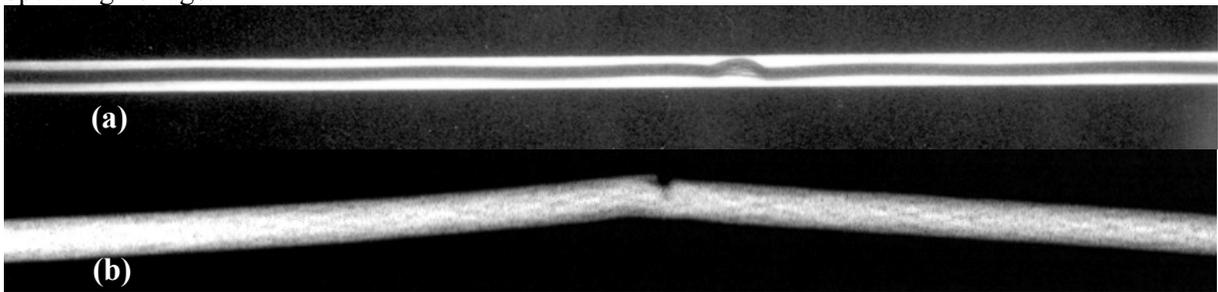


Figure 8. Wires damaged by severe bending: (a) x-ray film detection; (b) x-ray CCD detection

A comparison of the results obtained by using the x-ray film detection and the x-ray CCD detection modes is illustrated in the radiographs of Figure 8. Pulse x-rays were used to inspect two 18 AWG aircraft wires that each suffered from cracked and embrittled insulation. The damage to the Figure 8a wire was incurred while being bent and snapped after having been submerged in liquid nitrogen, while the cracking in the Figure 8b wire was the consequence of severe, repetitive bending. The radiograph in Figure 8a was recorded on film by means of 9 pulses from the pulser and the specimen was set back 150 mm from the x-ray collimator cap. The twist in the copper wire is evidence that the conductor has undergone a significant deformation in the vicinity of the embrittlement. The pulse x-rays also provide critical information on the position of the conductor within the insulation. For instance, on the top side of the contortion there is considerably less insulation than on the bottom side. The radiograph in Figure 8b was taken via the pulse x-ray CCD array detection system and digitally recorded. A total of ten x-ray pulses were fired at the specimen, which was positioned 250 mm back from the x-ray collimator cap. The penetrating power of the pulse x-rays permits a high resolution depiction of the individual strands of copper wire. Furthermore, the breach in the exterior insulation is also clearly discernible. The film detection method provides substantially more detail regarding the thickness and external state of the insulation, whereas the CCD detection method evidently provides more insight into the internal conditions of the wire conductor.



Figure 9. Pulse x-ray radiographs: (a) Burnt Wire; (b) Crimped Wire;
(c) Undamaged Metallic Braided Wire

All of the specimens shown in Figure 9 were irradiated with 10 pulse x-rays and each of the specimens was set back 250 mm from the pulser. The pulse x-ray radiograph in Figure 9a is of a wire that had experienced extensive charring damage. The segment of wire featuring the dramatic kink corresponds directly with the extent of the scorched area. The brightness of the wire rapidly fades in this burnt section and is consistent with an observable decrease in the amount of insulation present in this portion of the wire. Moreover, upon closer examination of the radiograph, only a few spindly threads of conductor are visible suggesting a possible degradation, or even loss, of copper wire in the damaged region. In Figure 9b, a wire that had been crimped was analyzed with pulse x-rays. Again, it is possible to demarcate the portion of the wire that has been impaired. Likewise, the individual strands of copper are also obvious; hence, a significant discontinuity in the conductor is clearly discernible in the contorted region that was crimped. Finally, a prominent decrease in light intensity in the crimped region is indicative of a loss of insulation and potentially wiring. An undamaged metallic braided wire was studied using the pulse x-ray system as well, as depicted in Figure 9c. Not surprisingly, the two insulated copper conductors buried beneath the metallic braiding are easily identifiable. The imaging system also uncovers the presence of the actual interwoven metallic braiding pattern.

Discussion: Several nondestructive techniques have been described which permit detection and assessment of defects in aircraft wiring specimens. Heating the wires with a heat gun and imaging the temperature profile with an infrared thermography camera provides a straightforward, portable method for a moderately trained technician to find defects in wire insulation. Time Domain Reflectivity (TDR) is a convenient, very sensitive technique of detecting and locating the position of defective wires within the insulation. Battery-operated, pulsed x-radiography with CCD array detection is an expedient, mobile means of identifying internal conductor flaws and recording images of wiring defects in-situ. Film detection does enable better identification of conductor position and insulation thickness. Overall, though, digital imaging using a CCD array affords superior processing, cost, and time advantages over film detection. While it would be impractical to x-ray entire wiring systems, this method would be suitable for detailed investigation of potential damage areas revealed by infrared thermography or TDR.

Conclusions: There is no silver bullet technique for detecting age degradation in aromatic polyimide insulated aircraft and spacecraft wiring. The three methods described here would greatly aid maintenance workers in identifying problem areas before they result in aviation incidents. To be truly effective, these inspection techniques must be part of a larger system of scheduled inspections, inspection record keeping and review, basic housekeeping practices, and

controlled maintenance work practices. In this context, sound engineering practices would allow supervisors the ability to extend aircraft service life while appropriately managing the known problem of age degradation to the aromatic polyimide (Kapton®) wiring insulation.

This research was supported by a grant from the NASA Langley Research Center, NDE Science Branch, Material Division to the Center for Nondestructive Evaluation at Johns Hopkins University. A special note of thanks in this regard is due Dr. Edward R. Generazio and Dr. William P. Winfree. Additionally, much appreciation is due to Dr. Robert Green of Johns Hopkins University for providing guidance and facilities for the project.

References:

- 1 White, Tucholski, Green, "Nondestructive Testing of Aircraft and Spacecraft Wiring," *Materials Evaluation*, v. 61, no. 12, Dec 2003, p1315.
- 2 Federal Aviation Administration, Intrusive Inspection Working Group, Christopher Smith, Chairman, *Transport Aircraft Intrusive Inspection Project*, 29 December 2000.
- 3 National Transportation Safety Board, "Aircraft Accident Report, In-flight Breakup Over the Atlantic Ocean, TWA Flight 800 Boeing 747-131, N93119 Near East Moriches, New York 17 July 1996," NTSB/AAR-00/03, Washington, DC, 23 August 2000.
- 4 Dupont, "Kapton® Polyamide Films, Summary of Properties," www.dupont.com/kapton/general/spaging.html referenced December 2002.