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Patron: DEPT.; STATUS.; Tucholski, Edward

Journal Title: Materials evaluation.

Volume: 61 **Issue:** 12

Month/Year: December 2003 **Pages:** 1315-1320

Article Author:

Article Title: White,; Nondestructive testing of aircraft and spacecraft wiring

Imprint: [Evanston, Ill.]; Society for Nondestru

ILL Number: 43785552



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Nondestructive Testing of Aircraft and Spacecraft Wiring

by John E. White,* Edward J. Tucholski† and Robert E. Green, Jr.‡

ABSTRACT

Spacecraft, and especially aircraft, often fly well past their original design lives and, therefore, the need to develop nondestructive testing (NDT) procedures for the testing of vital structures in these craft is extremely important. One of the more recent problems encountered is the degradation of wiring and wiring insulation. This paper describes several nondestructive testing methods which afford the possibility to detect wiring and insulation degradation in situ prior to major problems threatening the safety of aircraft and spacecraft.

Keywords: aircraft wiring, wire insulation, aromatic polyimide, infrared thermography, time domain reflectometry, pulsed X-radiography.

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, which are vital for control and operation. 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 it or replacing it with new wiring. Thus, it is essential that a less invasive, nondestructive method be developed to test 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 kilometers of electrical wiring on typical commercial jet aircraft. Currently, the wires are tested visually and only when there is a fault in the wiring or when modifications are made.

Problems Traced to Wire Insulation

The National Transportation Safety Board (2000) and the Transportation Safety Board of Canada (2001) both concluded that wiring has been involved in major aviation accidents. Table 1 presents a list of aviation incidents related to faulty wire insulation. The International Aviation Safety Association (2001) has identified 270 wire related accidents or incidents.

A study was conducted at the behest of the Federal Aviation Administration to analyze aging wire insulation and it 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 (Federal Aviation Administration, 2000).

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Table 1 Aircraft crashes and emergency landings attributed to electrical wiring

Date	Aircraft	Incident
24 November 1993	MD-87	smoke in cabin
17 July 1996	747	in flight breakup
2 September 1998	MD-11	fire and aircraft crash
28 November 1998	747	several arced wires
22 December 1998	L-1011	electrical wiring arced
29 March 1999	MD-11	evidence of insulation fire
29 December 2000	L-1011	electrical fire caused by arcing
10 January 2001	747	small cabin fire on landing

Arcing was found to be a major contributor in electrical fires involving degraded polymer insulated aviation wiring. It was found to be the source of electrical fires that spread along insulated wire bundles and contributed to the demise of Trans World Airline Flight 800 and Swissair Flight 111 (Furse and Haupt, 2001). Arcing involves the luminous discharge of electricity across the polymer insulation. The electrical discharge of an arc can have a temperature of several thousand kelvin. 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 were observed by Raytheon (National Transportation Safety Board, 2000). Scintillations and flashing (400 mJ) to 8.25 J [3.8×10^{-4} to 8.5×10^{-2} Btu]) caused substantial charring, discoloration and erosion of wire insulation and conductors, but circuit breakers rarely tripped. Strong arcing (of approximately 5 kJ [4.7 Btu]) occurred in tests involving aromatic polyimide wiring. Noncontact arcing between conductors separated by insulation may require several kilovolts to initiate arcing, 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 Transportation Safety Board of Canada discovered evidence indicative of a major electrical arcing event in the cockpit area of Swissair Flight 111. Substantial heat damage occurred to the ceiling areas in the vicinity of the cockpit bulkhead. Wires recovered from the ceiling area exhibited heat damage consistent with arcing, including discoloration, heavy charring and embrittlement of the wiring insulation. Two electrical bus feed wires exhibiting signs of electrical arc damage were located 51 mm (2 in.) from the cockpit overhead circuit breaker panel. Finally, 20 electrical wires were discovered that "displayed melted copper caused by an arcing event" (Maxwell, 1998). The National Transportation Safety Board found that the fuel tank indicator wiring on TWA Flight 800 had significant damage prior to the crash. The ignition source was traced to a

possible arc in the indicator wiring. The resulting fire would then have spread along the indicator wiring to the fuel tank assembly causing a massive explosion. There were 10 separate instances of recorded repair near or at the indicator wiring in the preceding 10 year span (National Transportation Safety Board, 2000). There are several types of wire insulation that have been used throughout the aviation industry and it is not uncommon for aircraft to contain bundles of mixed wire type.

There are several types of wire insulation that have been used throughout the aviation industry and it is not uncommon for aircraft to contain bundles of mixed wire types. Types of aviation wire insulation include: polyvinylchloride/glass/nylon; polyvinylidene fluoride; aromatic polyimide; polytetrafluoroethylene; extruded aliphatic polyimide; polyarylene; cross linked ethylene; tetrafluoroethylene; and polytetrafluoroethylene/polyimide composite. The most common aircraft wire insulation problems 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.

PRESENT RESEARCH

The principal technique used for testing aviation and spacecraft wiring components remains visual testing. These tests are not able to detect all discontinuities 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, which can result in further damage to already cracked insulation. It is imperative that an alternative method be developed to reliably assess 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.

Test Specimens

Wire test specimens were cut from wire bundles removed from a retired 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 aromatic polyimide. These samples included braided 16, 18 and 20 gage wires (measured according to the American wire gage standard) with nominal bare wire diameters of 1.3 mm (0.05 in.), 1.02 mm (0.04 in.), and 0.81 mm (0.03 in.), respectively. The maximum outer diameter with insulation was approximately twice the nominal diameter, consisting of two or three distinct layers. Aromatic polyimide experiences an 80% loss of tensile strength and degradation of dielectric properties at elevated temperatures (above 598 K [617 °F]) for extended periods of time (550 h). The coefficient of thermal conductivity of aromatic polyimide (Dupont, 2002) is 0.12 W/m·K (6.9×10^{-2} Btu/(hr·ft·°F)) at 296 K (73 °F).

Creation of Wiring Problems

There are three major types of problems common to in service aircraft wiring: chafed or frayed wires damaged mechanically by accidents occurring 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. 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

Infrared thermography promises to be an excellent technique for rapid testing of aircraft wiring. The major benefits of this technique reside in the portability of infrared cameras and the ability to rapidly examine large areas of wiring. 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 as to examine numerous wires at the same time and permits noncontact rapid testing 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 problems, 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. Two infrared systems were used during this phase of the experimentation: a general commercial model and a newer, high resolution model. The testing was conducted on wires approximately 305 mm (12 in.) in length which were affixed across the opening of an insulated styrofoam box with an open face of 229 by 305 mm (9 by 12 in.). A schematic of the infrared thermography system used is shown in Figure 1.

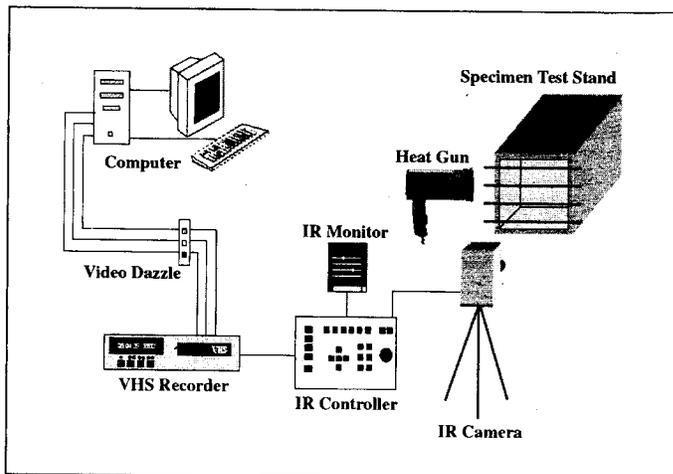


Figure 1 — Schematic of the infrared thermography system.

The infrared camera was placed at a standoff distance of approximately 0.6 m (2 ft). 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 of approximately 283 K (18 °F), 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 593 K (600 °F), 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, discontinuities in the wire insulation have significantly different absorptivity and emissivity, resulting in temperatures well above the bulk of the wire. This allows the discontinuities to stand out prominently in the display.

Initially, to determine the effectiveness of the infrared thermography technique, an 18 gage wire with a minor fray was taped to the open face of the test box. Approximately 25 mm (1 in.) below, a second undamaged control 18 gage wire was affixed to the box, as shown in Figure 2. While heating with a heat gun, both wires visibly began to heat up and became easily visible when viewed with the standard infrared camera system. Most importantly, the region in the vicinity of the fray turned a different color (or different shade of gray), representing a higher temperature and making it much more visible than when tested visually. The control wire, having no such fray, remained uniform in temperature.

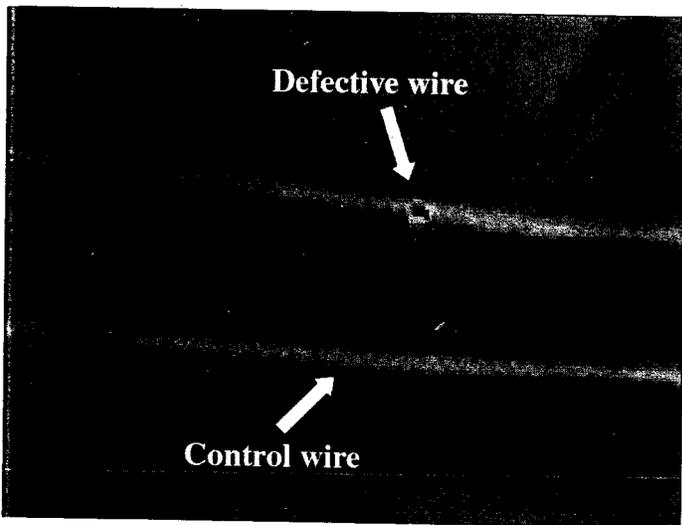


Figure 2 — Infrared thermography: single wire test.

A six wire test was performed to determine the relative sensitivity of this test to wires in close proximity containing various discontinuities. In this test, five 18 gage wires differing only in the magnitude, type and location of discontinuity 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.

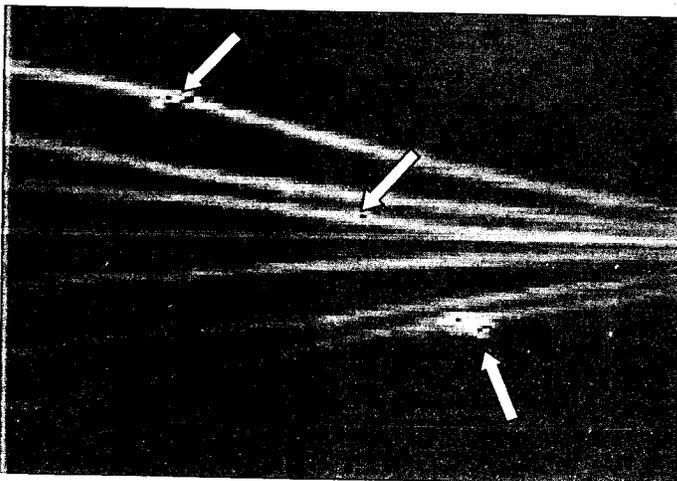


Figure 3 — Infrared thermography: multiple wire test.

A 0.3 m (1 ft) segment of a wire bundle containing 18 gage wires was removed from a larger aviation bundle specimen. Two separate wires of the 32 wire bundle were deliberately inflicted with discontinuities. 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. However, the more sensitive infrared system was able to detect this discontinuity at ambient temperatures without the benefit of a hot gun. The slight nick was also observed by both infrared systems. In Figure 4, a brilliant white orb radiates from the vicinity of the superficial nick using the high resolution system, whereas the other regions of the wire free of discontinuities retain a grayer hue under heating. The horizontal striation in this figure results from the infrared imaging of the outer wires in the bundle.

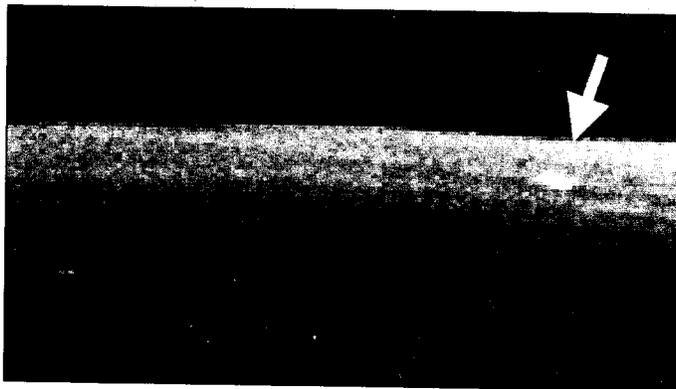


Figure 4 — Infrared thermography: wire bundle test.

TIME DOMAIN REFLECTOMETRY

Another primary focus of the present research was to nondestructively test 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. Time domain reflectometry 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.

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

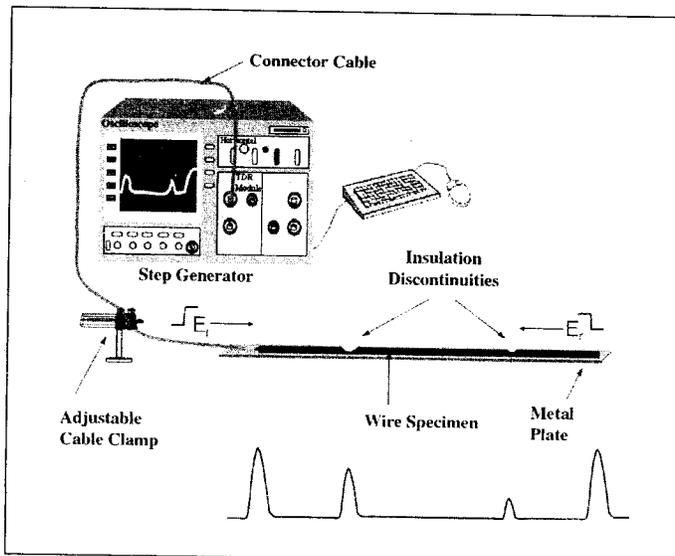


Figure 5 — Schematic of the time domain reflectivity system.

length of the wire or cable and the speed of the signal traveling through the wire. If a discontinuity 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 discontinuity and the magnitude of the returning pulse is related to the size of the discontinuity. 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.

In Figure 5, the connection to the test wire, the discontinuities 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 discontinuity in the wire lowers its overall capacitance. As an example, Figure 6 shows the results of a metal shard embedded in the aromatic polyimide insulation of a braided conductor wire. The wire specimen is a 250 mm (10 in.) section of 18 gage 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.

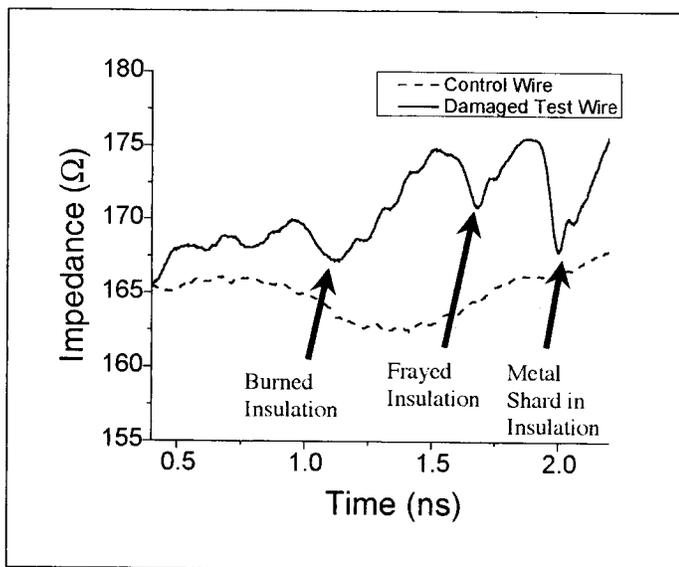


Figure 6 — Time domain reflectivity results of a metal object in wire insulation.

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 10 mm (0.4 in.) in length along the wire insulation surface.

Unfortunately, the time domain reflectometer is extremely sensitive, so 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. The required training of the operator using this test method will be more involved than the other nondestructive tests described in this paper.

PULSED X-RADIOGRAPHY

Once a more global technique, such as infrared imaging of heat generation or time domain reflectometry, indicated that a discontinuity existed 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

pulsed X-ray source. Either a film cassette or a charge coupled device flat panel, solid state array sensor with an active area of 36 mm by 26 mm (1.2 in. by 1.0 in.) coupled to a laptop computer was used for data acquisition and image display as illustrated in Figure 7. Use of the charge coupled device 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 kV, yet other pulsed X-ray sources are available ranging from 100 kV up to 2 MeV. High speed flash X-radiography can be performed using X-ray pulses having a 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 X-ray source is a pointed anode with an array of cathode wires arranged both circumferentially and longitudinally along its length.

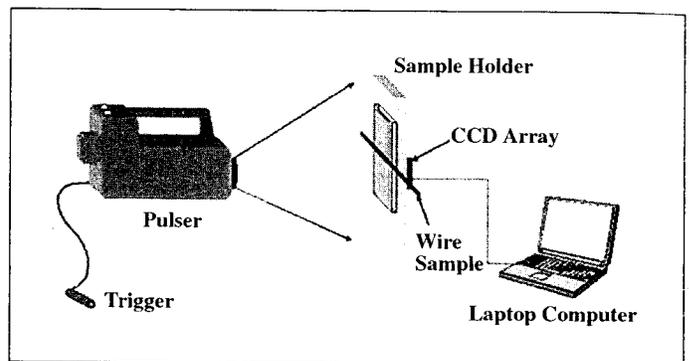


Figure 7 — Schematic of the pulsed X-radiography system (charge coupled device detection).

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 processing at some later time. This system can be used to locate discontinuities 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 pulsing operating voltage.

A comparison of the results obtained by using the X-ray film detection and the X-ray charge coupled device detection modes is illustrated in the radiographs of Figure 8. Pulse X-rays were used to test two 18 gage 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 nine pulses from the pulsed source with the specimen set back 150 mm (6 in.) 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

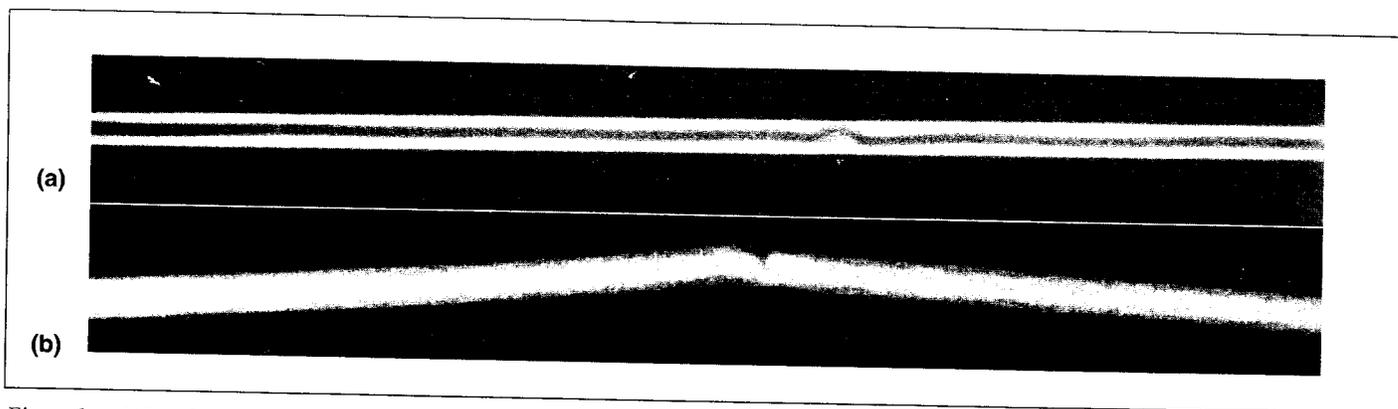


Figure 8 — Wires damaged by severe bending: (a) X-ray film detection; (b) X-ray charge coupled device detection.

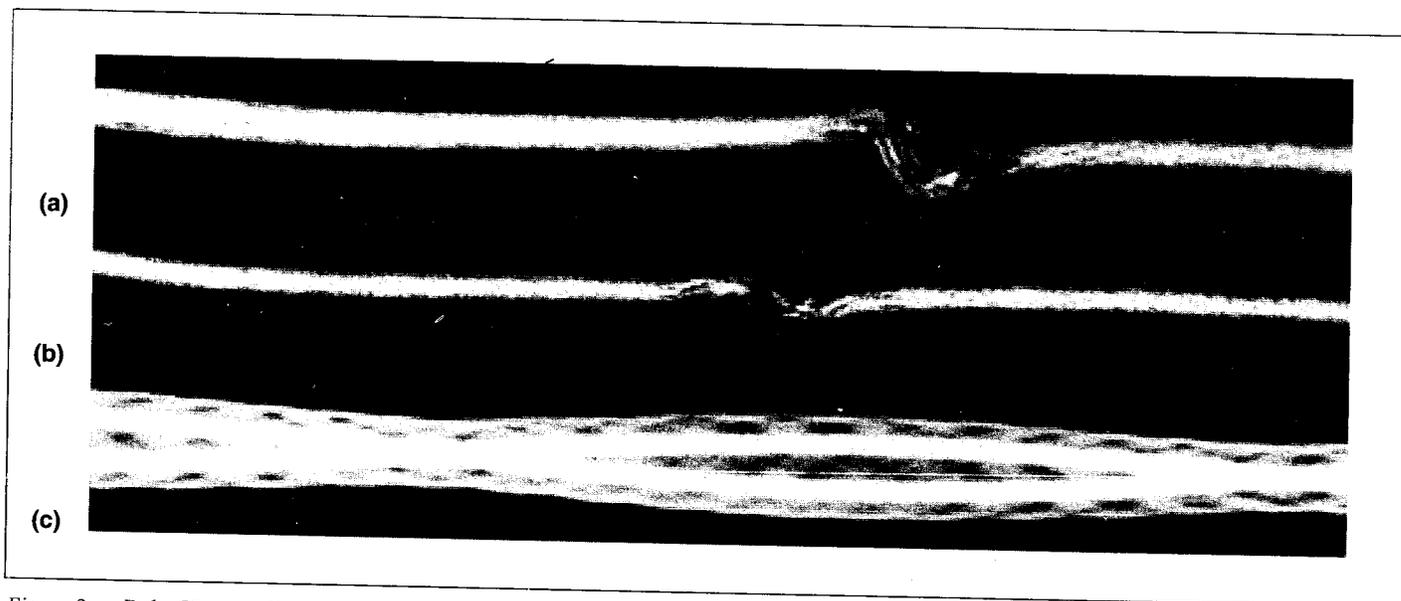


Figure 9 — Pulse X-ray radiographs: (a) burnt wire; (b) crimped wire; (c) undamaged metallic braided wire

insulation than on the bottom side. The radiograph in Figure 8b was taken via the pulse X-ray charge coupled device array detection system and digitally recorded. A total of 10 X-ray pulses were fired at the specimen, which was positioned 250 mm (10 in.) 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. Clearly, the film detection method provides substantially more detail regarding the thickness and external state of the insulation, whereas the charge coupled device detection method evidently provides more insight into the internal conditions of the wire conductor.

All of the specimens shown in Figure 9 were dosed with 10 pulse X-rays and each of the specimens was set back 250 mm (10 in.) 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 possibly 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.

CONCLUSIONS

Several nondestructive techniques have been described which permit detection and assessment of discontinuities 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 discontinuities in wire insulation. Time domain reflectivity is a convenient, very sensitive technique of detecting and locating the position of wires with discontinuities within the insulation. Battery operated, pulsed X-radiography with charge coupled device array detection is an expedient, mobile means of identifying internal conductor discontinuities and recording images of wiring discontinuities in situ. Film detection does enable better identification of conductor position and insulation thickness. Overall, though, digital imaging using a charge coupled device array affords superior processing, cost and time advantages over film detection.

ACKNOWLEDGMENTS

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 Edward R. Generazio and William P. Winfree.

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