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Aging Aircraft 2007

NEXT GENERATION WIRING

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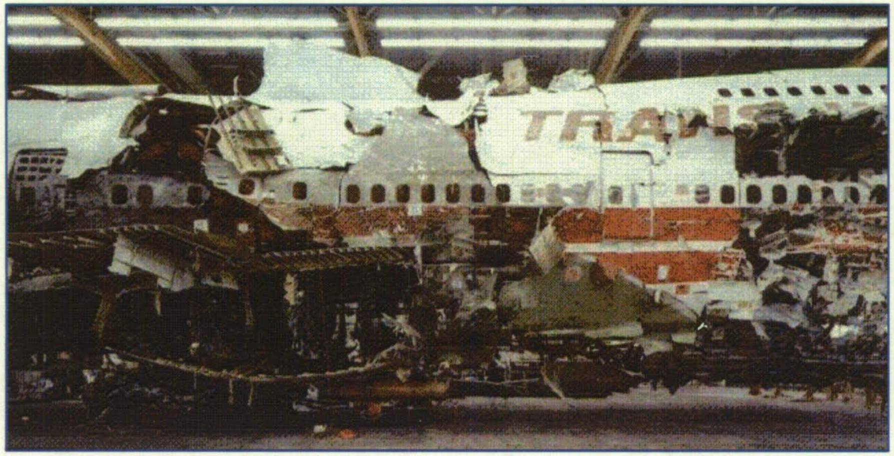
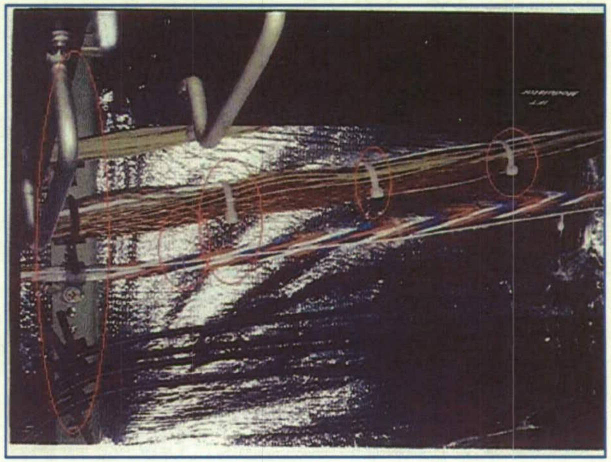
Overview

1) Background
2) Project Overview
3) Project Research Topics
   - Self-Healing Wire Insulation
   - Next Generation Conductors
   - Systems Integration
4) Future Research
5) Acknowledgements

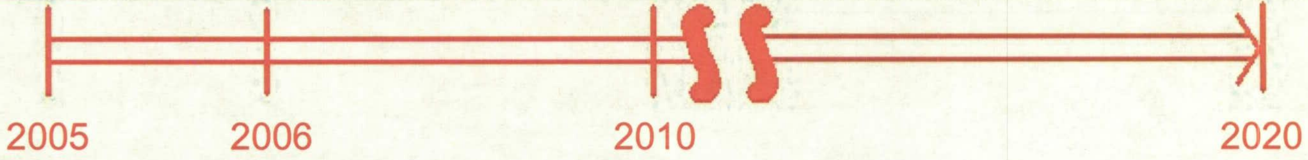
Project Background

- STS-93 (July 1999)
  - Short circuit in 14 AWG Kapton® insulated wire
- TWA 800 (July 1996)
  - Frayed Kapton® wire in center tank area
- SwissAir 111 (September 1998)
  - Damaged wire in plane's entertainment system





Project Overview

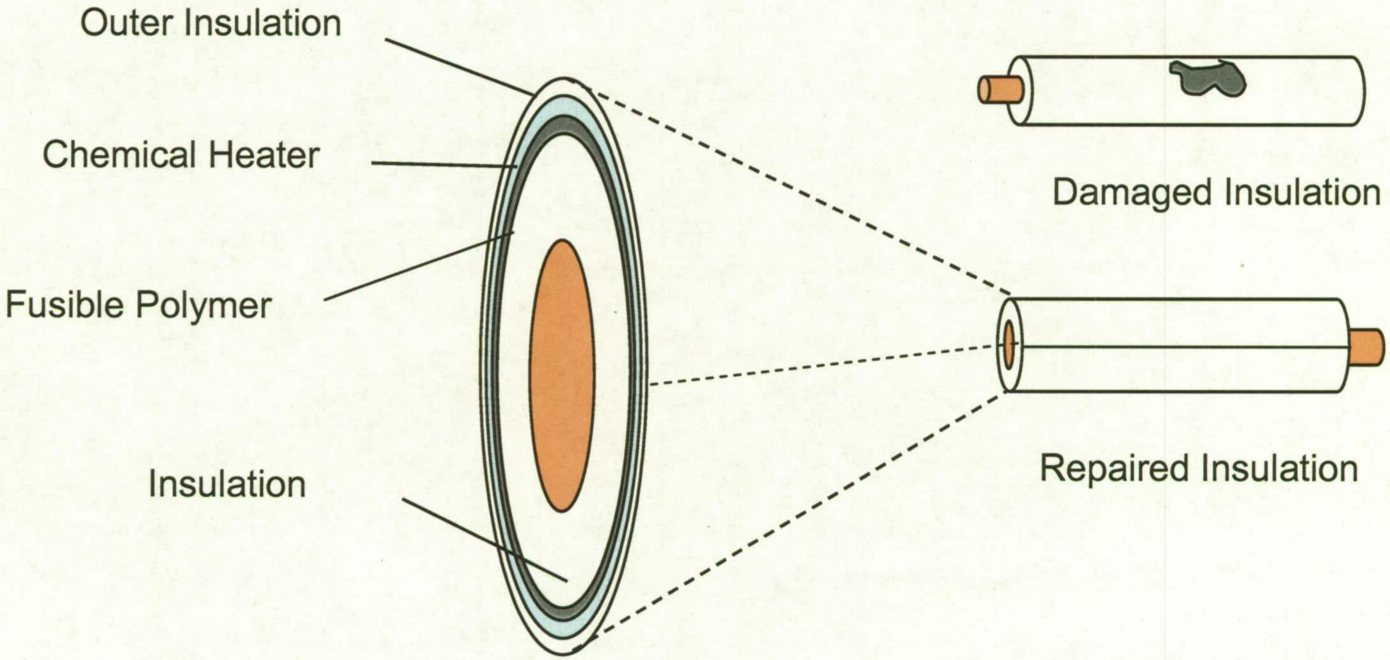
Project Topic Area	 2005 2006	2010	2020
Self-Healing Wire Insulation	Manual Wire Repair System for Kapton® and Teflon Wire Insulation	Self-Healing Initiation Concept Better Understood; Design of Self-Healing Wire Insulation Complete	Self-Healing Wire Insulation
Next Generation Conductors	High Conductivity Polymeric Conductors; High Conductivity Composite Conductors	High Conductivity Polymeric, CNT and Polymer/CNT Composite Fibers	Small, Lightweight, Next Generation Conductors
Systems Integration	Smart, Lightweight Connectors; In-Situ Wire Damage Detection System; Smart Signal Systems (Switches, Connectors, etc.)	Smart, Lightweight Sensors for IVHM; Smart Systems (Generation 1); Smart Connectors	Smart, Lightweight, Modular, Reconfigurable Wiring Systems; Smart Structures; Smart Textiles

Self-Healing Wire Insulation

- Manual wire insulation repair for Kapton® and Teflon® insulated wire
  - New materials development
  - Chemical heater development
  - Engineering development
- Self-healing wire insulation
  - New materials development
  - Initiation mode development
  - Engineering development

Self-Healing Wire Insulation Technical Accomplishments

Manual Repair Concept



Outer Insulation

Chemical Heater

Fusible Polymer

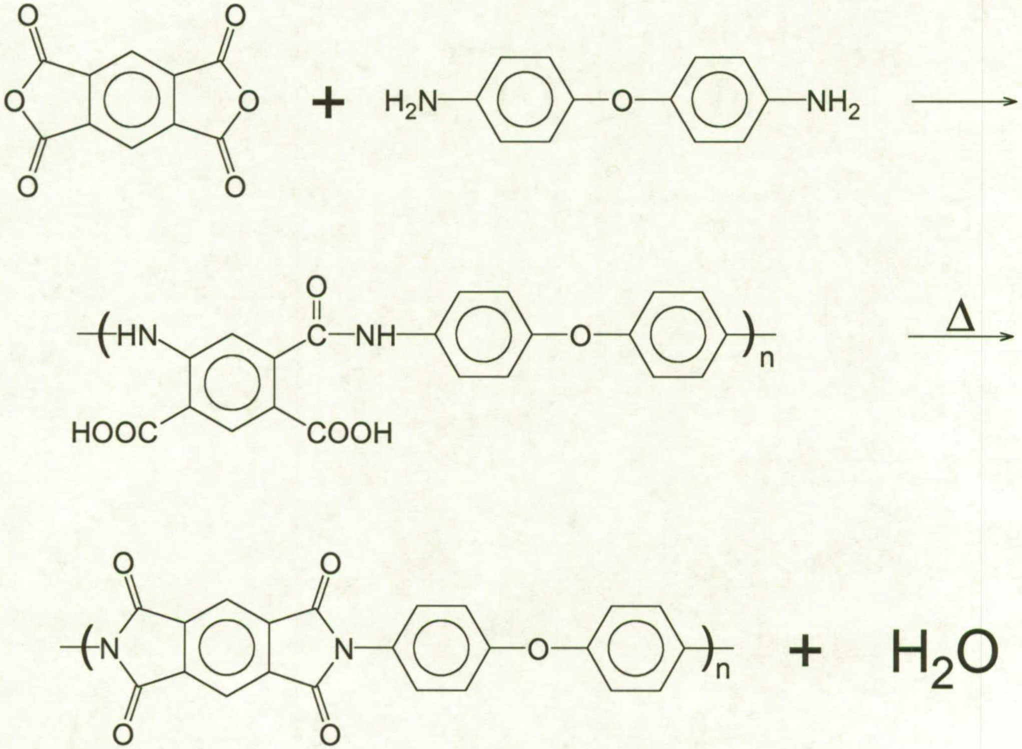
Insulation

Damaged Insulation

Repaired Insulation

Self-Healing Wire Insulation Technical Accomplishments

Kapton® Synthesis



Self-Healing Wire Insulation Technical Accomplishments

Manual Repair Materials

- More than 50 repair materials have been developed to date
- Materials differ in aromatic, aliphatic content as well as melt temperature
- All materials are stable to 330 ºC or greater in nitrogen environment
- Materials are evaluated for dielectric strength, surface/volume resistivity, and adhesion

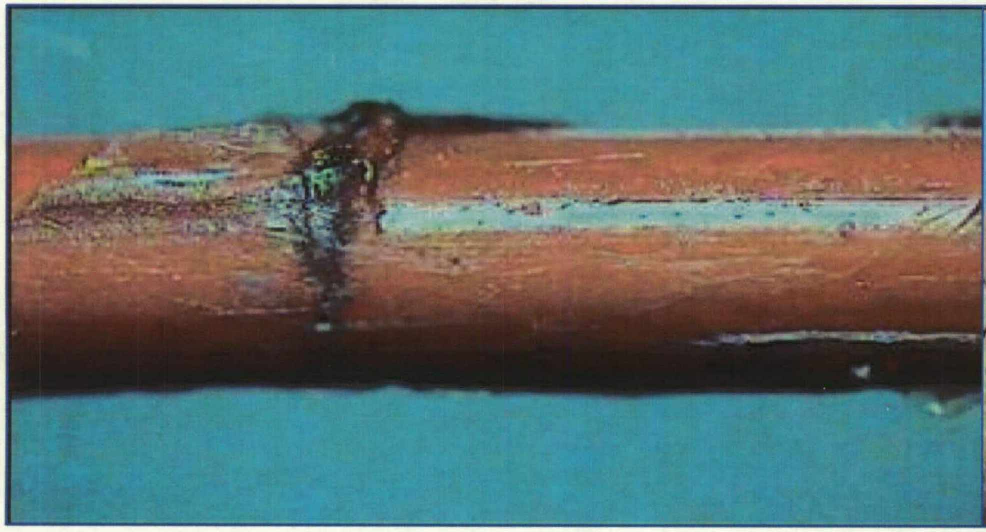
Self-Healing Wire Insulation Technical Accomplishments

Manual Repair Method

- Synthesize Repair Material
- Cut Material into Repair Tape
- Wrap Repair Tape Around Damaged Wire To Completely Cover Damaged Area
- Heat Repair Tape to Initiate Repair
- Remove Heater

Self-Healing Wire Insulation Technical Accomplishments

Examples of Manual Repair

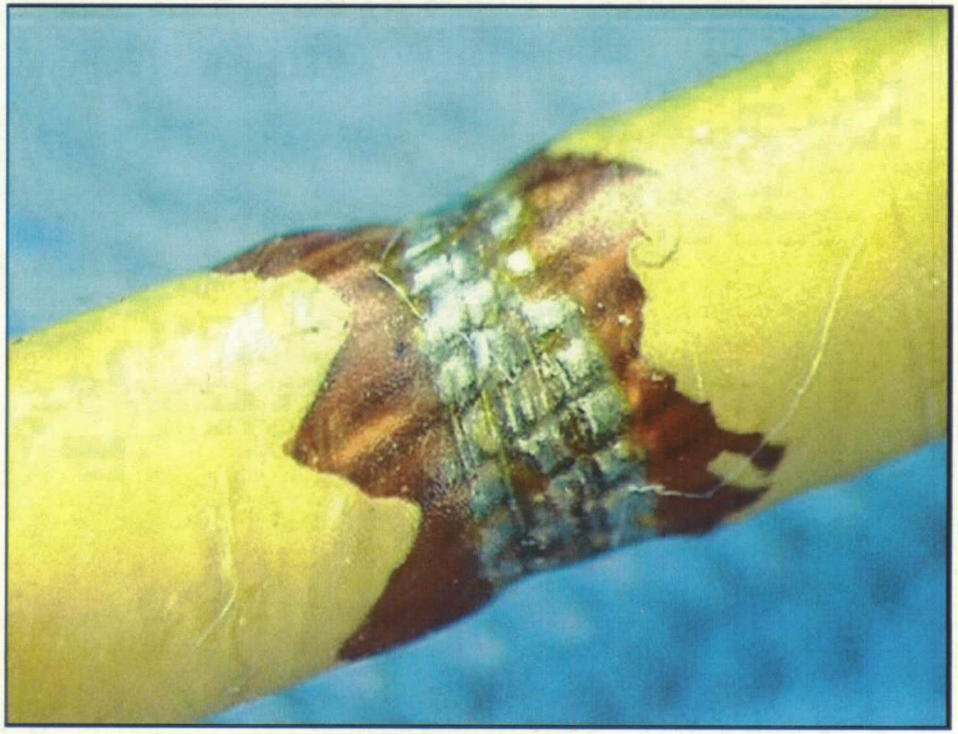


20 AWG Kapton® Coated Wire

12 AWG Kapton® Coated Wire

Self-Healing Wire Insulation Technical Accomplishments

Manual Repair, Preliminary Results



Self-Healing Wire Insulation Technical Accomplishments

Materials Properties

- Adhesion
  - Average Shear Load of 468 psi
- Electrical
  - Breakdown Voltage of 5.0 kV/mil
  - Surface Resistivity of $5.8X10^{15}$ Ω/square
- Thermal
  - Stable to > 330 °C

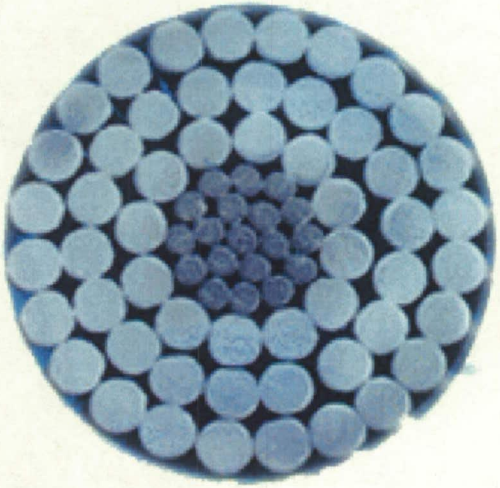
Self-Healing Wire Insulation Technical Accomplishments

Self-Healing Wire Insulation

- Multiple “modes” of self-repair incorporated in insulation
- Utilizes low-melting polyamic acids and polyimides
- Repair initiated by chemical, mechanical, and electrical stimulus
- Working with industry on engineering development

Next Generation Conductors

- Inherently Conductive Polymers (ICPs)
  - New materials development
  - ICP fiber processing
  - Engineering development
- Composite Conductors
  - New materials development
  - Composite fiber processing
  - Engineering development



3M™ Aluminum Conductor Composite Reinforced (ACCR)

Next Generation Conductors Technical Accomplishments

Typical ICPs

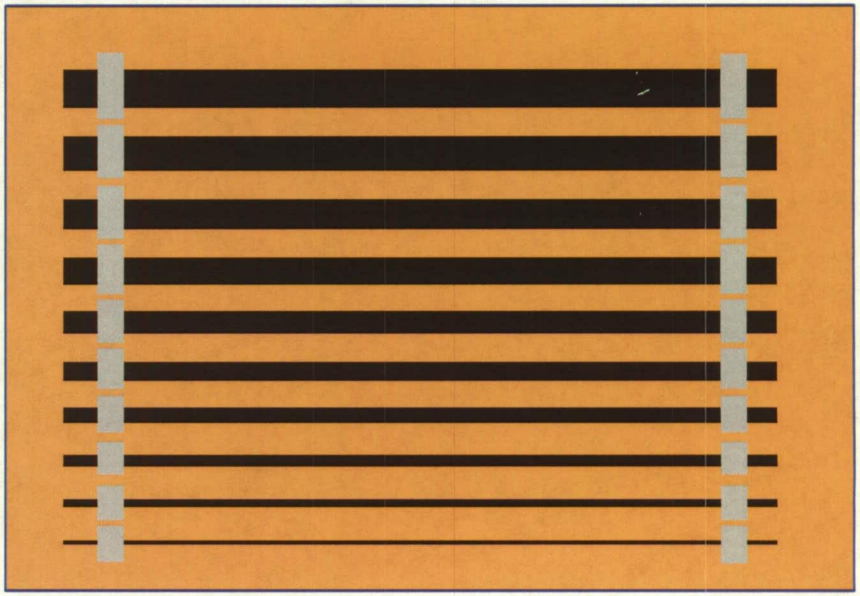
- Polyacetylene
- Polyaniline
- Polythiophene
- Polypyrrole

Typically unstable above 200 ºC

Next Generation Conductors Technical Accomplishments

Soluble ICPs

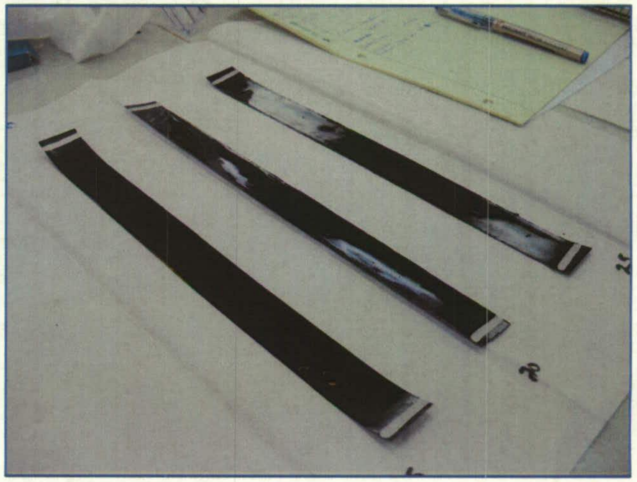
- Worked with soluble ICPs developed by Crosslink Polymer Research
- Printed conductive layers on Kapton® HN film
- Resistance values as low as 3.5 kΩ
- Stable to ~ 230 °C



Next Generation Conductors Technical Accomplishments

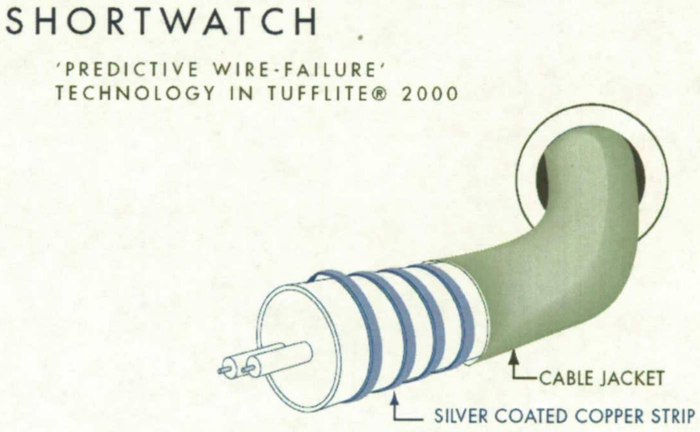
Composite Conductor Development

- Purchase commercially available conductive additives
- Chemically modify additives
- Incorporate into soluble ICPs
- Deposit layers of composite conductors on polymer film
- Perform testing



Systems Integration

- Smart Connectors
  - Small, lightweight, ultra reliable
- In-situ wire damage detection system
  - Capable of wire damage detection “on-the-fly”
- Integrated vehicle health monitoring (IVHM)
  - System-of-systems level, providing high level of reliability



Future Research

- Continue to develop new, high performance materials for wire insulation repair
- Focus on development of an “all-in-one” repair kit for manual wire insulation repair
- Develop self-healing wire insulation that “heals” under a wide variety of conditions (abrasion, heat, electrical stimulation, etc.)
- Develop portable NDE tool for wire damage detection
- Develop in-situ wire damage detection system, integrating self-healing insulation, ICPs, and smart connectors
- Continue to develop next generation conductor materials

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Next Generation Wiring

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I. Abstract

Wiring is a major operational component on aerospace hardware that accounts for substantial weight and volumetric space. Over time wire insulation can age and fail, often leading to catastrophic events such as system failure or fire. The next generation of wiring must be reliable and sustainable over long periods of time. These features will be achieved by the development of a wire insulation capable of autonomous self-healing that mitigates failure before it reaches a catastrophic level. In order to develop a self-healing insulation material, three steps must occur. First, methods of bonding similar materials must be developed that are capable of being initiated autonomously. This process will lead to the development of a manual repair system for polyimide wire insulation. Second, ways to initiate these bonding methods that lead to materials that are similar to the primary insulation must be developed. Finally, steps one and two must be integrated to produce a material that has no residues from the process that degrades the insulating properties of the final repaired insulation. The self-healing technology, teamed with the ability to identify and locate damage, will greatly improve reliability and safety of electrical wiring of critical systems. This paper will address these topics, discuss the results of preliminary testing, and remaining development issues related to self-healing wire insulation.

II. Introduction

In early 2004, President George W. Bush announced a new Vision for Space Exploration for the National Aeronautics and Space Administration (NASA). The Vision called for the return of humans to the Moon by 2020 in preparation for human exploration of Mars. To determine the best exploration strategy (architecture) needed to implement the President's Vision for Space Exploration, NASA established the Exploration Systems Architecture Study (ESAS) team. The ESAS final report contains information regarding technologies and potential approaches related to the implementation of the Vision for Space Exploration.

Failures of critical power or communication systems can have catastrophic implications during long duration space exploration. Wiring is a key component of spacecraft and accounts for substantial weight and space consumption. It is highly desirable that the next generation of wiring be made of smart materials; consist of highly integrated material systems that incorporate embedded electronics, sensors, and actuators; and be multifunctional and adaptive so they can be reconfigured in response to changing mission conditions. Also, the next generation of wiring must be reliable, affordable, safe, light weight, small in volume, and sustainable over long periods. The development of the next generation of wiring will provide space vehicles, robots, and habitats that are reusable, modular, as safe as is reasonable achievable, and reconfigurable. State-of-the-art aerospace vehicle wiring has remained essentially unchanged for decades.

There have been many instances of wiring failure on aerospace and commercial vehicles, dating as far back as the Gemini 8 mission where an electrical wiring short shortened the mission and nearly resulted in the loss of the crew. Shortly after the launch of STS-93, a primary and back-up main engine controller on separate engines dropped offline due to a short circuit of a 14-gauge Kapton®-insulated wire to a burred screw head. An arched wire in the in-flight entertainment network (IFEN) attributed to the loss of SwissAir 111 by causing fire ignition. And finally, the loss of TWA 800 was attributed to a frayed wire in the center tank area.

The impact of the next generation of wiring to future long-term space exploration is significant. Wiring systems will no longer have to undergo routine inspection after initial testing and acceptance, thus eliminating the potential of damage inflicted by the inspection team or the inability to inspect cables because of inaccessibility. Next generation wiring systems can be self-healing and reliable, which is critical in long-term exploration. The spin-offs to the aerospace and defense industry are also significant.

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III. State-of-the-Art

This paper will address three topics related to the next generation of wiring: 1) manual repair and self-healing wire insulation; 2) next generation conductors; and 3) systems integration. The state-of-the-art for each topic will be described in the following paragraphs in this section. Section IV will contain current development efforts in each topic area.

A. Manual Repair and Self-Healing Wire Insulation

1. Manual Repair of Wire Insulation

Based on literature reference there are three main technologies related to manual polymer repair: 1) liquid applied polymers; 2) adhesives containing fibers; and 3) polymer joining. Each of these topics will be discussed in detail below.

There are a number of references related to the use of liquid applied polymers for manual repair of polymers/composites. These systems involve the use of a solvent soluble polymer (aqueous or organic soluble) resin. The polymer solution is applied to the damaged area of the polymer or composite and cured. Curing may involve heating, the use of light or simply solvent evaporation.

Adhesive containing fibers have been used for the repair of composites.[1-2] The system involves using fibers such as silica, silica-alumina, and zirconia with liquid synthetic resins absorbed on the fibers.

Polymer joining is another method to provide manual repair of polymer and composite materials. In polymer joining, repair composites (polymers) of various types are bonded to each other and to metals using thermoset adhesives.[3] Some applications the involve polymer joining include adhesive bonding of crosslinked dental teeth to denture base resin,[4] electronic material fabrication, net shaping using thermosets, etc.

2. Self-Healing Wire Insulation

Many literature references exist on the development of self-healing thin films (most dealing with inorganic films) for corrosion and oxidation prevention. A significant number of references on scratch/mar healing in coatings as well as methods to heal cracks in cement/ceramic structures exist going back to the 1980s, but efforts to heal significant compromises in polymer structures did not begin until the turn of the 21st century.

Based on these literature references there are essentially five basic methods being actively research that have the goal of engineering a self healing capability into a polymer matrix. These methods are as follows:

- Microencapsulation techniques
- Other filled structures/architectures
- Nanoparticle migration
- Ionomer/non-covalent bond self-healing
- Ambient responsive materials

Microencapsulation techniques are the most common type of self-healing and involve the preparation of microcapsules containing a flowable liquid which, when comes into contact with a catalyst or other reactive influence, will polymerize into a solid polymer. These microcapsules are incorporated into the polymer composite which may, at some future time, experience some form of trauma such as stress, thermal expansion, etc. If such a trauma induces cracking in the polymer object, the microcapsules located along the crack line will rupture, releasing polymerizable liquid into the crack void. This liquid will then polymerize into a hard polymer, effectively sealing the crack.[5-8] This technology represents the most flexible method presently under evaluation today towards polymer self-healing. Microencapsulation technology is used extensively in industry, and it is expected that a wide range of healing materials could be used for self-healing in a number of different industrial polymers. This method, however, appears to loose its effectiveness as the architecture of the polymer to be engineered shifts to very small or thin materials.

The second most common type of self-healing system uses materials that exploit the breaking and reformation of noncovalent bonds, for example ionomers. Because of the unique nature of noncovalent bonding, these materials can undergo self-healing under severe damage. Large cracks, cuts, and punctures, including ballistics, will heal to a significant degree. In order for ionomers to undertake self-healing, they must possess a large number of ionic sites along the polymer backbone. These ionic sites can "associate" one with another and in fact, seek to do so to satisfy dynamic charge separation criteria. If positive and negative charges are separated due to a stress event, they will seek to recombine back to their original charge separation equilibrium, therefore, the closer opposite charges are in proximity, improvements in healing are observed. Thus materials based on acrylic acid coupled with a soft polymer such as polyethylene have shown good self healing. Several references use the term "supramolecular" to designate materials that can exhibit dynamic noncovalent bonding.[9-10]

A number of groups have begun work on using architectures other than microcapsules to hold/release healing liquid under stress conditions. These alternate architectures include using hollow fibers,[11-12] "microtubeules",[13] and structures that have liquid holding channels or voids that can be used to contain material for self healing.[14] The hollow fibers and "microtubules" function in a similar manor to microcapsules. The reference using vascular channels is somewhat unique in that it takes advantage of natural compartments within the composite to hold healing materials that can be released during a stress event.

Two references report the use of nanoparticles in polymer composite materials as a healing sealant.[15-16] These nanoparticles function by entropy driven migration to fill cracks or voids in these composites.

Another method involves the use of a polymer layer on the outside of a liquid containing vessel.[17] If a breach in the vessel wall occurs the polymer layer is designed to react or swell upon contact with the liquid thus sealing the hole.

All of the technology presently being researched under the concept of "self-healing" seeks to repair a polymer composite that has undergone a stress or compromise of one degree or another. The repairs obtained by the methods reported above do not profess to completely heal or repair the composite within which they work. Thus the repair will function for its intended use as long as further significant stress at that point is not encountered. As such these "smart materials" should be considered as a first generation of self-healing materials. It is most likely that a method of self-healing will have to be specifically tailored to each individual polymer composite use.

B. Next Generation Conductors

Polymers have long been considered an economically feasible replacement to metal and metal composites in applications where mechanical strength and decreased weight is desired. The performance success of engineering plastics and the successful synthesis of intrinsically conducting polymers (ICPs) led to the increased incorporation of macroscale and nanoscale additives into polymer matrices in hopes of fabricating stronger polymers and/or more conductive polymers. The resulting composite materials have exhibited enhanced properties as a result of the combination of properties from the filler and the polymer. One such additive, carbon nanotubes, has been shown to provide exceptional mechanical reinforcement to the polymer matrices as well as enhanced conductivity in both conductive and non-conductive polymers at very low loading levels. Carbon nanotubes are said to be as high as 100 times stronger than steel,[18-19] in addition to being more than 1000 times more conductive than copper[20] at the nanometer scale. The challenge to incorporating CNTs into a polymer matrix has been overcoming the bundling of CNTs and increasing interaction at the polymer/nanotube interface. A further challenge to incorporating nanotubes into conducting polymers is the obstacle of achieving soluble formulations of commonly used conducting polymers. The next several sections of this document will provide a historical background of conductive polymers and carbon nanotubes.

1. Intrinsically Conductive Polymers (ICPs)

In a joint effort between the Alan MacDiarmid, Alan Heeger and Hideki Shirakawa research groups the conductive form of poly(acetylene) was successfully synthesized in 1977.[21] While at this time several conventional (or non-conductive) polymers were of interest to many industrial markets for structural replacements to metals and ceramics, there still lacked a polymer material that could substitute for conductive metal materials; thus, the synthesis of a light weight polymer conductor was a needed commodity. However, initial forms of ICPs were hard to process and environmentally unstable. Despite these misgivings, the ability to alter the conductivity from a semiconductor comparable to silicon to a highly conductive material approaching the conductivity of copper remains attractive to the scientific community. ICPs have conductivities in the area of 10^{-1} to 10^{3} S/cm and 10^{4} for oriented conducting polymers. Since the 1970's these polymers have been used in light emitting diodes (LED), sensors, actuators, batteries, radio frequency interference shielding, nonlinear optical materials for telecommunications, EMI shielding, solar cells, and anti-corrosion coatings. The most commonly used ICPs are polyaniline, polypyrrole, and polythiophene, because they are the easiest to process and are more stable in their doped form than other conductive polymers.[22] However, due to success in overcoming processing challenges[23] and increased stability in the doped form as compared to the other ICPs, polyaniline is the most commonly used polymer for most applications.[22,24] Since the 1970's there has been several published papers on the progression of intrinsically conducting polymers and their infusion in various niche markets.[25-32]

The challenge in utilizing these polymers is to increase their conductivity to one that approaches copper. Several researchers have attempted to increase the conductivity of ICPs by the incorporation of additives, various dopants, and various processing techniques to bring about better orientation of the polymer structure. Furthermore, several companies market various formulations of in ICPs. Panipol and Ormecon market polyaniline powders, coatings and inks for ESD applications, anti-corrosion applications and printed electronic components. Smaller companies such as Fractal Systems, Inc., and Santa Fe Science and Technologies, Inc. perform research and development for niche customers such as the aerospace industry and military needs. The challenge facing the current technology is to further increase the conductivity of the doped polymer by increasing the conjugation of the polymer chain, manipulating dopants and dopant levels, and overcoming the solubility limitations of conducting polymers. The ultimate goal is to successfully fabricate a system with conductive additives and polyaniline that is thermally stable above 260°C, has conductivity above 10^3 S/cm, and can be processed in the form of a fiber that has mechanical tensile strength at or above 3200 MPa. One such conductive additive that has shown promise in further enhancing the conductivity of the ICPs and contributing to the mechanical strength is the carbon nanotube.

2. *Carbon Nanotubes*

The discovery of carbon nanotubes in the early 1990's launched a new interest in using this material in everything from gas sensors, components in electronic display systems and numerous nanodevices. The discovery of carbon nanotubes in the 1990's followed the successful synthesis of Kroto, Smalley, and Curl's buckminsterfullerene in 1985 and with the collective discovery of these unique forms of carbon created an explosion of research and innovations that defined nanoscience and nanotechnology. Multiwalled carbon nanotubes (MWNT) have found their way into field emitting devices and tips for Atomic Force Microscopy (AFM). Single walled nanotubes (SWNT) have been used in electronic devices and have been shown to be a potential substrate for hydrogen storage.[33]

Structurally, SWNT consist of a single graphene sheet rolled up and capped at either end with a five membered ring. SWNTs have diameters ranging from 1 to 2 nm and lengths as high as 700 nm (0.9 nm diameter).[33] MWNT consist of several layers of graphene sheets rolled up into cylinders capped at both ends with a five membered ring (half of a fullerene).[33] The layers have an estimated spacing of 0.34 nm, an outer layer diameter ranging from 2 and 25 nm, and an inner hollow ranging from about 1 to 8 nm. Carbon nanotubes are known to have large aspect ratios, thus making them efficient electron transport machines. The nanometer size, the helical structure, and the topology of carbon nanotubes give them their excellent mechanical (stability, strength, stiffness, and elastic deformability), electron transport, and surface properties. Further, depending on the diameter and helicity, CNTs can be metallic, semiconducting or semimetallic.[33-34]

Technology breakthroughs in carbon nanotube growth, purification, and production has allowed for an intense research effort at both the university and industrial levels that exploit the unique mechanical and electrical properties of these nanotubes. Several industrial companies such as Carbon Nanotechnologies, Inc. (CNI), Bayer, and Carbolex are marketing larger quantities and better purified carbon nanotubes. CNI and Carbolex are both spin-off's of successful research conducted at the university level. CNI is a product of Dr. Richard Smalley's research in fullerenes and carbon nanotubes at Rice University, and Carbolex is a spin-off of Dr. Peter Eklund's research at the University of Kentucky in Lexington. Furthermore, the reported mechanical properties of carbon nanotubes have generated much interest due to their ability to serve as reinforcement agents to polymers. The mechanical properties have been defined as being 50 to 100 times as strong as steel for a single tube. The Young's modulus has been reported to be as high as 1000 GPa, compared to around 200 GPa for steel. The tensile strength has been reported in the range of 63-600 GPa with that of steel being around 0.4 GPa, with a density around 1.3 g/cm^3. Further, due to the distinctive electronic structure of the graphene sheet and the nanometer size of the tube, nanotubes have exceptional electronic properties.[20, 35-36] As mentioned above, depending on their chiral structure nanotubes can possess metallic conductivity similar to copper or a semiconductor comparable to silicon and thus has the potential use in numerous electronic applications. Xintech, Inc., formerly Applied Nanotechnologies Inc., fabricates carbon nanotube devices for x-ray tubes, microwave amplifiers, gas discharge tubes and field emission cathodes. Also, due to their wide range of conductive behavior and their mechanical properties, research interest has increasingly focused on incorporating nanotubes into polymer matrices in hopes of fabricating light weight, mechanically strong, conductive composites. The potential uses of these composite conductors to replace metal conductors in electronic devices including wiring systems, computer components, and electronic sensors have become a reality.

3. Polymer-Carbon Nanotube Composites

There exist a flood of published articles, books and patents on polymer carbon nanotube composites and a good amount of these published sources are on ICP/carbon nanotube composites.[37-39] Research has proven that carbon nanotubes more efficiently enhance the mechanical strength of a polymer when aligned within the matrix.[40] It has also been shown that carbon nanotubes contribute to the conductive nature of the composite. However, many composites fabricated to date are application specific and a continued effort is under way to improve the dispersion quality and to optimize the percolation threshold to insure overlap in applicable uses. For example, processing a polymer-nanotube composite that is both mechanically strong and electrically conductive is still a challenge. Alignment is needed for mechanical strength, but too much alignment will not allow for an efficient conduction pathway. Although functionalization increases the interaction between the nanotube and polymer backbone, it alters the conductivity of the nanotube. Despite the challenges that still exist in the fabrication of these composites, several industrial entities are producing and selling composite solutions and hardware. Zyvex produces and sells their NanoSolve®, which is a polymer carbon nanotube solution prepared by their trademarked Kentera™ method (a non-covalently functionalization process). Nantero is a nanotechnology company that has incorporated carbon nanotubes in a memory chip called NRAM™, which is regarded as a replacement for the commonly used dynamic RAM (DRAM) and static RAM (SRAM). Further, scientists at the Rensselaer Nanotechnology Center at Rensselaer Polytechnic Center in collaboration with scientists at the University of Oulu in Finland have successfully formulated a nanotube ink that can be used in an off-the-shelf ink jet printer on various substrates for applications ranging from flexible conductors to chemical sensing devices.

At present, polyaniline, polypyrrole, polythiophene, their derivatives and their composites have been used or proposed as electronic components in wiring systems (including artificial muscles for biomedical devices), smart clothing with embedded biosensors, smart foam (a polypyrrole/polyurethane blend), fluid management systems, and optical switches and LED sensors, to name a few.[41-42] These composites have been fabricated via several processes including conventional film formation[37] and fiber forming techniques such as electrospinning and melt spinning. Furthermore, several articles by Wallace,[43] Mattes,[44] and Pomfret[45] have focused on wet spinning of polyaniline/carbon nanotube composites. The Air force Research Laboratory has developed a conductive wiring system consisting of poly(p-phenylene benzobisoxazole) (PBO) and metal plating via melt spinning. Although this system is reported to have a 300% strength and 50% weight advantage over current copper wire technology, PBO has known problems with UV stability and is also known to lose strength due to aging. Thus, great strides have been made in the field of carbon nanotube and intrinsically conducting polymer technology; however, there still is much work to do in overcoming many fundamental aspects such as processing and mechanisms to enhance the interaction between the polymer backbone and nanotube.

C. Systems Integration/Damage Detection

Based on literature references there are three main technologies related to damage detection in polymers and composites, along with several lesser-used technologies. The three main technologies are: (1) embedded optical fibers; (2) embedded conductive fibers; and (3) x-ray. The lesser used technologies include: (1) embedded shape memory alloys; (2) piezoelectric transducers; (3) Eddy current sensors; (4) proton NMR; (5) ultrasound; (6) laser pumped fluorescence; (7) diffuse reflectance infrared technique (DRIFT); (8) acoustic sensors; and (9) color change. For wire damage detection time domain reflectometry is the detection method of choice. Each of these topics will be discussed in detail below.

There are a number of references related to the use of embedded optical fibers for damage detection in composite materials. The advantages of optical fiber sensors over conventional sensor include resistance to corrosion and fatigue, similarity of their material properties to the reinforcing fibers, small, flexible and light weight in nature, immunity to electromagnetic interference and high response bandwidth.[46] These sensors are typically used for real-time monitoring of indention damage in composite laminates. Single-mode and multi-mode optical fibers have been used to detect damage in polymer matrix composites for many years and there are many examples of damage detection using this technology.[47-51] Single-mode optical fibers have been used for Fabry-Perot interferometric (EFPI) damage detection systems in composites.[52] Optical fibers are used for fiber-optic evanescent wave Fourier transform infrared (FEW-FTIR) damage detection for different types of soft, porous, foam, and rough polymer surfaces.[53] Optical fiber wrapped wire has been used in the development of wire damage detection systems (Slenski, Personal Conversation). These systems proved to be bulky and had limited flexibility. The system also had a significant increase in weight.

Embedded conductive wires have been used as resistive elements to heat composite materials, as communication links between embedded sensors to detect internal damage, and as electrical conductors to tune the electromagnetic properties of the material system.[54] In the case of damage detection the embedded wires act as a means to communicate with embedded sensors. Conductive wire wrapped wire has been used as a means to develop a self-diagnosing wire (Slenski, Personal Conversation). However, the system was bulky and provided limited flexibility. The system also had a significant increase in weight. Embedded conductive fibers have also been used to detect damage in fiber reinforced composites and thermosetting and thermoplastic polymers by allowing the monitoring of changes in resistance.[55-57]

X-ray techniques have been used to detect damage in carbon fiber reinforced composites, glass fiber reinforced composites, and general polymer materials.[58-61] Embedded shape memory alloys are used to detect strain, damage, or distortion in laminated carbon fiber-reinforced plastics.[62] These composites can detect the above mentioned properties and control and/or recover by restoring force of the shape memory alloy wires. Distributed piezoelectric transducers have been used to detect damage in polymer laminates.[63] Eddy current sensors are used for damage detection in multidirectional fiber composites by using superconducting quantum interference device (SQUID).[64] Proton nuclear magnetic resonance (NMR) spectroscopy has been used to detect thermal damage in epoxy resins reinforced by carbon fibers.[65] Ultrasound techniques have been used to detect damage in nylon-11 and glass fiber reinforced composites.[66-67] Laser pumped fluorescence has been used to detect damage in epoxy composites by monitoring changes in the fluorescence spectra with thermal exposure.[68] Diffuse reflectance infrared technique (DRIFT) has been used to detect heat damage in painted epoxy composites.[69] Acoustic sensors have been used to detect damage in carbon fiber reinforced composites.[70] Polymer color change has been used to monitor radiation damage in polyurethanes and various other polymers.[71]

Time domain reflectometry (TDR) has been used to develop a diagnostic capability for the detection of electronic wire interconnect system damage.[72] TDR measures changes in the electronic wire interconnect system characteristic impedance. Damage, such as chafe, nicks and corrosion, change the characteristic impedance of the system, thus producing a "signal" that is capable of being detected using TDR. This method is truly the only technology capable of detecting and locating the damage in an electrical wire.

IV. Current Development Efforts

A. Manual Repair and Self-Healing Wire Insulation

As has been mentioned previously, presently approved repair methods of high performance electrical wire insulation can be cumbersome or bulky and can lead to continued problems at interfaces where the repair material ends. Some of the approved repair materials can easily fail voltage breakdown testing if not applied with attention to detail.

Significant effort has recently been made to develop a repair material that will eliminate the problems inherent with present mystic tape/clamshell/shrink wrap methods approved for use on polyimide insulated electrical wiring. It is well known that, in most cases, the best repair material for any given need consists of the use of the same material that the item in need of repair was constructed from. Were it possible, repairs of Kapton® polyimide wire insulation would be best performed by using Kapton® as the repair material. Unfortunately, Kapton® and other similar polyimides can not be used as repair materials because of their high temperature properties and resistance to solvents. It has been found, however, that through chemical modification polyimides can be produced that have melting points far lower than traditional polyimides used as electrical insulation. These modified polyimides can be cast into thin films that can be used to wrap around a wire to be repaired or fabricated into small clam shells that can slip easily onto a damaged wire. The repaired area is then heated to effect the melting/flow of the repair layer. This ensures that the modified polyimide comes into intimate contact with the original insulation surface to be repaired. As the polyimide repair material is a near cousin in chemical composition to the original polyimide insulation, the adhesion is much more intimate than that which can be obtained through the use of any other repair chemistry. This intimate contact ensures a hermetic seal for this type of repair, a factor that can not be guaranteed for other presently approved methods of polyimide wire insulation repair. These modified polyimides exhibit thermal stabilities of greater than 300°C, maintain excellent insulation and voltage breakdown properties, and through the incorporation of a special cross linking mechanism allow these materials to be heated to melt the repair film and then crosslink, which provides a final repair that no longer remains a flowable material at the cure temperature (~200 to 225°C). These repairs are effective when wire coverage extends no more than ~ one half an inch beyond the damage point on either side. Repair film thickness, after application and cure, are ~ 5 to 10 mils thick. Given the resulting dimensions of a repair accomplished through the use of this new technology significant savings in weight and in the bulkiness of the repair are achieved as well.

B. Next Generation Conductors

Efforts in the development of the next generation of conductors have mainly focused on two areas: fiber production and thin film production from intrinsically conductive polymers (ICPs) solutions. Each topic will be discussed briefly in the following paragraphs.

Conductive fiber production has been accomplished by two methods: wet spinning and melt spinning. Wet spinning of soluble conductive polymers was performed using the fiber spinning apparatus depicted in Figure 1. The apparatus is a dual feed system, which allows in-situ doping of conductive additives. Early results indicate that a significant effort will be required to produce conductive fibers with significant strength; fibers currently being produced are relatively brittle. Parameters that are being optimized include, but are not limited to, viscosity of ICP, coagulation bath composition, coagulation bath temperature, and pump speed. For melt spinning, the apparatus shown in Figure 2 was utilized. The system is a single feed system and utilized insoluble conductive polymers as the feedstock.

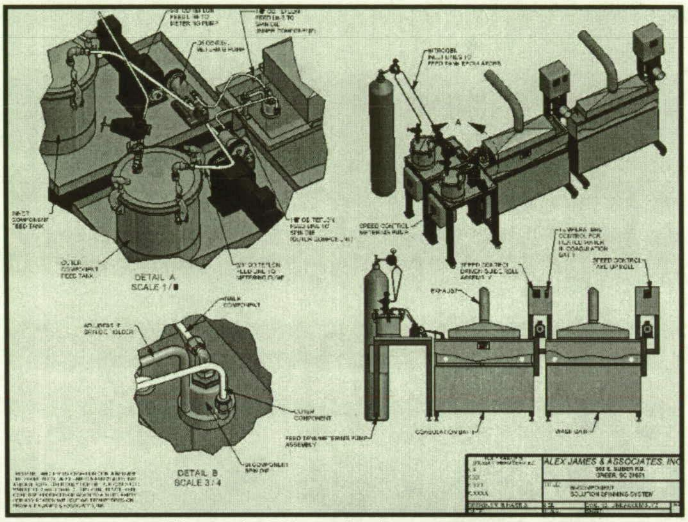

Figure 1. Wet spinning apparatus.

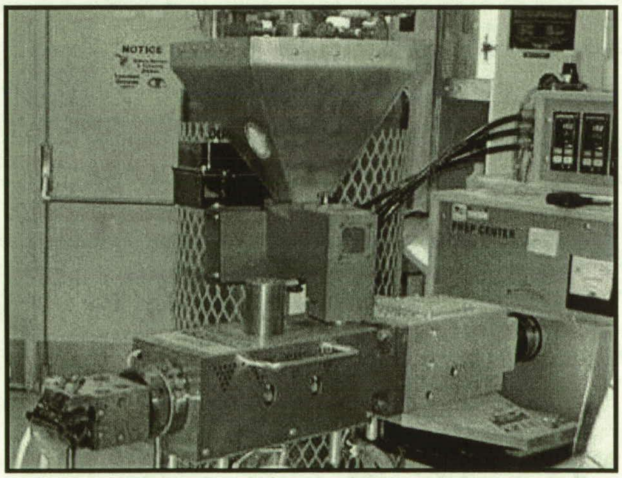

Figure 2. Melt spinning apparatus.

Thin film production was accomplished by two methods: casting and inkjet printing. All films that were produced were evaluated for conductivity, mechanical stability, and environmental stability. The conductivity of the cast ICP films was relatively low and the mechanical stability was limited; there was significant delamination of the ICP from the substrate. Ongoing efforts are addressing the delamination issue. ICP films that were inkjet printed were far more mechanically stable; very little delamination of the ICP from the substrate was observed.

C. Systems Integration/Damage Detection

Efforts in the areas of system integration/damage detection are at a very early stage. There are no results to be reported at the time this paper is being written.

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14. ABSTRACT

Wiring is a major operational component on aerospace hardware that accounts for substantial weight and volumetric space. Over time wire insulation can age and fail, often leading to catastrophic events such as system failure or fire. The next generation of wiring must be reliable and sustainable over long periods of time. These features will be achieved by the development of a wire insulation capable of autonomous self-healing that mitigates failure before it reaches a catastrophic level. In order to develop a self-healing insulation material, three steps must occur. First, methods of bonding similar materials must be developed that are capable of being initiated autonomously. This process will lead to the development of a manual repair system for polyimide wire insulation. Second, ways to initiate these bonding methods that lead to materials that are similar to the primary insulation must be developed. Finally, steps one and two must be integrated to produce a material that has no residues from the process that degrades the insulating properties of the final repaired insulation. The self-healing technology, teamed with the ability to identify and locate damage, will greatly improve reliability and safety of electrical wiring of critical systems. This paper will address these topics, discuss the results of preliminary testing, and remaining development issues related to self-healing wire insulation.

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