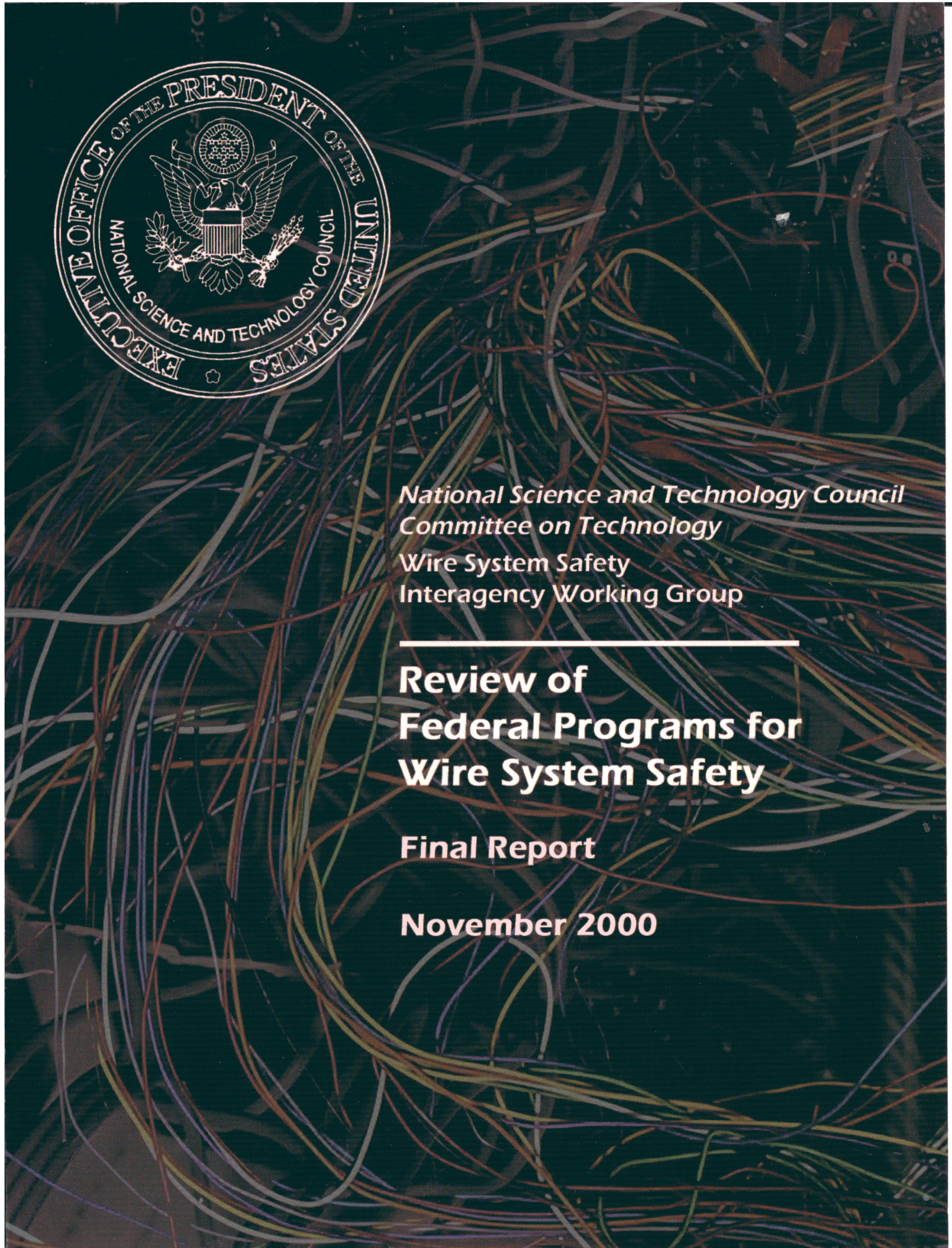

National Science and Technology Council
Committee on Technology
Wire System Safety
Interagency Working Group

Review of Federal Programs for Wire System Safety

Final Report

November 2000

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About the National Science and Technology Council

President Clinton established the National Science and Technology Council (NSTC) by Executive Order on November 23, 1993. This cabinet-level council is the principal means for the President to coordinate science, space, and technology policies across the federal government. NSTC acts as a "virtual" agency for science and technology (S&T). The President chairs the NSTC. Membership consists of the Vice President, Assistant to the President for Science and Technology, Cabinet Secretaries and Agency Heads with significant S&T responsibilities, and other White House officials.

Through the NSTC, Federal departments and agencies work cooperatively to ensure that Federal S&T investments support national goals. NSTC Committees prepare research and development strategies that are coordinated across the federal government to form a comprehensive investment package.

Call 202-456-6100 to obtain additional information regarding the NSTC.

THE WHITE HOUSE

WASHINGTON

November 15, 2000

I am pleased to present the final report, *Review of Federal Programs for Wire System Safety*. Though we might not see it or even think about it, wiring is everywhere around us. Miles of electrical wiring are present in the buildings where we live and work. Wiring allows us to operate a range of equipment, from simple toasters to the most highly automated systems that run nuclear power plants and fighter aircraft. Deterioration of wire systems can result in loss of critical functions in equipment powered by the wire system, or loss of information regarding equipment operation. This can result in loss of control, smoke, and fire. Consequently, the safety of the nation's wire systems is an important issue to all of us.

Aging of wire systems was first identified as an issue of national concern as a result of the White House Commission on Aviation Safety and Security. Efforts to address wiring issues in aviation revealed that aging wiring affects all electrical and information systems. Therefore, I asked the National Science and Technology Council Committee on Transportation to create a Wire System Safety Interagency Working Group (WSSIWG) to examine policy, programs, investment priorities, and direction across the Executive Branch. Seventeen agencies have joined together to form the WSSIWG.

This report identifies nine findings concerning wire system safety that are common to federal programs and documents forty two federal and eighteen industry science and technology projects that are currently underway. The report concludes that wire system safety is a national issue that transcends government agencies and is important to public health and safety. It recommends four basic strategies to improve wire system safety: altering the perception of wire systems; increasing collaboration between industry, academia, and the government; improving the management and functionality of wire systems; and developing advanced wire system technology.

Review of Federal Programs for Wire System Safety will serve as a benchmark for interagency efforts to optimize government research into technology to prevent accidents. It will also facilitate the formulation of a national strategy for wire system safety that includes collaboration among industry, academia, and the government for rapid implementation of advanced technology.

Neal Lane

Neal Lane
Assistant to the President
for Science and Technology

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EXECUTIVE SUMMARY

Wiring is so fundamental to our society that we often forget it is a system unto itself. The aging of a wire system can result in loss of critical functions in equipment powered by the system or in loss of critical information regarding the operation of certain parts of the equipment. Either result can jeopardize public health and safety and lead to catastrophic equipment failure or to smoke and fire. Consequently, the safety of the nation's wire systems is an issue of major importance to all of us.

The aging of wire systems was first recognized as an issue of national concern in commercial aviation. Through efforts underway at various federal agencies, however, it has become apparent that aging wiring is an issue that extends far beyond aviation.

With this realization in mind, the Office of Science and Technology Policy has expanded the focus of wire system safety initiatives beyond aircraft into other areas, including consumer products, homes and other buildings, nuclear power plants, public transit, and railroads. This expansion of focus led to the creation of the "Wire System Safety Interagency Working Group" (WSSIWG) as a task-oriented subgroup of the National Science and Technology Council's Committee on Technology. **Chapter 1, "Introduction"** describes the creation of the WSSIWG and the preparation of this report.

The WSSIWG serves as the internal deliberative body of the NSTC on wire system safety Science and Technology policy, programs, investment priorities, and direction for the Executive Branch. In support of its mission, the WSSIWG has prepared this report to document current federal programs in—and recommend strategies for—improving wire system safety. The report will also serve as a benchmark for interagency efforts to optimize government research and will facilitate the formulation of a national strategy for wire system safety.

Safety issues related to electrical wire systems are discussed in **Chapter 2, "Potential Wire Safety Issues."** During normal service life, all wire systems are subject to aging. If such aging causes a loss of critical functions or information, it can jeopardize public health and safety and even lead to catastrophic failure. Specific issues of concern include damage caused to wire systems by environmental stresses, improper installation, mishandling during routine maintenance, and the accumulation of aged wiring in buildings and other structures.

Chapter 3, "Current Practices" features an agency-by-agency review of the methods federal agencies are using to manage aging wire systems for which

they have regulatory or operational responsibility. These current practices flow from—and are limited by—the current state of wire systems in terms of design, installation, diagnostic technology and maintenance. In general, they fall into the following categories:

- Conformance with applicable regulations, codes, and standards
- Training of inspectors and maintenance personnel
- Inspection, assessment, and maintenance of wire systems
- Engineering improvements, including modification or modernization
- Safety investigations
- Analysis of wire system data.
- Exchange of technical information between agencies

Studies focused on wire system safety that are currently underway or planned by federal agencies are summarized in **Chapter 4, "Current Science & Technology Initiatives."** The goals of these initiatives are to identify precursors to failure, predict problems, preserve integrity and function, and ensure the continued safety of wire systems.

Chapter 5, "Analysis of Current Practices and S&T Initiatives," finds that the federal agencies have the following common issues and needs regarding aging wire systems. The findings from the analysis are as follows:

1. Faulty wire systems pose a risk to public health and safety and may lead to failure of essential functions and even to smoke and fire.

2. Managing aging wire systems is extremely time-consuming.

3. Inspection, testing, and maintenance of wire systems is a technical challenge. In most applications, wire systems are not inspected or tested—other than by visual inspection—unless an electrical defect exists.

4. Most diagnostic procedures currently in use for an electrical system can detect only "hard failures" that result in serious deterioration or complete loss of electrical integrity. Today's diagnostic procedures cannot detect and locate slight deterioration—such as chafing— before it results in system failure.

5. Knowledge about how wire systems age and how they fail is limited.

6. There are limitations to electrical codes and standards. Those pertaining to fixed structures (buildings) have historically governed only design and

installation and, thus, have tended to lead to a "fit and forget" approach to wire systems.

7. Wire systems are becoming more complex with increasing computerization of operations and of providing information about those operations.

8. Wire system maintenance is very expensive, and the lack of access to detailed wiring maintenance data has historically limited funding to address wire systems issues unless a major system breakdown occurs.

9. Current practices flow from—and are limited by—the current state-of-the-art of wire system technology in terms of design, installation, diagnosis, and maintenance.

The final chapter of the report is **Chapter 6, "Conclusions and Recommendations."** Based on the analysis of current practices and initiatives, **this report concludes that wire system safety is an important public health and safety issue that transcends government agencies.**

Aging occurs in all parts of all man-made devices and structures. Wire systems, which are an integral part of virtually all these devices and structures, are themselves subject to aging. While there is a tendency to ignore wire systems, there is a pervasive need to manage aging wire systems so that they continue to function safely.

The government has developed regulations, codes, and standards and both industry and the government have developed operational practices that maintain a high degree of safety. However, as they continue to age and become ever more complex, there needs to be a higher priority given to wire systems and a more proactive stance in their management.

Four basic strategies are necessary to improve wire system safety:

- Altering the perception of wire systems.
- Increasing collaboration between industry, academia, and the government.
- Improving the management and functionality of wire systems.
- Improving wire system technology.

Specific recommendations are proposed to implement each of these strategies. These recommendations along with the common issues discussed in this report should serve as catalysts for forging a strong partnership to revolutionize the way the nation manages its wire systems.

1. INTRODUCTION

SIGNIFICANCE OF WIRE SYSTEM SAFETY

Life is unimaginable without electricity and the wire systems that carry and distribute it. Though we might not see it or even think about it, wiring is everywhere around us. Miles of electrical wiring are present in the homes we live in and the buildings we work in—providing light, heating and cooling, and allowing us to operate all sorts of equipment from simple toasters to the most highly-automated machinery in factories and nuclear power plants. Likewise, wiring is integral in all modes of transportation, whether they be trains, planes, boats, or automobiles.

Along with the benefits of wire systems, however, come risks. Wire systems may become unreliable or fail altogether, due to poor design, use of defective materials, improper installation, or other causes. The risk of failure increases as wire systems age, due to the cumulative effects of environmental stresses (e.g., heat, cold, moisture, or vibration), inadvertent damage during maintenance, and the "wear and tear" of constant use.

The aging of a wire system can result in loss of critical functions in equipment powered by the system or in loss of critical information regarding the operation of certain parts of the equipment. Either result can jeopardize public health and safety and lead to catastrophic equipment failure or to smoke and fire. Consequently, the safety of the nation's wire systems is an issue of major importance to all of us.

BACKGROUND

The aging of wire systems was first recognized as an issue of national concern in commercial aviation. On February 12, 1997, the *White House Commission for Aviation Safety and Security*, chaired by Vice President Gore, issued a report to President Clinton identifying aging wiring as a safety issue in aviation. The Gore Commission, as it came to be called, recommended that three federal agencies—the Federal Aviation Administration (FAA), the Department of Defense (DOD), and the National Aeronautics and Space Administration (NASA)—expand their aging aircraft program to include the issue of aging wire systems in commercial aviation. As a result of this recommendation, these agencies now have an aggressive program of research initiatives and partnerships with industry to address wiring issues in aviation.

Through the efforts underway at DOD, FAA, NASA, and the National Transportation Safety Board, it has become apparent that aging wiring is an issue of national concern that extends far beyond aviation. With this realization in mind, the Office of Science and Technology Policy (OSTP) expanded the focus of wire safety initiatives beyond aircraft into other critical areas, including consumer products, homes and other buildings, railroads, and nuclear power plants. This expansion of focus led to the creation of the "Wire System Safety Interagency Working Group" (WSSIWG), as a task-oriented subgroup of the National Science and Technology Council's (NSTC's) *Committee on Technology*.

WIRE SYSTEM SAFETY INTERAGENCY WORKING GROUP

Scope of the WSSIWG

The WSSIWG serves as the internal deliberative body of the NSTC for wire system safety science and technology (S&T) policy, programs, investment priorities, and direction for the Executive Branch. Currently, federal agencies have a wide range of programs related to wire systems, and each agency addresses wire safety issues within its area of responsibility. The agencies also sponsor research on aging wire systems and promote the development of new technologies.

The WSSIWG will ensure that federal research is coordinated and targeted to work toward national interests and that the results are communicated in a timely way to protect public health and safety.

Membership of the WSSIWG

The WSSIWG is co-chaired by the representatives of NASA and the Department of Transportation. Membership currently includes representatives of the following agencies:

- Consumer Product Safety Commission
- Department of Commerce
- Department of Defense
    - Office of the Secretary of Defense
    - United States Air Force
    - United States Navy
    - United States Army

- Department of Energy
- Department of Transportation
    - Federal Aviation Administration
    - Federal Railroad Administration
    - Federal Transit Administration
    - US Coast Guard
- National Aeronautics and Space Administration
- National Science Foundation
- Nuclear Regulatory Commission

In addition, the following organizations are represented on the WSSIWG:

- Defense Nuclear Facilities Safety Board
- Office of Management and Budget
- Office of Science and Technology Policy
- National Partnership for Reinventing Government
- National Transportation Safety Board (observer)

Mission of the WSSIWG

In coordinating and conducting its activities, the WSSIWG seeks advice and participation from federal agencies, academia and industry. According to the Terms of Reference (Appendix D), the WSSIWG is to perform the following functions:

1. Define processes for federal agencies to collaborate on S&T initiatives in wire system safety.

2. Provide mechanisms for federal agencies to collaborate with industry, national laboratories, and academia.

3. Provide strategic direction for federal investment in wire system safety.

4. Accelerate development of advanced technology in wire system safety.

5. Ensure that the results of federal S&T initiatives are communicated in a timely way to facilitate their rapid implementation with the goal of improving public health and safety.

Scope of This Report

In support of its mission, the WSSIWG has prepared this report to document current federal programs in —and recommend strategies for— improving wire system safety. The report first assesses wire safety issues in the nation, describes the current practices of federal agencies in managing the aging of wire systems, and outlines specific S&T initiatives. Further, the report analyzes current practices and S&T initiatives, draws conclusions, and proposes recommendations to improve wire system safety.

This report is will serve as a benchmark for future interagency efforts to optimize government research and will facilitate the formulation of a national strategy for wire system safety.

2. POTENTIAL WIRE SAFETY ISSUES

Electrical wire systems are complex systems which include insulated power, control, and instrumentation conductors and fiber optic cables; connectors; and protection devices, such as circuit-breakers, current-limiters, and fuses (Figure 1). These systems perform vital functions, such as distribution of power, control signals, and information.

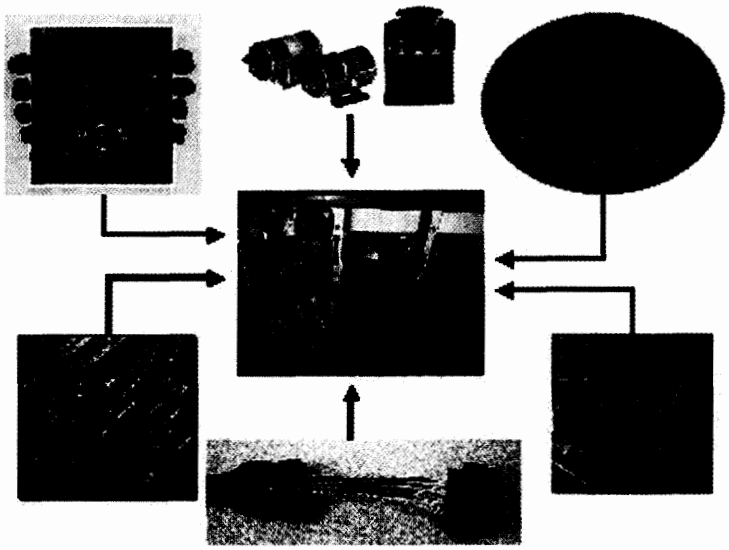


Figure 1. A wire system consists of multiple components.

Wire systems link electrical, electro-mechanical, and electronic systems. Wiring has emerged as vital in the control and safety of these systems, due to their increasing complexity. All electrical wire systems are subject to aging—the progressive deterioration of physical properties and performance of wire systems with use and with the passage of time. This aging is caused by accumulated damage to wire systems from exposure to the following stresses:

- Chemical, including corrosion and moisture intrusion (Figure 2).

Figure 2. Wire failure mechanisms: chemical.

- Thermal, including fluctuations in temperature which cause embrittlement (Figure 3).

- Electrical discharges (such as surges or arcs) and partial discharges (or transients) (Figure 4).

- Mechanical, including vibration, chafing, overload, and fatigue (Figure 5).

- Radiological, which also causes embrittlement.

Figure 3. Wire failure mechanisms: thermal.

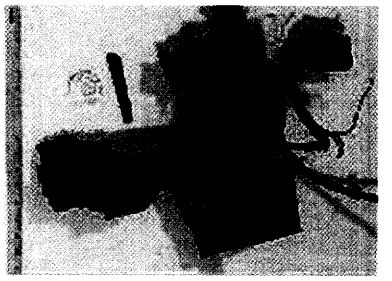


Figure 4. Wire failure mechanisms: electrical.

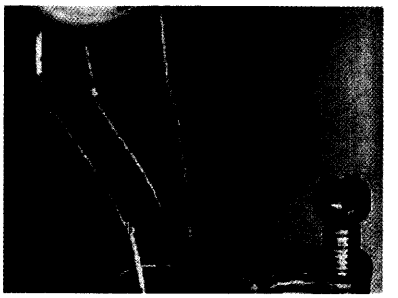


Figure 5. Wire failure mechanisms: mechanical.

Wire systems are exposed to these stresses by the ambient environment and by poor installation and maintenance practices. The aging of wire systems can jeopardize safety and even lead to catastrophic failure. Specifically, the deterioration caused by the aging of wire systems may result in any of the following consequences:

- The loss of critical functions in equipment powered by the wire system or the unintended function of such equipment.
- The loss of information regarding the operation of certain equipment or the generation of misleading information.
- Loss of system redundancy.
- Smoke or fire.

Since aging affects all components of devices or structures, understanding and managing aging in wire systems is important for ensuring continued functioning and protecting public health and safety. Understanding aging in wire systems requires knowledge not only of the environmental stresses which cause or accelerate it but also of the materials used, the ambient environment, the mechanisms of failure, and the interactions of these various factors over time.

Managing a wire system throughout its service life requires a combination of inspections, maintenance, and engineering improvements (as discussed in the following chapter) to ensure that the system continues to function safely and as intended. Some issues pertaining to this management which are of concern to the federal agencies on the WSSIWG are shown in Table 1.

Table 1. Common issues in wire system safety.

Wire insulation
Exposure to radiation and high temperature
Exposure to steam, water, and other fluids
Flammability of aged wire systems
Physical properties of aged wire systems
Jacket material (e.g., bonded vs. unbonded)
Chafing
Mishandling during initial installation
Mishandling during maintenance
Inaccessibility of certain wire systems
Conductors
Corrosion
Mechanical loading and vibration
Non-intrusive testing
Mishandling during maintenance
Inaccessibility of certain wire systems
Connectors
Corrosion
Non-intrusive testing
Contact resistance
Mishandling during initial installation
Bonding (electrical)
Splices
Corrosion
Non-intrusive testing
Mishandling during initial installation
Mishandling during maintenance
Penetrations
Mishandling during initial installation
Mishandling during maintenance
Shielding
Corrosion
Mishandling during initial installation
Mishandling during maintenance

3. CURRENT PRACTICES

Current practices within federal agencies are centered on managing aging wire systems for which they have regulatory or operational responsibility. In general, these practices fall into the following categories:

- Conformance with existing regulations, codes, and standards and preparation of revisions to them.
- Training of inspectors and maintenance personnel.
- Inspection, assessment, and maintenance of wire systems.
- Engineering improvements, such as modification or modernization of wire systems.
- Safety investigations.
- Analysis of wire system data.
- Exchange of technical information between agencies.

The current practices of the federal agencies with responsibility for wire system safety are described below.

CONSUMER PRODUCT SAFETY COMMISSION

Conformance with Existing Regulations, Codes, and Standards

The Consumer Product Safety Commission (CPSC) has a broad mandate to protect consumers from injury and death associated with an estimated 15,000 different products, including toys, clothing, and household products. With a budget of $49 million and 490 employees for fiscal year 2000, the agency must perform its mission by targeting the most serious hazards. CPSC then has to develop and implement effective strategies to reduce those hazards.

While CPSC has authority to mandate new safety rules and to take other regulatory actions, the Commission often selects strategies that gets the job done by other means. To address fires in homes caused by electrical wire systems, CPSC extended its influence by collaborating with other government agencies at all levels (local, state, and federal) and with the private sector.

CPSC technical staff participated in the development of the *Electrical Inspection Code for Existing Dwellings* [National Fire Protection Association (NFPA) 73], revision of the *National Electrical Code* (NEC) [NFPA 70], and development of the new product safety standard *Arc-Fault Circuit Interrupters*

[Underwriters Laboratories Inc. (UL) 1699]. Participation in further improvements of these model codes and product standards continues.

Inspection, Assessment, and Maintenance

The CPSC does not itself conduct inspections or maintenance of electrical wire systems in homes. However, the CPSC encourages use of the *Electrical Inspection Code for Existing Buildings*. The code may be used for guidance or for authorities with jurisdiction over housing construction to identify electrical wiring hazards in older homes. About one half of the residences in the United States are more than 50 years old, and wiring fires occur more frequently in such homes than in newer homes.

CPSC also prepares publications for consumers about the safety of electrical wire systems. For example, the CPSC provides repair options for aluminum wiring, based on its assessment of the risks of dangerous over-heating at connections and terminations involving aluminum-branch-circuit wiring. This wiring was installed in an estimated two million homes from the mid-1960s to the mid-1970s. Other publications describe the use of ground-fault circuit interrupters (GFCIs), arc-fault circuit interrupters (AFCIs), and extension cords.

Engineering Improvements

As a part of its project on home fires caused by electrical wire systems, in 1995 CPSC sponsored a study that identified promising technology for detecting and monitoring conditions that could cause such fires. This work, prepared for CPSC by UL, noted that arc-fault detection offered potential safety benefits that seemed to reduce the risk of electrical fires far more than ordinary circuit breakers and fuses. Following this study, numerous products using arc-fault detection were developed; they are available today in the form of enhanced circuit breakers, wiring devices, and power cords.

Safety Investigations

The CPSC conducts in-depth investigations of incidents related to the safety of consumer products, including electrical wire systems. (See Figure 7.) Some of these investigations are done on-site shortly after an injury or death. Reports of these investigations (with the names of victims withheld) are provided to the manufacturers of the products involved. Reports (with the names of victims and product brand names withheld) are available to the public

upon request. CPSC uses these reports to assist in developing strategies to reduce risk associated with use of consumer products.

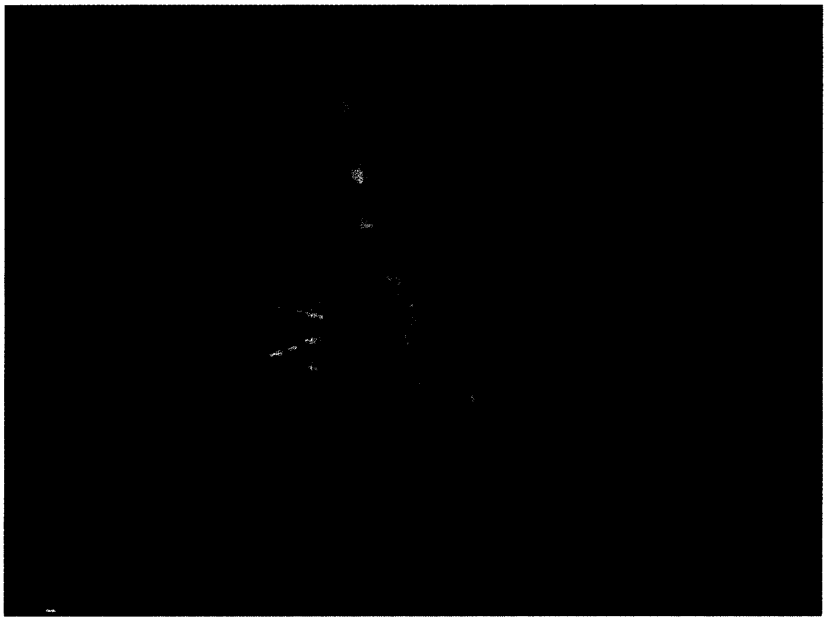


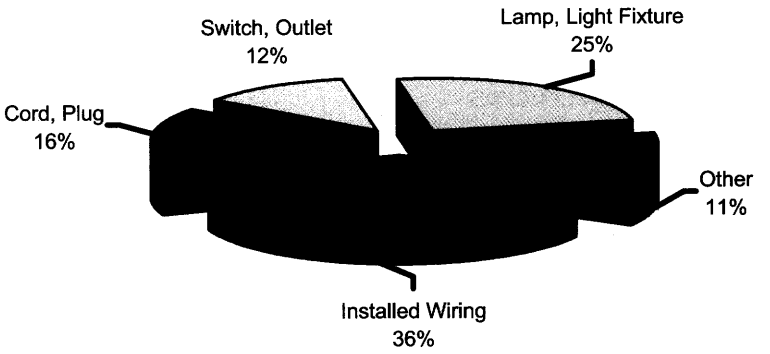
Figure 6. The CPSC conducts in-depth investigations of safety incidents.

CPSC has a laboratory for testing and evaluating the safety of products. In 1998 CPSC staff tested a new electronic device, the AFCI, which was developed to reduce electrical wiring fires in homes. This first-hand experience enabled the CPSC to participate in developing a new standard for residential use of AFCIs.

Analysis of Wire System Data

The CPSC develops annual estimates of product-related fire losses, based on fires in residences to which the fire department responds. The products include home electrical wire systems and electrical fixtures (see Figure 7).

Reports detailing the estimates are issued annually by the CPSC to cover the most recent year for which data have been analyzed. The latest report, "*1997 Residential Fire Loss Estimates,*" was released in July 2000. It estimates that in 1997 home wire systems caused over 40,000 fires which resulted in 250 deaths and over $670 million of property damage. CPSC implemented its project on home fires caused by electrical wire systems to address such losses.



(Source: CPSC information based on estimate of 40,300 electrical circuit fires attended by fire services in 1997.)

Figure 7. Residential fires involving electrical circuits.

Exchange of Technical Information

CPSC works with other federal agencies to coordinate efforts to address electrical wiring fires in residences. In an interagency agreement with the US Fire Administration, part of the Federal Emergency Management Agency, CPSC conducted an outreach effort to inform state and local electrical and fire officials about its findings concerning electrical wiring fires in residences. During its project on home fires, CPSC staff met on occasion with staff from the Department of Housing and Urban Development, the National Institute of Standards & Technology (NIST), and the Department of the Army.

DEPARTMENT OF COMMERCE/NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

Inspection, Assessment, and Maintenance

The Electronics and Electrical Engineering Laboratory (EEEL) at NIST conducts research for government agencies related to electrical insulation and its interaction with electrical breakdown. The EEEL began conducting research more than 25 years ago with funding from the Department of Energy (DOE).

Recently, the Laboratory has focused on diagnosing the condition of wiring insulation, using a technique called, "partial discharge detection." Related

areas of research include the formation and detection of highly toxic compounds in gas-insulated power systems and the occurrence of aging phenomena, such as corona discharges, in high-voltage cables used in space.

Engineering Improvements

NIST's Building and Fire Research Laboratory (BFRL) addresses reducing the damage caused by fires in electrical wire systems through both passive and active means. A passive means is one that makes the wire system less likely to ignite or spread fire, such as changing the material used or modifying the insulation or the geometry of the wire system enclosure. Figure 8 shows a typical test for fire spread through a cable bundle mounted vertically.

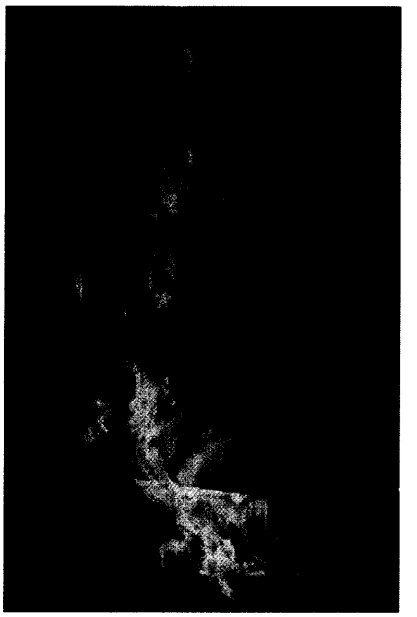


Figure 8. Fire spread through a cable bundle mounted vertically.

An active means of reducing the damage caused by fire is one that comes into play after ignition. Examples are earlier and more certain detection of the products of combustion and localized, automatic fire suppression with agents compatible with the electrical equipment. The BFRL conducts research into the following areas:

- Chemical and physical transformations that take place in cables and wires leading to smoldering and flaming combustion.
- Properties of soot and smoke that are produced in combustion
- Methods for sensing the earlier stages in the ignition of wire insulation.
- Effectiveness of options for controlling fire spread.

DEPARTMENT OF DEFENSE

Training

Training for the repair, modification, and inspection of aerospace wire systems continues to be an important effort in the armed services.

New training programs are in development throughout the aerospace industry as a result of the information gained in Department of Defense (DOD)

safety investigations and shared in interagency technical exchanges and at safety conferences.

Inspection, Assessment, and Maintenance

The DOD conducts regular assessments of the integrity of aging wire systems. Aggressive anti-chafing programs have also been instituted on many systems. DOD also conducts regular assessments of wire systems in new installations. The Navy, for example, employs a team of wiring experts that conduct such assessments. DOD has consistently found that wire systems are less susceptible to aging when they are constructed of proper materials and properly installed.

DOD has a structured three-level maintenance program that includes wire system maintenance. The three levels are organizational, intermediate and depot with each having defined roles. The organizational and intermediate wire system maintenance is relatively reactive, while the depot wire system maintenance is more proactive.

DOD expends significant manpower correcting wire system problems. For example, the Navy spends approximately 1.8 million work-hours a year troubleshooting and repairing aircraft wire systems in the fleet.

Available data suggests that many wire system failures are due to repetitive maintenance actions, repeated bending, and exposure to environmental stresses,. Most wire system failures are primarily attributable to "wear and tear" or cumulative exposure to mechanical damage rather than to material degradation, although material degradation can be a contributor.

Engineering Improvements

Prominent industry documents such as MIL-W-5088, SAE AS50881 and Federal Aviation Administration (FAA) Advisory Circular 43-13.2B are used as guidelines when designing and installing wire systems. Wire systems and other systems in aging vehicles are also routinely upgraded or replaced. In many cases, wire system components are replaced in conjunction with upgrading avionics (electronic equipment in aircraft) rather than being replaced to improve system reliability. Several aircraft types are currently undergoing limited or complete wire system replacement, using the most current materials and installation practices.

The services have planned research and technology transition programs to introduce new tools, processes, techniques, and materials to improve wire

system safety. These efforts are being accomplished through cooperative efforts with the FAA, the National Aeronautics and Space Administration (NASA), other federal agencies, academic organizations, technical societies, and industry.

Safety Investigations

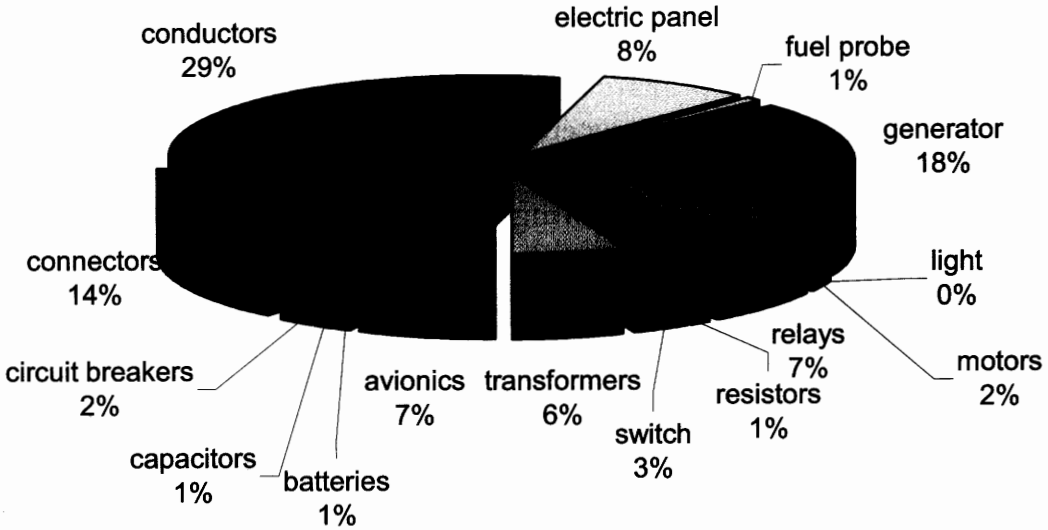
The armed services within the DOD employ field and laboratory engineers, technicians, and scientists to investigate and determine the cause of wiring-related mishaps. The services have well defined techniques for investigating such mishaps. Information gained during safety and engineering investigations are used to improve inspection, assessment, and maintenance; training; or other programs.

DOD also assists other agencies in investigation of accidents. For instance, DOD assisted the National Transportation Safety Board (NTSB) and the FAA in the investigation of the TWA Flight 800 accident. Lessons learned from non-DOD accidents are also fed back to DOD engineers and scientists to improve military aircraft design and safety practices.

Analysis of Wire System Data

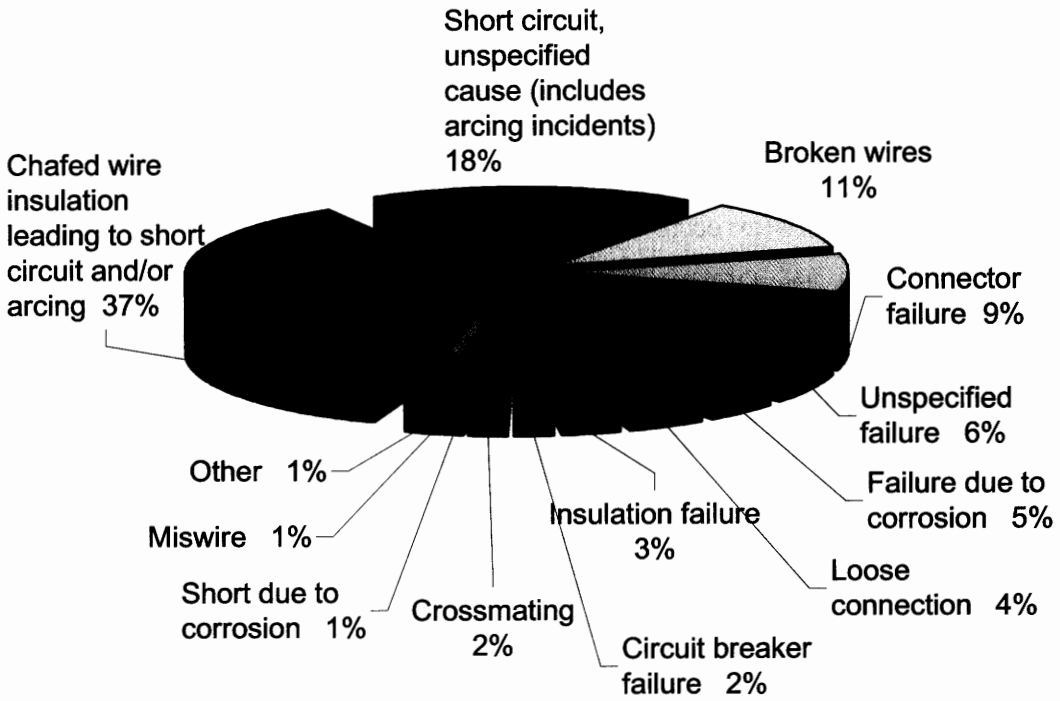
It is difficult to recover useful information on wire systems using the current DOD maintenance database. Several efforts are underway, therefore, to improve the quality of the data. The Navy is currently overhauling its system for collecting maintenance data with regard to wire systems and will be providing training to maintenance personnel and logisticians. The Air Force is assessing its system for collection of such data and is participating as a member of the Naval Air Vehicle Wiring Action Group, where new approaches in data gathering are being developed.

Some of the most useful wire system data pertains to mishaps and accidents, as shown in Figures 9 and 10. This information is being shared with the FAA's Aging Transport Systems Rulemaking Advisory Committee (ATSRAC) to assist in improving data quality.



(Based on data for electronics-related failures (1989-1999); source: Air Force Safety Center.)

Figure 9. Electrical components contributing to Air Force aircraft mishaps.



(Source: Navy Safety Center Hazardous Incident Data)

Figure 10. Typical wire system failure modes for aircraft (1980-1999).

DOD is also surveying users to identify wire system problems. Recent Air Force field and depot wire system surveys show that the following areas within an aircraft are of primary concern for wire system failures: fuel tanks; wheel well and anti-skid systems; generators, wing flaps, and leading edges; pylons; circuit breaker panels; control columns; equipment racks; and wiring nexus points, such as wing root areas, under wings, and cockpits.

Exchange of Technical Information

The services have dedicated specialists who provide technical analysis and engineering support, identify research needs, and develop solutions to wire system issues. Their work has helped to characterize wire system failures through analysis of field failure data and understanding of the mechanisms of failure of wire systems. Findings have been disseminated to industry through reports and papers given at technical symposia. A forum that has been particularly successful is the Navy-sponsored *Aircraft Wiring and Inert Gas Generator (AWIGG) Working Group*.

The services have developed and begun to use a new wire insulation that minimizes arc-propagation and provides improved mechanical and thermal properties. They have also sponsored the development of many of the current aerospace wiring guidelines for specific insulation, protective components, and installation procedures. Many of these military specifications have been successfully transferred to industry technical committees.

Finally, the DOD and the FAA have established Memorandums of Understanding for conducting joint projects. The MOUs provide a framework for a strategic partnership in Research and Development and Testing and Evaluation between the FAA and Naval Air Systems Command (NAVAIR) and between the FAA and the Air Force Research Laboratory (AFRL). The MOUs have been used to conduct several joint electrical systems programs with the FAA, such as one to develop arc-fault circuit breakers for aircraft and another to develop tools and techniques for managing the integrity of aerospace electrical interconnection systems.

DEPARTMENT OF TRANSPORTATION/ FEDERAL AVIATION ADMINISTRATION

The FAA is currently developing operational programs in accordance with the FAA's Aging Transport Airplane Non-structural Systems Plan. In addition to the FAA itself, the committee is comprised of representatives of

airplane manufacturers, the airlines, the Navy, the Air Force, and industry associations. A description of the program elements will be provided later in this section, following a description of the agency's current practices.

Conformance with Applicable Regulations, Codes, and Standards

The FAA has issued a number of regulations governing the type of wire systems to be used and the means of their installation. Conformance with these regulations is ensured through the engineers and inspectors at the Aircraft Certification Offices and Manufacturing Inspection District Offices throughout the country. In addition, a number of guidance materials, including advisory circulars, describe the installation of wire systems.

Training

Operators of airplanes must submit a training program for inspectors and maintenance personnel for FAA approval. This program becomes a portion of the Operational Certificate, issued to the operator.

While these programs provide training on wire inspection and maintenance, the FAA and ATSRAC have determined that there is room for improvement. Improvements being recommended include raising awareness of the causes of potential wire system problems, including drill shavings and other metal debris in bundles; lint accumulation; exposure to chemicals of various types; aging and deterioration of materials; extensive nicks, cuts, and chafes in wire system or insulation; poor workmanship; and inadequate segregation of different types of wiring.

The FAA is currently developing training for certification engineers and designated engineering representatives, along with training for manufacturing inspectors and flight standard inspectors to assist in the review of installations of wire systems. A portion of this training program is proposed to be on the Internet.

Inspection, Assessment, and Maintenance

Wire systems are inspected at initial installation and throughout the life of the airplane. When the wire system is installed in the factory, the FAA inspects it for conformity to design drawings. When the aircraft is put into service, the FAA re-inspects the wire system, according to the operator's approved maintenance program. Figure 11 shows the complexity of the wire system in a typical transport airplane.

Operator's maintenance programs consist of both scheduled (or routine) maintenance and non-routine maintenance. The scheduled maintenance program for wire systems consists of general visual inspections to identify obvious problems with the wire system and to repair them.

The aviation community has determined that a greater level of detail is needed to identify all the defects that may exist in the wire system. Revision of the requirements of the general visual inspection will be one of the recommendations made to the FAA by ATSRAC.

Non-routine maintenance is conducted following the report of a service difficulty. FAA regulations require that certain airplane failures be documented and corrected prior to returning the affected airplane to service.

In following the recommendation of the White House Commission on Aviation Safety and Security, the FAA has worked in cooperation with industry to develop the specifications for maintenance of wire systems. These specifications—compiled from manufacturers' investigations and operators' experience—describes causes of wire systems degradation as well as the best inspection and maintenance practices for wire systems. Many of the large airplane operators have incorporated the elements of this specification into their FAA-approved maintenance program.

Figure 11. Typical installation of wire systems in a transport airplane.

Engineering Improvements

In the past, improvement to the design or installation of wire systems has not been systemic, but has been driven by service difficulties and has affected only certain models. Now the FAA is requiring improvements to wire systems frequently, and airplane manufacturers are making improvements by providing service bulletins to aircraft operators and updates to the Standard Wiring Practices Manual used by aircraft operators and repair stations for maintenance and repair.

The FAA Technical Center, in cooperation with other agencies and various laboratories, often tests the components of wire systems . The performance-based regulations utilized by the FAA allow industry the freedom to develop new technologies for wire systems. As they are developed, the FAA works with industry to test these new technologies.

Safety Investigations

The FAA utilizes teams of inspectors, engineers, researchers and system safety specialists to conduct investigations of service difficulties and accidents involving wire systems. These investigations, often conducted in partnership with the NTSB, DOD, aircraft manufacturers, and aircraft operators, usually require follow-up action by aircraft manufacturers and operators.

Analysis of Wire System Data

The FAA promotes the open exchange of information in order to improve aviation safety. To further this basic objective, the FAA has established the National Aviation Safety Data Analysis Center (NASDAC).

The data collected by the FAA includes that from the Service Difficulty Reporting (SDR) system concerning a problem on an individual airplane. The objective of the SDR system is to provide information regarding conditions adversely affecting the continued airworthiness of airplanes, so that those conditions may be corrected quickly. Information from the SDR system is entered into a database; the data are analyzed; and the results are disseminated to interested parties.

Exchange of Technical Information

The FAA and DOD have established MOUs for conducting joint Research and Development and Training and Evaluation. The MOUs provide a framework

for a strategic partnership between the FAA and NAVAIR and between the FAA and the AFRL. The MOUs have been used to conduct several joint electrical systems programs, such as the FAA and NAVAIR program to develop arc-fault circuit breakers.

Operational Evaluation

Following the TWA Flight 800 accident, the FAA initiated the Fuel Tank Safety Program a key element of which has been extensive review of the wire systems in the fuel tanks of airplanes. This program has revealed the need for a comprehensive review of all aircraft wire systems. About the same time, the White House Commission on Aviation Safety and Security, informally known as the Gore Commission, recommended that the FAA, in cooperation with the airlines and aircraft manufacturers, expand its Aging Aircraft Program to cover non-structural systems in aircraft, i.e., those systems other than the fuselage, wings, and tail.

To address this recommendation, the FAA formed the Aging Non-Structural Systems Study team which made detailed on-site evaluations of three representative aging aircraft. Based on these evaluations as well as meetings with maintenance inspectors from Airbus and Boeing and analysis of aging systems—using service data from the NASDAC—a plan was developed to address aging transport airplanes.

This plan called for the establishment of "an Aging Transport Systems Oversight Committee to coordinate the various aging system initiatives within the FAA." This task led to the formation of ATSRAC to propose revisions to the Federal Aviation Regulations and to assure that the non-structural systems of transport airplanes are designed, maintained, and modified in a manner that assures their safety throughout the service life of the airplanes.

ATSRAC leverages the participation of industry to collect data from various inspections, service history reviews, and surveys as well as to gain industry's support for the FAA's science and technology programs. Analysis of the data collected will facilitate revisions to inspection and maintenance programs, training programs, and engineering improvements for wire systems.

Thus far, ASTRAC has or will recommend that the following steps be taken to improve wire system safety associated with aged wire systems:

- The FAA mandate that certain manufacturer's service bulletins be revised to upgrade wire systems in the aging fleet.
- The FAA mandate engineering modifications for the same areas rather than repetitive inspections of wire systems.

- Manufacturers and operators use a logic process to help prepare maintenance manuals which are clear and easy to understand.
- Manufacturers and operators use a logic process to ensure that sufficient attention is paid to age-related deterioration of wire systems.
- Manufacturers, operators, and repair stations develop procedures to minimize damage to wire systems associated with inspection, maintenance, and modifications.
- Manufacturers and operators revise their standard wiring manuals to make them easier to understand.
- Manufacturers, operators, and repair stations modify their training programs to ensure that they adequately address aging wire systems.

DEPARTMENT OF TRANSPORTATION/ FEDERAL RAILROAD ADMINISTRATION

Conformance With Applicable Regulations, Codes, and Standards

The Federal Railroad Administration (FRA) has issued regulations governing both signaling-and-train-control systems and signal systems at grade crossings. These regulations specify inspection intervals and performance standards for wire systems to insure that the "fail-safe" principles of the systems are not compromised. Other FRA regulations regarding govern the inspection of locomotives and electric multiple-unit cars to evaluate electric wire system integrity. There are no regulations regarding catenary systems.

Inspection, Assessment, and Maintenance

Railroad signal systems have been in place for many years, and much of the wiring is old. In a recent incident, deteriorated insulation on wires was responsible for short circuits in a wayside signal cabinet that led to a "false proceed" railroad signal to be displayed on a signal mast to an oncoming train. The brand of wire in question is no longer produced, and multiple short circuits are required to produce a false proceed signal. Most installations of that brand of wire were replaced long ago, and the remaining installations are being inspected more frequently or fitted with GFCIs until they can be replaced.

Signal systems at grade crossings, installed at 60,000 locations across the country, rely on the integrity of wire systems to ensure the safety of motorists,

commercial vehicle operators, train passengers, and crew members at these high-risk locations.

Overhead catenary (cable) systems for providing power to electrified trains are inspected regularly and replaced when they show signs of dangerous wear. When wires do fail, power is cut quickly, but the heavy gauge wire can injure passengers and crew members and damage rolling stock.

Engineering Improvements

Wire systems in locomotives and electric multiple-unit cars is usually completely upgraded whenever they are rebuilt. Wire pole lines are being replaced with radios and fiber-optic lines.

New catenary installations, such as between New Haven and Boston, are of a constant-tension design which greatly reduces fatigue of system components. The planned replacement of older variable-tension cable between Washington D.C. and New Haven, will significantly enhance safety and reliability.

DEPARTMENT OF TRANSPORTATION/ FEDERAL TRANSIT ADMINISTRATION

Hundreds of millions of dollars in Federal assistance are provided for subways and other tunnels annually for the construction, rehabilitation, modernization and safe operations of older systems. The cost to build and expand these systems continues to rise, with the major component being the civil infrastructure. On many occasions, tunnel inspections reveal that conduits for the electrical wiring were omitted. This implies that during construction the wires were improperly placed, exposing them to environmental elements causing dangerous and hazardous conditions. These environmental conditions affect the equipment as well as the safety of operating personnel. As newer systems are being constructed, awareness has been heightened regarding wiring issues. Designers understand the importance of including appropriate provisions for wiring as part of design phases and not waiting until the system is under construction.

As part of FTA's oversight function, "Risk Assessment" reviews are conducted by the Agency with its largest grantees that operate and maintain aging transit systems. These assessments include the issue of wiring.

DEPARTMENT OF TRANSPORTATION/ UNITED STATES COAST GUARD

Wire systems installed on commercial vessels certified by the Coast Guard must meet standards contained in the Code of Federal Regulations. These standards are adopted industry standards. Wiring is checked during vessel construction and modification for proper type and installation. Subsequent inspections focus on system performance rather than component performance. In general, vital engineering systems are provided with redundancies and alternative control options which minimize the consequence of a component failure.

While there is not currently any Coast Guard-sponsored research related to the impact of aging wire systems on the safety of commercial vessels, the Coast Guard will be an active participant in the WSSIWG.

The Coast Guard has experienced significant issues with aging wiring on its fleet of 93 HH-65A helicopters. Numerous incidents of wire bundle arcing and failure, with resultant loss of AC power in the cockpit are reported. Some of these incidents occurred over water at night; one nearly resulted in the loss of the aircraft. As a result, the Coast Guard is now completing a $12.7M project to rewire its entire fleet of HH-65A helicopters. Additionally, the Coast Guard is replacing aging wing wiring on some C130 Maritime Patrol Aircraft as part of a $10M aircraft preservation project.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA has been active in research, design and development, and testing of wire systems used under extreme conditions. Most of these efforts are conducted in conjunction with other government agencies, industry affiliates, and academic institutions. All hardware is designed and developed using wire system design specifications and tested for extreme environments as part of the certification process. All defects affecting safety or critical functions are thoroughly investigated and corrective actions are taken. Numerous forums are used to disseminate information and lessons learned concerning the results of NASA's research and anomaly investigations.

With the operation of its aircraft and space shuttle fleet, NASA has an awareness of the effects of design and of inspection and maintenance practices

on the operational integrity of wire systems. Though integrity programs are in place and have been effective, there is a need to address the management of wire systems, so that performance is not degraded over the service life. The following sections describe some current practices.

Inspection, Assessment, and Maintenance

Wire systems are inspected and tested at initial installation and throughout the service life of the systems. Quality inspection criteria are used to determine conformity to wire systems design specifications and to design requirements. Inspection and maintenance requirements are established to ensure continued performance and integrity of the system. All defects are documented and tracked using problem reporting and corrective action systems. Thorough investigations are conducted to determine the cause of any defect which could affect safety or mission success. Several initiatives are in place to improve data collection to provide timely analyses of defects and of observations made during maintenance. Maintenance and inspection practices are continually reviewed and improved. Technologies associated with training and visual aids, wire system diagnostics and the application of advanced information technology at the shop level will be important to the continued integrity of operational wire systems.

As it is difficult and economically infeasible to replace the wire system in an existing spacecraft,, technology must be developed to diagnose and repair existing wire systems. Commercially available repair technologies have proven to be technically capable of performance in the required environments. Partnership with industry and academia will be invaluable in developing advanced repair technologies.

Advanced Research

Technology development in the long-term might consider power and signal distribution systems which utilize approaches other than the current conductor/insulator. Fiber optic and wireless system technologies may be a few examples of research that could increase the safety of future wire systems.

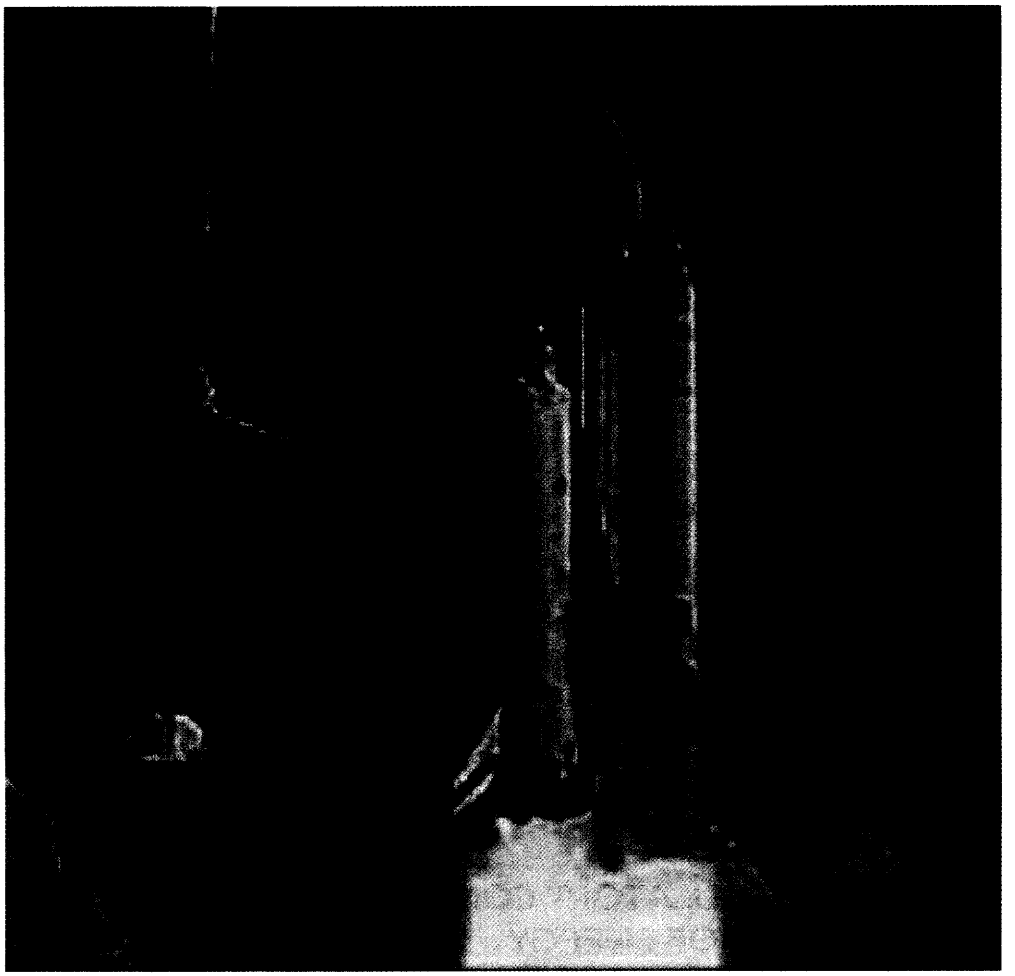


Figure 12. Launch and landing are the most stressful portions of a space shuttle mission.

NATIONAL TRANSPORTATION SAFETY BOARD

Exchange of Technical Information

The NTSB is an independent federal agency charged by Congress with investigating every civil aviation accident and significant accidents in other modes of transportation (railroad, highway, marine, and pipeline). The NTSB is also charged by Congress with issuing safety recommendations aimed at preventing future accidents. Accident investigations may lead to the coordination of research with other government agencies. The NTSB has issued safety recommendations pertaining to wiring issues to other government agencies as a result of aviation, marine, and rail accidents.

As one example, the NTSB has issued numerous safety recommendations stemming from the investigation of the TWA Flight 800 accident. The NTSB concluded that this accident may have been related to center wing fuel tank wiring. The following are portions of a recommendation that pertains specifically to the need to manage the aging of wire systems by:

- Improving training for maintenance personnel to ensure adequate recognition and repair of potentially unsafe wiring conditions.
- Improving documentation and reporting of potentially unsafe electrical wiring conditions.
- Incorporating new technology, such as arc-fault circuit breakers and automated wire test equipment.

Government agencies that receive NTSB safety recommendations, such as the FAA or FRA, give priority to such recommendations to ensure that they are addressed promptly. By law, an organization receiving a safety recommendation is required to send a substantive reply to the NTSB within 90 days.

NTSB accident investigations also lead to corrective actions without the formal issuance of safety recommendations

NUCLEAR REGULATORY COMMISSION/ DEPARTMENT OF ENERGY

Conformance with Applicable Regulations, Codes, and Standards

Wire system aging has been recognized as a potentially significant consideration in ensuring the safety of nuclear power plants. Federal regulations governing wire systems are included in 10 CFR 50.49, *Environmental Qualification of Electric Equipment Important to Safety.*

Because of the difficulties in performing periodic inspection or testing of wire systems in these large complex facilities, the regulations do not require such inspections. Instead they require rigorous testing of the components of the wire system and evaluation of its specific application prior to construction of the plant to assure that the wire system will function as designed throughout the 40-year licensed life of the plant.

Many plant operators are now seeking to renew their operating licenses for another 20 years, and aging of the wire systems must be addressed in their renewal applications to assure that the aging will be managed over the full period of the license.

Inspection, Assessment, and Maintenance

Periodic calibration and tests for actual function ensure functionality of safety-related circuits, including the wire system, in nuclear power plants. These tests are required by technical specifications developed for operating plants. While no regulatory requirements for periodic inspection of wire systems exist, the nuclear industry has developed inspection and condition-monitoring techniques to assess the integrity of such systems.

4. CURRENT SCIENCE & TECHNOLOGY INITIATIVES

Many federal agencies are currently sponsoring science and technology (S&T) initiatives focused on the safety of electrical wire systems. These initiatives are intended to identify precursors to system failures, predict problems, preserve the integrity and function of wire systems, and ensure the continued safety of critical systems. For the purposes of this document, S&T includes fundamental research, technology development, demonstration projects, education, and training.

This section summarizes S&T projects currently underway or planned by federal agencies with responsibility for wire system safety. Table 2, at the end of this section, lists information for each project, organized by the general category of research ("Diagnostics," "Failure Mechanisms," "Interconnection Technologies," and "New Materials"). Detailed project descriptions, organized by the sponsoring agency, are included in Appendix B of this report. Appendix C includes project descriptions of current industry S&T initiatives related to wire system safety.

The four S&T categories are defined as follows:

- **Diagnostics:** Projects evaluating non-destructive evaluation (NDE) techniques, inspection and detection technologies, and monitoring sensors for identifying wire system defects. This category includes the evaluation of data to determine either the condition of a wire system or the cause of the condition.
- **Failure Mechanisms:** Projects addressing the causes and mechanisms of wire system aging and failures. This category also includes projects to develop models of wire system failure and to analyze maintenance data
- **Interconnection Technologies:** Projects developing improved connectors, such as circuit breakers, in wire systems. This category also includes research addressing systemic issues, such as training, management tools, and advanced distribution approaches, such as modular wiring, fiber optics, and wireless technologies.
- **New Materials:** Projects developing new materials for wire system components, such as conductors and insulation. This category also includes novel approaches for wire systems, such as microelectronic machine technology.

CONSUMER PRODUCT SAFETY COMMISSION

The Consumer Product Safety Commission (CPSC) reports three relatively modest ongoing S&T projects related to safety of electrical wire systems in residences.

Two projects, in the category "Failure Mechanisms," focus on identifying measures to reduce the risk of fire involving aluminum wiring and wiring in older homes.

Another CPSC project, in the "New Materials" category, promotes the use of ground fault circuit interrupters (GFCIs) to reduce the risk of electrical shock and fire associated with 120/240-volt electrical power in homes.

DEPARTMENT OF COMMERCE

The Building and Fire Research Laboratory (BFRL), under the Department of Commerce's (DOC's) National Institute of Standards and Technology (NIST), has three projects, one each in these categories: "Diagnostics," "Failure Mechanisms," and "New Materials."

Research in the "Diagnostics" category is targeted toward early, reliable detection of smoke and fire in the cargo compartments of airplanes. Improvements in such detection in cargo compartments is expected to be useful in other areas of the aircraft.

The BFRL's research in the category "Failure Mechanisms" is concerned with the fire load posed by the accumulation of wiring in buildings. The research will address the hazard posed by this accumulation (i.e., how much accumulated wiring is too much?), the risk associated with the hazard (i.e., how likely is the accumulated wiring to cause a fire?), and the benefit of removing old wires or adding fire detection or suppression systems in the wire systems.

The BFRL's "New Materials" research seeks to develop insulation made from polyolefins with additives that are economical, have excellent physical properties, and are resistant to burning.

The Electronics and Electrical Engineering Laboratory (EEEL), under the DOC's NIST, has a single project in the "Diagnostics" category. This project is targeted toward the detection and analysis of partial discharges in cables and other insulating systems. Partial discharges are minute, localized electrical breakdowns that often are precursors to complete failure. Proper detection and analysis of the electrical signals generated by partial discharges in aging cables

can provide information about the location and severity of defects in cable insulation.

DEPARTMENT OF DEFENSE

The Department of Defense (DOD) has fourteen projects related to wire system safety S&T: three projects in the "Diagnostics" category, four each in "Failure Mechanisms" and "Interconnection Technologies," and three in "New Materials." The projects primarily pertain to wire systems on aircraft used by the Air Force and Navy.

The DOD projects in the category "Diagnostics" involve validating advanced NDE techniques for wire systems, developing a wire-testing system that will allow maintenance personnel to monitor wire systems integrity and locate wire systems defects in the field, and developing a wire system with technology embedded to allow monitoring of the "health" of the wire system. The DOD anticipates that this research will benefit other agencies, such as the Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA).

In the category of "Failure Mechanisms" are projects which involve locating wire system failures, identifying failure modes and mechanisms, developing new methods of inspection, and analyzing defects in wire systems. One of the projects also involves assessing data on the condition of materials and on current maintenance and inspection practices in naval aviation.

One of the DOD's projects in "Interconnection Technologies" seeks to develop a new type of circuit breaker, an "arc-fault circuit breaker" (AFCB), which will reduce in-flight electrical fires on aircraft by detecting electrical arcing and tripping the associated circuit. Other projects in this category involve development of training aids for inspecting and repairing wire systems and development of advanced techniques for inspecting and maintaining interconnection systems on aircraft.

Finally, the goal of one of the "New Materials" projects is to develop a material to replace copper wiring in signal-transfer and electro-magnetic interference shielding on aircraft. The new material is expected to be of lighter weight and higher strength than copper wiring. Products of this research are also expected to benefit NASA.

A second project seeks to develop a new type of wire insulation that is not only resistant to chafing but also has an extended life and built-in diagnostics. The third project seeks to develop a new material for connectors that is more

resistant than current materials to corrosion and damage resulting from routine maintenance and operation.

DEPARTMENT OF ENERGY

The Department of Energy (DOE) currently sponsors eight S&T projects addressing wire system safety, primarily related to wire systems in commercial nuclear power plants. Five projects in the category "Diagnostics" are intended to develop new techniques for monitoring the condition of electrical cables and predicting the remaining life of materials critical to safety.

Three projects in the category "Failure Mechanisms" seek to characterize the aging of insulation and jacket materials commonly used on wire systems in critical safety applications in nuclear power plants.

FEDERAL AVIATION ADMINISTRATION

The FAA reports seven S&T research projects related to the safety of wire systems on commercial aircraft.

One project, included in the "Diagnostics" category, is to develop testing and inspection systems, technology, and techniques to identify or characterize defects in wire systems that may interfere with the safe transmission of electrical power and signals.

The majority of the FAA's projects are in the category "Failure Mechanisms." Several projects in this category involve inspection and testing of aged wiring and insulation on retired transport-category airplanes. The aim of this research is to establish a technique to predict the condition of wiring as it ages and, thus, when corrective action should be taken.

Another project seeks to develop advanced risk assessment methodologies to evaluate wire systems. In addition, the FAA will assess the performance of existing circuit breakers and explore technology other than arc-fault detection to minimize the risk of aging electrical systems.

One project in the category "Interconnection Technologies" will investigate arcing in aircraft electrical systems and circuits and develop circuit breakers with arc-fault detection to replace existing circuit breakers.

FEDERAL TRANSIT ADMINISTRATION

FTA has included electrical wiring, along with safety issues, as being integral components of our Safety and Civil Infrastructure Research Programs. Also, FTA has an active Bus Technology Program which includes a more simplified method for maintenance of bus wiring systems.

FTA's Office of Research, Demonstration, and Innovation is working with the Federal Highway Administration on a cooperative civil infrastructure research project to address asset management issues, which includes wire system safety in highway and transit tunnels. This effort will include a national inventory on the conditions of tunnels. A Tunnel Management System will be developed with the appropriate software and databases. Condition codes for each component will indicate its severity (including wiring) and if preventive maintenance, rehabilitation, and reconstruction are needed to correct the problem. A replacement cost model is being developed as well. In addition, inspection manuals and training guides will also be developed. This information will be useful to decisionmakers in establishing their priorities.

Consistent with FTA's 5-Year Plan for Transit Research and Technology, FTA will develop, as part of the Asset Management component of the Civil Infrastructure Program, a future research initiative that will include wiring for subways and other tunnels. Also, this initiative will include wiring issues for bus technology and Intelligent Transportation Systems.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA reports four S&T projects concerning wire safety, specifically related to wire systems on the space shuttle. All are in the "Diagnostics" category. These projects involve developing methods and technology to assess the condition of wiring and insulation in the cramped conditions aboard the space shuttle orbiter and to detect and locate defects in this wiring and insulation. One of the projects will investigate the use of automated technologies for wire testing, which is intended to reduce the risk associated with aging wire systems in the space shuttle orbiter.

NUCLEAR REGULATORY COMMISSION

Since 1985, the Office of Nuclear Regulatory Research of the Nuclear Regulatory Commission (NRC) has been conducting research on the aging of wire systems. Past research included programs on wire insulating materials,

electrical connectors and penetrations, terminal blocks, fire retardants and wire flammability, and environmental qualification of safety-related cables for commercial nuclear power plants.

The NRC currently sponsors a comprehensive research program in the categories of failure mechanisms and diagnostics. The program addresses the effects of the high operating temperatures and radiation levels in commercial nuclear power plants on the degradation of polymer insulation used in wire systems. It also seeks to identify techniques for monitoring the condition of wire systems and to determine the effectiveness of these techniques in predicting the service life of wire systems.

The focus of the NRC's future science and technology initiatives is on (1) Determining the risk associated with the aging of wire systems, (2) Evaluating non-intrusive methods of monitoring the condition of these systems *in situ*, (3) Evaluating the long-term performance of power cables that are buried and inaccessible, and (4) Determine the remaining life of installed wire systems in operating nuclear power plants.

Table 2. Current federal initiatives in wire system safety S&T.

	Project Title	Sponsor(s)	Performer(s)	Dates (proj)	Description of Project
	Diagnostic				
1	Assessment of advanced NDE techniques for wiring	DOD (AFRL/MLSA)	AFRL/MLSA	2000	Evaluate advanced NDE techniques for wiring to validate most promising techniques.
2	Improvement of wire system integrity for legacy aircraft	DOD (ASC/SMA)	AFRL/MLSA	2000-2003	Develop a prototype wire-testing system that can be used in the field to monitor wiring integrity and locate wire system failures.
3	Smart Wire	DOD (ONR)	Naval Air Systems Command (NAVAIR)	1999-2004	Develop an aircraft wire system with embedded diagnostic and prognostic capabilities to monitor the "health" of the aircraft wire system and allow corrective action to be taken prior to failure.
	Develop condition-monitoring techniques for electrical cables	DOE and EPRI (joint management)		2000-2001	
4	**Task 1**: Develop condition-monitoring techniques for electrical cables		To be determined		Improve training of inspectors who perform visual and manual inspection of cables in nuclear power plants by developing cable specimens, whose aging has been accelerated, for use as training aids.
5	**Task 2**: Evaluate existing electrical NDE techniques		Ontario Power Generation Research Laboratory		Under simulated conditions, perform proof-testing of NDE method that uses ionized gas to provide a ground plane for unshielded cables. Perform proof-of-principles testing to determine if use of the test method can be expanded from detection of severe damage in walls to detection of partial damage and deterioration.
6	**Task 3**: Investigate modulus profiling and density measurement for cable polymer aging assessment		Sandia National Laboratories		Determine correlation between micromodulus measurements and mechanical degradation of nuclear jacket materials (polymers) and insulation.
7	**Task 4**: Compile condition-monitoring database		To be determined		Compile available condition-monitoring data from research organizations, universities and utilities; identify sources of information and cost of obtaining information. The database would be used for comparison with cables in the field or those removed from service.

Table 2. Current federal initiatives in wire system safety S&T.

	Project Title	Sponsor(s)	Performer(s)	Dates (proj)	Description of Project
8	Innovative chemi-thermal techniques for verifying hydrocarbon integrity in nuclear safety materials	DOE	Veridan-Pacific Sierra Research and University of Virginia	2000-2002	Explore new methods of assessing the condition of critical safety materials in nuclear power plants and provide diagnostic data on the remaining useful life of these materials.
9	Develop wire testing and inspection systems	FAA	William J. Hughes Technical Center, FAA Center for Aviation Systems Reliability	2000-2003	Identify or characterize material or structural flaws that may impair safe and effective transmission of power and electrical signals on aircraft in order to develop testing and inspection systems, technology, and techniques
10	Improved fire detection in aircraft cargo compartments	FAA/NASA	DOC/NIST	1999-2000	Examine response of various types of sensors to fire and nuisance sources that may occur in an aircraft cargo compartment; propose sensor combinations and alarm criteria to reduce false alarms and increase sensitivity to a range of sources.
11	Enhance inspection technique for improved wire integrity	NASA	NASA Langley Research Center	2000-2005	Develop advanced techniques using laser-generated ultrasonic waves in the wires to locate breaks and thinning of wire insulation to be used for *in situ* inspection of wiring in spacecraft and aircraft.
12	NDE of spacecraft and aircraft wiring	NASA	Johns Hopkins University	2000-2003	Investigate several methodologies for characterization of the condition of wiring in aerospace vehicles to be used for *in situ* inspection of wiring in spacecraft and aircraft.
13	Develop a non-intrusive cable tester	NASA	NASA Kennedy Space Center Engineering Development Directorate	To be deter-mined	Facilitate repair on the space shuttle by reducing the number of system re-tests caused by cable demates and by allowing rapid troubleshooting of system anomalies.
14	Wire Integrity Research (WIRe) pilot study	NASA	NASA Ames Research Center	2000-2000	Investigate the application of automated test technologies for reducing risks associated with aging wiring in the space shuttle orbiter.
15	Evaluation of condition-monitoring methods	NRC	Brookhaven National Laboratory	2001	Evaluate advanced electrical techniques for monitoring installed cable systems.

Table 2. Current federal initiatives in wire system safety S&T.

	Project Title	Sponsor(s)	Performer(s)	Dates (proj)	Description of Project
16	Applications of phase-correlated partial discharge detection to medium voltage cables	None	DOC/NIST	2001-2003	Develop condition monitoring techniques based upon partial discharge detection and analysis for application to aged cables.
	Failure Mechanisms				
17	Fire load posed by wiring in buildings	To be determined	DOC/NIST	To be deter-mined	Develop methods to estimate the fire hazard posed by the accum-ulation of old wires and cables in buildings and to determine the benefit of removing a portion of the wire or cables or adding fire detection or suppression systems to the cable runs.
18	Aluminum wiring	CPSC	CPSC	1973-1982	Studied and evaluated aluminum wiring and connectors in electrical branch circuits during the dates indicated. Low level monitoring of field experience and advising consumers regarding repairs is ongoing..
19	Home electrical system fires	CPSC	CPSC	1982-2001	Study and evaluate electrical wiring in older homes to identify wiring product failures and to develop and implement strategies to reduce the risk of fires related to electrical wiring in such homes.
	Develop empirical data to characterize aging degradation of polymers used in electrical cable	DOE	Sandia National Laboratories	2000-2001	
20	**Task 1**: Confirm and support development of cable polymer aging models				Confirm and support development of models of insulation and jacket materials (polymers) commonly used in cables. Produce empirical data and aging models to characterize the aging behavior of commonly used insulation and jacket materials (polymers) in critical safety applications in commercial nuclear power plants.

Table 2. Current federal initiatives in wire system safety S&T.

	Project Title	Sponsor(s)	Performer(s)	Dates (proj)	Description of Project
21	**Task 2**: Investigate bonded jacket cable failure mechanisms	DOE and EPRI	To be determined		Characterize the degree of swelling of ethylene propylene rubber/chlorosulfonated polyethylene insulation under aging regimes representative of actual plant conditions and determine the limits of allowable in-plant aging to preclude splitting during an accident.
22	**Task 3**: Evaluate moisture intrusion into coaxial connectors	DOE and EPRI	To be determined	To be determined	Determine if moisture intrusion is configuration-specific, an artifact of test configuration, or applicable to all plant configurations.
23	Aging wiring interconnection system support activities	DOD (AFRL/MLSA)	AFRL/MLSA	2000-2005	Characterize failure mechanisms related to wire systems and evaluate new NDT and failure analysis techniques.
24	Analysis of wire systems maintenance data	DOD (AFRL)	AFRL/MLSA	2000	Collect and analyze maintenance data related to wire system failures and determine most efficient use of collected data.
25	Wiring integrity study	DOD (AFRL)	GRC International, Eclypse	2000	Identify failure modes and mechanisms for field wiring, evaluate current field diagnostic tools, and develop diagnostic tools for locating wiring anomalies.
26	Fleet wiring survey	DOD	NAVAIR	10/00-09/00	Survey naval aviation maintenance activities to determine prevailing maintenance and inspection practices and ascertain material condition of assets.
27	Assessment of wire degradation	FAA	Sandia National Laboratories/ others	2001-2003	Research degradation characteristics of aircraft wiring.
28	Circuit breaker assessment and development	FAA	Sandia National Laboratories (for testing)/ undetermined (for technology development)	2000-2003	Evaluate performance of existing arc-fault circuit breakers and explore use of new technologies to overcome limitations of existing circuit breakers.
29	Establishment of a test and validation infrastructure	FAA	Sandia National Laboratories, Aging Aircraft Validation Center	1999-2004	Conduct inspections to determine condition of wire systems and, where condition of wiring is suspect, destructive testing of wire insulation on retired transport category airplanes.
30	FAA-industry intrusive inspection project	FAA	ATSRAC Intrusive Inspection Working Group	1999-2000	Conduct inspections; and perform on-aircraft and laboratory testing of wire installations on retired transport category airplanes.

Table 2. Current federal initiatives in wire system safety S&T.

	Project Title	Sponsor(s)	Performer(s)	Dates (proj)	Description of Project
31	Risk assessment for aircraft electrical interconnect systems	FAA	Sandia National Laboratories (tentative)	2001-2003	Develop advanced risk assessment methodologies for aircraft electrical systems.
32	Environmental qualification of low-voltage electric cables	NRC	Brookhaven National Laboratory	1993-2000	Research aging mechanisms, stressors, and failure modes of polymeric insulating materials used in commercial nuclear power plants and evaluate various condition-monitoring methods.
	Interconnection Technologies				
33	Training aids for wire system inspection and repair	DOD	Naval Air Warfare Center Training Systems Division	2000–2005	Develop a comprehensive training syllabus and instructional video on maintenance and inspection methods for legacy and modern aircraft wire systems. Monitor and track results once implemented.
34	Fiber optics	DOD	NAVAIR	2000–2003	Develop fiber-optic technology that allows for the replacement of copper-based data buses and sensor/control wires.
35	Development of tools and techniques for managing the integrity of aerospace electrical interconnection systems	DOD and FAA (AFRL)	AFRL/MLSA	2002-2005	Develop advanced techniques and processes for the inspection, maintenance, troubleshooting and repair of electrical interconnection systems on aircraft. (Dual Use program)
36	Development of arc fault circuit breakers	DOD	NAVAIR	1999-2002	Research arcing phenomena related to aircraft power systems and electrical circuits. (Dual Use program)
37	Development of arc fault circuit breakers	FAA	NAVAIR	1999-2002	Research arcing phenomena related to aircraft power systems and electrical circuits. (Dual Use program)
	New Materials/Technologies				
38	Fire-retarded polyolefins for cables	DOC/NIST	DOC/NIST	2001-2002	Develop polyolefin cables that have the same flammability as flame-retarded polyvinyl chloride cables, and examination of the effects of aging on flammability of cables.
39	Ground-fault circuit interrupters	CPSC	CPSC	1986-1992	Research new applications of GFCIs beyond electric shock protection, including use of GFCIs in interrupting arc tracking and other phenomena that can lead to deterioration of wiring insulation, which can cause charring and result in fires.

Table 2. Current federal initiatives in wire system safety S&T.

	Project Title	Sponsor(s)	Performer(s)	Dates (proj)	Description of Project
40	Advanced wire insulation development	DOD	NAVAIR	2000–2005	Increase insulation life, chafing resistance and provide built-in diagnostic capability.
41	Connector corrosion	DOD	NAVAIR	2000–2005	Develop connector material with: enhanced environmental tolerances to better manage effects of corrosion; improved durability for maintenance handling; more rugged to better withstand operational dynamics.
42	High-performance conductive polymer fiber	DOD (AFRL)	Syscom Technology, Inc.	2000-2002	Develop an integrated process to produce high-strength, high-modulus, conductive-metal-containing polymer fibers for signal transfer and electromagnetic-interference-shielding.

5. ANALYSIS OF CURRENT PRACTICES AND S&T INITIATIVES

CURRENT PRACTICES

Not all federal agencies have the same roles and responsibilities regarding wire system safety. Some of the federal agencies—such as the Department of Commerce's National Institute of Standards and Technology, which operates the Electronic and Electrical Engineering Laboratory and the Building Fire Research Laboratory—have responsibilities in technology development. Some of the agencies, such as the Navy, the Air Force, and the National Aeronautics and Space Administration, have responsibilities in both technology development and operations.

The Nuclear Regulatory Commission and the Federal Aviation Administration are responsible for regulating those who operate nuclear power plants and airplanes, respectively, and the Consumer Product Safety Commission regulates the safety of consumer products. Other agencies, such as the National Transportation Safety Board and Defense Nuclear Facilities Safety Board are independent agencies under Congress. The National Transportation Safety Board makes recommendations to other agencies that may lead to technology development, although research conducted by the Safety Board is closely tied to accident and incident investigations.

Each agency represented on the Wire System Safety Interagency Working Group (WSSIWG), however, has a role in protecting public health and safety, all have some responsibilities related to wire systems, and all use certain principal means of ensuring wire system safety. As we have seen, these means, or current practices, fall into the following categories:

- Conformance to regulations, codes and standards and preparation of revisions to them.
- Training of inspectors and maintenance personnel.
- Inspection, assessment and maintenance of wire system.
- Engineering improvements, such as modification of modernization of wire systems.
- Safety investigations.
- Data collection and analysis.
- Exchange of technical information between agencies.

Findings

Analysis of current practices in the management of aging wire systems collected from federal agencies reveals the following common findings:

1. Faulty wire systems poses a risk to public health and safety; it may lead to failure of essential functions and even to smoke and fire. A recent study of Air Force aircraft mishaps or accidents related to electronics revealed that 43 percent of them were related to the wiring interconnection system. The risks increase as wire systems age.

2. Managing aging wire systems is extremely time-consuming. The Navy, for example, spends approximately 1.8 million work-hours per year at the organizational level (on aircraft), troubleshooting and replacing aircraft wire systems.

3. Inspection, testing, and maintenance of wire systems is a technical challenge. In most applications, wire systems are not inspected or tested—other than by visual inspection—unless an electrical defect exists. The reason is that inspection techniques are intrusive and may inadvertently damage the wire system being inspected or adjacent systems and components.

4. Most diagnostic procedures currently in use for an electrical system can detect only "hard failures" that result in serious deterioration or complete loss of electrical integrity. Today's diagnostic procedures cannot detect and locate slight deterioration—such as chafing of wire insulation—before it results in system failure. A common theme in most federal programs is the identification and reduction of collateral damage to wire systems caused by the repair or replacement of chafed insulation.

5. Knowledge about how wire systems age and how they fail is limited. One lesson from our collective experience is that we need to know more about every phase in the life of a wire system from its design (or conception) to maintenance throughout its service life (from maturity to old age).

6. There are limitations to electrical codes and standards. For example, those pertaining to fixed structures (i.e., buildings) have historically governed only design and installation and, thus, have tended to lead to a "fit and forget" approach to wire systems.

7. Wire systems link the electrical, electromechanical, and electronic systems in machines, houses and other buildings, and vehicles. Wire systems, therefore, are becoming more complex with increasing computerization of operations and of providing information about those operations. The irony is that we rely on wire systems more than ever, so that if they do fail, the consequences may be more catastrophic than ever.

8. Wire system maintenance is very expensive, and the lack of access to detailed wiring maintenance data has historically limited funding for maintenance or modifications unless a major system breakdown occurs.

9. Current practices flow from—and are limited by—the current state-of-the-art of wire systems technology in terms of design, installation, diagnosis, and maintenance.

These findings lead to the following insights:

- **There is a persistent requirement to ensure wire system safety on a national scale.** The buildings, houses, utilities, and various modes of transportation that are a part of our everyday lives are aging. The wire systems integral to these indispensable items are not immune from the detrimental effects of aging phenomena. Therefore, the need to manage aging and ensure safety in wire systems is pervasive throughout the country.
- **The issue of wire system safety is getting more complex.** Industry and the government have developed practices and procedures that maintain a high degree of safety. As existing wire systems continue to age and new systems and components are introduced, the nation will need to improve our understanding of the aging processes and take a more proactive stance in the management of these systems and components.
- **National synergy is the best chance for success.** The national assessment of wire systems will undoubtedly yield new ideas and approaches. Communication between industry and the government in a national forum for information exchange will be essential to share these ideas, so that they may develop new technologies, assess their effectiveness, and accelerate implementation of the most promising of them.

S&T INITIATIVES

Given these challenges, work needs to be accomplished on several levels simultaneously. There needs to be more information about managing wire systems built with current or "old" technology, since these systems will be around for a long time to come. It is not feasible to replace or retrofit all of the existing wire systems, even if technology were to radically improve overnight. The focus, therefore, needs to be on how to detect and remedy defects in these existing wire systems.

At the same time, new technologies and new materials need to be developed to make revolutionary improvements in wire system integrity and in the ability to identify problems before system failure. These technologies will create the wire systems of tomorrow which will transform the "Current Practices" of the future. As previously discussed, the following types of research or S&T initiatives are now under way or being planned.

Failure Mechanisms (16 projects)

Research into the causes and mechanisms of the aging and ultimate failure of wire systems is identifying the accumulated effects of these mechanisms over time and developing models to predict the life of wire systems. Programs are needed that correlate failure mechanisms to field performance and develop computer modeling that can be used to design new wire systems and to predict failures in existing systems.

Diagnostic Methods (16 projects)

A common interest for all federal agencies is a prognostics system that would monitor the health of wire systems. A current challenge is to develop non-destructive evaluation (NDE) techniques—diagnostic systems—for inspection and detection technologies that can identify defects before they affect electrical system operation. This could lead to systems that automatically reconfigure to maintain critical circuit paths.

Several agencies are investing in research to assess standard NDE techniques. Diagnostic systems and advanced NDE techniques under evaluation will be capable of rapidly locating open circuits and short circuits as well as degraded electrical connections. If successful, these techniques could replace current visual inspection methods and could ultimately be used to monitor wire systems.

Additional work is required to validate and automate these systems and to identify and develop novel NDE diagnostic techniques to wire systems. Research is also being conducted on remote sensors that can be used to monitor wire system integrity. Such sensors could be embedded into wire systems.

Interconnection Technology (5 projects)

Research in this area addresses improved interconnection technologies, such as circuit breakers, connectors with greater resistance to corrosion, modular wire systems, and optical systems. The development of arc-fault circuit breakers is an excellent example of an interagency development effort. This technology can protect wire systems from arcs of short-duration, which are not detected by conventional circuit breaker devices. Originally designed for buildings, this technology is now being applied in aircraft.

Additional research is needed to improve the reliability of electro-mechanical devices, such as circuit breakers, relays, and switches. One approach uses microelectronic machines (MEMs) to improve reliability and reduce component costs. An area that merits further development is the use of wireless communication technology for critical control paths. This will require research in technologies that ensure secure and reliable communication channels.

New Materials (5 projects)

Many of the interconnection technologies currently in use have resulted from incremental improvements over the last 30 years. There have been few revolutionary changes. A common objective between agencies is to apply new design approaches and materials to achieve significant improvements in wire systems integrity. Meeting this objective will require not only new interconnection designs but also application of new materials, such as conductive polymers.

While several of the projects listed in this report appear from their titles to be duplications, each project is focused on issues that are unique to the applications involved. Through efforts of the WSSIWG, future S&T initiatives will be designed for more general application where possible, and information resulting from all initiatives will be shared between agencies and industry.

In completing the review of federal wire system safety S&T initiatives, it is important to recognize the excellent work that is being accomplished in industry and academia. During the review of federal initiatives, an announcement was placed in the *Commerce Business Daily* and provided to industry representatives.

This announcement asked non-government sources to provide a description of ongoing S&T initiatives to improve wire system safety. Appendix C contains the results of that announcement. Review of industry submissions shows that they are complementary to federal efforts. Future federal initiatives will actively consider these industry efforts to prevent duplication and encourage collaboration.

6. CONCLUSIONS & RECOMMENDATIONS

Based on the preceding analysis of current practices and science and technology (S&T) initiatives, **this report concludes that wire system safety is an important public health and safety issue that transcends government agencies.** While there is a tendency to ignore wire systems, there is a pervasive need to manage aging wire systems so that they continue to function safely.

The government has developed regulations, codes, and standards and both industry and the government have developed operational practices that maintain a high degree of safety. However, as they continue to age and become ever more complex, there needs to be a higher priority given to wire systems and a more proactive stance in their management. Four basic strategies are necessary to improve wire system safety:

- Altering the perception of wire systems.
- Increasing collaboration between industry, academia, and the government.
- Improving the management and functionality of wire systems.
- Developing advanced wire system technology.

Specific recommendations in each strategic area are as follows:

❖ Altering the perception of wire systems

Change the status of wire systems: Wiring is often treated as a "fit and forget" commodity rather than as an indispensable system. A significant cultural shift is necessary to ensure that wire systems be designed, installed, and maintained for long-term integrity. Such a cultural shift has been a crucial part of changing our approach on other matters of public policy in which risk to public health and safety is a concern.

Emphasize prevention of damage through prognostics and diagnostics: Damaged parts of a wire system must be located in a non-intrusive way, before the system fails to function properly or to function at all. To locate such damage will require a change in philosophy from a largely reactive to a more proactive approach to maintenance and a change in technology, involving improved prognostic and diagnostic techniques.

❖ Increasing collaboration among industry, academia, and the government

Improve data collection and sharing: It would be hard to over-emphasize the importance of good quantitative data. There is currently no common database across industry, academia, and the government and no common method for disseminating data. Furthermore, existing databases do not provide good data about wire system maintenance and failures.

To a considerable extent, good data leads to good policy. Data will provide the feedback needed to implement the four basic strategies. Certainly, the cultural shift in attitude toward wire system safety will be largely driven by data about the cost in time, money, and risk to public health and safety associated with aging wire systems. These data are also needed to help evaluate current practices and to set priorities for S&T initiatives.

Crucial to obtaining good data from companies and individuals is protection of the source from adverse results. Agencies need to protect proprietary and other voluntarily-disclosed data and information from uses other than safety analysis. Otherwise, the ability to identify safety problems before they become mishaps is in jeopardy. Safety should take precedence.

Facilitate communication: A partnership between industry, academia, and the government is essential to develop synergy and to take advantage of the abundant experience and expertise in wire system safety. Much communication is already taking place—through government advisory groups—formalizing the exchange of ideas by selecting forums for sharing of information on wire system safety is an important first step.

Maintain a focused and disciplined approach: Such an approach is essential to identify the principal risks in various applications of wire systems, to develop priorities for addressing these risks, and to evaluate methods for reducing risk, particularly that associated with aging systems.

❖ Improving the management and functionality of wire systems

Develop standardized design tools: Standardized tools are needed to develop and track design parameters and changes in the configuration of wire systems. These tools should alert those who design, maintain, and operate wire systems to conditions that may cause system failures or jeopardize system redundancy or increase the system's susceptibility to crossover voltage, (e.g., mixing power- and signal-carrying circuits).

Develop inspection and maintenance tools: Maintenance tools are needed for collecting reliable wire system data in the field, repair processes which are both rapid and reliable, and methods of automated replacement of wire systems. These tools include improved prognostic and diagnostic technologies. Failure characterization data and non-intrusive diagnostic tools should be integrated into a comprehensive wire management system. Research is also needed to develop models to ascertain when wire systems should be replaced or retrofitted.

Develop procedures for response to malfunctions: Those who operate or manage vehicles, electrical equipment, buildings or other facilities with complex wire systems need better methods to deal with false indications, unintentional operation, and other hazardous conditions associated with the aging of those systems.

Support training: More comprehensive training is needed in the installation, inspection, and maintenance of wire systems.

❖ Developing advanced wire system technology

Promote proactive technology development and use: Wireless, micro-electronic, multiplexing, and fiber-optic technologies offer great promise in reducing reliance on multiple copper conductors. The best opportunity to achieve revolutionary improvements in wire systems is to develop these and other new technologies and new materials through S&T initiatives.

Promote use of new technology. In conjunction with developing new technology, the government needs to remove obstacles and otherwise encourage its use. If existing regulations, for example, require the use of established "old" technology, the government needs to be able to make the changes necessary to facilitate technological progress.

These recommendations along with the common issues discussed in this report should serve as catalysts for forging a strong partnership to revolutionize the way the nation manages its wire systems.

APPENDIX A: ACRONYMS

APPENDIX A: ACRONYMS

AFCB	arc-fault circuit breaker
AFCI	arc-fault circuit interrupter
AFRL/MLBP	Air Force Research Laboratory/Materials Directorate Polymers Branch
AFRL/MLS	Air Force Research Laboratory/Materials Directorate System Support Division
AFRL/MLSA	Air Force Research Laboratory/Materials Directorate Materials Integrity Branch
ASC/SMA	Aeronautical Systems Center Aging Systems and Systems Planning Division
ATSRAC	Aging Transport Systems Rulemaking Advisory Committee
BFRL	Building and Fire Research Laboratory
CLPO	crossed-linked polyolefin
CPSC	Consumer Product Safety Commission
CSPE	chlorosulfonated polyethylene
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DSCU	dedicated signal conditioners
EEEL	Electronics and Electrical Engineering Laboratory
EMI	electro-magnetic interference
EPDM	ethylene propylene diene monomer
EPR	ethylene propylene rubber
EPRI	Electric Power Research Institute
FAA	Federal Aviation Administration
FRA	Federal Railroad Administration
GFCI	ground fault circuit interrupter
LOCA	loss-of-coolant accident
MOU	Memorandum of Understanding

NASDAC	National Aviation Safety Data Analysis Center
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NAVWAG	Naval Air Vehicle Wiring Action Group
NBS	National Bureau of Standards
NDE	non-destructive evaluation
NEC	National Electrical Code
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NRC	US Nuclear Regulatory Commission
NSTC	National Science & Technology Council
NTSB	National Transportation Safety Board
ONR	Office of Naval Research
OSTP	Office of Science and Technology Policy
PVC	polyvinyl chloride
S&T	science and technology
SDR	Service Difficulty Report
TOR	Terms of Reference (See Appendix D of this report.)
UL	Underwriters Laboratories Inc.
WSSIWG	Wire Systems Safety Interagency Working Group
XLPE	cross-linked polyethylene

APPENDIX B: FEDERAL S&T PROJECT DESCRIPTIONS

APPENDIX B: FEDERAL SCIENCE & TECHNOLOGY PROJECT DESCRIPTIONS

- The project descriptions in this Appendix are grouped by sponsoring organization, and then by category of research.
- The numbers correspond to the listing of the projects in Table 2, Chapter 4, of this report.
- An **index** of the project descriptions **by sponsoring organization** appears on page B-ii.
- An **index** of the project descriptions **by number** appears on page B-iv.

FEDERAL SCIENCE & TECHNOLOGY PROJECT DESCRIPTIONS

(Indexed By Sponsoring Organization)

CONSUMER PRODUCT SAFETY COMMISSION **B-1**

18. Aluminum Wiring B-1
19. Home Electrical System Fires B-3
39. Ground-Fault Circuit-Interrupters B-5

DEPARTMENT OF COMMERCE **B-6**

10. Improved Fire Detection in Aircraft Cargo Compartments B-6
17. Fire Load Posed By Wiring In Buildings B-8
38. Fire-Retarded Polyolefins for Cables B-9
16. Applications of Phase-correlated Partial Discharge Detection to Medium-Voltage Cables B-11

DEPARTMENT OF DEFENSE **B-13**

1. Assessment of Advanced NDE Techniques for Wiring B-13
2. Improvement of Wire System Integrity for Legacy Aircraft B-14
3. Smart Wire B-15
23. Aging Wiring Interconnection System Support Activities B-16
24. Analysis of Wiring System Maintenance Data B-17
25. Wiring Integrity Study B-18
26. Fleet Wiring Survey B-19
37. Arc-Fault Circuit Breaker B-20
33. Training Aids For Wiring System Inspection And Repair B-21
34. Fiber Optics B-22
35. Development of Tools and Techniques for Managing the Integrity of Aerospace Electrical Interconnection Systems B-23
42. High Performance Conductive Polymer Fiber B-24
40. Advanced Wire Insulation Development B-25
41. Connector Corrosion B-26

FEDERAL SCIENCE & TECHNOLOGY PROJECT DESCRIPTIONS

(Indexed By Sponsoring Organization—con't)

DEPARTMENT OF ENERGY **B-27**

Develop Condition-Monitoring Techniques for Electrical Cables (4 tasks)

4. Task 1: Develop Sensory Inspection Training Aids B-27
5. Task 2: Evaluate Existing Electrical NDE Techniques B-29
6. Task 3: Investigate Modulus Profiling and Density Measurement for Cable Polymer Aging Assessment; Populate Cable Database B-30
7. Task 4: Condition Monitoring Database Compilation (non-Sandia Data) B-31

8. Innovative Chemithermal Techniques for Verifying Hydrocarbon Integrity in Nuclear Safety Materials B-32

Develop Empirical Data to Characterize Aging Degradation of Polymers Used in Electrical Cable (3 tasks)

20. Task 1: Confirm and Support Development of Cable Polymer Aging Models B-33
21. Task 2: Investigation of Bonded Jacket Cable Failure Mechanisms B-35
22. Task 3: Evaluation of Moisture Intrusion into Coaxial Connectors B-36

DEPARTMENT OF TRANSPORTATION/FEDERAL AVIATION ADMINISTRATION **B-37**

9. Development of Wire Testing and Inspection Systems B-37
27 Assessment of Wire Degradation B-38
28. Circuit Breaker Assessment and Development B-39
29. Establishment of a Test and Validation Infrastructure B-40
30. FAA-Industry Intrusive Inspection Project B-41
31. Risk Assessment for Aircraft Electrical Interconnect Systems B-42
36. Development of Arc-Fault Circuit Breakers B-43

NASA **B-44**

11. Enhance Inspection Technique for Improved Wire Integrity B-44
12. NDE of Spacecraft and Aircraft Wiring B-45
13. Non-Intrusive Cable Tester B-46
14. Wire Integrity Research (WIRe) Pilot Study B-47

NUCLEAR REGULATORY COMMISSION **B-50**

32. Environmental Qualification of Low-Voltage Electric Cables B-50

FEDERAL SCIENCE & TECHNOLOGY PROJECT DESCRIPTIONS
(Indexed By Project Number)

1. Assessment of Advanced NDE Techniques for Wiring B-13
2. Improvement of Wire System Integrity for Legacy Aircraft B-14
3. Smart Wire B-15
4. Develop Condition-Monitoring Techniques for Electrical Cables/ Task 1: Develop Sensory Inspection Training Aids B-27
5. Develop Condition-Monitoring Techniques for Electrical Cables/ Task 2: Evaluate Existing Electrical NDE Techniques B-29
6. Develop Condition-Monitoring Techniques for Electrical Cables/ Task 3: Investigate Modulus Profiling and Density Measurement for Cable Polymer Aging Assessment; Populate Cable Database B-30
7. Develop Condition-Monitoring Techniques for Electrical Cables/ Task 4: Condition Monitoring Database Compilation (non-Sandia Data) B-31
8. Innovative Chemithermal Techniques for Verifying Hydrocarbon Integrity in Nuclear Safety Materials B-32
9. Development of Wire Testing and Inspection Systems B-37
10. Improved Fire Detection in Aircraft Cargo Compartments B-6
11. Enhance Inspection Technique for Improved Wire Integrity B-44
12. NDE of Spacecraft and Aircraft Wiring B-45
13. Non-Intrusive Cable Tester B-46
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16. Applications of Phase-correlated Partial Discharge Detection to Medium-Voltage Cables B-11
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APPENDIX B: FEDERAL SCIENCE & TECHNOLOGY PROJECT DESCRIPTIONS

CONSUMER PRODUCT SAFETY COMMISSION

18 Project Title: "Aluminum Wiring"

Category

Failure Mechanisms.

Sponsoring Organization

Consumer Product Safety Commission (CPSC).

Performing Organizations

CPSC, National Bureau of Standards (NBS) [now, National Institute of Standards and Technology (NIST)].

Project Dates (Projected)

Start: 1973, End: 1982. (Low level monitoring of field experiences continues.)

Project Description

Electrical wiring made of aluminum was installed in homes in the United States from the mid-1960s through the mid-1970s. Experience and research has shown that electrical contacts between aluminum and other metals, such as copper, brass, and iron alloy, at terminations and splices are prone to degradation and dangerous overheating. This project involved assembly of technical information regarding the use of aluminum wiring in electrical branch circuits in homes, testing and surveying aluminum-wired homes, performance of laboratory evaluations, and identification of remedial measures. Public information was developed and continues to be made available in order to assist consumers concerned with aluminum wiring issues.

Publications Stemming from Project (by Publication Date)

"Hazard Assessment of Aluminum Electrical Wiring in Residential Use," prepared for CPSC by NBS (now NIST), December 1974.

"National Controlled Study of Relative Risk of Overheating of Aluminum Compared with Copper Wired Electrical Receptacles in Homes and Laboratory," technical report prepared for CPSC by The Franklin Institute, April 1979.

"Test of 'Old Technology' Aluminum Wire," prepared for CPSC by Wright Malta Corporation, February 1981. This is a multi-volume set of reports on laboratory testing of aluminum wire and connection devices. The tests demonstrate the propensity of splices and terminations of solid aluminum conductors in residential branch circuit sizes to attain dangerous overheating conditions at the electrical contact interfaces with the aluminum conductors.

"Repairing Aluminum Wiring," CPSC publication #516, 1982. CPSC's recommendations to consumers for repairing aluminum wiring.

Other Key Products and Milestones Related to the Research

- March-April 1974. CPSC Public Hearings on Aluminum Wiring.
- October 1977. Civil Action: CPSC v. Anaconda et al., Complaint to Declare "Old Technology" Aluminum Wiring Systems Imminently Hazardous Consumer Products and For Other Necessary Relief. January 1982: US District Court dismissed action, citing lack of CPSC jurisdiction.
- April 18, 1996. Letter from CPSC staff to Underwriters Laboratories Inc. (UL) containing proposals to upgrade the UL safety standard for splicing wire connectors that can be used with aluminum wiring installed in homes during the mid-1960s through mid-1970s. UL responds by inviting comments by other parties, but takes no further action to change standard
- CPSC staff recommendations for consumers: Have No. 10- and 12-gauge conductors replaced with equivalent copper conductors or wire terminations and splices on the aluminum-wired circuits retrofitted with special compression connectors evaluated by CPSC and made available by one manufacturer for this purpose.

19 Project Title: "Home Electrical System Fires"

Category

Failure Mechanisms.

Sponsoring Organizations

CPSC, Federal Emergency Management Agency, US Fire Administration.

Performing Organization

CPSC.

Project Dates (Projected)

Start: 1982, End: 2001.

Project Description

The risk of fires resulting from electrical wiring in residences is greater in older homes due to the aging of wiring products, electrical appliance loads that exceed design limits, and wiring practices that violate safety codes. This project seeks to identify residential wiring product failures and develop and implement remedial strategies to reduce the risk of fires resulting from electrical wiring in older homes.

Publications Stemming from Project

"Analysis of Electrical Fire Investigations in Ten Cities," prepared for CPSC by NBS (now NIST), March 1983.

"Residential Electrical Distribution System Fires," CPSC, December 1987. These reports identify failure mechanisms associated with the electrical wire systems in homes, based on analysis of actual investigations of residential fires requiring a fire department response.

"Technology for Detecting and Monitoring Conditions That Could Cause Electrical Wiring System Fires," prepared for CPSC by UL, September 1995. This report identifies arc-fault detection technology and other promising technologies for reducing residential electrical fires.

"1997 Residential Fire Loss Estimates," CPSC, July 2000. This report analyzes product-related fire loss estimates that occurred in US residential structure

fires that required a fire department response, including estimates for the products that comprise the electrical distribution wiring and equipment. Reports of this type are issued annually by the CPSC, covering the most recent year that data has been analyzed. The latest report is for 1997.

Electrical Inspection Code for Existing Dwellings. Published by the National Fire Protection Association (NFPA), designated NFPA 73, 2000 edition. New electrical inspection code for existing dwellings, first issued in 1994, which complements the widely adopted *National Electrical Code.*

Other Key Products and Milestones Related to the Research

- Broadcast-quality videotapes showing electrical inspections of older homes utilizing NFPA 73 and correction of identified hazards. Produced for various audiences including homeowners, electrical inspection authorities, and electrical contractors.
- Outreach effort to inform state and local electrical and fire officials regarding the CPSC findings related to home electrical wiring fires. Underway in fiscal year 2000-2001.

39 Project Title: "Ground-Fault Circuit-Interrupters"

Category

New materials.

Sponsoring Organization

CPSC.

Performing Organizations

CPSC.

Project Dates (Projected)

Start: 1986, End: 1992. (Low-level monitoring continues to determine the operational status of ground-fault circuit interrupters (GFCIs) currently installed in homes and to foster the introduction of enhanced GFCIs with features, such as auto self-testing or monitoring.

Project Description

The primary function of the GFCI is protection from electric shock. However, the device may prove useful in interrupting arc tracking and other phenomena that can lead to deterioration of wiring insulation, causing charring and often resulting in a fire. The purpose of this project is to promote wider applications of GFCIs in order to reduce the risks of shock and fire inherent with 120/240-volt electric power in homes.

Publications Stemming from Project

"GFCI Technical Report," CPSC, February 1992.

"Fire Protection Features of GFCIs," CPSC. ASHI Technical Journal (Spring 1993 edition).

Other Key Products and Milestones Related to the Research

- Upgraded requirements in the National Electrical Code (NEC), resulting from CPSC staff proposals and comments formally submitted to the NEC Committee. Proposals and comments specified requirements for GFCI protection for receptacles in residential kitchens, basements, and garages. Also, proposals and

comments supported GFCI requirements for specific products including spas, hot tubs, and pressure washers.

DEPARTMENT OF COMMERCE

10 Project Title: "Improved Fire Detection in Aircraft Cargo Compartments"

Category

Diagnostics.

Sponsoring Organizations

FAA and NASA.

Performing Organization

DOC/NIST.

Project Dates (Projected)

Start: October 1999, End: July 2000.

Project Description

This project is concerned with early, reliable detection of smoke and fire in cargo compartments. Wiring overheats (shorts, arcing, etc.) are a significant source of smoke events in aircraft. While there is no exposed wiring in a cargo compartment, other areas of aircraft are filled with wiring. Smoke detection issues in the avionics bays and inaccessible areas of aircraft are similar to the cargo compartment, and improvements in detection of smoke and fire in cargo compartments should be directly translated to other areas of the aircraft.

The current industry practice for smoke detection in cargo compartments relies on the detection of smoke particles, mainly with photoelectric smoke detectors. Little confidence is placed in the these detection systems, however, as the rate of false alarms is high because the detectors may be set off by airborne contaminants other than smoke (such as dust, condensing water vapor, and other aerosols). Detectors with more than one type of sensor have the potential to significantly reduce false alarms, while providing greater sensitivity. Multi-sensor detectors have been developed for industrial, commercial, and residential building applications to reduce nuisance alarms and provide increased sensitivity for a variety of fire sources.

This project examines the response of different detection sensors to fire and nuisance sources that may occur in a cargo compartment. The data will be used to propose sensor combinations and alarm criteria to reduce false alarms and increase sensitivity for a range of fire events.

Key Products and Milestones Related to the Research

A report documenting this research will demonstrate to aircraft manufactures and their customers that there are viable alternatives to the extraordinarily high false alarm rates, and it will provide aircraft detector manufactures a baseline for developing improved detectors.

17 Project Title: "Fire Load Posed By Wiring In Buildings"

Category

Failure Mechanisms.

Sponsoring Organizations

To be determined.

Performing Organization

DOC/NIST.

Project Dates (Projected)

To be determined.

Project Description

Due to the expansion of technology in recent years, large quantities of wire and cable have accumulated in buildings. It is common practice when running new cable to abandon the old cable in place. (For example, the cable from the old National Bureau of Standards telephone system is still in the floor trenches.) This abandoned cable is a significant fuel load and a fire hazard. Regulatory bodies are adopting requirements that old cable be removed when replacement cable is installed, but, due to the high cost associated with removal, this is being resisted by many (especially telephone companies).

In addition, testing has shown that higher performing cables often required by building codes are overwhelmed and exhibit poor fire performance when mixed with "ordinary" cables of the type often installed by tenants or occupants themselves.

The key issues to be addressed by this research are:

- How to predict the realistic hazard posed by the accumulation of cables with mixed flammability ratings.
- How to estimate the risk associated with the hazard.
- How to determine the benefit of removing a portion of the load or of adding fire detection or suppression systems to the cable runs.

38 Project Title: "Fire-Retarded Polyolefins for Cables"

Category

New Materials.

Sponsoring Organizations

NIST/BFRL.

Performing Organization

NIST/BFRL.

Project Dates (Projected)

Start: 2001, End: 2002.

Project Description

Wires and cables made with fluorocarbons have excellent flammability and physical properties, but they are very expensive. Flame-retarded polyvinyl chloride (PVC) cables also have excellent flammability and physical properties and are not as expensive as fluorocarbon cables. However, the chlorine content of PVC cables is a concern for potential formation of dioxin during incineration of spent PVC cables. This concern is quite strong in Europe and Japan. Polyolefin cables could be an alternative to PVC cables, but they are quite flammable. It is a major technical challenge to make polyolefin cables which have the same flammability properties as the flame-retarded-rated PVC cables. One possible new approach is the combined use of nanotechnology (addition of nanoscale additives) with conventional non-halogen-based flame retardant additives. Another important issue is the effects of aging of the cables on the flammability properties. All current tests are conducted only with new cables.

This project will examine the flammability properties of polypropylene with various combinations of nanoscale additives, such as clays, mica, and nanosilica particles with phosphorous compounds or other flame-retarded additives. Dielectric constants and other physical properties will be measured for candidate flame-retarded polypropylenes having excellent flammability properties. Experimental cables will be made with the selected best performance materials. A limited number of large-scale tests will be conducted with the experimental cables, and various tests that are currently required for existing cables will be conducted.

Key Products and Milestones Related to the Research (proposed)

- September 2001: Develop flame-retarded polyolefin formulations for industrial use.
- November 2001: Develop method to accelerate aging of cables.
- March 2002: Complete various flammability tests of the experimental (non-aged) cables.
- May 2002: Complete the measurements of the flammability properties of the aged cables.
- June 2002: Conduct large scale tests of the experimental cables.
- September 2002: Write final report.

16 Project Title: "Applications of Phase-correlated Partial Discharge Detection to Medium-Voltage Cables"

Category

Diagnostics

Sponsoring Organizations

None

Performing Organization

DOC/NIST

Project Dates (Projected)

2001 - 2003

Project Description

Partial discharge testing is generally done during fabrication of medium- and high-voltage cables to ensure that the initial assembly is nearly discharge-free. After installation in power plants, however, cables are exposed to thermal, mechanical, and radiological stressors. Also, buried cables are exposed to moisture that causes chemical and physical changes in the cable, leading to an increase in partial discharges. The aging in distributed power plant cables is non-uniform, and it is desirable to locate sites of greater partial discharge activity to identify cable locations with a higher probability of failure.

However, distributed cables represent a severe challenge to *in situ* partial discharge measurements, primarily for two reasons:

- Random-partial-discharge signals are often too weak to detect in the presence of noise at normal operating conditions.
- Partial discharge may occur at multiple defect sites—such as water ,trees, cracks, or metallic protrusions—resulting in a wide range of strengths and characteristics of partial discharge signals.

Both of these issues presently represent critical limitations to application of partial discharge detection to cables.

A new partial-discharge-detection system developed at NIST can address both of these issues. The emphasis of the NIST approach has been phase-correlated stochastic analysis of partial discharge pulses, which allows the characterization of partial discharge signals from various sources and the

extraction of partial discharge signals in the presence of significant electrical noise.

The emphasis of this project is to modify the existing partial discharge detection and analysis system for application to medium-voltage cables, and to develop appropriate analysis techniques for determining the number, locations, and severity of insulation anomalies in cables. This technique is applicable to medium- to high-voltage signal cables, and requires no over-voltaging of the cables.

Key Products and Milestones Related to the Research

The development of an *in situ* diagnostic technique to determine the location of insulation flaws in medium-voltage control cables in electric power plants.

DEPARTMENT OF DEFENSE

1 Project Title: "Assessment of Advanced Non-Destructive Evaluation (NDE) Techniques for Wiring"

Category

Diagnostics.

Sponsoring Organizations

Air Force Research Laboratory/Materials Directorate System Support Division (AFRL/MLS).

Performing Organizations

Air Force Research Laboratory/Materials Directorate Materials Integrity Branch (AFRL/MLSA).

Project Dates (Projected)

Start: July 2000, End: September 30, 2000.

Project Description

This project will co-fund FAA research programs on diagnostic techniques for wire systems and will evaluate and validate selected advanced NDE techniques for wire system.

2 Project Title: "Improvement of Wire System Integrity for Legacy Aircraft"

Category

Diagnostics.

Sponsoring Organizations

Aeronautical Systems Center Aging Systems and Systems Planning Division (ASC/SMA).

Performing Organizations

AFRL/MLSA.

Project Dates (Projected)

Start: October 1, 2000, End: September 30, 2003.

Project Description

This project will develop a prototype of a wire testing system that can be used in the field. This system will allow efficient location of wire system anomalies and monitoring of wire system integrity, which will extend failure-free operating periods. Phase one of the project will entail procuring a wire testing system and optimizing it for evaluating wire system integrity. Phase two will evaluate the system at a field location. This effort will build upon technology being developed by the Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA), and can be used by the Navy and other agencies.

3 Project Title: "Smart Wire"

Category

Diagnostics

Sponsoring Organizations

Office of Naval Research (ONR).

Performing Organizations

Naval Air Systems Command (NAVAIR).

Project Dates (Projected)

Start: October 1, 1999, End: September 30, 2004.

Project Description

Currently, 1 to 2 million organizational work-years are spent by the Navy in troubleshooting and repairing aircraft wire system. This project will develop a "Smart Wire" system with embedded diagnostic and prognostic capabilities to manage wire system health. This system will allow monitoring of the "health" of the aircraft wire system and correction of anomalies prior to failure. The program will include development of a brassboard, performance of a smart wire integration study, development of a prototype system, and demonstration of the system in a laboratory and during flight. This program will potentially benefit both legacy and new aircraft. With respect to wire system incidents, "smart wire" technology will reduce maintenance work-hours by 20 percent, reduce mission aborts and non-mission-capable hours by 20 percent, and reduce in-flight electrical fires and loss of aircraft by 80%. This program is currently sponsored by the Navy but can benefit the Air Force, FAA, NASA, and other agencies.

23 Project Title: "Aging Wiring Interconnection System Support Activities"

Category

Failure Mechanisms.

Sponsoring Organizations

Air Force Research Laboratory /Materials Directorate System Support Division (AFRL/MLS).

Performing Organizations

AFRL/MLSA.

Project Dates (Projected)

Start: October 1, 2000; continuing over five years.

Project Description

This project seeks to reduce wire system failures by resolving high-failure-rate wiring conditions and providing new inspection tools to extend failure-free operating periods for wire systems. This project will characterize failure mechanisms in wire systems and develop new failure analysis and detection techniques for wire systems. Research will include in-house failure analysis and materials investigations on deployed wire systems, and evaluation of new failure analysis and NDE techniques, using probability-of-detection methodologies. This project will also provide technical expertise to NASA and FAA with research results disseminated to multiple organizations and industry.

24 Project Title: "Analysis of Wiring System Maintenance Data"

Category

Failure Mechanisms.

Sponsoring Organizations

ASC/SMA.

Performing Organizations

AFRL/MLSA.

Project Dates (Projected)

Start: September 2000, End: March 2001.

Project Description

This project will involve conducting field surveys on wire system maintenance on various aircraft. Researchers will collect and analyze field maintenance data related to wire system failures, including how wire system failures are recorded, in order to ascertain the most efficient method of using collected data for engineering analysis. This research will provide data on locations of wire system failures and failure modes and mechanisms, and will allow engineering organizations to reduce sustainment costs.

25 Project Title: "Wiring Integrity Study"

Category

Failure Mechanisms.

Sponsoring Organizations

AFRL/MLS and NAVAIR.

Performing Organizations

GRC International and Eclypse.

Project Dates (Projected)

Start: March 2000, End: September 30, 2000.

Project Description

This project involves field surveys of wire systems on various airplanes, including the S-3, C-2, F-16, B-1B, and KC-135. The research will identify the location of wire system failures and failure modes and mechanisms; identify current field diagnostic tools; and develop requirements for advanced diagnostic tools to efficiently locate wire system anomalies.

26 Project Title: "Fleet Wiring Survey"

Category

Failure Mechanisms

Sponsoring Organizations

NAVAIR (AIR-4.1).

Performing Organizations

NAVAIR (AIR-4.4.4).

Project Dates (Projected)

Start: October 1, 1999, End: September 30, 2000.

Project Description

The objective of this project is to determine current maintenance and inspections practices and determine the condition of wire systems in fleet assets. The program will consist of an in-depth survey that includes all three levels of maintenance. Project personnel will visit designated field activities. The team will conduct interviews of fleet personnel and inspections of fleet assets.

The project findings will be documented in a formal report and database. The survey will cover all aspects of wire system maintenance, material condition, and engineering support. Information gathered during the survey will be used to ensure wire system engineering and maintenance initiatives are addressing fleet issues.

37 Project Title: "Arc-Fault Circuit Breaker (AFCB)"

Category

Interconnection Technologies.

Sponsoring Organizations

ONR, FAA.

Performing Organizations

NAVAIR.

Project Dates (Projected)

Start: January 1, 1999; End: December 31, 2002 (M24571 Envelope), September 30, 2006 (M3320 Envelope).

Project Description

Existing circuit breakers installed in aircraft are designed to detect sustained current shorts and not intermittent arcing, which can result in arc propagation. This project will develop an AFCB with the same form, fit, and function as existing aircraft circuit breakers, that will also detect an electrical arcing event on the aircraft. The AFCB will be a form/fit/function replacement to aircraft circuit breakers installed on "legacy" aircraft, but it will also benefit new aircraft. With respect to power wiring incidents on aircraft operated by the Navy, the AFCB will reduce maintenance work-hours by 35 percent, reduce mission aborts and non-mission-capable hours by 35 percent, and reduce in-flight electrical fires and loss of aircraft by 80 percent. The program consists of development of a prototype and flight evaluation hardware and demonstration in the laboratory and in flight. Initial hardware will be built to meet the military's M24571 circuit breaker envelope. The follow-on effort will be to develop hardware to meet the military's M3320 circuit breaker envelope. This project is jointly funded and sponsored by the FAA and the Navy but will also benefit the Air Force, NASA, and other agencies.

33 Project Title: "Training Aids For Wiring System Inspection And Repair"

Category

Interconnection Technologies.

Sponsoring Organization

NAVAIR (AIR-4.1).

Performing Organizations

Naval Air Warfare Center – Training Systems Division (AIR-4.9).

Project Dates (Projected)

Start: October 1, 2000, End: September 30, 2005.

Project Description

Wiring has emerged as a critical system, because of the increasing complexity, high density, and critical interface between electrical and electronic sub-systems. The objective of this project is to develop a comprehensive training syllabus and instructional video on maintenance and inspection methods for legacy and modern aircraft wire systems.

Information from the fleet wiring survey and state-of-the art industry practices will serve as the basis for development of training aids. This program will build on ongoing initiatives in other DOD agencies, FAA, and NASA. Project personnel will monitor and track results after the training program is implemented.

34 Project Title: "Fiber Optics"

Category

Interconnection Technologies.

Sponsoring Organizations

NAVAIR (AIR-4.1).

Performing Organizations

NAVAIR (AIR-4.4.4).

Project Dates (Projected)

Start: October 1, 2000, End: September 30, 2003.

Project Description

Wire systems are susceptible to the effects of electro-magnetic interference (EMI). Conventional copper wires use plated copper shielding to protect against EMI. The shields can deteriorate over time due to environmental and operational conditions. Conventional wires are also limited in their bandwidth capacity.

The objective of this project is to develop fiber-optic technology that allows for the replacement of copper-based data busses and sensor/control wires. This will include developing materials and methods for time division and wave division multiplexing. The end product will include components that are lighter and smaller and have better signal integrity than conventional wires. There will also be a detailed system engineering approach for technology introduction and integration.

35 Project Title: "Development of Tools and Techniques for Managing the Integrity of Aerospace Electrical Interconnection Systems"

Category

Interconnection technologies.

Sponsoring Organizations

AFRL/MLS and FAA Technical Center.

Performing Organizations

AFRL/MLSA.

Project Dates (Projected)

Start: October 1, 2002, End: September 30, 2005.

Project Description

Develop advanced techniques and processes for the inspection, maintenance, troubleshooting and repair of electrical interconnection systems on aircraft. This research is intended to develop equipment and integrated process tools that will allow effective and safe management of electrical interconnection systems in legacy and new commercial and military aircraft. This program will build upon technology being developed by the Air Force, Navy, FAA, NASA, and industry and will be funded by the Air Force, FAA, and industry.

42 Project Title: "High Performance Conductive Polymer Fiber"

Category

New materials.

Sponsoring Organizations

Air Force Research Laboratory /Materials Directorate Polymers Branch (AFRL/MLBP). Transition program: AFRL/MLSA.

Performing Organizations

Syscom Technology, Inc.

Project Dates (Projected)

Start: March 3, 2000, End: March 3, 2002.

Project Description

This project will optimize the mechanical and electrical properties of a conductive polymer fiber for use as a replacement material for copper wiring in signal transfer and EMI-shielding applications. The new material is intended to be lighter weight and higher strength than the existing copper wiring. The purpose of this project is to develop and scale up an integrated process to produce high-strength, high-modulus conductive metal containing polymer fibers. Phase I of the project demonstrated the metal infiltration and reduction into the polymer, which created a highly conductive metal network in the fiber matrix. A transition program will be initiated in fiscal year (FY) 2001 to augment implementation. Products of this research can be used in space applications by NASA. This program is a Phase II small business, university-assisted (STTR) effort.

40 Project Title: "Advanced Wire Insulation Development"

Category

New Materials

Sponsoring Organizations

NAVAIR (AIR-4.1).

Performing Organizations

NAVAIR (AIR-4.4.4).

Project Dates (Projected)

Start: October 1, 2000, End: September 30, 2005.

Project Description

Data from the Navy Safety Center indicate that chafing of wire insulation and consequent short circuits are a common failure mode of wire systems in aircraft. The objective of this project is to develop a wire with increased insulation life, better chafing resistance, and built-in diagnostic capability. The project will consist of identifying performance, acquisition strategy, quality assurance, and a method of installing the new product in the aircraft.

The new wire type is expected to work well with a "Smart Wire" system. Once developed and fielded, the new wire type is expected to increase system safety, lower ownership costs, and reduce time spent in non-mission-capable and maintenance status.

41 Project Title: "Connector Corrosion"

Category

New Materials.

Sponsoring Organizations

NAVAIR (AIR-4.1).

Performing Organizations

NAVAIR (AIR-4.4.4).

Project Dates (Projected)

Start: October 1, 2000, End: September 30, 2005.

Project Description

Wire systems are exposed to a variety of environmental conditions. Wire systems often include metal or metallized connectors, which are susceptible to corrosion. Corroded connectors can affect system performance and require maintenance intervention in the form of cleaning and retreating or replacement of connectors.

The objective of this project is to develop connectors with enhanced environmental tolerances, improved durability, and more rugged construction. The connectors developed under this program will be a form/fit/function replacement for existing connectors.

DEPARTMENT OF ENERGY

4 Project Title: "Develop Condition-Monitoring Techniques for Electrical Cables/Task 1: Develop Sensory Inspection Training Aids"

Category

Diagnostic.

Sponsoring Organization

Department of Energy (DOE)/Electric Power Research Institute (EPRI) (joint management).

Performing Organization

To be determined.

Project Dates (Projected)

Start: FY2000, End: FY2001 (12 months).

Project Description

Some nuclear plant operators in the US are seeking renewal of their operating licenses to continue operation of their plants beyond the 40-year term of the original license. However, to gain renewal of their licenses, nuclear plant operators must show that cables can perform their safety functions for up to 60 years. Proven condition-monitoring methods are needed to provide this assurance.

The objective of this task is to develop sets of cable specimens to use as aids for training inspectors who perform visual and tactile inspections of wire systems. The specimens will consist of commonly used types of cables that are artificially aged to varying degrees of degradation. This task will also document the protocols for developing the training aids to allow additional sets to be generated when needed in the future.

Key Products and Milestones Related to the Research

- At least 10 sets of specimens will be developed. At minimum, the sets will include one specimen of cable of cross-linked polyethylene (XLPE) construction and two specimens of ethylene propylene rubber (EPR)/Hypalon (at least one bonded jacket) configurations. Both individual insulated conductors and cabled

configurations will be included in the sets. Each set of specimens will be appropriately packaged and labeled for use in training sessions. The labeling will describe the cable (manufacturer, materials, thickness, visually observable differences, and details of the bend characterization) and the degree of aging

- The protocols used to incrementally age the training aids will be described in a report.

5 Project Title: "Develop condition-monitoring Techniques for Electrical Cables/Task 2: Evaluate Existing Electrical NDE Techniques"

Category

Diagnostic.

Sponsoring Organization

DOE/EPRI (joint management).

Performing Organization

Ontario Power Generation Research Laboratory.

Project Dates (Projected)

Start: FY2000, End: FY2001 (12 months).

Project Description

Electrical testing using ionized gas to provide a ground plane for unshielded cables has been developed previously. This project will involve proof testing under simulated field conditions and proof-of-principles tests to determine if the method can be extended from detection of severe damage to detection of partial wall damage and deterioration due to aging. The test of simulated field conditions will be performed using the Electrical Cable Test Facility at Sandia National Laboratories.

Key Products and Milestones Related to the Research

A report will document the tests and results.

6 Project Title: "Develop condition-monitoring Techniques for Electrical Cables/Task 3: Investigate Modulus Profiling and Density Measurement for Cable Polymer Aging Assessment; Populate Cable Database"

Category

Diagnostic.

Sponsoring Organization

DOE/EPRI (joint management).

Performing Organization

Sandia National Laboratories.

Project Dates (Projected)

Start: FY2000, End: FY2001 (12 months).

Project Description

This project will improve condition-monitoring techniques by assembling data on aging of insulation and jacket materials (polymers) used in cables. This task will determine the correlation between micromodulus measurements and mechanical degradation of nuclear jacketing and insulation materials.

Key Products and Milestones Related to the Research

- The data and the techniques used to generate it will be described in a report.
- The results from this project, along with other existing data, shall be placed in a database format for translation into the database being developed under another task.

7 Project Title: "Develop condition-monitoring Techniques for Electrical Cables/Task 4: Condition Monitoring Database Compilation (non-Sandia Data)"

Category

Diagnostic.

Sponsoring Organization

DOE/EPRI (joint management).

Performing Organization

To be determined.

Project Dates (Projected)

Start: FY2000, End: FY2001 (12 months).

Project Description

This project will compile available condition-monitoring data (e.g., indenter modulus, density, and oxidation induction time) for cables from research organizations, universities, and utilities. The data will be used for comparison with cables in the field or removed from service. The data will be appraised and reviewed for validity and acceptability, the sources of information will be identified, the cost (if any) of obtaining the information will be determined, and the structure of the database will be finalized. The information that can be obtained will be entered into the database.

Key Products and Milestones Related to the Research

- A database structure, manipulation techniques, and basic digital reports, plus directions for use for the types of condition-monitoring data that are available.
- Entry of any useful data that are available at no additional cost into the database.
- A report detailing the availability of data at additional cost and the cost of data, including an assessment of the value of this data relative to its cost.

8 Project Title: "Innovative Chemithermal Techniques for Verifying Hydrocarbon Integrity in Nuclear Safety Materials"

Category

Diagnostic.

Sponsoring Organization

DOE.

Performing Organization

Veridian—Pacific Sierra Research and University of Virginia.

Project Dates (Projected)

Start: September 2000, End: August 2002.

Project Description

This research and development program explores new methods of assessing the condition and predicting the remaining life of critical hydrocarbon materials in nuclear power plants. Of these materials, safety control cable insulation is a primary focus.

Chemithermal assay techniques are being developed for application to critical safety materials (including cable insulation, O-rings, and lubricants) in nuclear power plants. These techniques exploit the chemical (oxidation) and thermal response of a material to assess degradation caused by exposure to radiation and thermal stresses. This technique not only assesses the condition of materials, but also provides data on the remaining utility of the material. Unlike conventional methods of assessing polymer materials, chemithermal methods are non-intrusive and nearly non-destructive because they require only a minute amount of sample material (approximately 8 mg). These advantages as well as its technical utility and low cost make the chemithermal assay technique an important asset in monitoring the safety of nuclear power reactors.

Key Products and Milestones Related to the Research

Key products include a material condition-monitoring database, standardized procedures, engineering development methodology, and intra-technology correlation analysis.

20 Project Title: "Develop Empirical Data to Characterize Aging Degradation of Polymers Used in Electrical Cable/Task 1: Confirm and Support Development of Cable Polymer Aging Models"

Category

Failure Mechanisms.

Sponsoring Organization

DOE/ EPRI (joint management).

Performing Organization

Sandia National Laboratories.

Project Dates (Projected)

Start: FY2000, End: FY2001 (12 months).

Project Description

This project seeks to develop a science-based understanding of polymer degradation to address certain Nuclear Regulatory Commission (NRC) safety concerns regarding the accuracy of current techniques (e.g., the Arrhenius equation) for predicting actual life for electrical cables and the limitations of the current techniques for predicting chemical degradation of electrical wires during thermal aging.

Task 1 of the project will produce empirical data and aging models to characterize the aging of insulation and jacket materials (polymers) commonly used in critical safety applications in commercial nuclear power plants in the United States.

Sub Task 1-1. Linearity of Arrhenius Curve (Oxygen Consumption Experiments)

The ultra-sensitive oxygen consumption approach will be used to check the Arrhenius extrapolation assumption for important cable jacketing and insulation materials mechanical aging properties. In addition, since these measurements can be taken over a very wide temperature range, much better estimates of activation energies and their potential dependence on temperature will be determined.

Sub Task 1-2. Characterization of Materials Exhibiting an Inverse Temperature Effect

For constant dose-rate conditions, some semi-crystalline materials [e.g., certain crossed-linked polyolefin (CLPO) and EPR/ethylene propylene diene

monomer (EPDM) cable insulations] can age more rapidly in a combined radiation/temperature environment as the combined-environment temperature is lowered A broad range of important semi-crystalline cable insulation materials will be subjected to combined radiation/temperature environments to identify those materials exhibiting inverse temperature effects.

Sub Task 1-3. Characterize materials that exhibit a "Lazarus" effect

Some materials exhibiting inverse temperature behavior appear to include a secondary behavior that has been termed the "Lazarus" effect. Preliminary studies indicate that when these materials are exposed to a high temperature, mechanical properties improve dramatically. The effort will confirm the existence or lack thereof in commonly used cable polymers.

Key Products and Milestones Related to the Research

- A report detailing the results of the oxygen consumption experiments
- Experiments to characterize at least one CLPO and one EPR/EPDM material commonly used in nuclear cable insulation systems, and a report describing the results of these experiments.

21 Project Title: "Develop Empirical Data to Characterize Aging Degradation of Polymers Used in Electrical Cable/Task 2: Investigation of Bonded Jacket Cable Failure Mechanisms (CSPE/EPR Insulation Swelling Aging Research)"

Category

Failure Mechanisms.

Sponsoring Organization

DOE/EPRI (joint management).

Performing Organization

To be determined.

Project Dates (Projected)

Start: FY2000, End: FY2001 (12 months).

Project Description

Task 2 of this project will produce empirical data to characterize the degree of swelling of EPR/chlorosulfonated polyethylene (CSPE) insulation material under aging conditions representative of actual conditions in commercial nuclear power plants in the US. This task will determine the limits of allowable aging of wiring installed in nuclear power plants to preclude splitting of wiring under accident conditions. Researchers will subject cable specimens from at least two different manufacturers to low-rate, accelerated thermal and radiation aging conditions, and then expose the specimens to steam. The degree of swelling will be measured immediately after steam exposure, and any splitting of the specimens will be correlated with the degree of accelerated aging performed.

Key Products and Milestones Related to the Research

A report will be prepared to describe the tests performed, the data from the materials that were tested, and the findings of the effort.

22 Project Title: "Develop Empirical Data to Characterize Aging Degradation of Polymers Used in Electrical Cable/Task 3: Evaluation of Moisture Intrusion into Coaxial Connectors"

Category

Failure Mechanisms.

Sponsoring Organization

DOE/EPRI (joint management).

Performing Organization

To be determined.

Project Dates (Projected)

Start: FY2000, End: FY2001 (12 months).

Project Description

Moisture intrusion into coaxial connectors has been observed in qualification tests and research efforts performed by industry and the NRC. This task will perform a study and testing to determine if the moisture intrusion is configuration-specific or an artifact of test configuration, or if it occurs in all nuclear power plant configurations. The task will evaluate and develop designs for moisture dams. The project will test coaxial connector specimens configured to match those used in typical applications in a nuclear power plant and will simulate plant conditions during an accident related to loss of coolant. The specimens will be placed under steam conditions that challenge sealing of the connector, and will be monitored electrically while they are subjected to pressurized steam conditions.

Key Products and Milestones Related to the Research

A report will be prepared to detail the results of the tests and describe the ability of the connector configurations to function under steam exposure.

DEPARTMENT OF TRANSPORTATION/FEDERAL AVIATION ADMINISTRATION

9 Project Title: "Development of Wire Testing and Inspection Systems"

Category

Diagnostic.

Sponsoring Organization

FAA, Transport Airplane Directorate.

Performing Organization

William J. Hughes Technical Center, Airport and Aircraft Safety, Research and Development Division, FAA Center for Aviation Systems Reliability.

Project Dates (Projected)

Start: 2000, End: 2003. (The Broad Area Announcement will be reissued annually and awards will be made according to research requirements and availability of funding. The duration of the projects will range from six months to several years.)

Project Description

This project supports the development of testing and inspection systems, technology, and techniques that identify or characterize material or structural flaws in wire systems that may impair the safe transmission of electrical power and signals. The proposed systems, technology, and techniques could be useful either for infrequent, comprehensive examinations or for more frequent, focused inspections as a part of maintenance by airplane operators.

Key Products and Milestones Related to the Research

- 1999: The FAA and Air Force PRAM Office co-sponsored the development and validation of a wire test system based on Eclypse Corporation's Automatic Test Equipment
- 2000-2002: The FAA has separately commissioned work at the Center for Aviation Systems Reliability to develop an impedance spectroscopy test system for polyimide wire.
- 2000-2003: A Broad Area Announcement was issued in FY 2000 and will be reissued each fiscal year from 2000 to 2003. A mixture of short to long-term projects, representing a variety of technologies, will be chosen for development.

- Projects will conclude with the development of a prototype system that will be validated with double blind testing.

27 Project Title: "Assessment of Wire Degradation"

Category

Failure Mechanisms.

Sponsoring Organization

FAA, Transport Airplane Directorate.

Performing Organization

Sandia National Laboratories and others.

Project Dates (Projected)

Start: 2001, End: 2003. [The start of this project was delayed from 2000 to 2001 to allow for enhanced laboratory testing in the Intrusive Inspection Project (see Project #30).]

Project Description

This project will determine degradation characteristics of aircraft wire systems. The purpose of this task is to establish, if possible, a technique to predict the condition of a wire system as it ages, in part to determine when corrective action should be taken. A broad-based oversight group (including airplane operators, manufacturers, and authorities) will review wire failure criteria, experimental procedures, and significant test parameters, to ensure the relevance of the effort. A metastatistical approach, which formally combines the results of several different experiments (pursuing the same objectives and adhering to the same "ground rules"), will be used to analyze the data. This approach will help to ensure the integrity and credibility of the results.

Key Products and Milestones Related to the Research

- June 2001: Completion of planning phase.
- June 2002: Completion of experiments.
- April 2003: Completion of metastatistical analysis of results.

28 Project Title: "Circuit Breaker Assessment and Development"

Category

Failure Mechanisms.

Sponsoring Organization

FAA, Transport Airplane Directorate.

Performing Organization

Circuit breaker testing: Sandia National Laboratories.

Technology development: To be determined.

Project Dates (Projected)

Start: 2000, End: 2003.

Project Description

Though the AFCB (see Projects #36 and #37) should result in significant improvements to aircraft electrical loads management, existing circuit breakers will remain in use. This project will evaluate the performance of existing circuit breakers and explore technologies beyond AFCB to minimize the risk of aging and failing electrical systems.

Key Products and Milestones Related to the Research

- September 2000: Circuit breaker performance assessment.
- Statement of work for technology development is to be determined.

29 Project Title: "Establishment of a Test and Validation Infrastructure"

Category

Failure Mechanisms.

Sponsoring Organization

FAA, Transport Airplane Directorate.

Performing Organization

Sandia National Laboratories' Aging Aircraft Validation Center.

Project Dates (Projected)

Start: 1999, End: 2004.

Project Description

Ensuring aviation safety requires a credible, independent organization capable of evaluating the efficacy of new products and maintenance technology. Industry is often perceived as too partisan.

In this project, researchers and airline inspectors will perform intensive visual inspections of the wire systems of a Boeing Model 747 with over 100,000 flight hours. Where the condition of wire systems is suspect, researchers will perform destructive testing of wire insulation. In addition, select electrical systems on both Boeing Model 747 and McDonnell Douglas Model DC-9 testbed aircraft will be baselined using a state-of-the-art wire test system. Aged and new specimens of electrical interconnections and technologies will be acquired routinely.

Key Products and Milestones Related to the Research

- 1999: Acquisition of Boeing 747.
- 2001: Baseline assessment of electrical systems on the testbed aircraft.
- Ongoing: Acquisition of aircraft electrical interconnect systems components.

30 Project Title: "FAA-Industry Intrusive Inspection Project"

Category

Failure Mechanisms.

Sponsoring Organization

FAA, Transport Airplane Directorate.

Performing Organization

Aging Transport Systems Rulemaking Advisory Committee (ATSRAC) Intrusive Inspection Working Group.

Project Dates (Projected)

Start: June 1999, End: September 2000.

Project Description

The Intrusive Inspection Working Group will plan and oversee an "autopsy" of wire systems installations on six retired transport-category aircraft. Research will involve visual inspections, on-aircraft testing, and laboratory testing. This project will provide data on certain latent defects, invisible degenerative conditions, and degraded performance of wire and insulation (as indicated by variation from some manufacturer-established or observed baseline) that could not be provided by an earlier research effort (the Air Transport Association Non-Intrusive Inspection Project), which collected data on the condition of electrical interconnect systems.

Key Products and Milestones Related to the Research

- June-September 1999: Development and validation of protocols.
- September 1999 - June 2000: Intrusive inspection of six aircraft.
- December 1999 – July 2000: NDT of six aircraft.
- May – August 2000: Laboratory analysis of wire specimens.
- September 2000: Report to ATSRAC.

31 Project Title: "Risk Assessment for Aircraft Electrical Interconnect Systems"

Category

Failure Mechanisms.

Sponsoring Organization

FAA, Transport Airplane Directorate.

Performing Organization

Sandia National Laboratories (tentative).

Project Dates (Projected)

Start: 2001, End: 2003.

Project Description

This project seeks to develop advanced risk assessment methodologies for aircraft electrical systems. Risk assessment is called for by the Federal Aviation Regulations, and accurate and sophisticated risk assessment tools will ensure the minimization of safety hazards associated with electrical interconnect systems.

Key Products and Milestones Related to the Research

Statement of work under development.

36 Project Title: "Development of Arc-Fault Circuit Breakers"

Category

Interconnection Technologies.

Sponsoring Organization

FAA, ONR.

Performing Organization

NAVAIR.

Project Dates (Projected)

Start: January 1999, End: December 2002.

Project Description

Circuit breakers currently installed on commercial airplanes do not detect and react to arcing faults associated with the chafing and consequent intermittent arcing between wires and metal airplane structure or other conductors. Successful development of AFCB technology will mitigate the effects of arcing by rapidly de-energizing the circuit prior to the ignition of surrounding materials or damage to electrical circuits.

This research examines the arcing phenomena related to aircraft power systems and electrical circuits. Electrical loads data will be collected from a variety of military and commercial transport aircraft. This project will develop prototype circuit breakers incorporating arc-fault detection hardware, but with the same form, fit, and function of current thermal breakers. Both the Navy and the FAA will conduct flight tests over an extended period to validate the operation and safety of the devices.

Key Products and Milestones Related to the Research

Forty flight-ready prototypes of the AFCB will be provided to the government for flight test by the Navy and the FAA.

NASA

11 Project Title: "Enhance Inspection Technique for Improved Wire Integrity"

Category

Diagnostics.

Sponsoring Organization

NASA Langley Research Center.

Performing Organization

NASA Langley Research Center.

Project Dates (Projected)

Start: April 2000, End: September 2005.

Project Description

This project will develop advanced NDE methods to determine the condition of wire systems in aerospace vehicles. Techniques include using laser-generated ultrasonic waves in the wires to locate breaks and thinning of the wire insulation and a thermographic method to enable quantitative assessment of the degradation of the wire. Advanced analysis techniques will be developed to reduce acquired data to a physical assessment of the condition of the insulation.

12 Project Title: "NDE of Spacecraft and Aircraft Wiring"

Category

Diagnostics.

Sponsoring Organization

NASA Langley Research Center.

Performing Organization

Johns Hopkins University.

Project Dates (Projected)

Start: July 2000, End: June 2003.

Project Description

This project will develop advanced NDE methods to determine the condition of wire systems in aerospace vehicles. Techniques will include using guided acoustic waves in the wires and rapid radiography to determine the condition of the insulation and using pulsed X-ray and microwave methods to determine the condition of the conductor.

13 Project Title: "Non-Intrusive Cable Tester"

Category

Diagnostics.

Sponsoring Organization

NASA.

Performing Organization

NASA Kennedy Space Center Engineering Development Directorate.

Project Description

The space shuttle uses dedicated signal conditioners (DSCUs) for conditioning transducers outputs and other signals to make them compatible with orbiter telemetry, displays, and data processing systems. The DSCUs are located throughout the orbiter, often in difficult-to-access locations in the vehicle fuselage. When troubleshooting a potential instrumentation problem, Vehicle Engineering personnel frequently have to demate cables to verify that the cable is not the source of the problem. Due to their inaccessibility, the DSCUs sometimes have to be removed to determine the cause of the problem. Once any cable is demated, all systems that have a wire passing through the connector have to be re-tested when the cable is reconnected. This results in many hours of revalidation testing on systems which were unrelated to the original problem.

This project developed two instruments to reduce the number of system re-tests caused by cable demates and to facilitate rapid troubleshooting of system anomalies. The first instrument, the end-to-end tester, performs a non-intrusive test to detect anomalies in a section of cable. The second instrument is used to determine the distance from the end of the cable to the short or open condition in the cable, once the end-to-end tester has determined that a section of cable has a flaw. These instruments will greatly facilitate the repair process in the cramped conditions of the space shuttle, and there is potential for similar commercial applications.

14 Project Title: "Wire Integrity Research (WIRe) Pilot Study"

Category

Diagnostics.

Sponsoring Organization

NASA, Office of Space Flight.

Performing Organization

NASA Ames Research Center.

Project Dates (Projected)

Start: January 2000, End: June 2000.

Project Description

This project will investigate the use of automated test technologies for reducing risks associated with aging wire in the space shuttle orbiter.

Three application areas of test automation are being researched:

- Automated verification and validation of vehicle wiring configurations, including auto-checking of CAD design files against as-built configurations, design verifications, and risk/reliability assessments.
- Automated condition assessment for maintenance, including noninvasive fault detection technologies and condition-based maintenance intelligent systems.
- Integrated in-flight wire integrity health management, including sensor technologies and health management intelligent systems.

Key Products and Milestones Related to the Research

A final report documenting the team's findings and recommendations, including follow-on work, will be produced.

NUCLEAR REGULATORY COMMISSION

32 Project Title: "Environmental Qualification of Low-Voltage Electric Cables"

Category

Failure Mechanisms.

Sponsoring Organization

NRC.

Performing Organization

Brookhaven National Laboratory.

Project Dates (Projected)

Start: 1993, End: 2000. (The NRC plans to continue research in FY 2001 to confirm regulatory positions on high-voltage, high-current wiring, overall wire system integrity, and condition monitoring techniques.)

Project Description

This project addresses the effects of the nuclear power plant operating environment on the degradation of polymer insulation for wire systems (wiring, splices, and connectors) and addresses NDE techniques to evaluate the integrity of the insulation. The current focus is on degradation of insulation on electric wiring in nuclear power plants, due to exposure to thermal and radiation stresses within the plants. Instrumentation and control wiring is one type of wiring that is important to reactor safety. Should the polymeric insulation material become embrittled and cracked during service or during an accident, the wiring may not be able to fulfill its intended safety functions. Therefore, the research program includes testing to evaluate the age-related degradation of wiring insulation and the ability of aged wire systems to withstand accident conditions.

The objectives of the NRC's research program are to:

- Assess the effects of operating temperature and irradiation conditions on the long-term degradation of wiring insulation.
- Assess the ability of the wire systems to perform under simulated accident conditions without losing its ability to function effectively, and

- Identify condition monitoring techniques that may be used to determine the effective lifetime of wire systems.

The wiring insulation materials being tested include EPR and XLPE. Accelerated aging (thermal and radiation) to the equivalent of 20, 40, and 60 years of service was performed, followed by exposure to simulated accident conditions. The effectiveness of chemical, electrical, and mechanical condition monitoring techniques also is being evaluated.

Key Products and Milestone Related to the Research

- Completed aging evaluation of XLPE and EPR cables for 40 years and 60 years of service life in nuclear power plants.
- Completed evaluation of various condition-monitoring methods for their effectiveness in detecting age-related degradation in bulk insulating materials and in installed wire systems.

Publications Stemming from Project

Acquisition Plan for Non-Aged and Naturally Aged Cable Samples from Nuclear Facilities (Technical Report: TR-6168/69-01-9/95). Brookhaven National Laboratory, November 1995.

Condition Monitoring Research Plan for Low-Voltage Electric Cables (Technical Report: TR-6168-69-03-95). Brookhaven National Laboratory, February 1996.

Preaging and Loss-of-Coolant Accident (LOCA) Test Plan for Low-Voltage Electric Cables (Technical Report: TR-6168/69-04-95). Brookhaven National Laboratory, March 1996.

Environmental Qualification Research Program Quality Plan (Technical Report: TR-6169-05-95). Brookhaven National Laboratory, April 1996.

"Volume 1: Summary of Past Work" & "Volume 2: Literature Analyses and Appendices," Literature Review of Environmental Qualification of Safety-Related Cables. NUREG/CR-6384, April 1996.

Baseline Condition Monitoring Data for LOCA Run No. 1 Cables (Technical Report: TR-6465-03-97). Brookhaven National Laboratory, March 1997.

Aging and LOCA Testing of Electrical Connections. NUREG/CR-6412, January 1998.

Supplemental Literature Review on the Environmental Qualification of Safety-Related Electric Cables (Technical Report: TR-6169-9/97). Brookhaven National Laboratory, January 1998.

Interim Report: Results of Test Sequence 1 on Electric Cables with Cross-Linked Polyethylene Insulation and Neoprene Jacket (Technical Report: TR-6465-01-98). Brookhaven National Laboratory, March 1998.

Environmental Qualification Research Literature Database and User's Manual (Technical Report: TR-6169-06-96). Brookhaven National Laboratory, May 1998.

Interim Report: Results of Test Sequence 2 on Electric Cables with Ethylene Propylene Rubber Insulation and Hypalon Jacket (Technical Report: TR-6465-05-98). Brookhaven National Laboratory, June 1998.

Interim Report: Results of Test Sequence 3 on Electric Cables with Cross-Linked Polyethylene Insulation and Neoprene Jacket Preaged to 40 Years (Technical Report: TR-6465-01-99). Brookhaven National Laboratory, January 1999.

Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-Voltage Electric Cables. NUREG-CR-XXXX, December 2000 (forthcoming).

APPENDIX C: INDUSTRY S&T PROGRAMS

APPENDIX C: INDUSTRY S&T PROGRAMS

Introduction C-1

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Lectromechanical Design Co.

I-7. Extension of Accuracy of Modified Arrhenius Life Model for Polymers C-10
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Ogden Environmental and Energy Services Company

I-11. Evaluation of Cable Polymer Aging Through Indenter Testing of In-Plant and Laboratory-Aged Specimens C-18

Hazardguard Safety Wire, Inc.

I-12. Hazardguard C-20

Square D

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Underwriters Laboratories

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APPENDIX C: INDUSTRY SCIENCE & TECHNOLOGY PROGRAMS

INTRODUCTION

On June 30, 2000, the *Commerce Business Daily* published an announcement regarding the formation of the Wire System Safety Interagency Working Group (WSSIWG). The announcement requested input from representatives of US industry, academia, and non-profit organizations regarding existing science and technology initiatives that will predict or detect problems in copper, optical, or other wire systems where a malfunction of the wire system can result in adverse safety and health effects. The following parties submitted information in response to the announcement.

- Electric Power Research Institute
- Hazardguard Safety Wire Inc.
- Lectromec Design Company
- Northrop Grumman
- Ogden Environmental and Energy Services Company
- Square D Company
- Underwriters Laboratories Inc.
- Universal Synaptics
- Veridian-PSR
- Wyle Laboratories, Inc.

Many industry initiatives are similar to federal S&T initiatives (as described in Chapter 4 of this document). It is significant to note that the government is not diverging from the path taken by industry, but that industry efforts and government efforts complement one another.

Table C-1 summarizes current non-governmental projects for wire system safety. It is likely that these projects are only a sampling of industrial work in this area, and that the input received does not represent the full range of work being done. Certain entities doing applicable work may not have seen the announcement or may have chosen not to submit information in response to it. Specific project descriptions received in response to the *Commerce Business Daily* announcement follow Table C-1.

Table C-1. Current industry initiatives in wire system safety.

	Project Title	Performer(s)	Sponsor(s)	Description of Project
I-1	Early Warning Wire Detector System	X-98 Inc.	T. Perkins Consultings, Inc.	The "Early Warning Wire Detector System" detects an electrical short in its early stages at the junction box or conduit.
I-2	Review of Polyimide Insulated Wire in Nuclear Power Plants	EPRI	EPRI	Evaluated the polyimide (Kapton®) problems identified in naval aircraft with respect to nuclear plant applications.
I-3	Diagnostic Matrix for Evaluation of Low-Voltage Electrical Cables	EPRI	EPRI	Summarizes the available chemical, physical and electrical tests for evaluating the condition of cable polymers and for troubleshooting circuit problems on low-voltage; presents a matrix linking these tests to various cable aging concerns and application problem.
I-4	Detection of Localized Cable Damage Using a Preionized Gas Technique and Testing of Power Plant Cables in the Presence of an Ionizable Gas	EPRI	EPRI	Electrical testing of unshielded cables located in metallic conduits through use of an ionizable gas as a ground plane.
I-5	Evaluation of Cable Polymer Aging through Indenter Testing of In-Plant and Laboratory-Aged Specimens	EPRI	EPRI	Test method for *in-situ* testing of cables for evaluating aging from thermal and radiation stresses.
I-6	EPRI Plant Support Engineering—Cable Condition Monitoring Working Group	EPRI	EPRI	Working Group helps direct research and disseminate the results related to the development of cable condition-monitoring techniques that are applicable to low-voltage cable.
I-7	Extension of Accuracy of Modified Arrhenius Life Model for Polymers	Lectromechanical Design Co.	Lectromechanical Design Co.	Development of a model for service life projection, which is used in testing wiring of 13 military and 4 commercial aircraft types.
I-8	Improvement of Existing DelTest™ Inspection Technique	Lectromechanical Design Co.	Lectromechanical Design Co.	Development and implementation of wire flaw detection equipment
I-9	Analysis of Interaction of Insulation Arcing and Arc-fault Circuit Breakers	Lectromechanical Design Co.	Lectromechanical Design Co.	Improvement of performance of wiring systems with respect to arc-generated fires and intermittent equipment operation is the possibility of using the arc voltage and current signatures to trip circuits.

Table C-1. Current industry initiatives in wire system safety.

	Project Title	Performer(s)	Sponsor(s)	Description of Project
I-10	Wiring Fault Detection/Isolation Improvement Program Using a Smart Automatic Wiring Analyzer (AWA)	Northrop Grumman	Northrop Grumman	Portable, compact device that can be used to automatically test continuity, resistance, shorts, open circuits, crossed wires, capacitance, and diodes in cables and harnesses.
I-11	Evaluation of Cable Polymer Aging Through Indenter Testing of In-Plant and Laboratory-Aged Specimens	EPRI	Ogden Environmental and Energy Services Company	Demonstrates use of Indenter Polymer Aging Monitor ("Cable Indenter") as non-destructive method to detect current aging problems and predict future aging problems in wiring systems.
I-12	Hazardguard	Hazardguard Safety Wire, Inc.	TBD	Detection and location of wire system problems through coating on outside of wire.
I-13	Arc-Fault Current Interrupter (AFCI) Technology Initiative	Square D	Square D	Addresses protection from arcing faults in electrical wiring systems.
I-14	Technology for Detecting and Monitoring Conditions That Could Cause Electrical Wiring System Fires	Underwriters Laboratories	Consumer Product Safety Commission	In-depth study of technologies to detect and monitor precursory conditions that could lead to or directly cause fires in residential wiring systems.
I-15	Arc-Fault Detection Circuit Breakers	Underwriters Laboratories	National Electrical Manufacturers Association	Objective of an arc-fault detector is to discern abnormal arcing that can be hazardous from operational arcing that is part of the functioning on many products.
I-16	High-Reliability Prognostics of Wiring and Other Connectivity Elements by Directly Testing for Age Related Failure Mechanisms	Universal Synaptics	Air Force	Studies problem of aging in wiring and avionics and clearly illustrates the problems effect on logistics and safety.
I-17	Innovative Chemithermal Techniques for Verifying Hydrocarbon Integrity in Nuclear Safety Materials	Veridian—Pacific Sierra Research and University of Virginia	DOE	Explores new methods of assessing condition and predicting remaining life of critical hydrocarbon materials in nuclear power plant environments.
I-18	Assessment of Environmental Qualification Practices & Condition Monitoring Techniques for Low Voltage Electrical Cables	Wyle Laboratories Inc.	NRC	Development of better understanding of degradation mechanisms and detection/inspection techniques.

I-1 Project Title: "Early Warning Wire Detector System"

Performing Organization

X - 98, Inc.
8000 South Prairie
Chicago, IL 60619
773-776-6223 or 773-723-7575
Fax: 773-776-6230
boyden@aol.com

Sponsoring Organization

T. Perkins Consultings, Inc.
34308 Pink Hill Road
Grain Valley, MO
816-224-9310
tperkins@discovery.net

Project Description

The "Early Warning Wire Detector System" detects an electrical short in its early stages at the junction box or conduit.

This system can be calibrated for aircraft vehicles. The EWDS -1001A uses a series of sensors (electrical devices used to measure heat) which are connected to transmitters placed strategically throughout the entity. When a malfunction occurs, the sensor triggers the transmitter, which in turn communicates by a microprocessor within these monitoring devices. The EWDS-10 01A begins to sound the alarm. It notifies designated parties via telephone to the tower and pilot of the location down to the very box as well as the temperature of the potential fire while also locally displaying a three-dimensional pictorial of the problem on the main monitor along with a local voice-synthesized announcement.

The Early Warning Detecting System - 1001A was patented; a mock prototype, built to test the theory, worked.

I-2 Project Title: "EPRI NP-7189: Review of Polyimide Insulated Wire in Nuclear Power Plants"

Sponsoring/Performing Organization

EPRI
1300 W.T. Harris Blvd.
Charlotte, NC 28262
Attn. Gary J. Toman
704-547-6073
gtoman@epri.com

Project Dates

The research is complete.

Project Description

This report evaluated the polyimide (Kapton®) problems identified in naval aircraft with respect to nuclear plant applications. It provides a summary of the naval air problems as well as a discussion of Kapton® properties and problems. While the naval aircraft problems do not affect nuclear applications, the report will allow modern researchers to readily understand issues related to Kapton® insulation.

Concerns regarding the use of Kapton® insulation on naval aircraft in which cracking and arc-tracking flashover were recognized required a review of the material for nuclear plant use. The report is an excellent summary of the issues related to Kapton® insulation in airframes, the design of the insulation system, and its aging mechanisms. Detailed property information and failure discussions are provided.

Key Products and Milestones of the Research

This research was completed in February 1991 subsequent to the identification of naval aircraft problems. The failure mechanisms are the same as those being recognized in non-naval aircraft today.

I-3 Project Title: "EPRI TR-106108: Diagnostic Matrix for Evaluation of Low-Voltage Electrical Cables"

Sponsoring/Performing Organization

EPRI
1300 W.T. Harris Blvd.
Charlotte, NC 28262
Attn. Gary J. Toman
704-547-6073
gtoman@epri.com

Project Dates

This research was completed in November 1997.

Project Description

The available chemical, physical and electrical tests for evaluating the condition of cable polymers and for troubleshooting circuit problems on low-voltage cable (less than 1,000 volts) are summarized with details relating to degree of difficulty and cost of testing. A matrix linking these tests to various cable aging concerns and application problems is presented. The matrix allows the user to determine available tests and tests under development that can be applied to management of aging systems and troubleshooting for cable applications.

I-4 Project Title: "EPRI TR-104025, Detection of Localized Cable Damage Using a Preionized Gas Technique" and "ERPI TR-112235, Testing of Power Plant Cables in the Presence of an Ionizable Gas"

Sponsoring/Performing Organization

EPRI
1300 W.T. Harris Blvd.
Charlotte, NC 28262
Attn. Gary J. Toman
704-547-6073
gtoman@epri.com

Project Dates

This base research was completed in June 2000. A follow-on program is underway to determine if more sensitive electrical tests can be performed to evaluate partial wall damage and to identify significant aging of cable polymers. The follow-on task will be completed in mid-2001.

Project Description

These reports describe electrical testing of unshielded cables located in metallic conduits through use of an ionizable gas as a ground plane.

The ionizable-gas technique allows improvement of the ground plane around an unshielded cable during electrical tests. The technique allows detection of through-wall-insulation cuts, pin holes and gouges at voltages much lower than would be required when testing in air. The results approximate testing performed with the conduits filled with tap water.

The test technique may be applicable when cables are located in confined metallic spaces, such as may occur inside the sheath of an aircraft.

I-5 Project Title: "EPRI TR-104075, Evaluation of Cable Polymer Aging through Indenter Testing of In-Plant and Laboratory-Aged Specimens"

Sponsoring/Performing Organization

EPRI
1300 W.T. Harris Blvd.
Charlotte, NC 28262
Attn. Gary J. Toman
704-547-6073
gtoman@epri.com

Project Dates

This research was completed in January 1996.

Project Descriptions

This report describes a test method for *in-situ* testing of cables for evaluating aging from thermal and radiation stresses. The technique is called "Indenter modulus method" and is performed with a portable test device.

The Indenter presses a small probe against the wall of an insulated conductor at a constant velocity while measuring the force exerted by the probe tip. The slope of the force versus position curve, the Indenter modulus, has been found to change in proportion to the degree of aging of many cable insulation and jacket polymers.

EPRI developed the technique and the test equipment. An Indenter test system can be made available for demonstration.

I-6 Project Title: "EPRI Plant Support Engineering—Cable Condition Monitoring Working Group"

Sponsoring/Performing Organization

EPRI
1300 W.T. Harris Blvd.
Charlotte, NC 28262
Attn. Gary J. Toman
704-547-6073
gtoman@epri.com

Project Dates

Periodic meetings of the Cable Condition Monitoring Working Group are on-going. The next meeting will be in Albuquerque, New Mexico, on September 13-14, 2000.

Project Descriptions

The Cable Condition Monitoring Working Group helps direct research and disseminate the results related to the development of cable condition-monitoring techniques that are applicable to low-voltage cable.

This working groups meets once to twice a year to discuss progress in test techniques including oxidation-induction time and oxidation-induction temperature testing, density change evaluation, Indenter modulus testing, micro-profiling, and chemical analysis of polymers. Researchers are also apprised of issues related to applications of these techniques to practical cable applications.

EPRI will allow key personnel in the Wire System Safety Interagency Working Group to participate in the Cable Condition Monitoring Working Group.

I-7 Project Title: "Extension of Accuracy of Modified Arrhenius Life Model for Polymers"

Category

Failure mechanisms

Performing Organization

Lectromechanical Design Co.
45,000 Underwood Ln, Ste L
Dulles (Sterling), VA 20166
703-481-1233
lectromec@aol.com

Sponsoring Organization

Please contact Lectromec for customer list.

Project Dates

Work has been in progress since 1985.

Project Cost (estimated)

Typical specific program and research, including the applied work, exceed $3 million.

Project Description

Lectromec has developed the model for service life projection, the Wire Insulation Degradation Analysis System (WIDAS), which is used in testing wire systems of 13 military and 4 commercial aircraft types to date. The model has led to operator decisions such as rewiring and retiring aircraft from inventory (this wire management program has been very useful to the Navy for their fleet of P-3 and E2C aircraft). This model is now being used for life extension strategy-planning for a European fleet of 800 military aircraft. The present stage of the program is pointed toward achieving higher accuracy and physical chemistry understanding of the relevant factors for aromatic polyimide and other polymers.

Work to date has consisted of refining the *in situ* sampling and testing of aging wiring systems; collecting data on active aircraft and in the test lab; testing of many types of aircraft such as the commercial Boeing 747 airplane and the military C-130, P-3, A-10, and F-16 airplanes; and extending the test period.

Present work includes incorporating various types of mechanical stressors, such as chafing and cut-through into the calculation model and comparison with epidemiological data.

Key Products and Milestones of the Research:

- This program started at the Naval Research Laboratory in 1985, and Lectromec played an integral role in the basic thermodynamics of wiring. Lectromec has continued this work both in the laboratory and on in-service aircraft to the present. Work has included testing wire from Lockheed A-10 military airplanes and one of the space shuttle orbiters. We are hopeful that this work will serve a useful purpose for many years to come, especially as the aging systems issue continues to receive great attention.
- A sampling test method for prediction of service life is presently being used. The accuracy for use of aircraft in the range of 20 to 40 years is presently being improved for application to a specific type of military aircraft. Work is proceeding, with an indefinite end date, for application to a more types of insulation and aircraft.

I-8 Project Title: "Improvement of Existing DelTest™ Inspection Technique"

Category

Diagnostics

Performing Organization

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lectromec@aol.com

Sponsoring Organization

Please contact Lectromec for customer list.

Project Dates

This program started on the Navy's EA-6B in 1987. Lectromec has continued both active aircraft and laboratory work to the present. The end date for the technology work is uncertain.

Project Description

Lectromec has approximately four years' experience developing and implementing wire flaw detection equipment, specifically called **DelTest™**. Most recently we have used this inspection technology as part of the FAA's Aging Systems Research Program intrusive inspections. In 1999, the **DelTest™** was used to assess the trailing edge of Navy P-3 aircraft. It was determined that the condition of the wire was such that all P-3s are now undergoing a rewire in that zone. Additionally, an in-field comparison revealed that our technology detected three times as many insulation flaws as a general visual inspection, which is currently a standard commercial industry practice.

We choose to categorize all wire insulation failures into two groups:

1. Mechanical properties of insulation polymers may degrade under certain normal environments. The Navy's problem with Kapton® degradation in moist, high-temperature environments illustrates this phenomenon.

2. Applied mechanical stresses, such as maintenance trauma, may also cause failure.

Lectromec recognizes the standard "DITMCO"-type test for cable systems which has been used for 50 years as a high-quality test to locate some types of wiring-related anomalies. In fact, several other technologies may complement Lectromec initiatives, including TDR (time domain reflectometry) and wiring system modeling database software. The **DelTest™** is one of the only methods which has proven itself in finding common types of chafing and fracture flaws in wiring insulation. Lectromec uses a very sensitive current-sensing technique with low voltage to detect small microcracks as well as hidden chafing. This system measures the current "delta" to locate specific fault points.

Lectromec has an active research program, in cooperation with a technical representative of a major chemical company, to screen temporary conductivity enhancements that are appropriate for use both in the repair shop and on the flight line. It is expected that a successful program will lead to a hand-held system appropriate for use by electricians at military depots and at the thousands of FAA-licensed commercial aircraft repair centers.

Key Products and Milestones of the Research

- As stated, we presently have instrumentation and techniques for locating micro and larger breaches in wire insulation. A milestone which we have targeted is to find a material that will require less "housekeeping" than the current water recovery system. *Note*: Water has not proven to be a major problem in practice, with the use of appropriate recovery techniques. At the same time, the problems of thermoelectric, galvanic, and EMI currents presently require sophisticated operators.
- Work has been supported by contracts for testing of active aircraft.

I-9 Project Title: "Analysis of Interaction of Insulation Arcing and Arc-fault Circuit Breakers"

Category

Improved Wiring Systems

Performing Organization

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lectromec@aol.com

Sponsoring Organization

Please contact Lectromec for customer list.

Project Description

One of the more promising techniques for improvement of performance of wiring systems with respect to arc-generated fires and intermittent equipment operation is the possibility of using the arc voltage and current signatures to trip circuits (Arc-fault Circuit Protection). Extensive work on this type of breaker has been attempted in the past. EPRI had a large multimillion-dollar program in this area in the 1970s. Allis Chalmers also spent millions of dollars on this technology. The results were promising until units were placed in practical operation. The variation in signatures coupled with differences in fault and material conditions lead to nuisance tripping and poor protection. Our in-house expertise and extensive work in the area of electrical arcing research can prove very useful to the ongoing development of Arc-fault Circuit Breakers. As an independent lab, we would look forward to working with these manufactures to produce the most effective possible device.

Lectromec has a theoretical model of arcing based on the experimental measurement of arc temperature by Dr. Maecker of Siemens Schuckert Werke of Berlin in the 1950s and Dr. Bruning's (President of Lectromec) Ph.D. dissertation on the subject. We are presently recording the signatures of approximately 2,000 arcing faults of aircraft wire systems for the NASA space shuttle orbiter. These two aspects are the fundamentals for examining the variability in arcing response of the arc-fault protector.

Key Products and Milestones of the Research

- We expect to be able to act as a disinterested evaluator of proposed arc-fault protectors. The work is proceeding with:
  1. First stage: Collect arc signatures for variations in circuit constants and the arc quenching characteristics of both fluorinated and hydrogen-carbon-nitrogen insulation polymers.
  2. Second stage: Work with the circuit breaker design personnel to subject proposed units to the full range of practical signatures.
- Lectromec has built a number of Arc Track Test Resistance Systems for wire manufactures and certification laboratories. We have installed our refinement of this type of equipment and are proceeding to test both new and used wire for many operators. We expect to have even more data as our testing of Kapton® wire on the space shuttle continues through early next year.

I-10 Project Title: "Wiring Fault Detection/Isolation Improvement Program Using a Smart Automatic Wiring Analyzer (AWA)"

Sponsoring/Performing Organization

Northrop Grumman
E-2C ILS Dept.
M/S C04-15
Bethpage, New York 11714
Principal Investigator: Stan Teich
516-346-7044
teichst@mail.northgrum.com

Project Description

The Smart AWA is a key product recently developed by Northrop Grumman as a result of a company-sponsored wiring fault detection/isolation program. It represents an improvement and expansion of the capabilities of COTS cable scanner/tester assemblies. The product is a portable, compact (less than 1 cubic foot), and light-weight (24 pound) cable/harness test set, which can be controlled by a laptop computer via a standard RS 232 interface. The Smart AWA can be carried on-board an aircraft on the flight line, or to other vehicles including ships, submarines, tanks, trains, missiles and spacecraft. It can be used to automatically test continuity, resistance, shorts, open circuits, crossed wires, capacitance, and diodes in cables and harnesses. A further improvement, which will allow it to control relays or contactors and enable it to test power distribution assemblies, is under consideration. The unit is ruggedized to meet harsh military environmental and electromagnetic requirements, and operate in harsh conditions, including salt spray and fuel-rich environments (such as those found on an aircraft carrier deck or flight line). The Smart AWA test set is designed to ensure that it will not activate any military ordinance, nor ignite any flammable vapors. It can also be operated in a continuous mode, which enables it to detect intermittent wire systems faults.

The Smart AWA is a self-programming test device. When it is hooked up to a good cable or harness, it automatically learns the wiring connections of that unit. The Smart AWA software then automatically generates a test program for that cable or harness, and stores the test program in its database. This eliminates the need to manually generate or code software test programs to operate the device. The Smart AWA can also import a wire list in a text file format and automatically generate a cable test program. The "learn" feature can be also used

to determine the wiring connections of an unknown cable/harness. Net lists and error report printouts are automatically generated.

Control of the Smart AWA is performed via a mouse and a graphical user interface menu program stored in the laptop. Although a standard laptop can be used, Northrop Grumman has developed a ruggedized laptop for the Navy's E-2C and F-14 aircraft. This laptop has five ISA/PCI expansion card slots available. The E-2C laptop contains a TDR (Time Domain Reflectometer) and 1553 Bus Test card. The TDR supplements the Smart AWA by automatically determining the distance to a wiring fault from one end of a cable.

I-11 Project Title: "Evaluation of Cable Polymer Aging Through Indenter Testing of In-Plant and Laboratory-Aged Specimens,"

Performing Organization

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Blue Bell, PA 19422
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Sponsoring Organization

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94304

Project Dates

The project began in 1992 and was completed in 1996

Project Description

This project demonstrated that the Indenter Polymer Aging Monitor ("Cable Indenter") could detect current aging problems and predict future aging problems in wiring systems using non-destructive methods.

The objective of the research project was to develop a non-destructive technique that could be used *in situ* to evaluate the aging of cables that have been subjected to normal or abnormal service conditions. The project evaluated changes in compressive modulus, a mechanical property of the insulation and jacket material, as measured by the Indenter. The research showed that the change in force divided by change in position of a probe pressing at a constant velocity against the jacket or insulation of a cable provided a systematic indication of aging of the material. Therefore, the relative age of cable insulation can be evaluated for any material that has a systematic change in properties.

Key Products and Milestones of the Research

The in-plant trials of the Indenter proved that the system is practical and readily usable, and produced reasonable consistency in results in the field. A projected wire life can be determined based on actual condition, and Life Projection criteria have been developed for a number of cable types. The research convinced both government agencies and private companies in the USA, Canada, England, France, Sweden, and Russia to begin using the Indenter on a regular basis to evaluate wire and cable aging.

I-12 Project Title: "Hazardguard"

Performing Organization

Hazardguard Safety Wire Inc.
113 Fallen Timber Rd.
Point Marion, PA 15474
724-725-1340

Sponsoring Organization

United Airlines, the FAA, 3M, the National Transportation Safety Board, and the Navy have expressed interest. Potential sponsors include Excite, General Electric, M.A. Hanna, and pigment and raw material producers.

Project Dates

Ongoing. (Technology is ready now.)

Project Description

Hazardguard Technology can detect and locate problems such as already loose or corroded connections, loose or corroded splices, internal conductors that are broken or partially broken, grounded short circuits to exact spot depending on breaker or fuse types, wet and dry arc tracks even before flashover (flashover is needed for an arc-fault breaker to kick), internal dielectric breakdown within the insulation (this may come from impurities or aging), and bad electrical parts. The technology can also indicate overloads and bad breakers ahead of time, during the event, and even after (depending on which developed features are utilized).

This new wiring technology makes a new wire out of the old wire (any wire type) by giving wire a new feature: non-destructive self inspection. This feature is an attention-getting means on the outermost layer of the cable. It can be inked on or impregnated into the insulation, and the same technology has been applied to heat-shrink and electrical tape. It can be bottled for sale, for existing cabling. The new or modified existing wiring which incorporates the Hazardguard Technology would not need any expensive instruments, special monitors, or fault-finding equipment. The wire itself will let you know, if it is going bad.

Key Products and Milestones

Products:

- Newly manufactured wire and cable that have the Hazardguard feature.
- A retrofit electrical tape and heat shrink which also have the Hazardguard feature that can be used on any existing wire no matter what kind of conductor and no matter what kind of insulation.
- A paint-on ink.

Milestones:

- General engineering rules for design practices.
- A manufactured cable.
- A manufactured extension cord (inked and extruded versions).
- Confirmation test in an independent lab.
- Coordinated efforts between pigment companies and ink vehicle companies to make a constant supplier or pipeline of raw materials needed for ink manufacture.
- Patent (number 5922996).
- Presently working with pigment, concentrate, and plastic company to make a steady supply of raw extrudable material.
- Letter from Underwriters Laboratories (UL) confirming that this technology does not violate any old UL listings using the technology for wire markings and indicating purposes.

I-13 Project Title: "Arc-fault Current Interrupter (AFCI) Technology Initiative"

Performing and Sponsoring Organization

Square D Company
Colin Cornhill, Program Director
3700 6th Street SW
Cedar Rapids, IA 52404
319-369-6637
cornhilc@squared.com

Project Descriptions

Square D's proprietary technology development initiative is aimed directly at arcing faults in electrical wiring systems of all types.

Square D has been involved in wire systems safety technologies for almost a century. Since 1993, the company has driven a focused effort to understand the basic science behind arcing faults in wire systems. From that understanding ,Square D has developed fault recognition and interruption technologies. The company has concentrated on understanding the electrical characteristics and signatures of normal functional loads and of defective loads and wire systems faults. Square D has also characterized the effect of the wire systems environment on the signatures. The company has cooperated with UL to understand arc-fault fire ignition. Building on this comprehensive scientific basis ,Square D has sought to provide the highest possible level of sensitivity to faults consistent with avoidance of nuisance interruption on valid signals. The company's work is ongoing in all applications where AFCI can offer enhanced protection.

Key Products & Milestones

- In July 1998, Square D released 15-amp and 20-amp single-pole AFCI circuit breakers to the market. These were aimed at protection of residential wire systems.
- In January 2002, the National Electrical Code will require AFCI breakers for bedroom circuits in new construction. Square D has geared up its production capability to deal with the demand.
- Square D continues its developments of this proprietary technology for application in aerospace (400Hz) wire systems and for various other applications. *The product-release milestones for these developments are company confidential.*

I-14 Project Title: Technology for Detecting and Monitoring Conditions That Could Cause Electrical Wiring System Fires

Performing Organization

Underwriters Laboratories Inc.
333 Pfingsten Rd.
Northbrook, IL 60062
Project Manager: David A. Dini
847-272-8800 x42982
david.a.dini@us.ul.com

Sponsoring Organization

U.S. Consumer Product Safety Commission

Project Dates

Completed: September 1995.

Project Cost

$80,000

Project Description

The objective of this project was to conduct an in-depth study of technologies to detect and monitor precursory conditions that could lead to or directly cause fires in residential wire systems in general, and how these technologies could be applied to older residential wiring systems in particular. The project included:

1. Conducting a comprehensive review of published and unpublished literature on devices and systems that could decrease the likelihood of residential fires.

2. Conducting a survey of industry organizations and manufacturers for new products and systems that could decrease the likelihood of residential fires

3. Acquiring and analyzing promising devices and systems for ease of installation, reliability, cost and effectiveness in decreasing the likelihood of fires in residential wiring systems, particularly older residential wiring systems.

Eleven different products were procured in order to evaluate five different technologies that they were intended to exemplify. These five technologies included:

1. Arc-Fault Detection Technology.
2. Modified-Trip Circuit-Breaker Technology.
3. Ground-Fault Interrupting Technology.
4. Supplementary Protection Technology.
5. Surge-Protection Technology.

From the products and technologies analyzed, arc-fault detection appeared to be very promising, especially when added to residential branch-circuit breakers and combined with other proven technologies, such as ground-fault protection.

I-15 Project Title: Arc-Fault Detection Circuit Breakers

Performing Organization

Underwriters Laboratories Inc.
333 Pfingsten Rd.
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Project Manager: David A. Dini
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Sponsoring Organization

National Electrical Manufacturers Association
Rosslyn, VA 22209

Project Dates

Completed; report issued March 15, 1996.

Project Description

Arcing in an electrical circuit produces characteristics in the current that can be monitored and detected. The objective of an arc-fault detector is to discern abnormal arcing—that can be hazardous—from operational arcing that is part of the functioning on many products. For example, arcing switch contacts, motor commutators, etc., should not cause tripping nor should they confuse the signal of hazardous arcing to preclude desired tripping. The objective of this research project was to identify problems and achieve practical solutions to the certification and test technology that needed to be developed concurrently with the emergence of arc-fault detection technology.

Several different arc-fault generating tests were described in this project as a means of producing "real world" arcing in a laboratory test environment. An arcing test involving carbonized-path arcing faults was used to gather data in order to develop a current versus time ignition threshold curve. For these tests, surgical cotton was used as the fire indicator. Conditions that could lead to unwanted or "nuisance" operation, and inhibition of operation were also identified for residential wiring systems. Information and data from this work was used to develop requirements for an arc-fault circuit interrupter to enhance the effectiveness of conventional overcurrent protection devices.

I-16 Project Title: High-Reliability Prognostics of Wiring and Other Connectivity Elements by Directly Testing for Age Related Failure Mechanisms

Performing Organization

Universal Synaptics
1801 West 21st Street
Ogden, UT 84401
801-731-8508
President@usynaptics.com

Sponsoring Organization

US Air Force

Project Dates

Project is commercial and is on-going.

Project Cost

Approximate $1 million (direct costs and labor).

The Commercial-Off-the-Shelf (COTS) sales price of the IFD-2000 is in the $50,000-range ,depending on options. In a typical defense- or space-related repair facility, the IFD-2000, if put into use, would be paid for by noon on its first day of operation.

Project Description

Our research on this problem, if not the most comprehensive, is the longest running and provides conclusive answers to the problem of aging in wire systems and avionics and clearly illustrates the effect on logistics and safety. This research on aging encompasses much more than just the wire systems. It includes all the connectivity elements found in the sensors, computers and control circuits and the electrical-mechanical devices that control the various physical components of complex aerospace systems. We have studied the aging problem at the molecular level, the systems level and the functional or organizational level. We cover in detail why systems age, why present testing philosophies, constraints and equipment do not discern age related failures and show how this testing void eventually reduces reliability, safety and life cycle expectations.

It is a mistake to believe that the whole aging problem is due to a technological defect in our wiring systems. All things wear out, even wiring. The

problem is a lack of understanding of the failure mechanism involved with aging—intermittency—which, in turn, leads to a lack of testing to fix these failures as they arise. Over time, these untested and unresolved failures accumulate and give rise to the notion that suddenly all the wire systems are mysteriously failing and therefore the systems are "worn-out". All electronic failures can be divided into just two categories: HARD failures that are seen over the lifetime of a system, and INTERMITTENT failures that begin to creep in as a system ages. HARD failures are dealt with efficiently while INTERMITTENT failures are not. Huge, unexplained, Can-Not-Duplicate (CND/NFF) rates of 50 to 60 percent in older systems maintained with a multi-level maintenance scheme, are a reminder of this testing oversight. To overcome this testing void, we have developed a massively parallel hardware neural network, that for the first time allows you to directly test for age related failure mechanisms in wire systems, LRU's, motherboards, etc. The improvement this new technology offers over traditional INDIRECT testing methods when looking for age-related intermittent problems is around 1,000,000 to 1. It is the answer you are seeking!

Key Products and Milestones

- Began research into the causes of CND on the F-4.
- 197x: Developed one of the first data acquisition systems to track and monitor signals of the F-4's LN-12. Inertial Navigation System, for intermittent anomalous events. Techniques also applied to Minuteman missile.
- 197x-1985: Researched and developed fixes for all of the LN-12's engineering type CND defects. Recognized and developed basic understanding of aging mechanisms on electronic components.
- 1985-1993: Researched the measurement mechanics and test programming limitations of dozens of popular Automatic Testing Equipment (ATE) to detect anomalous intermittent events associated with the replacement for the LN-12 and for various F-16 avionics systems.
- 1994: Developed a prototype version of the IFD-2000, Intermittent Fault Detector/Analyzer, and demonstrated the technology to an enthusiastic audience at AutoTestCon94.
- 1995-1997: Developed marketable version of IFD-2000. Improved software and hardware sensitivity and added additional testing modes. JAST studied the technology as a catch-net for finding

those inevitable intermittent problems that would slip past various on-board "advanced diagnostic" schemes being evaluated.

- 1998: Patent received with 19 claims for a new way to test for randomly occurring intermittent faults, using a hardware neural network.
- 1999: Boeing, while initially skeptical evaluated the IFD-2000 analyzer in their test lab for 6 months and verified all claims and specifications. Demonstrated a new testing paradigm to fix wiring problems at Airline Maintenance Conference (AMC) and various airlines.
- 2000: Research and Marketing continues.

I-17 Project Title: "Innovative Chemithermal Techniques for Verifying Hydrocarbon Integrity in Nuclear Safety Materials"

Performing Organization

Veridian—Pacific Sierra Research and University of Virginia

Sponsoring Organization

U.S. Department of Energy

Project Dates

September 1, 2000 through August 31, 2002

Project Cost

$	355,387	(Year 1)
$	356,860	(Year 2)
$	354,067	(Year 3)
$	1,066,314	(Total)

Project Description

This research and development program explores new methods of assessing the condition and predicting the remaining life of critical hydrocarbon materials in nuclear power plant environments. Of these materials, safety control cable insulation is a primary focus, which can be extended to many other areas where cables are exposed to adverse conditions.

Chemithermal assay techniques are being developed for application to critical safety materials in nuclear power plants. These techniques exploit the chemical (oxidation) and thermal response of a material to assess degradation caused by high stress radiation and thermal operating environments. Oxidation induction time (OIT), oxidation induction temperature (OITP) and thermogravimetric (TGA) measurements show strong potential for this application that not only assesses the condition of materials, but also provides prognostic data on the remaining utility of the material. The chemithermal suite of condition-monitoring tools is being applied to critical hydrocarbon materials that include cable insulation, o-rings, and lubricants. Unlike conventional methods of polymer material assessment, chemithermal methods are non-intrusive and nearly non-destructive because they require only a minute amount of sample material (approximately 8 mg). These advantages coupled to its technical utility and low cost make the chemithermal assay technique an important asset in monitoring the safety of nuclear power reactors.

Key Products/Milestones

This three-phase applied research program will provide industry with new innovative methods to conduct a pragmatic material condition-monitoring program. The key products include a material condition-monitoring database, standardized procedures, engineering development methodology and intra-technology correlation analysis.

I-18 Project Title: "Assessment of Environmental Qualification Practices & Condition-Monitoring Techniques for Low Voltage Electrical Cables"

Performing Organization

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Huntsville, AL 35807
256-837-4411
service@wylelabs.com

* As subcontractor to Brookhaven National Laboratory, Upton, NY

Sponsoring Organization

Nuclear Regulatory Commission, Office of Nuclear Regulatory Research

Project Dates (projected)

August 1996 to May 2000 (testing)

Project Description

Relevance of project:

- **Better Understanding of Degradation Mechanisms:** Compares cables that were aged by accelerated methods to naturally aged cables; compares cable failure mechanisms.
- **Detection/Inspection Techniques:** Investigates techniques for monitoring of cable condition.

Wyle understands that the objective of this project is to provide information to help resolve specific issues related to the environmental qualification process for low voltage instrumentation and control (I&C) cables. The project sought to study:

- If accelerated aging predictions using the Arrhenius model for thermal aging and the equal-dose/equal-damage model for radiation aging would provide adequate estimates of the degradation experienced due to actual service aging.
- If data obtained related to differential swelling of jacket and insulation materials due to moisture absorption would provide evidence that this phenomenon can contribute to rupture or cracking of the materials during steam exposure.

- If bonded jacket cables would have different failure mechanisms than unbonded jacket cables, and if so, whether these unique failure mechanisms are properly accounted for in the qualification process.
- If there are any effective condition-monitoring techniques for determining cable condition *in situ*
- If condition-monitoring techniques can be used to predict loss of coolant accident (LOCA) survivability.

Key Products and Milestones of the Research

Wyle has published six test reports. A report encompassing Wyle's reports will be published by NRC as a NUREG/CR in the near future.

APPENDIX D: TERMS OF REFERENCE

National Science and Technology Council
Committee on Technology
Wire System Safety Interagency Working Group
Terms of Reference

Preamble

The Wire System Safety Interagency Working Group (IWG) is hereby established under the Committee on Technology by action of the National Science and Technology Council (NSTC). The IWG serves as the internal deliberative body of the NSTC on Wire System Safety Science and Technology policy, program, investment priorities and direction for the Executive Branch. The NSTC Committee on Technology shall serve as the forum for developing consensus and resolving issues raised by the Working Group.

For purposes of this document, a wire system is defined as hardware which provides power, control and information distribution. Science and Technology (S&T) includes fundamental research, technology development, demonstrations, engineering, education and training. The focus of wire system safety S&T is to identify pre-cursors to system failures, predict problems, preserve wire system integrity and provide the ability to ensure the continued safety of critical systems. This will include electrical, optical or other wiring systems where a malfunction of the wiring system can result in adverse safety and health effects.

Purpose

The IWG, in partnership with other national stakeholders including industry and academia will perform the following functions:

- Define a process to collaborate among agencies and to coordinate wire system safety S&T initiatives between agencies;
- Present options for accelerating development and facilitating deployment of advanced wire system safety technology;
- Provide strategic direction for establishing federal wire safety investment priorities;
- Provide mechanisms for federal cooperation with industry, national laboratories and academia; and
- Ensure that the results of federal research are communicated in a timely way to improve health and safety.

Scope

The IWG is focused on the effects of wire system integrity (such as aging, deterioration and damage). Environmental damage is degradation due to exposure to the atmosphere, damaging fluids, vibration, heat, ultraviolet exposure, or other effects. Accidental damage includes wear and tear due to normal maintenance activities. In administering this focus, the IWG will conduct the following activities:

- Coordinate, plan, assess and recommend S&T for wire system safety technology that affects multiple agencies;
- Encourage and facilitate interagency collaborations in research and development programs and related applications;
- Coordinate newly developed wire system standards, technology and testing methodologies; and

- Foster and coordinate activities with universities and other educational organizations that are partnered with federal agencies.

S&T initiatives of operating agencies should be focused on the highest near term safety priorities. This results in current agency activities focusing mainly on electrical wire. Technology development agencies should focus on longer-term technology including wireless and fiber-optics. Wireless and optical systems will have their own set of issues and mitigations. The IWG will not duplicate technology initiatives that industry already has underway. Technology developed by each agency will be shared by all and transferred to industry as quickly as possible.

Functions

The IWG will perform the following activities:

- Conduct semi-annual and ad-hoc meetings, record meeting activities, and publish meeting minutes;
- Provide a forum for exchange of information about wire safety S&T activities;
- Foster collaborations among federal agencies, and with private sector and academic organizations;
- Identify shortcomings of federal wire safety S&T programs and identify program options to address gaps;
- Coordinate planning activities with Office of Science and Technology Policy (OSTP) and budget activities with Office of Management and Budget (OMB); and
- Coordinate with other NSTC Committees, subcommittees and interagency working groups with an interest in wire safety.

Organization/Membership

The IWG is a task-oriented subgroup of the NSTC Committee on Technology. The IWG is chaired by the Associate Director of the Office of Science and Technology Policy and co-chaired by two IWG member agencies. Inclusion as a participating agency member of the working group is at the discretion of the IWG. The IWG may establish subgroups to address specific issues as necessary.

Membership includes representatives of the following agencies:

- Consumer Product Safety Commission
- Department of Commerce
- Department of Defense
  - Office of the Secretary of Defense
  - United States Air Force
  - United States Navy
  - United States Army
- Department of Energy
- Department of Transportation
  - Federal Aviation Administration
  - Federal Railroad Administration
  - Federal Transit Administration
  - US Coast Guard
- Food and Drug Administration
- National Aeronautics and Space Administration

- National Science Foundation
- Nuclear Regulatory Commission.

In addition, the following organizations shall also be represented on the IWG:

- Defense Nuclear Facilities Safety Board
- Office of Management and Budget
- Office of Science and Technology Policy
- National Partnership for Reinventing Government
- The National Transportation Safety Board (Observer)

Deliverables/Milestones

- November 2000: Complete a report to the President containing:
  - A description of existing wire safety S&T initiatives by agency,
  - An assessment of common issues that transcend agencies (including non-financial barriers to deployment),
  - An analysis of gaps in current S&T efforts and recommendations.
- March 2001: Organize and recommend a national strategy to the NSTC Committee on Technology.
- March 2001: Establish procedures for cooperation and information sharing between agencies.

Resources

To the extent practicable and permitted by law, departments and agencies shall make resources, including but not limited to, personnel, office support, and printing, available to the IWG.

Other Stakeholders

In coordinating and conducting activities, the Wire System Safety IWG will seek advice and broad participation from federal departments and agencies, academia and industry. The IWG will actively solicit information from industry, academia and representatives of the nonprofit sector on existing S&T initiatives that will predict or detect problems in electrical, optical or other wiring systems where a malfunction of the wiring system can result in adverse safety and health effects.

Termination Date

Unless renewed by the Committee on Technology prior to its expiration, the Wire System Safety IWG shall be terminated no later than June 30, 2002.

Determination

I hereby determine that the formation of this Interagency Working Group is in the public interest in connection with the performance of duties imposed on the Executive Branch by law, and that such duties can best be performed through the advice and counsel of such a Group.

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ACKNOWLEDGEMENTS

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