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Proceedings of the International Conference on Wire System Aging

Held at
DoubleTree Hotel
Rockville, Maryland
April 23-25, 2002

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research

Proceedings prepared by
Brookhaven National Laboratory

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Abstract

This document provides the proceedings of the International Conference on Wire System Aging held April 23-25, 2002 in Rockville, Maryland, USA. The conference had a three-fold purpose: 1) to review current practices and programs for understanding and managing wire system aging, 2) to exchange information on the current status of research related to the technical issues in this area, and 3) to identify additional technical issues and programs of interest related to wire system aging and safety for collaborative research. This conference was sponsored by the Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission. Included herein are copies of the papers presented at the conference, as well as highlights from the audience discussion. In some cases, where a full paper was not written, copies of the presentations are included.

Proceedings of the
International Conference on Wire System Aging

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Executive Summary

On Tuesday April 23 through Thursday April 25, 2002 the ***International Conference on Wire System Aging*** was held at the DoubleTree Hotel, in Rockville, Maryland. This conference was organized and sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission with the assistance of Brookhaven National Laboratory (BNL).

The conference had a three-fold purpose: 1) to review current practices and programs for understanding and managing wire system aging, 2) to exchange information on the current status of research related to specific technical issues in this area, and 3) to identify additional technical issues and programs of interest related to wire system aging and safety for collaborative research. Four specific topics were focused on at the conference as they relate to wire system aging:

- Reliability Physics Modeling of Wire System Aging
- Fire Risk Assessment of Wire System Aging
- Risk Significance of Wire System Aging
- Prognostics and Diagnostics for Installed Wire Systems

In the opening session on Tuesday, April 23, Michael Mayfield, Director of the Division of Engineering Technology, in the NRC Office of Nuclear Regulatory Research (NRC/RES), presented his opening remarks, and Ashok C. Thadani, Director of NRC/RES, gave the keynote speech entitled "The Importance of Wire System Safety in the Nation's Infrastructures." Jitendra Vora of NRC/RES then presented an overview of the conference format and the objectives of the conference. This was followed by a presentation by Robert Lofaro of BNL on the preliminary list of technical issues related to wire system aging that need to be addressed.

Technical sessions on each of the four specific topic areas were then held Tuesday and Wednesday. Each session included technical papers, followed by question and answer periods. On Thursday morning a general session on initiatives and insights on wire system aging was held. This session contained presentations by international experts on wire systems regarding initiatives that are ongoing in their countries to address wire system aging, along with presentations on initiatives in the USA.

On Thursday afternoon, April 25, an expert panel discussed the issues related to wire system aging that remain unresolved, along with the future direction of collaborative research to address these issues. Panel members were Nilesh Chokshi, NRC Office of Nuclear Regulatory Research; Kent Brown, Tennessee Valley Authority; John Brewer, U.S. Department of Transportation; Glen Schinzel, South Texas Project; and Elliot Cramer, NASA Langley Research Center.

Technical exhibits were on display all three days of the conference. These exhibits demonstrated state-of-the-art cable monitoring techniques, as well as new advances in cable construction.

The conference was open to the public and 104 people registered and attended. Nine foreign countries were represented; Belgium, Canada, Czech Republic, Finland, France, Japan, Korea, Norway, and the United Kingdom.

The following observations were made from the papers presented and discussions held at the conference.

- There is a great deal of interest in wire system aging by all participants since it impacts a multitude of industries both nationally and internationally. This is an important topic that should continue to receive attention.

- A great deal of significant research has been performed in the area of wire system aging and safety, and much knowledge is already available related to this subject. However, there are still technical issues that are unresolved and need to be addressed. Collaborative research would be an effective means of addressing these unresolved issues.

- There are differences in the specific research needs related to wire system aging for different industries, such as the aircraft industry compared to the nuclear industry. However, there are also a number of similarities that would benefit from collaborative research efforts. Therefore, collaborative research opportunities should be encouraged and pursued.

- A number of topics related to wire system aging and safety that would be of interest for collaborative research were identified at the conference. These are the following:

  - Development of effective in situ condition monitoring techniques for installed wire systems that can be used to determine the current condition of the wire system and predict its remaining useful life,

  - Additional testing of wire systems to obtain performance data for verifying existing models used to predict the performance of aged wire systems,

  - Updating of existing aging models to address changes in wire formulations,

  - Surveys and performance testing of wire systems to obtain flammability and fire frequency data that can be used to determine the increase in fire risk due to age degradation,

  - Development of reliability physics models that can be used to predict the failure probability of aged cables and wire systems in the absence of empirical data,

  - Correlation of mechanical wire system properties to electrical properties to better understand the significance of reaching the limits of mechanical properties for aged insulating materials, and

  - Development of a database of failure probability data for wire systems during accident conditions that can be used in risk studies to more accurately predict the impact of wire system aging on plant risk.

1. INTRODUCTION

There is a continued interest worldwide in the safety aspects of wire (cable) system aging since it impacts many industries, including transportation, defense, and power generation. Aging of a wire system, which includes wires or cables, splices, terminations, and penetrations, can result in the loss of critical safety functions or in the loss of critical information relevant to a decision making process and/or operator actions. In either situation, the unanticipated or premature failure of a wire system due to aging can compromise public health and safety.

In the United States, over the past two decades, significant research has been conducted by various institutions and organizations on aging-related issues for wire systems and cables. The focus of most research has been on the long-term behavior of polymeric insulating materials, condition monitoring techniques, and environmental qualification of electric cables for nuclear power applications. Both the U.S. Department of Energy (DOE) and the Electric Power Research Institute (EPRI) conduct cable research for the advancement of existing technologies, and to improve the state-of-the-art in material characterization and diagnostics. Under the auspices of the Institute of Electrical and Electronics Engineers (IEEE) relevant consensus standards are either being revised or developed for testing and qualifying wire systems.

On November 15, 2000, the U.S. White House National Science and Technology Council Committee on Technology issued a report entitled, "Review of Federal Programs for Wire System Safety" [1]. The report concludes that the safety of wire systems is a national issue that transcends various government agencies and is important to public health and safety. In the report, the interagency working group recommends four basic strategies to improve wire system safety: (1) altering the perception of wire systems; (2) increasing collaboration between industry, academia, and the government; (3) improving the management and functionality of wire systems; and (4) developing advanced wire system technology. The White House report will serve as a benchmark for interagency efforts to optimize research related to wire system aging.

Domestically, a wide range of research programs related to wire system safety has been implemented by the Department of Defense (DOD), Department of Transportation (DOT), National Aeronautics and Space Administration (NASA), National Institute of Science and Technology (NIST), and other institutions and organizations. Their programs range from the development of smart sensors and wires, to advanced diagnostic methods and data collection techniques, to quality assurance. Future wire system safety research programs can benefit significantly from collaborative research programs and information exchange with these organizations.

Similarly, initiatives in other countries are ongoing and collaborative research with foreign institutions and organizations, as well as the exchange of technical information would be beneficial to avoid duplication of effort, provide lessons learned from the experiences of participating organizations, and focus efforts on common issues of interest related to wire system safety. For example, the recently published two-volume IAEA report (TECDOC-1188, December 2000) [2] on the results of a cooperative research program provides significant insights into the management of aging in instrumentation and control (I&C) cables. Among other things, the report discusses condition monitoring, predictive modeling of cable aging, and aging management of I&C cables.

While significant research has already been completed in the area of wire system aging and safety, there remain a number of technical issues that still need to be resolved. An effective means of addressing these unresolved technical issues is through collaboration, as recommended in the White House report, in which the resources of international organizations with interest and expertise in wire systems can be shared to optimize research efforts. It was recognized that collaborative research programs on wire system aging and safety must take into consideration the results of all completed and ongoing work relevant to the topics of interest, therefore, a forum for international experts to meet and discuss the unresolved technical issues, as well as ongoing research, was needed.

To provide a forum for wire system experts to meet, and to facilitate the initiation of collaborative research programs related to the aging and safety of wire systems, the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission (NRC/RES) organized the ***International Conference on Wire System Aging***. The conference was held on Tuesday April 23 through Thursday April 25, 2002 at the DoubleTree Hotel, in Rockville, Maryland. This conference was organized and sponsored by NRC/RES, with the assistance of Brookhaven National Laboratory (BNL).

The conference had a three-fold purpose: 1) to review current practices and programs for understanding and managing wire system aging, 2) to exchange information on the current status of research related to specific issues related to wire system aging, and 3) to identify technical issues and programs of interest related to wire system aging and safety for collaborative research. Four specific topics were focused on at the conference as they relate to wire system aging:

- Reliability Physics Modeling of Wire System Aging
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In the opening session on Tuesday, April 23, Michael Mayfield, Director of the Division of Engineering Technology, in the NRC Office of Nuclear Regulatory Research (NRC/RES), presented his opening remarks, and Ashok C. Thadani, Director of NRC/RES, gave the keynote speech entitled "The Importance of Wire System Safety in the Nation's Infrastructures." Jitendra Vora of NRC/RES then presented an overview of the conference format and the objectives of the conference. This was followed by a presentation by Robert Lofaro of BNL on the preliminary list of technical issues related to wire system aging that need to be addressed.

Technical sessions on each of the four specific topic areas were then held Tuesday and Wednesday. Each session included technical papers, followed by question and answer periods. On Thursday morning a general session on initiatives and insights on wire system aging was held. This session contained presentations by international experts on wire systems regarding initiatives that are ongoing in their countries to address wire system aging, along with presentations on initiatives in the USA.

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Technical exhibits were on display all three days of the conference. These exhibits demonstrated state-of-the-art cable monitoring techniques, as well as new advances in cable construction. The conference program is included in Appendix A.

The conference was open to the public and 104 people registered and attended. Nine foreign countries were represented; Belgium, Canada, Czech Republic, Finland, France, Japan, Korea, Norway, and the United Kingdom.

A list of registered attendees is included in Appendix B. Highlights of each session are provided in the following paragraphs, along with comments and observations from the panel session discussions.

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2. OVERVIEW OF CONFERENCE SESSIONS

Highlights of each of the conference sessions are presented in the following paragraphs. Copies of the full papers presented are included in the Appendices to this report. In cases where a full paper was not written, copies of the presentation view graphs are included.

For convenience, the highlights of the panel session held on the last day of the conference are incorporated directly into each of the individual session highlights.

2.1 Opening Session

The opening session included a keynote speech by Ashok Thadani, Director of the NRC Office of Nuclear Regulatory Research. This was followed by a conference overview and a paper on potential issues of interest for collaborative research on wire system aging. These presentations are included in Appendix C.

2.1.1 Presentation Highlights

The following are highlights from these presentations:

- The keynote address noted the importance of wire system aging and why it needs to be studied.
- A White House report concluded that aging of wire systems is an important public health and safety issue that transcends all government agencies.
- This conference is part of an ongoing effort to identify the technical issues related to wire system aging and safety that need to be addressed, and initiate collaborative research efforts to resolve these issues.
- A preliminary list of potential issues of interest for collaborative research on wire system aging has been developed. This list is a starting point and should be updated based on industry input.

2.2 Technical Session 1: Reliability Physics Modeling of Wire System Aging

Technical session 1 included four technical presentations dealing with reliability physics modeling (see Appendix D). The topics covered were:

- The role of voids in the failure of polymer cable insulation
- Improved modeling approaches for predicting the lifetimes of cable materials
- The relationship of wire, insulation and frequency
- Micro-structure assessments for determining insulation remaining life

2.2.1 Presentation Highlights

The following are highlights from the presentations on reliability physics modeling of wire system aging:

- The time-temperature superposition technique is an improvement of the Arrhenius methodology for modeling aging degradation. Also, the "wear-out" approach can be used for predicting remaining cable life.

- Chemistry-based modeling is the most prevalent type of modeling used to predict the effects of aging degradation, therefore, the term "physics" modeling may be inappropriate.

- Void growth in wire insulation is being studied as a mechanism for cable degradation, along with the correlation of void growth to degradation of the insulation properties.

- Most faults in aircraft electrical wire systems are human-related. Also, chemical aging and hydrolysis of the insulating materials are the most important mechanisms leading to age degradation of aircraft wire systems. For nuclear plant wiring, oxidation is the most important mechanism leading to age degradation. Therefore, there are differences in the predominant aging mechanisms leading to degradation between nuclear and aircraft wires.

- To summarize the current state of degradation modeling for wire systems in nuclear plant applications - it includes combined radiation and temperature stressors; there are several models that currently exist, including those in the IEC report and a JAERI model; and it involves very complex chemistry, therefore, further progress in refining the models will be difficult.

- To summarize the current state of degradation modeling for aircraft wire systems - it includes combined humidity and temperature stressors; models currently exist, however, experiments at constant relative humidity vs. temperature would be useful to refine them.

- Research on the aging of materials used in nuclear weapons has found an important synergism between the effects of water and oxygen on age degradation of the material.

- There are 3 critical applications in which aging of wire systems needs to be addressed - nuclear power plants, aircraft, and nuclear weapons (huge current effort). Collaboration/interaction with ongoing nuclear weapons aging research programs may be fruitful.

- Research on condition monitoring of wire insulation materials is being performed as part of the ongoing weapons aging research. The ultra-sensitive oxygen consumption technique, the wear-out technique, the modulus profiling technique, and the nuclear magnetic resonance monitoring technique were all developed from weapon aging research.

- The wear-out technique satisfies the critical need for a method of predicting residual lifetime of wires. It is predictive even when other CM methods are useless.

- It was stated that reasonable models for predicting age degradation of wire system components exist, however, more testing is needed to refine these models.

2.2.2 Panel Discussion Highlights

The following panelist comments and observations were noted during the panel discussion on reliability physics modeling of wire system aging:

- It was noted that reliability physics modeling of wire system aging is a difficult subject with little work currently ongoing.

- There is not much experimental evidence to support the theory of void growth as a cause of insulation degradation. Simple experiments on polymer samples might be useful to provide supporting data for this theory.

- The large number of failures in aircraft wiring systems that are attributed to human errors suggests that additional training is needed related to maintenance and monitoring of wiring systems.

- There are differences in the wiring system service environments and primary aging mechanisms for nuclear plants as opposed to aircraft. In aircraft, the environment is constantly changing and hydrolysis is the principle aging mechanism. In a nuclear plant, the environment is relatively constant and oxidation is the principal aging mechanism.

- The environment in an aircraft is influenced by flight profiles, as well as the geographic location of the aircraft. These changes make it very difficult to accurately characterize the wire system service environment.

- Aging of wire systems in nuclear weapons is currently a big effort that could benefit from collaborative research.

- In regard to modeling of wire system degradation, reasonable models currently exist, however, more testing is needed to provide data to validate and improve the models.

2.2.3 Audience Discussion Highlights

The following audience discussion highlights were noted during the panel discussion on reliability physics modeling of wire system aging:

- In nuclear plant applications, there is already a good understanding of the degradation end points for wire systems, i.e., random failure versus guaranteed failure.

- There is interest in performing energy input experiments on electrical wires, in which the wires are energized to various levels, to determine the impact on wire system degradation and performance.

- A number of older aircraft were examined and it was found that the environment directly impacts the number of wire system failures. Also, the environments vary between aircraft due to different flight profiles and geographic location. It was noted that the home base of an aircraft can be determined by examining the condition of the wires.

- It was noted that there are a number of aircraft sitting idle that would make good test beds for the development and verification of new wire system condition monitoring technology.

- There are many different formulations for each wire insulation material, and each formulation can behave differently. This makes it difficult for test programs to reach their goal of characterizing wiring materials. It is important to first know what materials we are working with.

- A concern with existing aging degradation models is that they do not account for changes in formulations of wire insulation. For example, we may not be able to use current aging models to characterize old wires.

2.3 Technical Session 2: Fire Risk Assessment of Wire System Aging

Technical session 2 included four technical presentations dealing with the assessment of fire risk due to wire system aging (see Appendix E). The topics covered were:

- Properties of halogen free cables

- Electrical cabling system performance related to nuclear plant fire safety

- Reducing residential electrical system fires

- Dealing with fire risk in aged cabling

2.3.1 Presentation Highlights

The following are highlights from the presentations on the assessment of fire risk due to wire system aging:

- PVC insulating materials used on electric cables have been found to produce high levels of smoke and acidic gases in ***some*** tests.

- Cables using insulating materials made from EPR/EVA+PE zero halogen formulations have been found to perform well even after aging.

- Past testing has shown that even high performance cables can be made to burn.

- A question that needs to be addressed is how test performance can be translated into real hazard in real installations.

- Aging studies can be inconclusive with regard to the fire risk of aged wire systems.

- Arc-fault and ground-fault circuit breakers are valuable for mitigating the effects of wire system failures due to aging degradation, and minimizing risk due to the initiation and propagation of fires.

- Standard fire tests currently used for qualifying wire systems are not always representative of "real" fires.

- Many problems exist with cables that are packed into hidden spaces in walls, floors, and ceilings, such as the following:

  - There can be many generations of good and poor cables installed in these hidden spaces,

  - A high fire load can build rapidly when cables are packed into hidden spaces,

  - Reduced oxygen can be problematic for cables installed in hidden spaces since it can lead to increased smoke production, and

  - Cables installed in hidden spaces rarely have suppression or detection systems to mitigate the effects of fires, should they occur.

2.3.2 Panel Session Highlights

The following panelist comments and observations were noted during the panel discussion on the assessment of fire risk due to wire system aging:

- There is a need for additional research in the area of cable flammability to obtain more performance data on the impact of age degradation on fire risk.

- Research in the UK has shown that, for low-smoke materials in real life scenarios, reductions in oxygen concentration can occur during a fire leading to increased smoke production. Tests in air may not show these effects.

- A global survey of installations and fire frequencies in nuclear plants would be beneficial to provide a statistical database to assist in a risk assessment of aged cable fires.

- A review and an experimental study of cable flammability in hidden spaces is needed to determine the relevance of standard fire tests and whether improvements in these standard tests are needed to more accurately simulate real-world applications.

- Additional research is needed for the investigation of new fire risk technologies. Specific areas needing research are the use of nano-composites, the effects of oxygen depletion, emissions during cable fires, and the effects of smoke, toxicity, irritancy, and corrosivity on cable performance.

- The preparation of guidance/code of practice documents (including risk assessment tools) would be beneficial for specifiers, installers, users, etc. of wire systems.

- Further studies on the reliability of arc-fault and ground-fault circuit breakers in mitigating the effects of faults due to age degradation would be beneficial.

2.3.3 Audience Discussion Highlights

The following audience discussion highlights were noted during the panel session on the assessment of fire risk due to wire system aging:

- Past work looking at aging effects on wire systems found that fire retardant compounds are stable, and some cables perform better with respect to their fire resistance and propagation when aged.

- Large scale tests of cable fire performance, such as IEEE-383, only evaluate a material's fire resistance properties. They are not intended to be predictive of performance in real world fires, and are only used to screen out unacceptable materials.

- In the aircraft industry, when off-the-shelf commercial grade items are purchased, there can be a large amount of variability in the construction and quality from one product to another. For safety-related applications, this variability results in the need to re-qualify many items each time they are purchased. This leads to a higher level of engineering evaluation required to use commercial grade equipment.

- Regarding the use of commercial products in nuclear plant applications, if the application is safety significant there should be no change in the level of quality. If it is non-safety-significant, a lower quality may be acceptable. The licensee is responsible for putting in the right material or component to meet the performance specifications.

- In nuclear plants there is a dedication process that must be followed to use commercial grade equipment. This process ensures the equipment meets the performance specifications required for the application.

2.4 Technical Session 3: Risk Significance of Wire System Aging

Technical session 3 included four technical presentations dealing with the risk significance of wire system aging (Appendix F). The topics covered were:

- Core damage frequency due to cable failures

- The contribution of cable aging to nuclear plant risk

- Risk assessments for aircraft electrical interconnect subsystems

- Component importance and using risk insights

2.4.1 Presentation Highlights

The following are highlights from the presentations on the risk significance of wire system aging:

- Each of the risk analyses presented made use of the event-tree/fault-tree methodology for performing probabilistic risk assessments.
- A method for including cables and the effects of aging on the cables into a PRA was presented.
- A risk-informed approach is used by South Texas to determine component importance and identify changes in the treatment of components based on their importance. Many safety-related components (approx. 90%) are not safety-significant, and a small number (approx. 1%) of the components are not safety-related, but are safety-significant
- The results of sensitivity studies for a PWR and a BWR, given the increase in core damage frequency if cables failed, were discussed. In these studies, one system was taken at a time, cables in redundant trains were considered failed, and human error probabilities were treated parametrically.
- The application of risk methods to aircraft wire systems was discussed. It was noted that conventional methods of ensuring safety goals for aircraft flight may not be adequate without the inclusion of wiring failures. Some "basic events" on the fault tree were at the system train level, while in other cases basic events were at the wire level.

2.4.2 Panel Session Highlights

The following panelist comments and observations were noted during the panel discussion on the risk significance of wire system aging:

- There is a need for additional work in the development of reliability physics models that can be used to predict the failure probability of cables. Work is also needed to determine the value of the parameters used in the models.
- Information on new plant designs is needed to update models currently used to predict the risk significance of wire system aging.
- Current models for predicting the risk significance of wire system aging should be updated to include steam environments due to accidents.
- If condition monitoring techniques were used in nuclear plants to determine the condition of installed wire systems, it would mitigate concerns with increased risk due to cable aging.

2.4.3 Audience Discussion Highlights

The following audience discussion highlights were noted during the panel session on the risk significance of wire system aging:

- Most of the models used for predicting the risk significance of wiring systems are focused on mechanical degradation of the wires, with little correlation to changes in electrical properties. For example, in the space shuttle it is known that there are cracks in the wiring. Their location, size, and the consequence of the wire failing are evaluated to make a determination as to whether the wire should be replaced. Work needs to be done to determine the significance of reaching the mechanical limit of a wire in terms of its electrical properties.

- Cracks are not acceptable in aircraft wiring since they will set up standing waves, which will damage avionics.

- Contaminants on wires are also a problem in aircraft wiring since they can act synergistically with other aging stressors to adversely impact the ability of the wire to perform its function.

- The question was raised as to why it is important to look at the risk of aged wires since their required performance duration in an accident is so short. The response was that there is currently insufficient information on failure probabilities for wires, therefore, failures can still occur during this period, even though it is short.

- In the nuclear industry the fragility limits of cables are well known, however, failure probability data are not available. Additional work is needed to obtain failure probability data of aged cables.

- An opinion was expressed that the biggest challenge in the nuclear industry is human-related failures of wire systems; for example, leaving the insulation off a steam pipe located near a cable causing the cable to degrade and fail.

- Aircraft wiring failures are driven by common-cause initiating events, and there are data to show this. Therefore, the research priorities for the aircraft industry are different than those for the nuclear industry.

2.5. Technical Session 4: Prognostics and Diagnostics for Installed Wire Systems

Technical session 4 included eight technical presentations dealing with prognostics and diagnostics for installed wire systems (Appendix G). The topics covered were:

- Wire inspection techniques under development at NASA Langley Research Center

- New methods for monitoring the condition of aged cable materials

- The use of optical diagnosis for monitoring aged cable insulation

- Visual/tactile and indenter evaluation of cables

- A broad band impedance technique for monitoring cables

- An excited dielectric technique for monitoring cables

- Monitoring cables using capacitance and insulation microstructure
- A non-intrusive condition monitoring technique

2.5.1 Presentation Highlights

The following are highlights from the presentations on prognostics and diagnostics for installed wire systems:

- At NASA Langley several CM techniques are being evaluated, including, 1) infrared evaluation of cable with ohmic heating excitation from the conductor, in which cyclic current excitation and evaluation of the surface at the same point on an excitation curve identifies significant flaws and physical damage in conductor insulation; and 2) combustion by-products analysis, in which micro-sensors distributed throughout a wire system can be used to locate faults and over-temperature conditions, which produce detectable volatiles (work in development phase using portable gas chromatograph)

- At Sandia several CM techniques are being evaluated, including nuclear magnetic resonance (NMR), which requires placing a small polymer specimen in solution at 70 C to perform NMR. Order of magnitude changes are observed from the unaged through the aged condition. This technique is useful for common insulations (XLPE, EPR) that are difficult to test by mechanical means. Another technique is Micro-Modulus, which requires a small specimen and is a physical test that can detect small changes in hardness. It can evaluate differences in aging through the depth of the material.

- The optical diagnosis technique is being evaluated by Hitachi. This involves the evaluation of absorption of light by a cable surface with aging. The range of wavelengths evaluated and the slope of the line indicating the amount of absorption indicates the degree of aging.

- The electric Power Research Institute has been performing inspection of cables in nuclear plants using visual/tactile techniques and has found them very useful for detecting aged degradation. Also, the indenter technique has been used with good results for some insulating materials.

- A condition monitoring technique using broad band impedance measurements is being studied by the Boeing Company together with Rockwell Scientific. Results thus far are promising for detecting age degradation of aircraft wiring.

- CM Technologies is evaluating a condition monitoring technique based on excited dielectric measurements, which combines time domain reflectometry and dissipation factor measurements to detect age degradation of aircraft wiring and nuclear plant cables. This technique also shows promise for in situ use.

- A condition monitoring concept being studied by Advent Engineering involves the use of capacitance measurements to provide an indication of micro-void content in cable insulation. The presence and growth of the micro-voids may be correlateable to the performance of the insulation.

- A non-intrusive method of monitoring cable condition is being studied by GLS Enterprises. The technique will use performance measurements from the electrical system to provide condition monitoring information.

2.5.2 Panel Session Highlights

The following panelist comments and observations were noted during the panel discussion on prognostics and diagnostics for installed wire systems:

- There were 5 new techniques for monitoring the condition of installed wire systems discussed and all are promising for in situ use. Each of the new condition monitoring techniques presented requires either access to the surface of the cable, or removal of a specimen of cable insulation for laboratory testing. Insights on the aging of the overall wire system are based on assessments of a local site where testing is performed or a sample of insulation has been removed and tested in the laboratory.

- Several existing condition monitoring techniques were also presented and discussed, including visual/tactile inspections, the indenter technique, dissipation factor and impedance measurements. These techniques have been found to be useful in situ methods of determining cable condition.

- The problem with risk assessment of cables under LOCA conditions is that there are currently no failure rate data available for cables in a LOCA environment related to the degree of aging. It would be beneficial to have a series of informal workshops including experts on risk assessment, environmental qualification, systems operation, and materials to discuss the known and unknown parameters, and what can be done to improve PRAs and assure the accuracy of PRA results.

- The Sandia Cable Test Facility was built by DOE and has cables with documented flaws installed within a conduit system. This facility allows the blind testing of proposed electrical assessment techniques.

- There are many CM techniques developed, however, few have been tried in an actual nuclear plant environment or on plant cable specimens. A shakedown and proof of the CM methods is highly desirable to identify needed improvements and practicality considerations under plant conditions.

- Two areas for potential collaboration between FAA, NASA and the nuclear industry were identified; 1) Software for documenting the assessment results for long-lived cable systems; this would allow later assessors to understand and use the results from previous assessments; and 2) Mission success risk assessment (flights and assurance of generation) based on the criticality of cables important to operation/mission.

- The EPRI Cable Condition Monitoring Working Group (CCMWG) brings researchers together with senior utility cable personnel. The group guides research and provides feedback to the utility industry. It is open to all cable researchers and utility personnel. Contact: "gtoman@epri.com."

2.5.3 Audience Discussion Highlights

The following audience discussion highlights were noted during the panel session on prognostics and diagnostics for installed wire systems:

- A host utility is needed to demonstrate the effectiveness of the new condition monitoring techniques being developed. It was suggested that the techniques first be tried on the Sandia facility to screen them and determine the effect of the technique on neighboring circuits. Also, many cable specimens are routinely removed from plants each year; these should be used as test specimens.

- At the Kennedy Space Center there is a major modification program ongoing on the Columbia space shuttle. Approximately 50,000 wire system problems have been identified due to aging. Real-time condition-based monitoring is very important for this type of application and should be pursued. Also, human intervention should be minimized since it can lead to wire system faults.

- It is very difficult to interface some CM techniques to existing wire systems since the wire systems were not designed to be monitored. Wire systems must be designed for testing to achieve the desired objectives of condition monitoring.

- It would be desirable if software code could be added to existing built-in testability in electrical circuits for the purpose of checking wire systems condition.

- At NAVAIR the smart wire program is looking at putting diagnostics and prognostics into wire harnesses for next generation aircraft. However, legacy aircraft are currently the most pressing concern in terms of how to monitor the condition of aged wire systems.

- Ongoing efforts at NAVAIR in the area of wire system condition monitoring include 1) the "smart connector" program, which is looking at measuring wire performance parameters to determine what's going on in the wire system; 2) the "smart wire" program, which is looking at the using the capability to send signals down a wire and trend the results for the purpose of monitoring changes in the wire system performance; and 3) the "fiber optics" program, which is looking at the installation of fiber optics in the wire braid to detect degradation of the wire.

- Walk-downs in nuclear plants include visual inspections that have detected age-related damage to cables. This confirms the need for a totally non-intrusive test to monitor the condition of the cables as they age. Research on a dye penetrant/flourescent test to detect cracking in cable insulation is one possibility that should be considered for future work in this area.

- A question was raised as to whether there is consensus on what constitutes the end of life for a cable. One opinion was that 50% elongation has been used as the end of life criterion, however, the basis for this criterion is not documented and there is no standard currently available for determining end of life.

- It was noted that in the aircraft industry the definition of what constitutes a wire "failure" is still unclear.

2.6 General Session: Initiatives and Insights on Wire System Aging

The general session included five technical presentations dealing with initiatives and insights on wire system aging (Appendix H). The topics covered were:

- The present status and future plans for evaluating cable aging in Japan
- Managing cable aging in Korea
- Uncertainties in environmental qualification cable testing
- Assurance of aged cable performance in nuclear power plants
- Aircraft wiring system integrity initiative in the US Air Force

2.6.1 Presentation Highlights

The following are highlights from the presentations on initiatives and insights on wire system aging:

- Aging of cables is a concern and is being addressed in Japanese nuclear plants since several plants have operated over 30 years. Aging studies of cables are being performed to characterize the effects of temperature and radiation. Test data confirm changes in activation energy with aging temperature.
- Cable aging in Korean nuclear plants is also a concern and is being studied. In the Kori plant no qualification documents exist, therefore, condition monitoring to determine cable condition is considered very important. A CM technique based on the 3rd harmonics is being evaluated and shows promise.
- Qualification testing is performed for cables installed in nuclear plants in the Czech Republic. Uncertainties in the aging parameters are recognized as impacting the cable life.
- In U.S. nuclear plants, the administrative process used to qualify and track safety-related cables is seen to be just as important as the technical activities in designing and monitoring cables to manage aging and ensure performance.
- Aging management of wire systems in the U.S. Air Force has mainly been reactive since few tools currently exist to be proactive. Several initiatives are underway to provide new tools and materials for monitoring the condition of aged wire systems.

2.6.2 Panel Session Highlights

The following panelist comments and observations were noted during the panel discussion of initiatives and insights on wire system aging:

- Research is ongoing on the synergism in cable degradation including slow thermal and low radiation dose-rate aging.
- Research is ongoing on the effects of beta radiation (0.2 – 0.6 Mev) on polymer degradation.
- Research is ongoing on the 3rd harmonics and the relationship to cable aging.
- Development of a reliable simulation model for predicting the DBE and post-DBE performance of wire systems would be beneficial.
- Visual inspection is the leading method to detect failures for wire systems in aircraft and nuclear applications. The question now is whether a uniform method to predict wire system performance can be developed.

2.6.3 Audience Discussion Highlights

The following audience discussion highlights were noted during the panel session on initiatives and insights on wire system aging:

- It was noted that an issue exists related to un-grounded electric power systems being subject to problems with transient over-voltages under grounding situations. This could be a problem for age-degraded cables. An IEEE transaction paper was written on this topic.
- It was noted that the discussions indicate a distinction between the wire system aging issues for the aircraft industry and the nuclear industry. In the aircraft industry it is known that problems related to aging of wire systems exist and fixes are being worked on. In the nuclear industry the concern is cable performance under accident conditions; not problems during normal operation.
- It was suggested that research on the use of coatings to repair cracks in cable insulation would be valuable and should be considered for future work.

2.7 Panel Session

On the last day of the conference a panel session was held during which each of the subject areas were discussed. Each session chair presented the highlights of their session, then the topic was opened for discussion with an expert panel and the audience. The presentations made during the panel session are included in Appendix I of this report. The panel session discussion highlights are included in the appropriate section above for convenience.

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3. OBSERVATIONS

The conference provided an excellent forum for researchers from around the world to meet and discuss past and ongoing research in the area of wire system aging and safety. Technical issues that remain to be resolved were discussed, as well as areas of interest for future research. The panel session, along with the audience discussions, provided a unique opportunity for international experts to express their opinions on the direction of future research related to wire systems.

The following observations were made from the papers presented and discussions held at the conference.

- There is a great deal of interest in wire system aging by all participants since it impacts a multitude of industries both nationally and internationally. This is an important topic that should continue to receive attention.

- A great deal of significant research has been performed in the area of wire system aging and safety, and much knowledge is already available related to this subject. However, there are still technical issues that are unresolved and need to be addressed, and that would benefit from continued research.

- There are differences in the specific research needs related to wire system aging for different industries, such as the aircraft industry compared to the nuclear industry. However, there are also a number of similarities that would benefit from collaborative research efforts. Therefore, collaborative research opportunities should be encouraged and pursued.

- A number of topics that would be of interest for collaborative research were identified at the conference. These are the following:

    - Development of effective in situ condition monitoring techniques for installed wire systems that can be used to determine the current condition of the wire system and predict its remaining useful life

    - Additional testing of wire systems to obtain performance data for verifying existing models used to predict the performance of aged wire systems

    - Updating of existing aging models to address changes in wire formulations

    - Surveys and performance testing of wire systems to obtain flammability and fire frequency data that can be used to determine the increase in fire risk due to age degradation

    - Development of reliability physics models that can be used to predict the failure probability of aged cables and wire systems in the absence of empirical data

    - Correlation of mechanical wire system properties to electrical properties to better understand the significance of reaching the limits of mechanical properties for aged insulating materials

- Development of a database of failure probability data for wire systems during accident conditions that can be used in risk studies to more accurately predict the impact of wire system aging on plant risk

4. REFERENCES

1. National Science and Technology Council Committee on Technology,"Review of Federal Program for Wire System Safety," U.S. White House, Wire System Safety Interagency Working Group, November 2000.

2. International Atomic Energy Agency, "Assessment and Management of Ageing of Major Nuclear Power Plant Components Important to Safety: In-containment Instrumentation and Control Cables," IAEA TECDOC-1188, December 2000.

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Appendix A: Conference Program

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Organized by:
Office of Nuclear Regulatory Research
United States Nuclear Regulatory Commission
Washington, DC 20555

PROGRAM FOR THE

INTERNATIONAL CONFERENCE ON

Wire System Aging

April 23-25, 2002 • DoubleTree Hotel • Rockville, Maryland USA

Tuesday April 23, 2002

8.00 am to 4:00 pm – Registration

Time	Topic	Presenter
8.30 am	Welcome and Opening Remarks	Mike Mayfield Director Division of Engineering Technology, NRC
8·45 am	Keynote Address *The Importance of Wire System Safety in Nations' Infrastructures*	Ashok Thadani Director Office of Research NRC
9:15 am	Conference Overview	Jit Vora, NRC
9 30 am	*Wire System Safety-Potential Issues of Interest for Collaborative Research* J Vora, NRC and R. Lofaro, BNL	Bob Lofaro
9:45 am	**BREAK**	

Technical Session I

Reliability Physics Modeling of Wire System Aging

Chair: Ken Gillen, Sandia National Laboratory
Vice Chair: Bill Larsen, Federal Aviation Administration

Time	Topic	Presenter
10.00 am	*The Critical Role of Voids and Virtual Voids in the Mechanical Failure of Polymer Cable Insulation* D. C. Martin, Univ. of Michigan	David Martin
10 30 am	*Review of Several Improved Modeling Approaches for Predicting the Lifetimes of Cable Materials* K Gillen, M. Celina, R Clough, R Bernstein, SNL	Ken Gillen
11.00 am	*Wire, Insulation & Frequency* W Larsen, FAA C. Teal, Eclypse International, Inc.	Bill Larsen

Time	Topic	Presenter
11:30 am	*Microstructure Assessments for Determining Electric Cable Insulation Remaining Life* D A. Horvath and R L Steinman, Advent Engineering Services, Inc.	Dave Horvath
12:00 n	**LUNCH BREAK**	

Technical Session 2

Fire Risk Assessment of Wire System Aging

Chair: Peter Fardell, Fire and Risk Sciences
Vice Chair: Steve Nowlen, Sandia National Laboratory

Time	Topic	Presenter
1:30 pm	*Mechanical, Electrical, and Fire Propagation Properties of Halogen Free DBE (LOCA) Resistant Cables for Nuclear Power Plants* M. Kirschvink, G. Beyer, S. Coenen, Kabelwerk Eupen AG	Manfred Kirschvink
2.05 pm	*Electrical Cabling Systems and Nuclear Power Plant Fire Safety* S. Nowlen, SNL	Steve Nowlen
2:40 pm	**BREAK**	
2:55 pm	*Reducing Residential Electrical System Wiring Fires* A.M. Trotta, CPSC	Andrew Trotta
3:30 pm	*Dealing with Fire Risk in Aged Cabling-Guidance from Fire Research in the UK* P. J. Fardell, Fire and Risk Sciences Div., Building Research Establishment	Peter Fardell
4:30 pm	**ADJOURN**	

EXHIBITS ON DISPLAY: 8:00 AM TO 12 N AND 1:30 PM TO 6:30 PM

Wednesday April 24, 2002

8:00 am to 4:00 pm – Registration

Technical Session 3

Risk Significance of Wire System Aging

Chair: Art Buslik, NRC/RES
Vice Chair: Glen Schinzel, South Texas Nuclear Project

Time	Topic	Presenter
8:30 am	*A Scoping Study on the Core Damage Frequency Impact of Cable Failures Due to Harsh Environment in a PWR and a BWR* P. Samanta and G. Martinez-Guridi, BNL	Pranab Samanta
9.00 am	*Contribution of Cable Aging to the Risk of Nuclear Power Plant Operation* A. Buslik, NRC/RES	Art Buslik
9:30 am	*Risk Assessment for Aircraft Electrical Interconnect Subsystems (EIS)* D. Wood, R. Steinman, Advent Engineering Services, Inc., V. L. Press, Lectromec Design Co.	Doug Wood
10 00 am	*Component Importance Determination and Treatment Changes Using Risk Insights* G. Schinzel, STNP	Glen Schinzel
10:30 am	**BREAK**	

Technical Session 4

Prognostics & Diagnostics for Installed Wire Systems

Chair: Gary Toman, Electric Power Research Institute
Vice Chair: Paul Shemanski, NRC/NRR

Time	Topic	Presenter
10:45 am	*Wire Inspection Technologies Under Development at NASA Langley Research Center* K. E. Cramer, E. I. Madaras, R. F. Anastasi, W. T. Yost, NASA	Elliott Cramer
11:15 am	*New Methods for Monitoring the Condition of Aged Cable Materials* R.A. Assink, K.T. Gillen, SNL	Roger Assink
11:45 am	*Application of Optical Diagnosis to Aged Low-voltage Cable Insulation* H. Shoji, J. Katagiri, Y. Takezawa, K. Ootaka, C. Takeuchi, Hitachi	Hiroshi Shoji
12:15 pm	**LUNCH BREAK**	

Continuation of Technical Session 4

Chair: Jit Vora, NRC/RES
Vice Chair: Elliot Cramer, NASA

Time	Topic	Presenter
1:45 pm	*Visual/Tactile and Indenter Evaluation of Nuclear Plant Cables* G. Toman, EPRI	Gary Toman
2:15 pm	*Prognostics of Aging Wiring Using Broad Band Frequency Impedance* D. Rogovin, Boeing, M. Kendig, Rockwell	Dan Rogovin
2:45 pm	*Assessing the Conditions of Cables and Wiring Using the Excited Dielectric Test Method* G. Allan and R. Van Alstine, CM Technologies	Greg Allan
3:15 pm	**BREAK**	
3:30 pm	*Assessing the Condition of Inaccessible Cables through Correlation of Capacitance and Insulation Microstructure* R.L. Steinman, D.A. Horvath, Advent Engineering Services, Inc.	Rebecca Steinman
4:00 pm	*Non-intrusive Condition Monitoring* J. F Gleason, GLS Enterprises, Inc	Jim Gleason
4:30 pm	**ADJOURN**	

EXHIBITS ON DISPLAY· 8:00 AM TO 12 N AND 1:30 PM TO 6:30 PM

Thursday April 25, 2002

8:00 am to 12:00 n – Registration

General Session

Initiatives and Insights on Wire System Aging

Chair: Cornelius Holden, NRC/NRR
Vice Chair: David Johnson, USAF Research Labs

8 30 am	*Present Status and Future Study on Aging Evaluation of Cables in Japan* T. Yamamoto, JAPEIC	Toshio Yamamoto
9 00 am	*Managing Cable System Aging of Nuclear Power Plants in Korea* C Goo, KINS	Cheolsoo Goo
9 30 am	*Uncertainties in Environmental Qualification Cable Testing* B. Bartonicek, NRI REZ	Bohumil Bartonicek
10:00 am	**B R E A K**	
10 15 am	*Assurance of Aged Cable Performance in Nuclear Power Applications* P. Holzman, Strategic Technology & Resources, Inc W. Horin, Winston & Strawn	Phil Holzman Bill Horin
10 50 am	*Aircraft Wiring System Integrity Initiative* G Slenski and D. Johnson, USAF Research Labs	David Johnson
11:30 am	**L U N C H B R E A K**	

Panel Session

Wire System Aging Collaborative Research Issues and Future Directions

Moderator: Mike Mayfield, NRC/RES
Panel Members: Nilesh Chokshi, NRC/NRR
Kent Brown, TVA, John Brewer, DOT, Glen Schinzel, STNP, Elliot Cramer, NASA

1.00 pm	Opening Remarks • *Collaborative Agreement* • *Coordination of Research* • *Potential Collaborators* • *How to proceed from here*	Mike Mayfield

The Chair of each technical session will provide a summary of the issues discussed and potential collaborative research programs identified in their session. The Panel will then discuss and obtain concurrence from participants on the issues and collaborative research programs to pursue for each of the technical areas.

1:15 pm	**Session 1** *Reliability Physics Modeling*	Ken Gillen
1 25 pm	Panel discussion	
1 40 pm	**Session 2** *Fire Risk Assessment*	Peter Fardell
1.50 pm	Panel Discussion	
2:05 pm	**Session 3** *Risk Significance*	Art Buslik
2:15 pm	Panel Discussion	
2 30 pm	**Session 4** *Prognostics & Diagnostics*	Gary Toman Jit Vora
2 40 pm	Panel Discussion	
2.55 pm	**General Session** *Initiatives and Insights*	Cornelius Holden
3 05 pm	Panel Discussion	
3 20 pm	**Closing Remarks**	Mike Mayfield Nilesh Chokshi
3:30 pm	**A D J O U R N**	

Exhibits

Exhibits on display, Randolph Room: **Tuesday, & Wednesday:** 8 00 am to 12.00 n & 1:30 pm to 6 00 pm, **Thursday:** 8 00 am to 12.00 n

Topic	Exhibitor
DOE/EPRI Cable Condition Monitoring Database	Tom Hencey Scientech
Mechanical, Electrical, and Fire Propagation Properties of Halogen-free DBE (LOCA) Resistant Cables for Nuclear Power Plants	Manfred Kirschvink Kabelwerk Eupen AG
Indenter Evaluation of Nuclear Plant Cables	Gary Toman EPRI
Assessing the Conditions of Cables and Wiring Using the Excited Dielectric Test Method	Greg Allan CM Technologies
The Benefits of Using Optical Fiber Distributed Temperature Sensing Systems to Monitor Wire System Aging	Paul Nicholls Sensa

EXHIBITS ON DISPLAY 8.00 AM TO 12 N

Appendix B: Registered Attendees

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International Conference on Wire System Aging

April 23-25, 2002 - Rockville, Maryland USA

Organized by the U.S. Nuclear Regulatory Commission

Office of Nuclear Regulatory Research

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Appendix C: Papers and Presentations from the Opening Session

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Appendix C - Table of Contents

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The Importance of Wire System Safety in the Nation's Infrastructures

Keynote Address
by
Ashok C. Thadani, Director
Office of Nuclear Regulatory Research
U. S. Nuclear Regulatory Commission

at the
International Conference on Wire System Aging
Rockville, Maryland U.S.A.
April 23, 2002

I. Introduction and welcome!

Good morning ladies and gentlemen! It is my great pleasure to welcome you to this International Conference on Wire System Aging. As I look out into the audience, I see a number of familiar faces, along with many new faces, and I am pleased to see such interest in this important topic. As many of you know, the NRC's Office of Nuclear Regulatory Research has been interested in equipment aging and wire system safety for a number of years. Our perspective is one of nuclear plant safety. Degradation of wire systems in a commercial nuclear power plant can result in loss of critical safety functions in equipment powered by the wire system or loss of information regarding system operation. However, wire systems are ubiquitous and impact all of our lives in many ways. Therefore, it is appropriate that such a broad spectrum of participants is represented here today. In reviewing the registration list, I noted representatives from the Department of Energy, Consumer Product Safety Commission, Federal Aviation Administration, National Aeronautical and Space Administration, Department of Transportation, Electric Power Research Institute, and the electric power industry in general. We are also privileged to have representatives from several foreign countries here with us to share their insights and expertise, including Norway, Finland, Canada, Japan, Korea, France, Belgium, the Czech Republic, and the United Kingdom. We are honored that you were able to join us for this conference, and we welcome you to the Washington metropolitan area. For those of you who missed the cherry blossoms, they were simply spectacular this year. Spring time in Washington is always breathtaking.

II. What are wire systems and why are we interested in their aging?

I would like to start by talking about what we mean by "wire systems" and why they are so important. In today's complex, high technology world, we rely on wire systems for many important aspects of our lives, in our infrastructures, including aircraft and spacecraft, ground transportation systems, communication systems, and the very homes we live in. As I thought about this conference and why we should be so concerned about wire system safety, I was struck by the vast number of ways that wire systems really do influence us on a daily basis. Not only do they allow us to fulfill our dreams of space exploration with engineering marvels like the space shuttle, but they also help us perform ordinary, everyday tasks that we probably don't even think of. For example, they enable us to send an e-mail on our computers; they allow us to talk to someone in another part of the world via satellite communication systems; they make it possible for us to go from the 1st floor to the 10th floor of a tall building in an elevator; they allow us to fly across the world in an airplane, and, of course, they allow us to generate electricity and operate the many modern conveniences in our homes and in our daily lives. Indeed, the sound system I am using right now to speak to you functions only because of wire systems. Can you imagine what life would be like without them? Well, for one thing you wouldn't have to listen to me talk this morning, so maybe it wouldn't be all that bad! But life certainly would be different. I recognize that significant progress is being made in the development of optical and wireless systems. But, until we have reliable and cost effective advanced systems, we need to continue to focus our attention on existing wire system technology and safety.

In spite of their importance, we tend to take wire systems for granted. Over the years, they have proven themselves to be highly reliable systems that typically require little monitoring or maintenance. So we have come to take a "fit and forget" attitude toward them. We design and build them to perform a desired function; we install them, and then we forget about them, thinking they will last forever . . . that is, until a failure occurs unexpectedly! Then we scratch our heads and ask why we didn't see that coming. We are all aware of the incidents that took place over the last several years in which degraded wiring is believed to be at fault. And I am sure each one of us can think of a situation in which we rely on the proper functioning of a wire system to prevent a disaster from occurring.

I personally feel that in our technology-driven society, the importance of wire systems will continue to grow as we become increasingly more reliant upon sophisticated devices, information gathering, and communication in our daily lives. And as they become more important, it becomes increasingly vital that we understand how these wire systems will degrade with age and what impact premature or unanticipated degradation will have on system performance. Further, we must be able to monitor these wire systems and be able to predict when they need attention. Waiting for safety critical wire systems to fail before we recognize that there is a problem is just not acceptable!

As a starting point, we need to understand the scope of the technical issues and the safety implications of installed wire systems. When we speak of "wire systems," we are referring to much more than just the electrical wiring or cable itself. While the wiring is clearly an important component, we must also consider many other components and interfaces associated with these components that, when assembled, make up a functioning electrical circuit. These include the components used to connect the wires, as well as the various switches, relays, circuit breakers, connectors, splices, terminal blocks, and other components used to control the end device being operated. Obviously, there are many different types and designs of components involved, and each component, along with its interfaces, can have its own unique degradation mechanisms. The electrical wiring itself can take on many different forms, consisting of thin wires or thick wires, solid wires or stranded wires, bare wires or insulated wires. To truly understand aging of wire systems, we must understand how each of the various subcomponents is affected by age, and how aging of that subcomponent will impact the performance of the wire system. So, we begin to see the magnitude of the problem we are faced with.

While this may appear to be a daunting task, we must realize that much progress has already been made in addressing aging of wire systems. For example, a great deal of research has already been performed to study the polymers that are used to insulate wires, so we know quite a bit about their aging characteristics. We have also studied the effects of aging on many of the components used to connect wires. This work is vital and it provides an excellent knowledge base that we can build upon, however, it is not enough. There are still questions that we need to answer, and issues that we need to address. For example, we still do not know how to effectively monitor wire systems in situ and predict their remaining life. We still do not have data and methods to estimate the overall affect of aging on risk for safety applications. And, we still do not know how aging will affect the vulnerability of wire systems to fires. There is still much work that needs to be done!

III. What efforts are under way now to address aging of wire systems?

As I mentioned in my opening remarks, the NRC's Office of Nuclear Regulatory Research has taken an active role in studying equipment aging for many years, and we continue to perform research in this area. Obviously, the focus of our research program is for nuclear applications. In work related to wire systems, we recently completed a comprehensive program to look at the environmental qualification practices for instrumentation and control cables in nuclear power plants. This program provided a wealth of information on how cables age, and how we simulate aging degradation for qualification purposes and for establishing long-term operability and integrity of installed wire systems. Currently, we are studying power cables and cable splices to determine if we are addressing aging properly in our qualification practices, and we will continue to study other electrical components in the future. We recognize the need to understand the aging process for these important components and are committed to fulfilling this need. However, NRC is not the only organization that should be interested in wire system aging.

Recognizing the safety of the nation's wire systems as an issue of major importance to all of us, the Wire System Safety Interagency Working Group (WSSIWG) was established under the Committee on Technology by action of The White House National Science and Technology Council (NSTC). In November of 2000, the White House Office of Science and Technology Policy issued a report in which Federal programs for wire system safety were reviewed. This report took a giant step forward in focusing attention on the issue of wire systems in our nation's infrastructures and bringing it to the forefront of our research needs involving various Federal agencies. One of the conclusions from that report was:

> "...wire system safety is an important public health and safety issue that transcends government agencies."

I am in full agreement with this conclusion. This is an issue that must be addressed at the national and international level by all of us since it affects many different industries. That is why, we are extremely fortunate to have such a wide spectrum of participants here today. I firmly believe that, through information exchanges and collaboration between our various organizations, we can more efficiently move toward an understanding of wire system aging that will benefit all of us. Much of the work performed by the NRC, DOE, national laboratories, and the nuclear industry in general will be useful to other industries and organizations, and we want to share this information with you. Similarly, I'm sure that there is much useful information you have that would benefit us. Through collaborative efforts we can resolve, efficiently and effectively, many issues and questions that are still unanswered. Some questions will require additional work, and we should work together to answer them. This conference provides a vehicle to bring together experts from around the world to work together to address this issue.

As an outgrowth of the White House report, the Wire System Safety Interagency Working Group (WSSIWG) has formed a subgroup to develop a national strategy document. This special subgroup will be focusing on the implementation of the recommendations made in the November 2000 report. Dr. John Brewer of the Department of Transportation is chairing that subgroup. Mr. George Slenski from the Department of Defense is heading up a subgroup on Prognostics and Diagnostics, and Dr. Jim Cockrell of NASA-Ames is the chair of the WSSIWG Wire Data subgroup. In addition, there are many professional societies and organizations that have expertise in these areas, such as the IEEE, IEC, EPRI. We should draw upon all of these expertise to meet the challenges that face us.

IV. What is the purpose of this conference?

I would like to turn now to what we hope to gain from this conference. From my previous remarks I hope I have made the point that safety of wire systems is an issue that is important to all of us, and we need to focus our efforts on several questions that I would like to pose as a focal point for discussion. They are:

1) How can we better monitor the condition of an installed wire system to ensure that it will function when it is supposed to, even when it is near the end of its design life? Perhaps, even beyond the original design life. For example, for commercial nuclear power plants we are in the midst of extending their licenses from 40 years of service life to 60 years.

2) If we don't have a means of monitoring them directly, can we model the degradation phenomena and make predictions with regard to their functionality over time?

3) How will aging of these components affect their vulnerability to fire?

4) How will aging of wire systems affect risk for safety-related applications?

This morning you will hear a paper that addresses some of the issues that are still left to be resolved. This is just a starting point, and we would like to hear from each one of you as to what significant issues are of concern and would be of interest for collaborative research.

As this conference proceeds, we will hear a number of very interesting technical papers related to wire system safety. I encourage each of you to participate in technical discussions on these topics in the hope of eliciting new ideas on how we can go about resolving them. In addition to the excellent technical papers, there will be exhibits on display across the hall in the Randolph Room. Please stop by and see these exhibits, which include some of the state-of-the-art condition monitoring techniques, as well as advances in wiring designs.

V. Where do we go from here?

My hope is that this conference will culminate in the identification of areas for collaborative research that will benefit Federal agencies and the industries represented here today. Each of you bring relevant expertise that can be utilized to ensure that the worker and the public health and safety are maintained by fully understanding the failure mechanisms of wire systems and by detecting and mitigating their detrimental effects before safety is compromised.

VI Closure

In closing, I would like to say again that I am delighted to see such a wide spectrum of talent here to address the important topic of wire system safety. I wish you all a successful conference and look forward to collaborating with you in the future. To our out-of-town guests, enjoy your stay in Washington metropolitan area and best wishes to you all.

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United States Nuclear Regulatory Commission

Conference Overview

Jit Vora, General Conference Chair
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research

April 23, 2002

Page 1

United States Nuclear Regulatory Commission

Purpose

- Aging of wire systems has been identified as an important public health and safety issue that transcends all government agencies.
- This conference is part of an ongoing effort to identify the technical issues that need to be addressed and initiate collaborative research efforts to resolve them.

Page 2

United States Nuclear Regulatory Commission

Format

- The conference includes four technical sessions, which focus on specific areas:
  - Reliability Physics Modeling of Wire System Aging
  - Fire Risk Assessment of Wire System Aging
  - Risk Significance of Wire System Aging
  - Prognostics and Diagnostics for Installed Wire Systems

Page 3

United States Nuclear Regulatory Commission

Format (continued)

- Following the technical sessions, a general session will be held to discuss topics of generic interest
  - Initiatives in other countries
  - Insights from different industries

- On the final day a panel session will be held
  - Chairman's summary of each session
  - Discussion of issues and topics for collaborative research

Page 4

United States Nuclear Regulatory Commission

Participation

- All attendees are welcome to participate to help make this a successful conference. An open dialogue and good technical discussions are encouraged.

- This is an open public meeting. Sensitive information should not be presented or discussed.

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United States Nuclear Regulatory Commission

Logistics

- All sessions will be plenary sessions and will take place in this room (Plaza I Ballroom)

- Exhibits of new products and condition monitoring methods will be set up across the hall in the Randolph Room

- A message board will be set up next to the registration desk - please check at the desk for the conference phone number

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United States Nuclear Regulatory Commission

Logistics (continued)

- If you have not registered and received a name badge, please stop at the registration desk outside this room and register
- Following the conference, proceedings will be published and a copy will be sent to all registrants
- Information on local restaurants and an area map are included in your conference package - please ask any one of the conference organizers for additional assistance

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United States Nuclear Regulatory Commission

Let's Get Started!

- Again, welcome to all our visitors and conference participants
- Have an enjoyable and successful conference!

Page 8

Wire System Safety - Potential Issues of Interest for Collaborative Research

Jitendra P. Vora
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission

Robert J. Lofaro
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Abstract

There is a continued interest worldwide in the safety aspects of electrical wire (cable) system aging in nations' infrastructures, including operating nuclear power plants. Aging of a wire system, which includes cables, splices, terminations, circuit-breakers, relays, protective devices, and penetrations, can result in loss of critical functions of the equipment energized by the system, or in loss of critical information relevant to the decision making process and operator actions. In either situation, unanticipated or premature aging of a wire system can lead to unavailability of equipment important to safety and compromise public health and safety.

While a significant amount of research has been performed related to wire system safety, there are still a number of issues that remain unresolved and should be addressed. This paper presents a preliminary list of those issues in the area of wire system safety. This list represents a good starting point, and it should be updated as new issues are identified. Further, it is proposed that the most effective way to address these issues is through a collaborative research effort in which the expertise and capabilities of various national and international experts can be focused on the resolution of these issues.

Introduction

Aging of wire systems is an issue that impacts virtually all industries in all countries, and research to properly manage it continues to be a priority. Domestically, over the past two decades, significant research has been conducted by various institutions and organizations on aging related issues for cables. The current focus of the ongoing U.S. Nuclear Regulatory Commission (NRC) research in this area is on the long-term behavior of polymeric insulating materials, condition monitoring techniques, and environmental qualification of electric cables. Both the U.S. Department of Energy (DOE) and the Electric Power Research Institute (EPRI) conduct cable research for the advancement of existing technologies, and to improve the state-of-the-art in material characterization and diagnostics. Under the auspices of the Institute of Electrical and Electronics Engineers (IEEE) relevant consensus standards are either being revised or new standards are being developed for wire systems. The various industry groups and contractors continue to support the resolution of issues related to wire system safety.

Even with the great deal of research already completed, there are a number of important issues that remain to be resolved. Future collaborative research on wire system safety must take into consideration the results of the completed and ongoing work relevant to the topics of interest under this program. In a continuing effort to better understand and manage the effects of aging on electrical wire systems, national and international collaborative research efforts are being encouraged by the NRC, Office of Nuclear Regulatory Research (NRC/RES).

In a collaborative research program, a committee needs to be formed in which members from various organizations sharing a common interest in addressing aging and safety of electrical wire systems will work together to share their knowledge, experience and resources. As a starting point for this effort, past work related to wire system safety was reviewed and experts in the field were interviewed to obtain insights into the issues that are unresolved and need to be addressed. A preliminary list of issues has been developed, and is discussed herein. This list should be expanded and modified as new issues are identified to obtain a comprehensive list of issues to be addressed by the research effort. Collaborative research should then be performed to resolve these issues.

The preliminary list of technical issues are categorized into four subject areas, which are:

- Reliability Physics Modeling of Wire System Aging
- Fire Risk Assessment of Wire System Aging
- Risk Significance of Wire System Aging
- Prognostics and Diagnostics for Installed Wire Systems

The technical issues identified from a review of past and current work in these areas are discussed below.

<u>Reliability Physics Modeling of Wire System Aging</u>

In many cases, empirical data are not available to accurately characterize the effects of aging on equipment performance and reliability. In these cases, theoretical models of the various aging mechanisms may be an effective substitute. However, the accuracy of these models will depend on an understanding of how the various aging stressors interact and affect the physical structure of the materials of construction. Research in this area may prove beneficial in providing an alternative means of estimating future performance of wire systems and predicting remaining life.

Technical issues that remain to be resolved in the area of physics modeling of aged wire systems are presented in Table 1.

Table 1 Issues to be addressed related to physics modeling of aged wire systems

Physics Modeling Issues	Rank
• What are the limitations in current models for predicting wire system age degradation and performance?	High
• What performance data should be collected to validate and improve current failure models?	High
• What models/scenarios should be used for simulating and predicting service life of wire system components?	High
• Can better degradation models be developed for use in estimating accelerated aging requirements for qualification testing?	Medium
• What additional models are needed, in addition to existing models, for predicting wire system age degradation and performance?	Medium
• What expertise is needed for the development of suitable models and their availability?	Medium

<u>Fire Risk Assessment of Wire System Aging</u>
As wire systems age there is an increased chance that their performance will degrade, possibly making them more susceptible and vulnerable to arcing, overheating, or faults that can initiate or propagate a fire. There are a number of factors that influence the probability that a fire could be initiated, and that it will propagate and adversely impact the performance and/or reliability of safety-related equipment. While a significant amount of research has been performed in this area, a number of questions remain unanswered. Thus, the fire risk related to aging of wire systems is an area that warrants additional research.

Technical issues that remain to be resolved in the area of fire risk are presented in Table 2.

Table 2 Issues to be addressed related to fire risk of aged wire systems

Fire Risk Issue	Rank
• What are the factors affecting the frequency of self-initiating wire system fires? What are the relative strengths of these factors? How does age affect these factors?	High
• What are the factors affecting the propagation of wire system fires? What are the relative strengths of these factors? How does age affect these factors?	High
• How does aging affect the vulnerability of wire systems to fire induced damage?	High
• What is the best means of evaluating the effectiveness of fast-acting circuit protective devices for fire protection and mitigation?	High

Fire Risk Issue	Rank
• What impact does aging have on the reliability of fire detection and suppression systems?	High
• What methods, tools, and data should be collected to predict the frequency of cable fires and their likelihood of propagation?	High
• How does aging affect the fire retardant capabilities of cables? How long will each of the common cable types survive in a fire as a function of age?	High
• How do the fire retardants added to cable insulation materials affect the aging degradation rate due to other stressors, such as temperature, radiation and humidity?	High
• Is there any difference in fire risk between cables qualified per IEEE-383-1974 and cables that are not qualified? How does this difference change with age?	Medium
• What is the impact of aging on the integrity of passive fire protective features, such as barrier penetration seals, cable tray fire retardant coatings, cable tray fire barrier systems, and cable tray protective wraps?	Medium
• What effect do currently accepted installation techniques have on the fire risk of wire systems, such as locations where circuits are routed in close proximity (e.g., at the load end)?	Medium
• How does aging affect the vulnerability of wire systems to damage induced by inadvertent actuation of fire suppression systems?	Medium
• What is the impact on risk from environmental stressors imposed in response to a fire, such as water spray or falling objects? How can these risks be quantified? How do these risks change with age?	Medium
• What is the fire risk impact related to new cable designs, such as fiber optic cable?	Medium
• What are the limitations in currently accepted cable flame tests? What improvements can be made?	Medium

Risk Significance of Wire System Aging

As wire systems age there is an increased chance that their performance will degrade, causing a decrease in reliability. Failure rates used in probabilistic risk assessments may not accurately represent wire system performance later in life. Due to the increased use of probabilistic risk assessments (PRAs) in providing regulation and guidance for activities ranging from routine inspections to periodic maintenance, research is warranted in this area to determine the significance of wire system aging as it relates to plant risk.

Technical issues that remain to be resolved in the area of risk significance of aged wire systems are presented in Table 3.

Table 3 Issues to be addressed related to risk significance of aged wire systems

Risk Significance Issues	Rank
• What is the relative importance of the various wire systems in a plant in terms of their contribution to plant risk?	High
• Of the components commonly found in a wire system, which are the most likely to have a failure rate affected by age degradation? How does this impact the reliability of the wire system?	High
• How can inspection, maintenance, and replacement strategies be most effectively optimized to manage the effects of wire system aging and mitigate potential increases in failure rate?	High
• What operational data can be obtained to more accurately characterize the failure rate of wire system components and their ability to withstand different severity levels of harsh environment?	High
• What are acceptable assumptions in assessing the risk of wire system aging considering the available limited information currently available?	High
• What types of training and information should be provided to human operators to enable them to understand and deal with the potential impact of wire system aging?	High
• What approaches can be used to assess human operator performance and response with respect to wire system failures that could limit expected indications and control information?	High
• What is the impact of prolonged exposure to harsh environment on wire system performance and aging?	Medium
• What criteria can be applied to better define the severity level of harsh environments?	Medium
• What is the impact on failure rate of the various installation techniques for wire system components, such as conduits and cable trays? What are the advantages and disadvantages of each?	Medium
• Can risk be used as a criterion for determining post-accident performance duration for qualified wire systems?	Medium

<u>Prognostics and Diagnostics for Installed Wire Systems</u>
Methods of monitoring the condition of wire systems have long been researched in an attempt to identify an effective technique that can be used to determine the existing condition of wire systems, as well as predict their future performance. A recently published White House report

[National Science and Technology Council, November 2000] identifies wire system safety as a national concern, and one of the recommendations made is to emphasize prevention of damage, along with improved availability and reliability, through prognostics and diagnostics. While a number of promising techniques have been identified through past research, each has limitations that make it unsuitable under certain conditions. No single technique has yet been found that can effectively monitor the condition of all wire systems in situ.

Technical issues that remain to be resolved in the area of prognostics and diagnostics of wire systems are presented in Table 4.

Table 4 Issues to address related to prognostics and diagnostics of aged wire systems

Issue	Rank
• How can wire system defects be detected in the incipient state, and located prior to their impacting wire system performance or causing failure?	High
• What types of models, analyses, and data trending are needed for determining the remaining service life of wire systems?	High
• What techniques can be developed for monitoring the current condition of wire systems in situ without disturbing or damaging any components of the wire system?	High
• How can in situ wire system performance data be used to predict the future performance of the wire system and estimate its remaining life?	High
• What acceptance criteria should be considered in determining if a wire system is fit for continued service?	High

Conclusions

While a great deal of work has already been performed in this area, there are still issues that need to be addressed related to aging of wire systems. The technical issues identified above are open for discussion and should be modified, as needed, to formulate a specific topic suitable for collaborative research. This is not meant to be a comprehensive list of issues, and many other issues of interest for collaborative research may exist.

Since the issues related to wire systems span a number of different industries and countries, a collaborative research program would be the most effective approach to address these unresolved issues. Each participant would be able to share their knowledge and expertise related to aging of wire systems, and, jointly, teams of researchers would be able to meet the challenges that lie ahead.

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Appendix D: Papers and Presentations from Technical Session 1
Reliability Physics Modeling of Wire System Aging

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Appendix D - Table of Contents

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The Critical Role of Voids and Virtual Voids in the Mechanical Failure of Polymer Cable Insulation

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The long-term stability of polymer materials in electrical cable insulation has extremely important implications for the safety and reliability of power plants and transportation systems. There is a need to improve our fundamental understanding of this technological problem. Previous work has confirmed that there are chemical changes in polymers over the long term, but there has been little work done to couple these changes to the microstructure and fracture mechanics of the material. There has been some experimental evidence that voids can form in polymers over the long term. However, even if there is not the formation of a true void, processes leading to the formation of a region of material that is not mechanically well connected with the remainder of the sample are also likely to promote the early onset of failure.

This paper explores the potential for applying a known mechanical model for metal failure to cable insulation polymer systems. In polymers, it is possible to envision that long-term degradation behavior, perhaps involving chemical changes such as main chain scission, could lead to regions of material within the structure that are no longer mechanically coupled to the surrounding the matrix. This concept of a "virtual void" would then correspond to a zone of material that remains intact within the polymer matrix, but is not well connected to the rest of the polymer, much like an inclusion in a metal. Under electrical stress and/or mechanical loading, it would be reasonable to conclude that these virtual voids would promote the nucleation and growth of ordinary, detectable voids, much like solid secondary phase inclusions are known to do in metals.

A number of studies have shown evidence for void formation in polymers after extended periods of aging. More work is now necessary to evaluate the size, density, and growth rate of these voids. We believe that a variety of complementary methods to detect void formation in polymers need to be pursued more aggressively. Additionally, studies of mechanical embrittlement as a function of time, temperature, and exposure to radiation need to be conducted and compared with microstructural investigations.

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Review of Several Improved Modeling Approaches for Predicting the Lifetimes of Cable Materials

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Abstract

We have been interested for many years in deriving improved methods and models for utilizing accelerated aging experiments to predict polymeric material lifetimes and are currently developing and applying such approaches to cable materials as part of the Nuclear Energy Plant Optimization (NEPO) program. Many of our studies involve situations where oxidation dominates degradation and this paper will review several approaches developed to address such instances. We will first describe a data analysis approach based on time-temperature superposition principles that utilizes every data point generated during accelerated tests instead of a truncated set. We will then describe an ultrasensitive oxygen consumption technique that allows data to be taken under much lower temperature aging conditions that correspond to the "extrapolation range" of conventional laboratory aging experiments. This allows much more confidence in extrapolated lifetime predictions. Finally, we will briefly describe an approach for predicting residual material lifetimes that we refer to as the Wear-out approach.

Introduction

From a historical point-of-view, most accelerated aging studies of oxidation have utilized the Arrhenius approach, where the temperature dependence of the degradation is assumed to be proportional to $\exp(-E_a/RT)$, with E_a denoting the activation energy and R the gas constant. Typically, one degradation value is determined at each accelerated temperature (e.g., the time to an arbitrary failure criterion such as loss of 50% of some property), and the log of this value is plotted against inverse temperature to test consistency with the linearity expected from the Arrhenius model. If Arrhenius behavior is confirmed over the accelerated temperature range, a linear extrapolation is made to obtain a prediction at lower temperatures.

Our approach [1] improves on the traditional method in two ways. We first recognize that the Arrhenius methodology assumes that raising the temperature increases the degradation chemistry by a constant factor, implying that the time-dependent degradation curves at two temperatures should be related by a constant multiplicative factor. This leads to a concept commonly referred to as time-temperature (*t-T*) superposition, where all of the data points are utilized in the analyses instead of a single processed data point at each temperature. We next consider the other main problem with the Arrhenius approach, which is the unconfirmed extrapolation from high temperature accelerated results to much lower use temperatures. To address this weakness, we have developed an ultrasensitive oxygen consumption approach [1,2] that allows us to take data at temperatures 40°C to 60°C lower than the typically achieved lower temperature limit of conventional mechanical property measurements. These measurements allow us to determine whether the activation energy remains constant in the extrapolation region.

Besides using accelerated aging studies to predict the lifetime of unaged materials, it is often desirable to determine the remaining lifetime of a material after it has already aged for an extended period of time in the actual application environment. Utilizing a combination of *t-T* superposition and cumulative damage concepts, we have derived a method for predicting such residual lifetimes that we refer to as the Wear-out approach [3]. We will briefly describe this approach and show for an EPR cable insulation how it can transform very non-predictive, non-linear degradation behavior into linear predictive plots.

Results and Discussion

Arrhenius Methodology

Historical Approach and Problems

For most polymer types, when oxygen (air) is present during aging, the degradation is dominated by oxidation reactions. The basic idea underlying the Arrhenius approach for accelerated aging studies is that the chemical (oxidative) degradation reactions can be increased (accelerated) by raising the temperature. Since the rate constant k of simple chemical reactions has an Arrhenius dependence on the absolute temperature T given by

$$k \propto \exp\left[\frac{-E_a}{RT}\right] \qquad (1)$$

it implies that the degradation rate will have an Arrhenius dependence on temperature. Thus a plot of log degradation rate, or log of the time to a certain amount of damage (or to failure) against inverse absolute temperature should follow straight-line behavior where the slope gives the activation energy. By assuming that the same reaction(s) dominate the degradation as the temperature is lowered, the Arrhenius dependence can then be extrapolated to lower temperatures corresponding to long-term aging conditions. Figure 1 shows induction (failure) time data analyzed in this fashion for three degradation parameters (ultimate tensile elongation, modulus and density) of an EPDM material. Arrhenius behavior is confirmed for the induction time data and the linearity is extrapolated to 25°C, leading to a predicted lifetime of 55,000 years.

Although long life is predicted, the large extrapolation distance gives little confidence in the result. In fact, there are numerous phenomena that can lead to non-Arrhenius behavior [1]. For instance, the actual oxidation chemistry responsible for degradation usually involves a series of complex reactions that lead to a rate expression much more complex than that shown in eq. (1). Even for relatively simple kinetic situations, analyses of the rate equations indicate that non-Arrhenius behavior might be expected [1]. For polymers in which data is being acquired or extrapolated through a physical transition such as a crystalline melting point region for semi-crystalline materials (relevant to many EPR/EPDM and XLPO cable insulations), deviations from the Arrhenius assumptions should be anticipated. Whenever diffusion-limited oxidation (DLO) effects are present (common for typical accelerated aging conditions for cable insulation and jacketing materials), anomalous non-Arrhenius effects can occur [4]. The importance of DLO is often dependent upon whether oxidation hardens the material and whether cracks that initiate in hardened areas of the material quickly propagate to failure [1,2]. All of these and other effects [1], that can lead to non-Arrhenius behavior as the temperature changes, imply that any extrapolation of higher temperature "Arrhenius" results to lower-temperature, application conditions is potentially misleading. Finally, it should be noted that traditional Arrhenius approaches often use a single data point (e.g., time to loss of 75% of initial tensile elongation) at each temperature, effectively discarding much of the experimentally generated data.

Time-temperature superposition analyses

The first objective of the current paper is to describe two improvements to the standard Arrhenius approach that will result in more confident lifetime predictions made from extrapolated data. The first improvement involves the use of time-temperature superposition analyses [1,2], which uses all of the experimentally generated data instead of a single processed data point at each temperature. The whole concept behind accelerated aging is the assumption that raising the temperature will raise all of the underlying degradation processes by a constant amount. This implies that the degradation curves at two different temperatures should be related by a constant multiplicative factor, further implying that they should have the same shape if plotted versus log time. Figure 2 shows normalized tensile elongation results versus aging time for a Kerite chlorosulfonated polyethylene (CSPE) cable jacket at five different aging temperatures. As anticipated for the constant acceleration assumption underlying the Arrhenius model, the curves at the various temperatures have similar shapes when plotted versus log of the aging time. This means that such log time plots should superpose if shifted horizontally. If the data at the lowest temperature is considered to be at the reference temperature condition, the data at each higher temperature is horizontally shifted by the constant multiplicative factor (a_T) that gives the best overall superposition with the reference curve ($a_T = 1$ at the reference temperature). Figure 3 shows the time-temperature superposition of the data from Fig. 2 versus aging time at the reference temperature of 91°C (bottom x-axis). Since excellent superposition occurs, one immediately has evidence that raising the temperature did in fact lead to a constant increase in the overall degradation rate, adding significant confidence to the results. Once the empirically determined shift factors are generated, they can be tested with various aging models. For instance the Arrhenius model would imply that a plot of log (a_T) versus inverse absolute temperature would yield a straight line with the Arrhenius activation energy available from the slope [1]. When the empirical shift factors used to create the superposed results of Fig. 3 (noted versus temperature on Fig. 3) are plotted on an Arrhenius plot (Fig. 4), it is clear that Arrhenius behavior is confirmed for this material. Extrapolation of these results to lower temperatures is shown as the dashed line in Fig. 4. If we were interested in the estimated lifetime of this material at 50°C (1000/T = 0.003094), this extrapolation would yield a shift factor a_T of ~0.01. This implies that the superposed results at 91°C in Fig. 3 (lower x-axis) would have to be multiplied by $1/a_T \sim 100$ to predict the time scale at 50°C. Figure 3 shows the extrapolated time scale at 50°C as the upper x-axis. Extrapolated predictions at other temperatures could be handled in a similar fashion. The extrapolation of data to temperatures lower than the tensile elongation data range incorporates the unproven assumption that the same Arrhenius behavior remains valid at the lower temperatures. We will see below, that ultrasensitive oxygen consumption (UOC) measurements offer a means of gaining more confidence in such extrapolations.

Ultrasensitive oxygen consumption (UOC) measurements

One of the most important aspects of the normal Arrhenius method is the extrapolation of high temperature results to lower temperatures with the assumption that the activation energy found at elevated temperatures remains constant in the extrapolation region. In order to test this assumption, an extremely sensitive analytical technique that measures a parameter correlated to the oxidative degradation must be found. Since oxidation normally drives the degradation, we felt that measurements of the oxygen consumed during degradation might offer a promising method of achieving this objective. We have therefore been developing the oxygen consumption approach over the past several years [1,2,4]. The approach uses gas chromatography techniques to determine the amount of oxygen consumed after aging a closed container holding a known amount of polymeric material and a known initial quantity of oxygen. Since careful experimental technique allows us to achieve oxygen consumption sensitivities better than 1e-13 mol/g/s, and since 10-20 cc of oxygen absorption is typically necessary to mechanically degrade polymers, our sensitivity allows measurements to be made at temperatures corresponding to hundreds of years of polymer lifetimes. This allows us to probe temperatures down to application conditions for most materials. By making measurements at higher temperatures that overlap the temperature range used for traditional mechanical property measurements, we are able to confirm/test the correlation between oxygen consumption and traditional (e.g., mechanical property) measurements. Extending the UOC measurements into the extrapolation region then allows us to determine whether the oxidation mechanism changes or remains constant in this region. For certain materials we find that the activation energy remains unchanged in the extrapolation region [1], whereas for other materials we find significant changes. Figure 5 shows typical oxygen consumption results for a nitrile rubber material. For this material, traditional mechanical property measurements could not be conveniently made below ~65°C (significant decay of tensile elongation takes several years at this temperature). Time-temperature superposition of the mechanical property data (elongation, modulus) for temperatures of 65°C and above led to shift factors that showed Arrhenius behavior with an activation energy of 90 kJ/mol as seen in Fig. 6 (crosses and diamonds on right-hand line). In contrast to the traditional mechanical measurements, oxygen consumption measurements were easily made down to room temperature (Fig. 5). The results of Fig. 5 were then integrated to obtain the total oxygen consumed versus time at each temperature; the results are shown in Fig. 7. These results can then be time-temperature superposed in the usual way by shifting the higher-temperature curves horizontally by the multiplicative shift factors that give the best superposition with the 23°C reference curve. This is shown in Fig. 8, with the empirical shift factors indicated on the figure. When we normalize these shift factors so that they overlap the shift factors for elongation and modulus (triangles in right-hand data of Fig. 6), we see that they show excellent agreement with conventional data in the high-temperature region as expected. At lower temperatures in the extrapolation region, the oxygen consumption results appear to indicate that a minor change in slope may be occurring, although the slight changes will only moderately reduce the lifetime that would be predicted from an Arrhenius extrapolation of the high-temperature mechanical property results. This result leads to much more confidence in the extrapolation of the higher temperature mechanical property data. In contrast, oxygen consumption results for the EPDM material of Fig. 1 are superimposed on the traditional mechanical property results (left-hand data of Fig. 6). In this instance, the results indicate much more curvature in the Arrhenius plot, implying a much-reduced extrapolated lifetime estimate.

We are currently applying the UOC approach to several important cable jackets and insulations. The first steps involve a number of high-temperature screening experiments to determine approximate consumption numbers and rough behavior of the consumption versus time. These have been largely completed on a few jacketing and insulation materials. The next step, currently underway, is running a multitude of experiments at various temperatures ranging from the temperatures used for the conventional mechanical property measurements down to ambient nuclear power plant aging conditions (e.g., ~50°C).

Wear-out Approach for Predicting Remaining Lifetimes

Besides predicting and monitoring the condition of ambiently-aged samples, it would be advantageous to use field-aged samples for estimating the material's remaining lifetime in the ambient environment. This section of the paper briefly summarizes a new approach for achieving this goal that we refer to as the Wear-out approach [3]. The Wear-out method is a generalization of cumulative damage failure models that have been used mainly for fatigue life predictions for metals and composite materials. The aging time to reach failure takes the place of the number of fatigue cycles to failure. For thermal aging of polymers, the usual accelerated aging assumption is that an increase in temperature will lead to a constant increase in the reaction rate underlying degradation (again the time-temperature superposition concept). The Wear-out approach takes samples that have aged for a certain time at one temperature (e.g., ambient temperature, T_a) and completes the degradation to "failure" at a higher temperature, T_w. When time-temperature superposition is valid, the approach predicts that the remaining lifetime at T_w should be ***linearly*** related to the aging time prior to the temperature step. It should therefore be possible to estimate the service lifetime by completing the aging of ambiently aged samples at the Wear-out temperature.

One important advantage of the approach comes from its potential for converting totally non-predictive results to linear predictive behavior. For example, many important cable materials exhibit so-called "induction-time" behavior, where the degradation property of interest changes very little until large changes occur at failure. Figure 9 shows density results versus aging time for an Anaconda Durasheeth EPR cable insulation aged at four different temperatures. At each temperature, the point where the density abruptly increases corresponds to the time where the tensile elongation quickly plummets to zero (Fig. 10). Such behavior provides little warning of impending failure. To test the Wear-out approach, we took samples that had aged for various times at 110°C and switched them to a 140°C oven to continue their aging. Figure 11 shows time-dependent density results versus aging time at the Wear-out temperature (140°C) for samples that had been previously aged at 110°C for the indicated times. Induction-time behavior typically implies that failure occurs quickly once the stabilizer in the material has been used up. It can be seen in Fig. 11 that the data from three different pieces of unaged material (solid circles) fail at slightly different times. A likely cause of these differences is that the amount of stabilizer may vary slightly along the length of the insulation. By comparing density and elongation results from Figs. 9 and 10, we see that if elongation "failure" corresponds to the time required for the elongation to reach 50% absolute, density "failure" corresponds to the region where the density rapidly increases. We therefore select 1.45 g/cc as the density "failure" criterion and determine the times required to reach this density under Wear-out conditions (Fig. 11). These Wear-out times at 140°C are plotted versus the aging times at 110°C in Fig. 12 (squares); also plotted on this figure are the density results versus aging time at 110°C (diamonds). As anticipated, the Wear-out approach transforms totally non-predictive "induction-time" behavior for the CM parameter into linear predictive results. It is also interesting to note that the scatter in the results for the unaged material (solid circles in Fig. 11) had minimal influence on the observed linearity shown in Fig. 12. Because of the potential of this innovative approach, we are currently testing and applying it to several important cable materials using samples exposed to low-level accelerated aging conditions. We will also be applying the approach to ambiently aged samples obtained from actual nuclear power plants.

Acknowledgment

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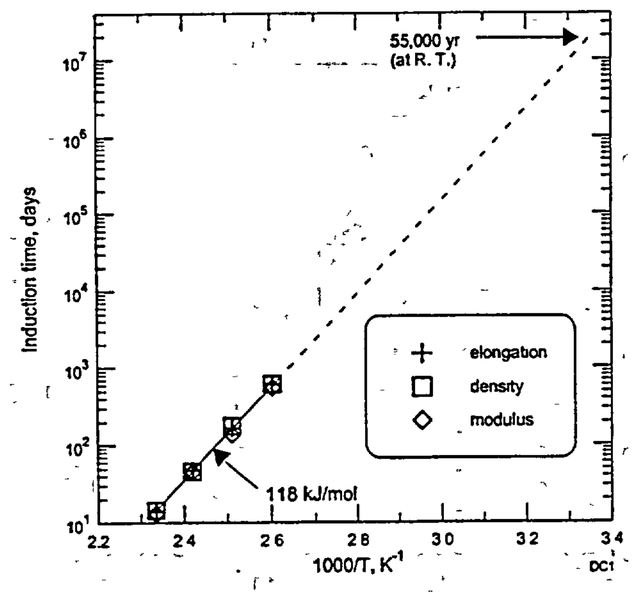

Figure 1. Arrhenius plot and extrapolation of EPDM induction times.

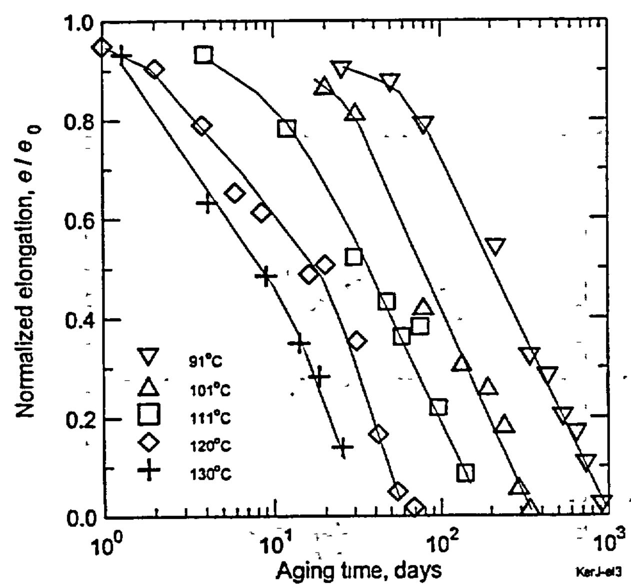

Figure 2. Normalized elongation versus time at the indicated temperatures for a CSPE cable jacket.

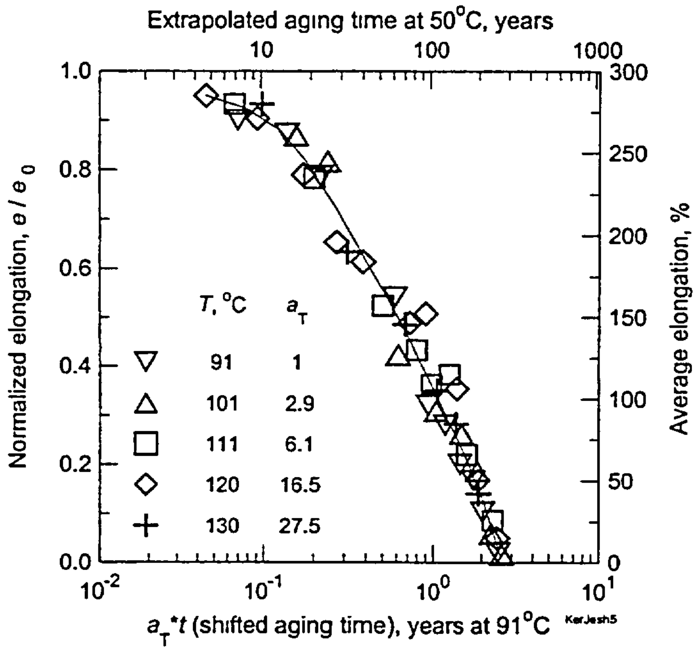

Figure 3. Time-temperature superposition of the elongation data from Fig. 2.

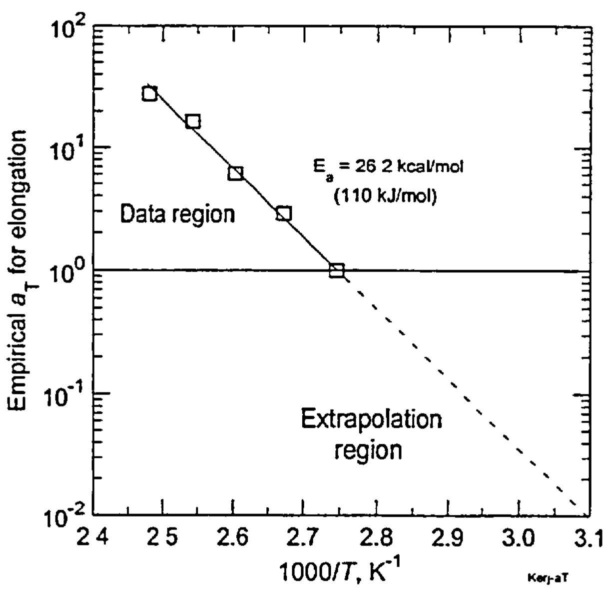

Figure 4. Arrhenius plot of the empirically derived shift factors from Fig. 3.

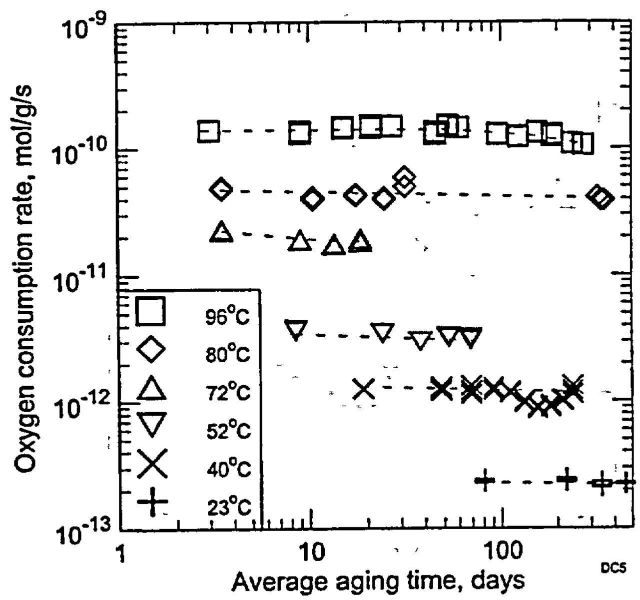

Figure 5. Oxygen consumption results versus time at the indicated temperatures for nitrile rubber.

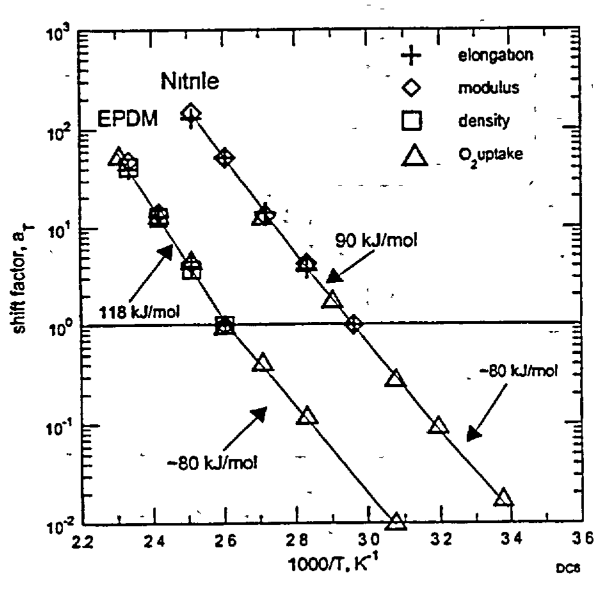

Figure 6. Arrhenius plots of the indicated shift factors for the nitrile and EPDM rubbers.

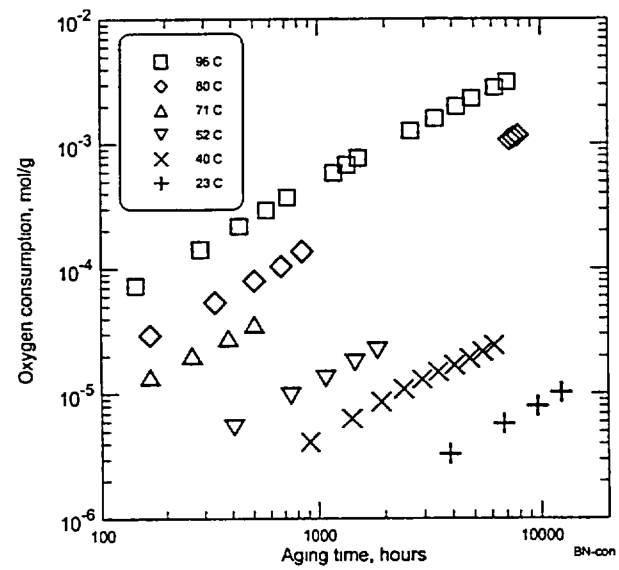

Figure 7. Integrated oxygen consumption versus time at the indicated temperatures for the nitrile rubber.

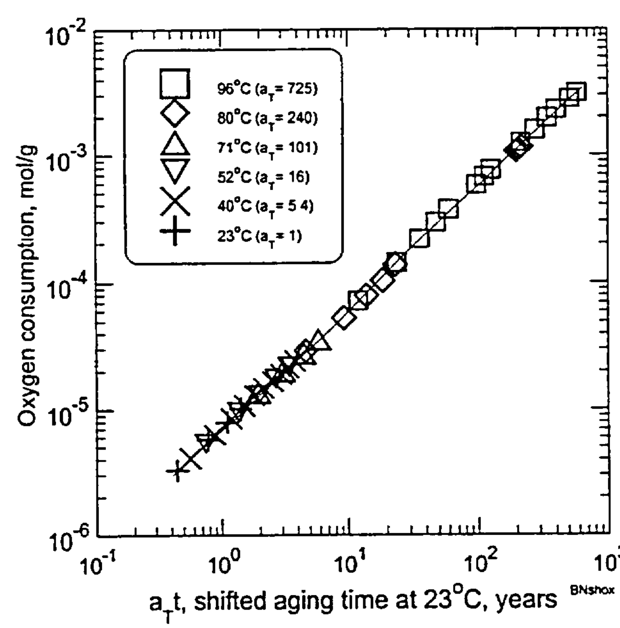

Figure 8. Time-temperature superposition of the oxygen consumption results from Fig. 7.

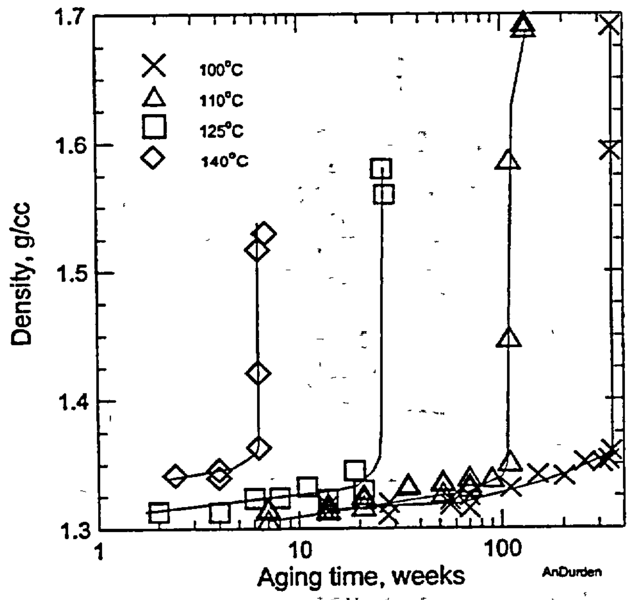

Figure 9. Density results versus time at the indicated temperatures for an Anaconda EPR cable insulation.

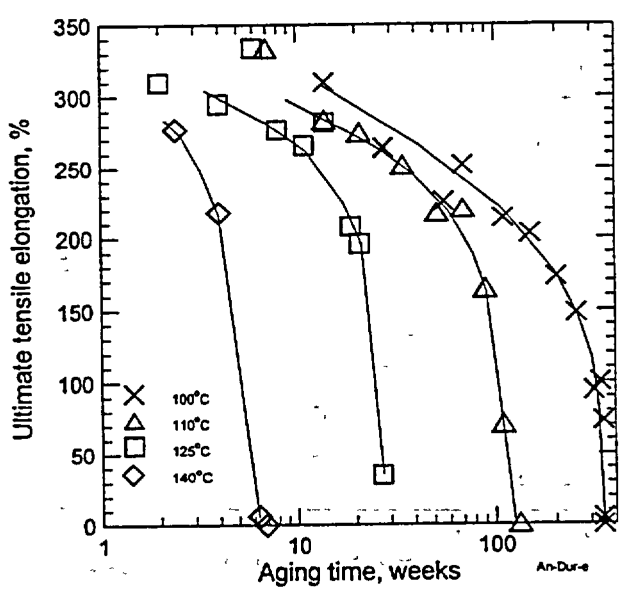

Figure 10. Elongation results versus time at the indicated temperatures for the Anaconda EPR cable insulation.

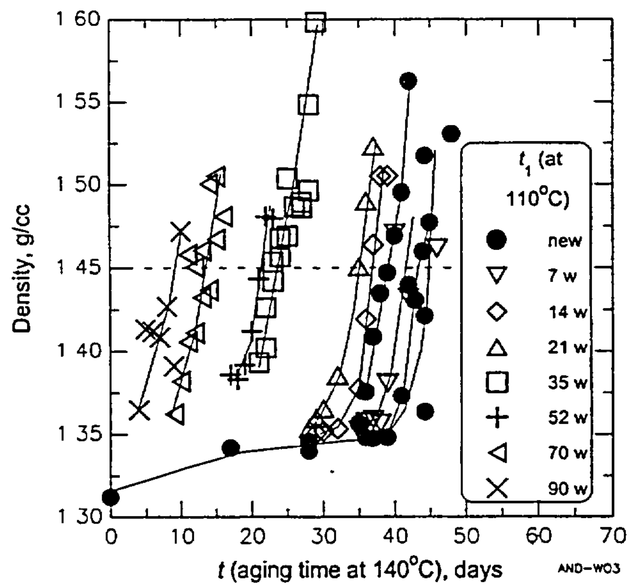

Figure 11. Density results versus aging time at 140°C for the EPR samples previously aged at 110°C for the indicated times.

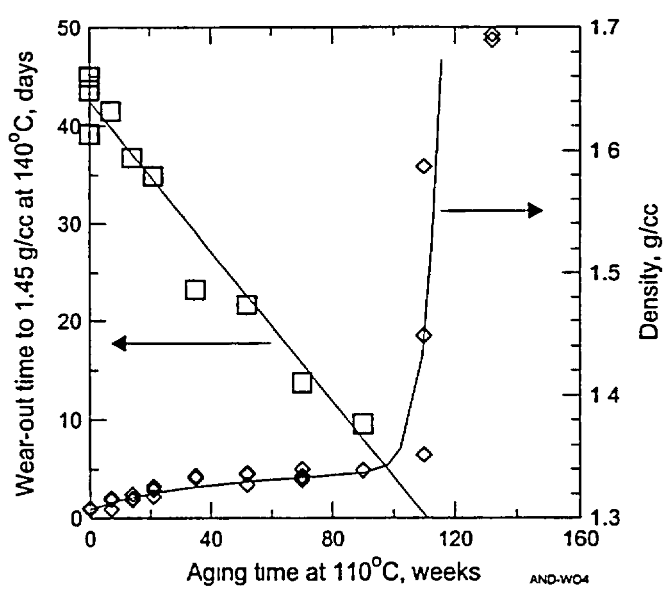

Figure 12. Wear-out results (squares) and density results (diamonds) for samples aqed at 110°C.

Wire, Insulation & Frequency

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Abstract

Electrical insulation used on wiring is known to deteriorate from a number of environmental, chemical, electrical and physical processes that are related to the molecular structure of the insulation polymer and the environmental stress encountered during installation and normal operations, (Ref. 1-4). *As the physical and chemical properties of the wire system deteriorate due to the environment similar degradation takes place in the electrical properties.* Detailed examination of the chemical and physical degradation phenomenon has been well documented by various contributors to the technical journals and conference authors. However, the equivalent electrical degradation properties have not been documented or tied to electrical system performance. This paper will attempt to do so by relating the systems performance and systems electrical properties to the operational environment, human interaction, design and application.

Insulated copper wire has been in use for more than 100 years. In recent years the electrical requirements placed on copper wire by high speed electronics has exceeded the wires performance capability making it a lesser choice for certain functions than other technologies. Copper wire performs well particularly for power distribution, DC, analog and digital signal circuits to 300 MHz at which time non-linearitys begin to be introduced. Since computerized and electronic systems began operating well into the UHF frequencies circuit stability has become an important consideration in design and as a failure mode.

Most electronic circuits that we use everyday are inherently and mathematically considered having lumped circuit elements and the wires connecting them to be perfect conductors. This assumption works well for low frequency applications. Lumped circuit elements have the desirable feature that they introduce no phase shift into the circuit resulting from propagation delays. The amount of phase shift depends on the electrical circuit length. This shift directly affects the phase relationship between current, voltage and system stability. Above 300 MHz real world component characteristics, distributed parameters and phase/gain margins start to become critical from the standpoint of systems performance and systems stability. At approximately 300 MHz and above ideal circuit components start to exhibit nonlinear behavior. At this point computer aided design tools such as SPICE are necessary to examine the electrical parameters of the wiring as a transmission line including the combined effects of the multiple nonlinear behaviors such as: skin effect, leakage conductance, capacitive reactance, inductive reactance and electromagnetics have on the circuit. These characteristics of copper wire result in a substantial reduction in the effective bandwidth, linear dynamic range and introduce performance limitations at elevated frequency. The question must be posed: Is copper wire obsolete for high frequency applications? The answer may be yes for frequencies well above 2 GHz. At approximately 2 GHz the waveguide may be used.

Introduction

Electrical wiring performance is known to deteriorate from a number of reasons that are related to the molecular structure of the insulation polymer, the stress of installation, environmental stress experienced during normal aircraft operation including maintenance and the frequency of electrical systems operation. Many of these stresses directly affect the electrical characteristics of the electronics thus its intended systems performance making it necessary to approach the wiring issues from a systems view point.

Table 1 addresses those areas where transmission line theory applies. This type of failure does not pose a severe risk of fire. However, systems performance is affected.

To locate faults in information transfer systems such as voice and computer communications a systems approach must be taken and must address variation from normal operation plus the addition of a safety margin, allowing for a proactive response instead of a reactive response (Ref. 5 -7).

Training Is Key

Where change is to take place education must take place first. Today s lack of understanding in electrical and electronic systems characteristics is a major cause of wiring problems particularly where non electrical tradesmen are concerned. To rise above electrical wiring issues of today obviously requires a higher level of understanding of wiring systems and the systems that wiring are connected. Training in wire related technologies and aided by advanced computer information collection and processing is key to the electrical repairman s competency and the elimination of the majority of today s wire problems (Ref. 5).

Electrical Fault Causation

Percent Faults	Specifics Concerning Wiring Faults
90 %	Faults repeated application to application of a single type by kind & location
10%	Fault types that are seldom encountered and hard to detect
80 %	Faults that are human induced
25 % 95+%	Effectiveness of visual inspection Effectiveness of *advanced* wire inspection techniques
20 X	The number of times a fault may have to be repaired until it is correct

Table 1: Antidotal causation of electrical faults

Defining Some of the Areas Where The Electrical Rules Change At Increased Frequency

This paper was written to clear up some of the basic details of transmission lines and coax cables, which are universal for most applications. Further information on this subject may be obtained from various reference texts. The ideal book depends on the reader s background in physics, chemistry, electrical engineering, electromagnetics, systems engineering and control theory (Ref. 5, 10 -13).

Signal Wire Functionality

Direct Current Instrumentation
Alternating Current Analog
Twisted pair *
Digital bus *
Digital, not a bus *
Synchro, 2 & 3 phase *
Emergency ground bus

* Systems affected by transmission line characteristics & special RF rules

Figure 1: Systems that require analysis as a Transmission Line

The process of hydrolytic scission or water treeing causes the polymer dielectric molecule to split substantially reducing the dielectric qualities of the electrical insulation allows for an increase in the current conductance or leakage current. This alters the electrical properties of the wire and produces standing waves in the circuit, corrupts the data transmission and results in eventual systems failure. This is one of many typical modes of failure (Fig. 2).

What Is Cable Impedance And How Is It Used

The basic concept is that a conductor at RF frequency no longer behaves like a standard wire. As the length of the conductor (wire) approaches approximately 1/10 the wavelength of the signal it carries the conventional circuit analysis rules no longer apply. This is the area where cable impedance and transmission line theory start to come into play.

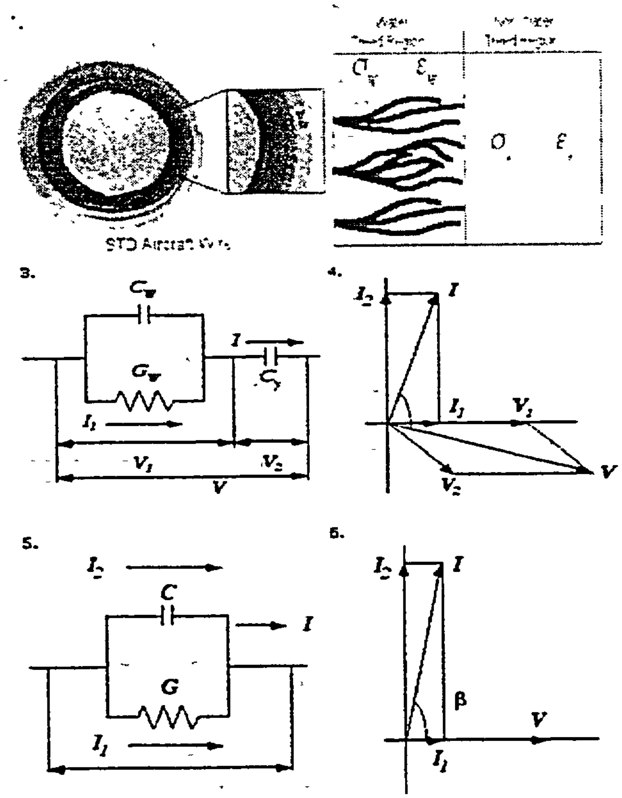

Figure 2: Hydrolytic Scission Alters Electrical Characteristics and Can Cause System Failure

The basic rule of transmission lines is that the source impedance must equal the load impedance in order to achieve maximum power transfer and minimum signal reflection at the load. In the real world this generally means that the source impedance is the same as cable impedance and load impedance.

Defining Cable Impedance

The characteristic impedance of a cable is the ratio of electric field strength to the magnetic field strength for waves propagating in the cable (Volts/m / Amps/m = Ohms). Ohm's Law states that if a voltage (E) is applied to a pair of terminals and a current (I) is measured in this circuit, the following equation can be used to determine the magnitude of the impedance (Z). This relationship holds for either direct current (DC) or alternating current (AC).

$$Z = E / I$$

Characteristic Impedance is usually designated Zo. When the cable is carrying RF power, without standing waves, Zo also equals the ratio of the voltage across the line to the current flowing in the line. Thus the characteristic impedance is defined by:

$$Zo = E / I$$

The voltages and currents depend on the inductive reactance and capacitive reactance in the cable. Therefore the characteristic impedance can be written as:

$$Zo = \mathrm{sqrt}\,((R + 2 \times pi \times f \times L) \div (G + j \times 2 \times pi \times f \times C))$$

Where:

R = The series resistance of the conductor in ohms per unit length (DC resistance)
G = The shunt conductance in mhos per unit length
j = A symbol indicating that the term has a phase angle of +90 degrees (imaginary number)
pi = 3.1416
L = Cable inductance per unit length
C = Cable capacitance per unit length
sqrt = square root function

For materials commonly used for cable insulation, G is small enough that it can be neglected when compared with 2 (3.1416) f × C. At low frequencies, 2 × (3.1416) f × L is so small compared with R that it can be neglected. Therefore, at low frequencies, the following equation can be used:

$$Zo = \mathrm{sqrt}\,(R \div (j \times 2 \times pi \times f \times L))$$

If the capacitance does not vary with frequency, the Zo varies inversely with the square root of the frequency and has a phase angle, which varies from -45 degrees near DC and decreases to 0 degrees as the frequency increases. Polyvinyl chloride and rubber decrease somewhat in capacitance as frequency increases, while polyethylene, polypropylene, and Teflon are stable in this respect. When f becomes large enough, the two terms containing f become so large that R and G may be neglected and the resultant equation is:

Zo = sqrt ((j × 2 × pi × f × L) ÷ (j × 2 × pi × f × C))

Which can be simplified to the form:

Zo = sqrt (L / C)

Characteristics of Cables at High Frequencies

At high frequency the cable acts as a waveguide. The characteristic impedance for electromagnetic waves is the load the cable poses at high frequency. The high frequency usually starts at (dependent of cable) 100kHz and increases. If a sinusoidal AC signal of reasonable frequency is fed into one end of a coax cable, the signal will travel as an electrical wave down the cable. If the cable length is an extremely large number of wave lengths at the frequency of that AC signal, and is the ratio of AC Voltage to AC current in that traveling wave measured, then that ratio is called the characteristic impedance of the cable. In practical cables cable geometry and the dielectric constant determine the characteristic impedance. The cable length has no effect of its characteristic impedance.

The Coaxial Cable Model

The coax is represented schematically by a series of capacitors and inductors in the form of a ladder, the particular values unique to the coax type. At a given frequency, if correctly chosen, that arrangement passes most of the signal; while at higher frequencies attenuates the signal (Fig. 3).

Coaxial Cable Characteristics Defines the Impedance

Wire length does not affect the coaxial cable impedance. The characteristic impedance is determined by the size and spacing of the conductors and the type of dielectric used between them. For ordinary coaxial cable used at reasonable frequency, the characteristic impedance depends on the dimensions of the inner and outer conductors, and on the characteristics of the dielectric material between the inner and outer conductors.

The following formula can be used for calculating the characteristic impedance of the coaxial cable: (formula taken from Reference Data for Radio Engineers published by Howard W. Sams & Co.

Impedance = (138 ÷ e^(1/2)) × log (D/d)

Where:
log = logarithm of 10
d = diameter of center conductor
D = inner diameter of cable shield
e = dielectric constant (= 1 for air)

The characteristic impedance of a coax cable is the square root of (the per unit length inductance divide by the per unit length capacitance). For coaxial cables the characteristic impedance will be typically between 20 and 150 ohms. The length of the cable makes no difference whatsoever in regard to the characteristic impedance.

If the frequency is much too high for the coaxial cable, standing waves will propagate in undesired modes (i.e., have undesired patterns of electric and magnetic fields), and causes the cable not to function properly.

What Kind Of Electrical Model Is Used For Long Coaxial Cable

If you know the inductance and capacitance of a certain length of cable you can use the following electrical model for it:

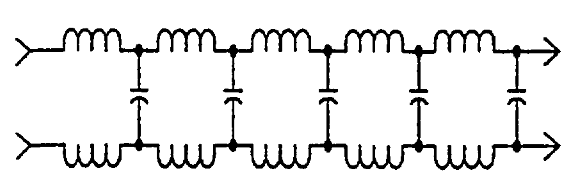

Figure 3: Typical Transmission Line Model

The transmission line electrical characteristics controls the transfer of all high speed data transfer and computer communications. It is desirable to understand how the electrical characteristics of this model can assist or hamper the operation of the total system

$$Z = \text{sqrt}(L / C)$$

Can Cable Impedance Be Measured Using A Multimeter

Cable characteristic impedance is only valid for high frequency signals. Multimeters use DC current for resistance measurements and can't measure cable RF impedance. It is usually best to check the cable type (usually printed on the cable) and it's characteristics impedance from a handbook instead of trying to measure it.

How Is Cable Impedance Measured

A relationship exists which makes determination of Zo rather simple with the proper equipment. It can be shown that if, at a given frequency, the impedance of a length of cable is measure with the far end open (Zoc), and the measurement is repeated with the far end shorted (Zsc), the following equation may be used to determine Zo:

$$Z_o = \text{sqrt}(Z_{oc} \times Z_{sc})$$

Where:

Zoc = impedance of a length of cable and is measured with the far end open

Zsc = impedance of a length of cable and is measured with the far end shorted

NOTE: The Zoc and Zsc measurements both have magnitude and phase, so the Zo will also have magnitude and phase. High frequency measurements of Zo are made by determining the velocity of propagation and capacitance of the cable or by reflectometry

When Does Cable Impedance Effect the Signal

In order for the cable's characteristic impedance to make any difference in the way the signal passes through it, the cable must be at least a large fraction of a wavelength long for the particular frequency it is carrying.

Most wires will have a speed of travel for AC current of 60 to 70 percent of the speed of light, or about 195 million meters per second. An audio frequency of 20,000 Hz has a wavelength of 9,750 meters, so a cable would have to be four or five kilometers long before it even began to have an effect on an audio frequency. That's why the characteristic impedance of audio interconnect cables is not something most of us have anything to worry about.

Normal video signals rarely exceed 10 MHz. That's about 20 meters for a wavelength. Those frequencies are getting close to being high enough for the characteristic impedance to be a factor. High-resolution computer video signals and fast digital signals easily exceed 100 MHz so the proper impedance matching is needed even in short cable runs.

How Impedance Matching Works

First the cable should be driven by an electrical source that has an output impedance equal to the characteristic impedance of the cable, so that all of the source's output power goes into the cable, rather than being reflected from the cable's input back into the source. Secondly the electrical load of the output of the cable must have input impedance equal to the characteristic impedance of the cable. This allows all of the power to be consumed in the load rather than reflected back into the cable.

There are many exceptions to this normal driving method, but those are used for special effects. An impedance can be chosen to match for maximum power transfer at low bandwidth, or by mismatching the impedance for a flatter frequency response.

Why Is Impedance Matching Needed

If you have mismatches between the source's output impedance, the cable's characteristic impedance, and load's input impedance, then the reflections critically depend on the length of the cable. If the cable has been distorted by crushing, kinking, or if connectors have been installed incorrectly standing waves will occur causing a loss in power reflections, with resulting power loss. Sometimes reflected power can damage the power source if its power is reflected into the cable. An anomaly that is not often considered occurs when the antenna reflects power back to the source due to an improper termination at the antenna. The return path of this reflected power will either be the inside or outside of the outer shield, depending on the path of least impedance, This means the RF can travel on the outside of the coax. The most difficult concept concerning coax is that neither XL nor XC exists at the source if the cable is terminated.

The most common reason for listing cable impedance is due to its reliable electrical characteristics. Coax is often used to carry low level high frequency signals that are separated. Separations are very expensive in terms of signal loss, even with a perfect impedance match. Nominally, half the signal power in the transmission line is lost. A slight mismatch is also quite costly, particularly at transmitter power levels. Carefully matched carriers, like coax, are necessary to preserve signal at reduced noise.

What Effect Does the Nominal Capacitance Have On the Cable's Performance or Transmission Capabilities

Capacitance of the cable has nothing to do with the signal if the coax is terminated. The transmitter will see absolutely no capacitance or inductance. This transmission line characteristic is used to hide capacitance in high frequency PCB's. Engineers can design the PCB traces so that they have the proper capacitance and inductance values allowing the source to see nothing but a proper impedance.

Why is characteristic impedance important in data transmission

If a cable is terminated in its matching characteristic impedance there is no way of telling from the sending end that the cable is not infinitely long - all the signal that is fed into the cable is consumed by the cable and the load.

If the impedance is not matched, a portion of the power will be reflected back into the cable termination distorting the outbound signal. When this reflected signal format returns to the source it is again reflected and mingles with the outbound waves so that it is difficult to tell which waves are original and which are re-reflections.

The same thing happens when pulses are sent down the cable - when they encounter impedance other than the characteristic impedance of the cable, a portion of their energy is reflected back to the signal source. If the pulses encounter an open circuit or a short circuit, all of the energy is reflected except for the losses due to attenuation. For other terminations, a smaller amount of power is reflected.

This reflected energy distorts the pulse, and if the impedance of the pulse generator is not the same as the characteristic impedance of the cable, the energy will be re-reflected back down the cable, appearing as extra pulses.

Is Coaxial Cable Useful Without Impedance Matching

If the coaxial cable is very short, the cable impedance does not have much effect on the signal. Usually the best way to transmit signal through coaxial cable is to do the impedance matching, although there are some applications where the normal impedance matching on both ends is not done. In some special applications the cable might be impedance matched at only one end or intentionally mismatched at both ends. Those application are special cases, where the cable impedance is taken into account though the combination of cable and cable terminations which produce the desired transmission characteristics for the whole system. In this kind of special application the cable is not considered as a passive transmission line, but a signal-modifying component in the circuit.

Velocity Of Propagation Ratio

The velocity of propagation ratio percentage is based on the speed of light in a vacuum. The percentage identifies the speed of the signal in the cable compared to the speed of light in a vacuum. In coax cable, under reasonable conditions, the propagation velocity depends on the characteristics of the dielectric material.

Why Does The Signal Attenuation Tend To Increase With Increasing Frequency

This is usually due to the limited penetration of current into the inner and outer conductors (the skin effect). With increasing frequency, the current penetrates less deeply into the conductors, and thus is confined to a thinner region of metal near the surface. Therefore the attenuation is higher. It also can be caused partly by energy loss in the dielectric material.

How To Minimize The Attenuation In Coax

For a line with fixed outer conductor diameter, and whose outer and inner conductors have the same resistivity, and assuming a dielectric is used with negligible loss (such as polyethylene or Teflon in the high-frequency range), then a minimum loss is experienced if the expression:

$$(1/d + 1) \div \ln (1/d)$$

is minimizing where d is the ratio of inner conductor diameter to outer conductor inside diameter. An approximation is = 3.5911. The formula is derived in *Reference Data for Radio Engineers* published by Howard Sams.

Note: minimum loss does not directly yield line impedance. The line impedance depends on the dielectric constant. If the line is insulated with solid polyethylene, the minimum attenuation is about 50.6 ohms or RG-58 cable which is used for antenna feeds and test equipment leads. Note that a foam-dielectric line with the same impedance and outer diameter as a solid-dielectric line will have lower loss. To get the same impedance, the foam line will have a larger inner conductor. The larger conductor has a lower RF resistance, and therefore lower loss.

Using Coaxial Cables In Applications

What happens if a 50 ohm cable video 75 ohm cable is used? If a 50 ohm cable sees a 75 ohm load a substantial part of the signal will be reflected back to the source. Since the source is also 75 ohm, this reflected signal would substantially be reflected back to the load. Because of the delay, it will show up as a nasty ghost in the picture. Multiple ghosts like this look like ringing. Also, the reflections cause partial signal cancellations at various frequencies.

Impedance Matching Between Different Impedance

If two cables with different impedance are connected together or a cable is connected to a source which has different impedance then some kind of impedance matching is needed to avoid the signal reflections in the place where the cables are connected together (Ref. 7 and 8).

Conclusions and Recommendations

Where change is to take place education must take place first. Today's standard wiring practices are the major cause of aircraft wiring problems particularly where tradesmen lacking an understanding of the wiring issues are concerned. To rise above electrical wiring issues of today obviously requires a higher level of understanding of the wiring systems and the systems wiring is connected. Training in wire related technologies and aided by advanced computer information collection and processing will greatly aid in the electrical repairman's competency and eliminate the majority of today's wire problems.

System designed to operation at or near 2 GHz into a balanced coax line or set of coax lines may be very sensitive to circuit anomalies and can be a losing proposition due to minor changes in circuit elements. Above approximately 2 GHz fiber optics or a waveguide is a viable option. The coax wire system would have been operating at a frequency where there was little headroom to allow for any systems variation due to environmentally degrading effects. When circuit elements are designed for operation in areas of transition system robustness is substantially reduced allowing for only slight variations of electrical component characteristics leading to instability and ultimate system failure. By analyzing the system characteristic equation in the frequency domain and plotting the loci of roots the potential for instability or robustness can be determined.

This applies wherever the rules governing communication media (wire systems) operation is transitioning from one mode to another. That is:

1. DC to 300 MHz (bulk components, I=E/R),
2. Coax cable and transmission line, (distributed components and RF rules),
3. Wave guides, electromagnetics,
4) Fiber optics (virtually unlimited bandwidth and linear dynamic range) In experiments earlier this month Scientists at Bell in New Jersey shuttled 2.56 terabits per second of data 2500 miles over fiber optic cable. Anaheim (AP)

GUIDELINES FOR WIRE HUSBANDRY (Ref. 14 — 15)

- Introduce concept of BIT at LRU or a wire sensor. Conduct fault detection of entire electronic subsystems end to end. Collect the systems performance and fault location data in real time. Data for determination of systems health may be downloaded and processed on demand or automatically for a single system or the entire aircraft. After prognostics process settles out maintenance need only be scheduled for depot level unless an unscheduled anomaly occurs.
- Recognize the Navy has been able to achieve an 88% reduction in wire events through improved husbandry practices.
- Audit and introduce training, which supports advanced wire husbandry practices to prevent sustained wire faults from poor work practices.
- Training is key to moving beyond an attitude of fit and forget.
- Consider multiplexed operation and fiber optic as a communication medium for high-speed communication to reduce the faults incurred in conventional wire design practices. Recognize the severe threat to safety from arc burning of certain types of insulation such as Kapton or Aromatic polyamide. Consider replacing with wire using insulation having less safety hazards and/or different characteristics.
- Focus on having an insulation system with a minimum of insulation breaks.
- Where possible use the most advanced fielded test procedures and equipment in-order to overcome the fact that visual inspection is only 25% effective in identifying wiring faults.
- Wiring is the communication link governing the operation of electronic systems. Based on this point of view wire husbandry must be the focus in all wire mechanical trades, engineering design and wire insulation choices. Work and inspection procedures must consider the consequences of ignoring or missing a wire fault.

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Microstructure Assessments for Determining Electric Cable Insulation Remaining Life

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Abstract

The concern of electrical insulation aging covers the gamut of industry, military, government, and private arenas with an existing short-term focus on nuclear power plants, aircraft, electrical transmission and distributions systems, fossil power plants, and aging industrial facilities. Both the nuclear and aircraft industries have an immediate need for an acceptable electrical insulation monitoring technique. Ideally, this technique would be non-destructive and capable of predicting the remaining life of installed insulation. Many techniques currently exist for electrical and mechanical testing of insulation to confirm the present integrity of the insulation, but none of the current methods are both non-destructive *and* predictive of acceptable future life. This paper reports on a promising technique for assessing remaining cable insulation life based on microvoid content.

The mode for insulation failure differs as a function of the operating voltage regime. At higher voltages, the failures are dominated by partial discharge effects. At lower voltages, the failure mode is related to loss of integrity (breaks or cracks in the insulation material), which could then cause a circuit failure problem in high moisture or high humidity environments. Our research indicates that both failure modes can be shown to be related to microvoid content growth.

New (and good) insulation has been found to have voids of 2 to 20 microns in diameter and densities of 100 to 1000 per cubic millimeter. More research is needed to determine growth rates and levels at which the various failure modes occur. This paper will report on techniques available to image or otherwise assess void content and correlate to remaining life.

1. Introduction

Nuclear power plants in the US were initially designed and licensed for forty years of operation. Because no new nuclear plants have been ordered and built in recent years and consistent with our continually growing power needs, efforts are now underway to extend the license of many of these plants an additional 20 years. This process requires that the effects of aging on electric cable insulation be evaluated and resolved for the license renewal term. In many ways the aging of electric cable insulation in nuclear power plants is similar to what occurs in other facilities such as commercial and military aircraft, fossil power plants, and industrial facilities.

During a research project undertaken in the early 1990s, staff members at Advent Engineering, Ann Arbor, Michigan explored the microstructure of several electric insulation materials using optical, acoustic, and electron microscopy. We examined unaged, naturally aged, and artificially aged samples. In all cases evidence of microvoid formation was found. We also found the microvoid content to be notably higher in the naturally aged samples compared to the more newly manufactured cable insulation samples [1]. Both the size of the voids and their number were noted to be higher for the aged sample cases. One explanation considered was that manufacturing processes had improved during the time frame of the insulation's original development. Another explanation was that the microvoid content had increased as a result of aging. Although both explanations are likely, it was this second postulate that offered itself as a potentially valuable property to consider for assessing electric cable insulation aging.

This paper will report on our efforts to date to evaluate this promising approach for developing a portable, non-destructive method of determining remaining life in electric wire insulation. This approach will be applicable for all polymer insulation materials commonly used in low to high voltage applications and will be based on monitoring and correlating changes occurring due to aging at the micro-structural level. Although this concept has not yet been fully explored and verified, some evidence exists demonstrating these micro-structural changes to be manifesting themselves as increasing microvoid content.

2. Existence of Microvoids

What are microvoids? Microvoids are microscopic cavities within a solid dielectric insulation, often as small as 1 to 10 microns. In general terms, the bulk of a polyolefin polymer, such as polyethylene, has a crystalline texture determined by the rate at which the polymer material was cooled when originally formed. During the initial cooling process some non-crystallized material is left trapped between the spherulites formed during primary crystallization. At temperatures below the primary crystallization temperature, this initially non-crystallized material begins to slowly revert from its amorphous form to create a new crystalline state, such as a folded or extended chain. As this secondary crystallization occurs, the newly crystallized polymer material occupies less volume, resulting in microvoids or discontinuities forming between the rigid bulk polymer material.

The secondary crystallization process may occur over a number of years at ambient temperature. Thus, microvoid content has been found to change with age in response to environmental and operational stress factors. These microvoids have the potential to become sites of ionization and eventual tree growth when exposed to an electric field. For this reason, microvoids are thought to be the precursors for eventual mechanical failure in high voltage insulation and may also play a role in medium and low voltage cable integrity failures.

A paper by Kageyama [2] found that steam cured cross-linked polyethylene cable insulation contained microvoids several microns in size at densities of one million per cubic millimeter. If a heating medium other than steam was used, the number of microvoids was reduced to 10,000 per cubic millimeter, but it was concluded to be extremely difficult to bring this concentration down to 0. Another paper by Namiki [3] reported densities of 100 to 1000 per cubic millimeter for dry cured XLPE. Other recent papers (primarily based on work being performed in France, Great Britain, and Japan) continue to report on microvoid content in electric polymer insulation.

3. Polymer Structure and Electric Insulation Acceptance Criteria

In order to explore the potential value of assessing aging through evaluation of the insulation's microstructure it is first necessary to consider a brief description of a polymer material's internal structure and then to define some acceptance criteria for end of life.

The internal structure of polymers consists of molecules of high relative molecular mass. Each molecule is comprised of multiple repetitions of smaller units (monomers). After formation and during cooling, islands of crystals are formed separated by amorphous layers of polymer chains.

The various interfaces between crystalline and amorphous layers of polymers are of primary interest and represent potential sites for microvoid formation and growth.

In general, the advanced polymer insulation materials developed over the last couple decades and now commonly used in most industrial applications have been found to have very long lives and indeed almost indefinite lifetimes for some environmental conditions and applications. However, in all cases, there will exist at least three acceptance criteria for defining end of useful life:

- For all electric insulation, even instrument and control cable in low and medium voltage applications, a loss of cable structural integrity occurs.
- For instrument cable (and to a lesser extreme control cable), unacceptable leakage current occurs.
- For the power cable in medium and high voltage applications, excessive partial discharge takes place.

4. Evidence for Microvoid Content Growth During Aging

Three mechanisms for polymer aging exist: physical, chemical, and electrical. Physical aging occurs due to residual and applied mechanical stresses. Chemical aging occurs in response to exposure to oxygen and other reactants. Electrical aging takes place when voltage-induced stresses are high, typically above 3kV. All three mechanisms account for polymer aging in most applications.

It is well accepted that microvoids become sites for partial discharge and eventual tree initiation and growth in high voltage regimes. Growth during normal service conditions is expected, but evidence is less direct; however, such growth has not been disproved. In addition to our studies others have reported on evidence for microvoid content growth in response to aging.

Dissado and Fothergill in their often referenced textbook *Electrical Degradation and Breakdown in Polymers* [4] provide an excellent introduction to polymer science and aging effects. Of particular note, Chapter 3 provides an overview of low level degradation in polymers. Three major relevant points are made in support of the contentions in this paper.

1. The effect of mechanical stresses of a sufficiently high level is to increase the microvoid density and size [within polymer materials].
2. Microvoid production in polyethylene was observed in cable samples that had been unused and exposed only to a service environment.
3. Local density increases due to secondary crystallization is compensated by a generation of microvoids and discontinuities. [Thus density increases can occur in concert with microvoid production.]

Dissado and Fothergill derived these conclusions from two published works reporting on research projects conducted separately in the US and the UK.

In the first paper, Barlow, Hill, and Marino [5] describe their research conducted for US Industrial Chemicals of Columbus, Ohio. The purpose of their work was to investigate an alternative cause of void formation based on an inherent property of polyolefins. They report as a result of their testing and analyses that microvoid formation continues with time as a result of secondary crystallization with such polymers.

The second paper by Stevens, Perkins, and Champion [6] discusses a joint project of the Central Electricity Research Laboratories and City of London Polytechnic both in the UK. The authors experimentally tested for and found evidence for microvoid growth as a result of aging from the separate and independent effects of mechanical and electrical stressing.

Many other papers report on the high voltage regime relationship of microvoid growth in electrical insulation and consequential tree growth effects.

Thus it is considered reasonable to explore use of this material property for assessing aging effects.

5. Using Microvoid Content to Assess Aging

Based on the research and observations discussed above, it is surmised that determining microvoid content has high potential value for age assessments. To perform such assessment, Advent is proposing imaging and capacitive measurements as two viable candidate options. The following discussion extracted from [7] explains how acoustic microscopy can be applied. Use of capacitive measurements is presented in a separate paper.

Figure 1 outlines how such a system would work. The transducer (A) converts electrical signal to acoustic signal and converts return (reflected) acoustic signal to electrical signal. The signal transmitter (B) sends an electrical signal of the required frequency and pulse shape / width to satisfy the control setting. The control setting (C) inputs the desired insulation depth window to be viewed / analyzed. The control setting can be adjusted to ignore any reflections from the cable jacket or electrical conductors. The amplifier / discriminator (D) boosts the received signal and screens to minimize noise and optimize the desired signal characteristics. (For example, discriminate to view only the reflections indicative of the control setting depth range, which corresponds to a window of reflected time for each transmitted pulse.) An output signal is also available for display of an image representative of actual void sizes and dispersion within the insulation medium.

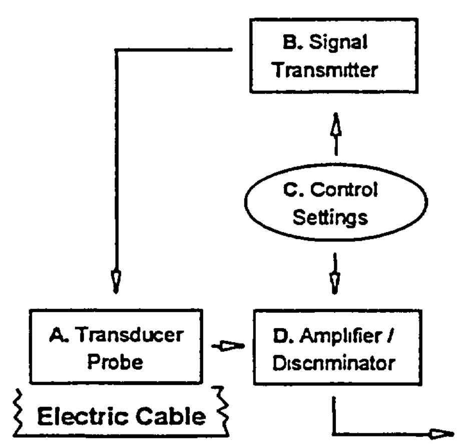

Figure 1 Void Detection and Processing

The principle of acoustic microscopy is that sound waves reflect at interfaces of material density decreases such as from solid polymer to a gaseous void site. The sharper the discontinuity in density, the stronger the reflected wave. Sonoscan, Inc. volunteered use of its C-Mode Scanning Acoustic Microscope (C-SAM) Series D6000 for this research. This C-SAM operates at 10 to 100 MHz, which was found to provide the desired resolution. Through adjustment of the observed time interval of the reflected wave, the C-SAM was found to be capable of filtering out reflections from the cable's jacket material. Therefore, images of the electric insulation's internal void characteristics were readily apparent. Figures 2 and 3 provide two sample views of electric insulation using acoustic microscopy. Figure 2 is a view of a jacketed cable as it would appear if monitored in the field (in situ). Figure 3 is a prepared (cut) sample view.

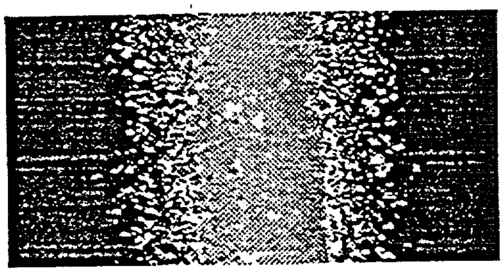

Figure 2 Aged Ethylene Propylene Viewed with C SAM at 15 MHz. The bright spots are reflected void formations.

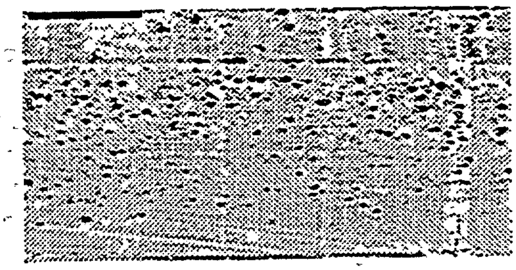

Figure 3 Aged Polyethylene Viewed with C SAM at 50 MHz. In this inverted image the voids are dark spots.

Void size and density are indicative of remaining life through comparison to end of life criteria values. Such a correlation can be performed as shown in Figure 4 and described below. Note that this technique requires no baseline or trending. It is not necessary to know past void history. Only the present level of proximity or margin to limiting void parameters is required to establish remaining life.

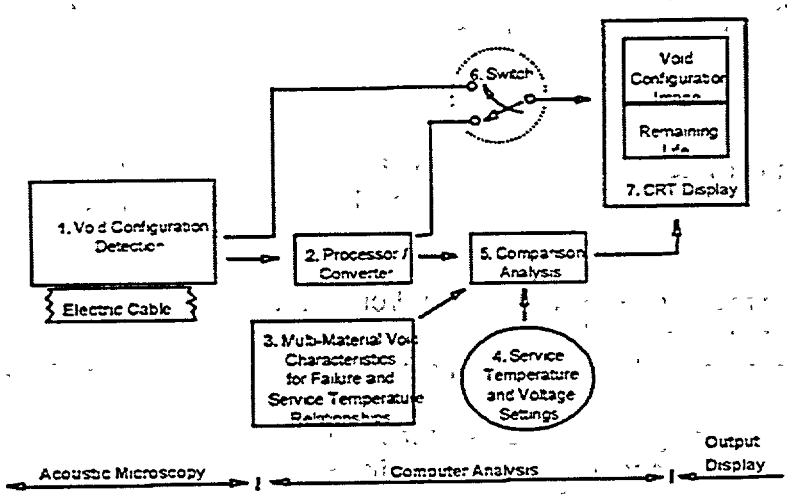

Figure 4 Electrical Insulation Life Determination Using Acoustic Microscopy and Void Analysis

Void information is detected (1) using a system similar to that shown in Figure 1 and sent to a Switch (6) as well as to a Processor / Converter (2). The Processor / Converter allows a conversion to a digital signal which is analyzed and converted to an equivalent insulation medium of uniform void size and density (homogeneous dispersion throughout the insulation medium). Equivalent is defined as the same (or somewhat more limiting in terms of) susceptibility for production of an electrical partial discharge path across the electrical insulation medium under design potential conditions. This equivalent void size and density configuration is provided as one input to the comparison analysis device (5). An analog output signal representative of this "equivalent configuration" could also be made available for display (7) via switch (6).

Using void characteristics and partial discharge failure prediction techniques, relationships for service temperature and limiting void size and density corresponding to the appropriate failure criterion are available for various insulation materials [from data base (3)] as the second input to the comparison analysis performed by device (5).

Desired future service temperature and design voltage conditions are set in via setting (4). Inputs from (2), (3), and (4) are used to determine remaining life in device (5) by first determining the margin between actual equivalent void configuration and the limiting (impending failure) configuration and then calculating void growth rate, which is a function of temperature and material type. The output is a numerical or temperature dependent signal, which is sent to the display monitor (7) such that either remaining life for a given temperature or a graph of remaining life vs. temperature can be displayed.

The Display Switch (6) allows monitoring on device (7) of either a "raw" (unprocessed) reflected signal representative of the actual void configuration within the insulation medium or the equivalent void configuration.

This display device (7) is envisioned to be a CRT such as that typically used by a personal computer. The upper portion of the display will show an image of the insulation medium's void configuration (processed or unprocessed). The lower portion will provide the remaining life result (for a specified temperature or as a function of temperature).

6. Work to Go

Much research and development work remains to assure feasibility and to establish the required material data bases for predicting remaining life. The following five phase program has been established:

1. Refine acoustic microscopy technology and/or investigate other imaging and assessment techniques (currently available) to better investigate and evaluate small void sizes.
2. Develop database of limiting void parameters for commonly used electrical insulation materials.
3. Establish void content growth rates as a function of the following exposures: temperature, radiation, voltage, and harsh environment effects.
4. Develop software to convert 3D void images to a numeric void content value.
5. Develop software to perform comparison analyses and to generate any necessary displays.

7. Conclusions

It is concluded that something is continuously happening at the microstructural level (as a result of aging), which later when some threshold level for external property observation is exceeded, insulation failure becomes visible. As reported by others, we also believe that this "something" is related to microvoid formation and growth especially in the anomalous areas of the polymer. Microvoids represent "weak" areas in the structure of the polymer. These weak areas increase in size and are the likely sources of integrity failure of the polymer insulation. More research is needed to prove that microvoids are indeed the mechanism to failure. Even if microvoid growth is not the all conclusive answer, research in this area will identify the correct mechanism or combination of mechanisms causing aging degradation and failure.

Thus evaluating microstructure effects has high potential value for performing age assessments. Also, we believe that Imaging and capacitive measurements hold high promise for performing such investigations and evaluations.

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Appendix E: Papers and Presentations from Technical Session 2
Fire Risk Assessment of Wire System Aging

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Appendix E - Table of Contents

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Mechnical, Electrical and Fire Propagation Properties of Halogen Free DBE (LOCA) - Resistant Cables for Nuclear Power Plants

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Simon Coenen, SCK-CEN, Nuclear Research Center, Mol, Belgium

Abstract
A range of halogen free1E-LOCA resistant cables has recently been qualified in accordance to IEEE 383.
Thermal and radiation ageing of the cable materials have been determined. The fire propagation properties of the conductors and the cables placed in bundles have been tested before and after ageing; no major changes have been found.
A complete LOCA and Post-LOCA test has been performed and the elongation at break (ELB) as well as the insulation resistance of the cables have been monitored at the different test stages. At the end of the Post-LOCA test, the ELB still reaches 50% and the insulation resistance has approximately recovered its initial value of 3000 MOhm.km.

Introduction
A new range of halogen free 1E - LOCA resistant cables has recently been qualified in accordance to the Standard IEEE 383.

This range comprises :

- Medium Voltage Power Cables [1, 4]
- Low Voltage Power Cables [2, 4]
- Instrumentation & Control Cables [3, 4]

The MV-Cables are XLPE insulated and equipped with a vapour-tight metallic shield and a radiation-cross linked LSZH-FRNC (Low Smoke Zero Halogen - Fire Retardant Non Corrosive) sheath.

The LV Power Cables and the Instrumentation & Control Cables are equipped with a double layer insulation. The first layer is an EPR-insulation; this layer assures excellent insulation resistance values. The second layer is an EVA resin filled with a high amount of Aluminium Trihydroxyde (ATH) powder. This layer is flame retardant. The outer sheath of these LV-Cables is also based on an EVA resin highly filled with ATH.

1. NPP Operator Requirements

The operator of Nuclear Power Plants (NPP) has the following requirements regarding the cable system installed in the plant:

- Compliance with international standards such as IEEE, RCCE (France), KTA (Germany) and others;
- Resistance of the cables to thermal ageing for a service life of 40 years and more;
- Resistance of the cables to irradiation ageing;

- No fire propagation of cables installed in various manners;
- Design Based Event (DBE) or Loss Of Coolant Accident (LOCA) resistance;
- Traceability of the installed cables;
- In many countries halogen free (LSZH-FRNC) cables are a major requirement.

2. Thermal Ageing

Thermal ageing of polymers is a complex matter. The ageing process depends mainly on three factors:

- the polymer itself;
- the service environmental conditions;
- the time scale.

Ageing provokes macroscopic changes of the cable materials:
- a decrease of elongation at break (ELB), often associated with a decrease of tensile strength;
- an increase of the hardness or the compressive modules;
- an increase of density and
- changes of the electrical properties, e.g. decrease of the insulation resistance.

An accelerated thermal ageing is achieved by exposing the materials to significantly higher temperatures than the service temperature; the end of life is reached when the elongation at break (ELB) is 50 %.

An Arrhenius-diagram is drawn based on the measured figures; permitting to determine the life time at 90 °C and the activation energy of the cable materials, as shown in the following table.

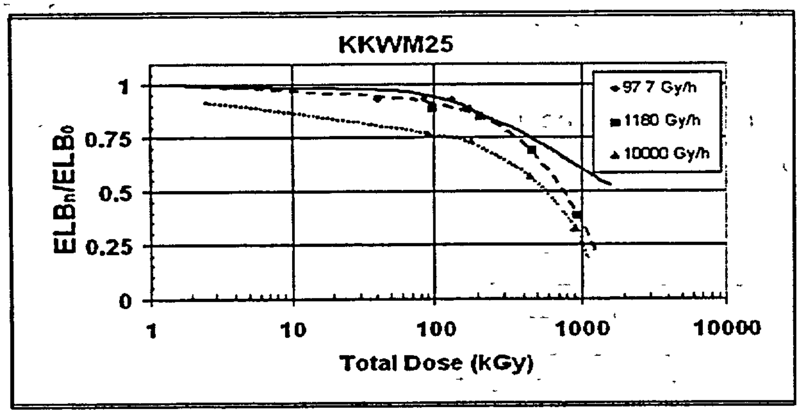
Compound	Calculated Life Time @90°(	Activation Energy [eV]
XS	185 years	1,42
XLPE	75 years	1,36
RXS	61 years	1,30
2-XI	44 years	1,26

*** XS : XL sheath**
*** XLPE : MV Insulation**
*** RXS : Radiation XL sheath**
*** 2-XI : XL-2 layer insulation**

3. Radiation Ageing

The radiation ageing investigation has been performed by the Belgian SCK-CEN Nuclear Research Centre. Tests on the used cable materials have been carried out with dose rates of 100, 1.000 and 10.000 Gy/h for total doses ranging from 50 to 1.000 kGy (1 Gy = 100 rad).
The results of the mechanical test performed after irradiation are shown by fig. 1 and fig. 2 for the sheathing material used for the LV-Power and Instrumentation & Control Cables.

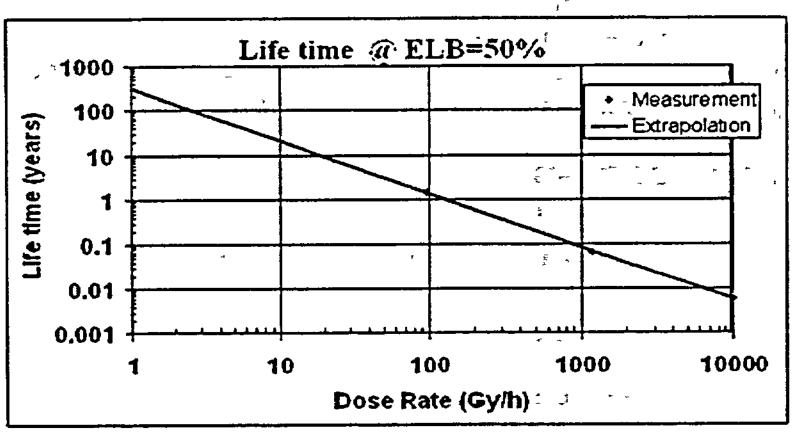
Test Results : XS - Mechanical tests



XS: XL sheath

Fig. 1: ELB_n / ELB_0 versus dose and dose rate

Test Results : XS - Life Time vs Dose Rate



XS: XL sheath

Fig. 2: Life time versus dose rate

The life time at lower dose rates of this sheathing material reaches more than 100 years.

4. Assessment of Fire Hazards

Basically, two tools are used to determine the fire behaviour of cables:

- laboratory level : a Cone Calorimeter [5] is used, which allows to collect all relevant fire related figures, such as heat release, time to ignition, combustion gas analysis, etc. at one time of the tested material.
- small and large scale test : these tests are performed on single conductors or cables or on cable bundles according to different international standards, such as UL 1581-1100, IEEE 383, IEC 60332-1, IEC 60332-3, etc.

The requested properties of flame retardant cables in point of view of safety of people and equipments are presented by fig. 3.

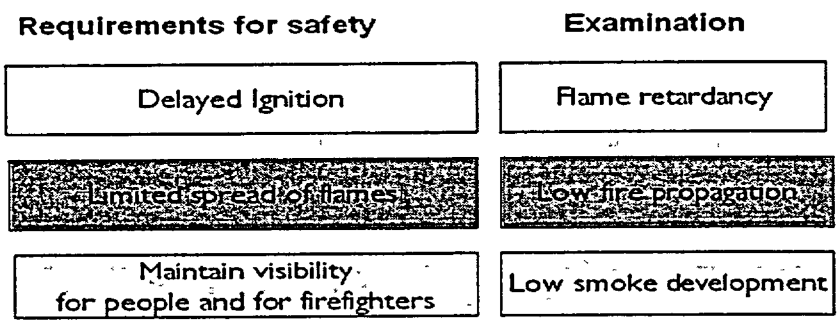


Fig. 3: Profile for fire testing

<u>4.1. Performed Flame Test</u>

The LV Power Cable and the Instrumentation & Control Cables have successfully been tested according to the standards UL 1581-1100 and IEC 60332-1. These tests are performed on a single conductor or cable with a 1 kW burner.
Tests on vertically placed bunched cables are realised with powerful burners according to IEC 60332-3, where 3 categories of severities are defined, as shown in fig. 4.

IEC 60332-3
Flame Propagation Test

- **Bunched cables mounted on a vertical ladder (h = 3,5 m)**
- **20 kW burner**
- **Flame exposure time 20 or 40 minutes, depending on test category**
- **Test categories: volume of combustible material**
  - **Category A: 7,0 liter / meter (40 min)**
  - **Category B: 3,5 liter / meter (20 min)**
  - **Category C: 1,5 liter / meter (20 min)**
- **Max. extent of damaged area: < 2,5 m**
- **Test performed before & after thermal + radiation aging**

Fig. 4: IEC 60332-3 Flame Propagation Test Conditions
These tests are performed before and after ageing (336 h @ 150 °C and 250 kGy @1 kGy/h).

The fig. 5 and 6 show schematically the flame height versus time.
The burner is shut down after 40 minutes. A post-combustion duration of 1 hour is permitted and the charred portion of the cable bundle may reach 250 cm in height.

The tested Instrumentation Cable performs very well before and after ageing; the charred portion reaches only 80 cm and the post-combustion lasts 1 minute.

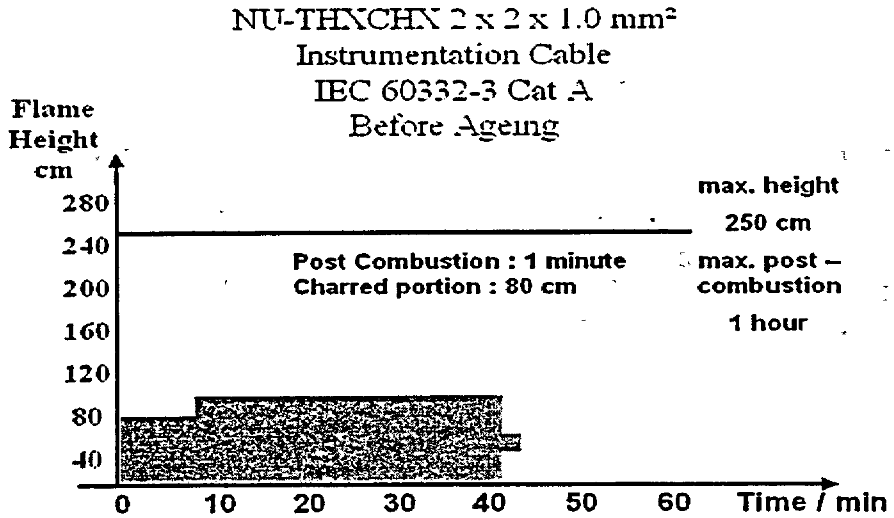


Fig. 5: Flame spread before ageing

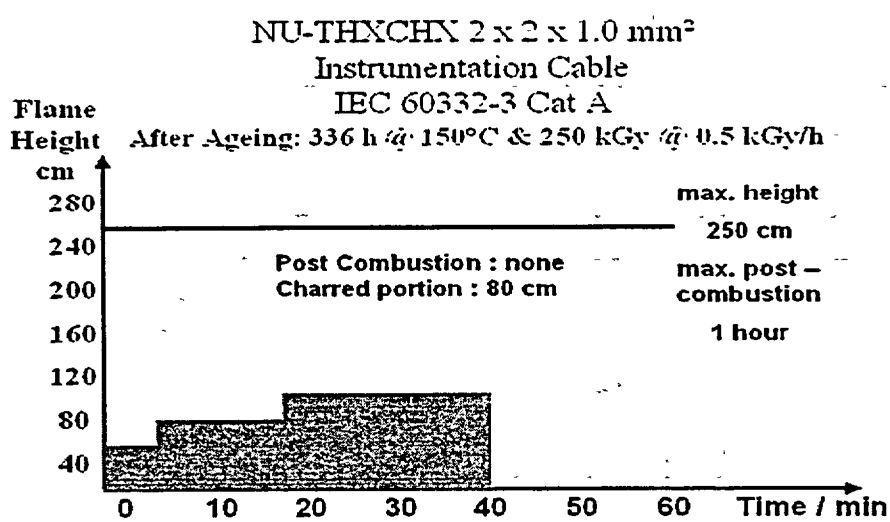


Fig. 6: Flame spread after ageing

4.2 Self-Ignition Test

The LV-Power Cables have also been tested according to the Swiss Specification AS-E-

P 82001. By injection of a current, the conductors of the tested cable are brought to a temperature of 500 °C within 3 minutes.
The conductor temperature of 500 °C is maintained during 10 minutes. No self-ignition is permitted during this test.
A Power Cable NU-EHXHX 3 x 2,5 mm² was tested by injecting a current of 500 A on the 3 conductors connected in parallel.

The cable dissipated a pale smoke but no self-ignition occurred.

5. Smoke Density Measurement

PVC and Hypalon sheathed cables produce large quantities of corrosive fire gases and dense smoke.
Low smoke density is important for a fast escape of the people and for the rapid access of the fire fighters to the fire.
The measurement of the smoke density is performed according to the IEC 61034 Standard, where a determined length of cable is burned in a 3 m-side cubicle. The light transmission through the cubicle is measured by means of a light beam and a photocell. The comparison between a PVC-Power Cable 3 x 2.5 mm² and a LSZH-FRNC-Power Cable NU-EHXHX 3 x 2,5 mm² is shown by fig. 7.

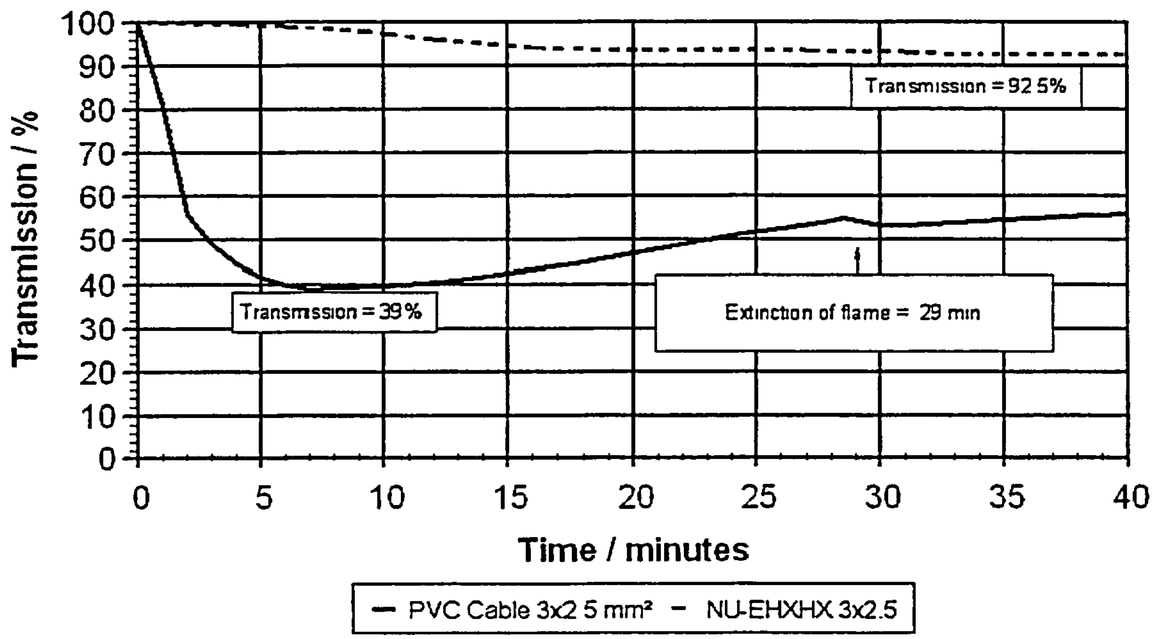


Fig. 7: Comparison of smoke light transmission, PVC-Cable and LSZH-FRNC-Cable
The dark and dense smoke of the PVC-Cable cuts the light transmission to 15 %, while the pale smoke of the FRNH-Cable permits a light transmission of more than 90 % over the whole test duration.

6. Corrosivity of Combustion Gases

Corrosive combustion gases attack especially electrical contacts and electronic circuits; therefore the follow-up damages of a cable fire are important to consider.

The corrosivity of the combustion gases of cable materials is determined according to the IEC 60754-1&2 standard. A sample of the cable material is burned under determined conditions in a tubular ceramic oven; the combustion gases are captured in a cell filled with distilled water. The pH-value and the conductivity σ of that water is measured and the following values must be respected:

$pH \geq 4.3$
$\sigma \leq 10\ \mu S/mm$

The following table shows an example of measured values:

Compound	pH-value	Conductivity µS/mm
PVC	2.6	194
Hypalon 40	1.73	378
FRNH	6.7	0.6

These results demonstrate that the combustion gases of the LSZH-FRNC material are much less aggressive than those of PVC or Hypalon.

7. 1E-LOCA Type Test

The complete type test of the 1E-LOCA Cables have been performed according to the block-diagram of fig. 8.

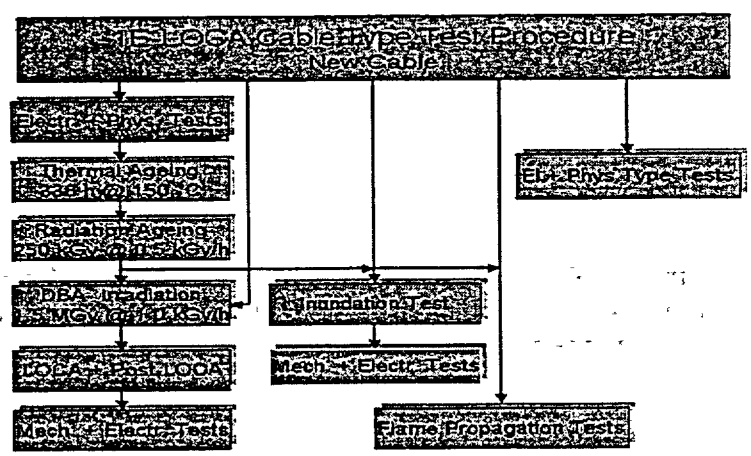
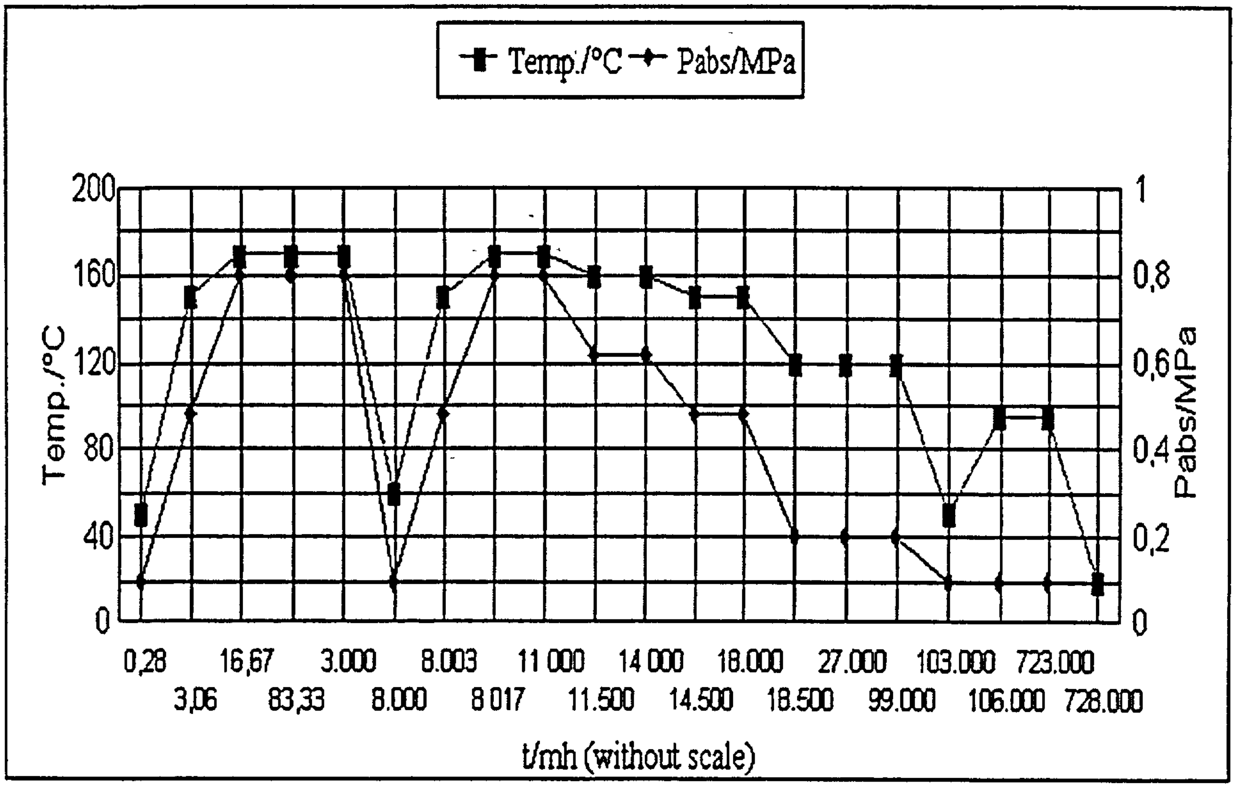


Fig. 8: LOCA-Test Procedure

The LOCA-test is performed according to the temperature & pressure versus time diagram with saturated steam as shown by fig. 9.



1 MPa = 142 psi

Fig. 9: Typical LOCA- temperature / Pressure Diagram

The cables are energised during the LOCA and Post-LOCA test; the current corresponds to the maximum allowed ampacity at 50 °C.

8. Mechanical and Electrical Properties

8.1 The mechanical properties of the cable insulation and sheath and the electrical properties of the insulation have been measured at different stages during the type test. Fig. 10 and 11 show the relevant elongation at break figures.

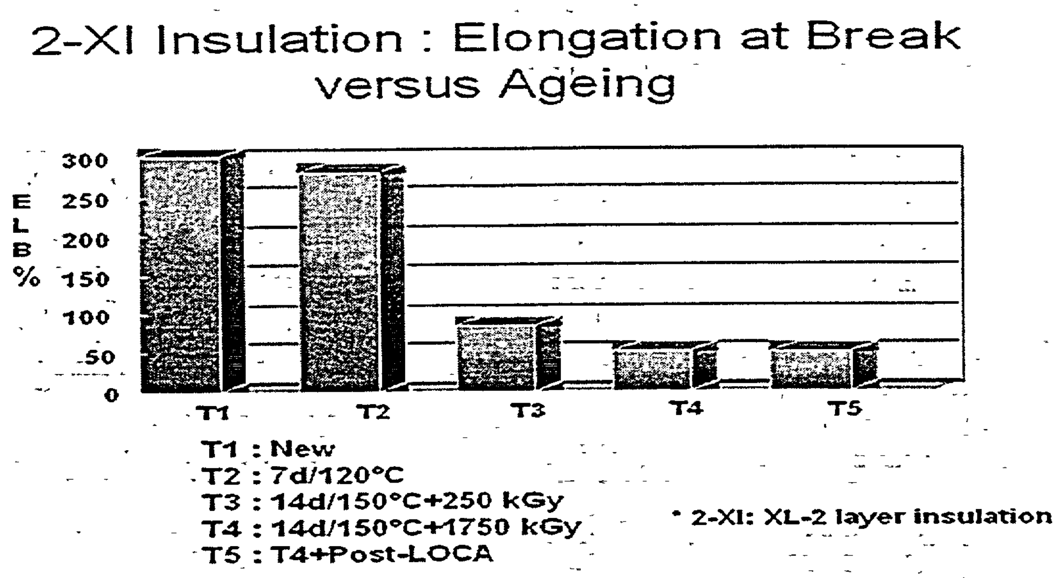


Fig. 10: LSZH-FRNC-XL double layer insulation, ELB versus ageing

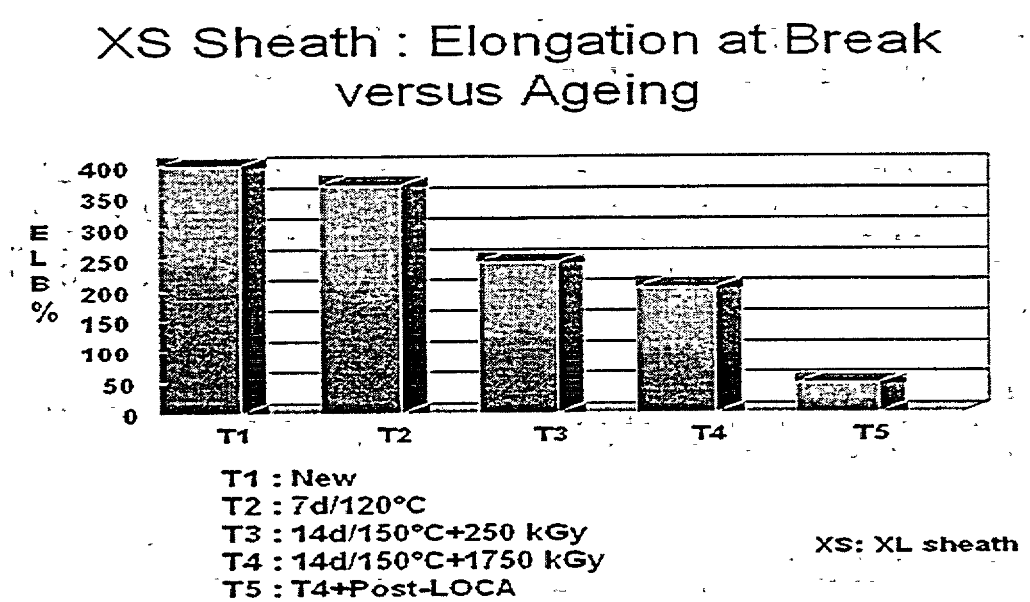


Fig. 11: LSZH-FRNC-XL sheath, ELB versus ageing

The elongation at break of both materials is approx. 50 % at the end of the Post-LOCA test. The cable therefore shows a good flexibility and mechanical performance at the end of all tests.

8.2. The electrical properties of the cable insulation have also been monitored at different stages. The relevant figure is the insulation resistance, expressed in MΩ.km, shown for an Instrumentation Cable NU-THXCHC 2 x 2 x 1.0 mm² by fig. 12.

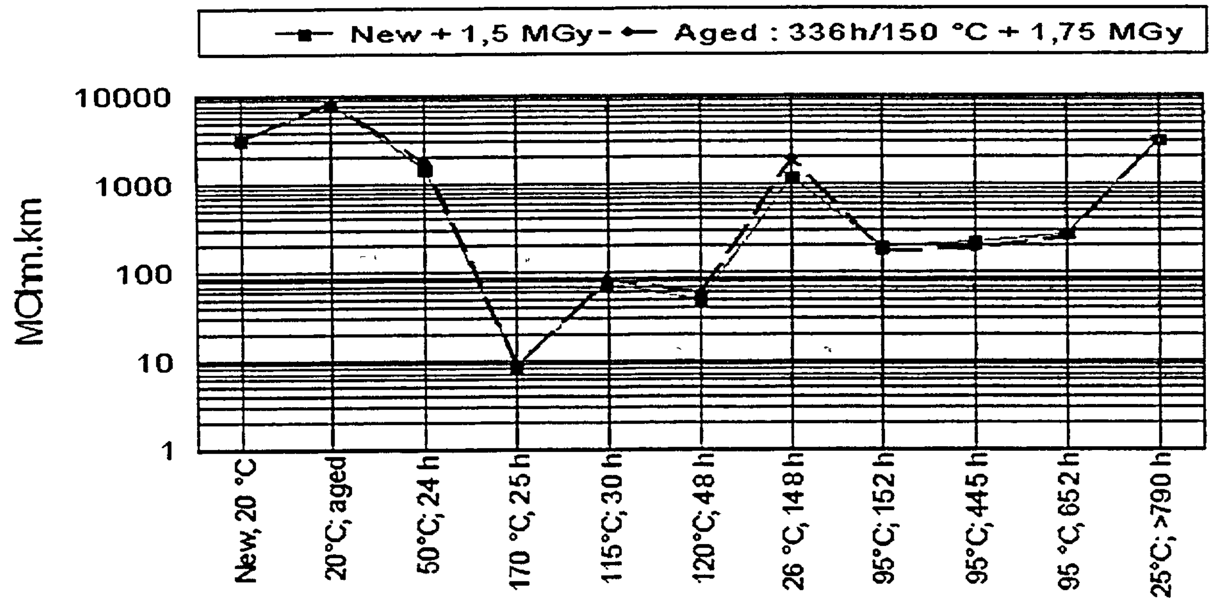


Fig. 12: Insulation Resistance of an Instrumentation Cable NU-THXCHX 2 x 2 x 1.0 mm² Before and after ageing, as well as before, during and after LOCA & Post-LOCA test

The initial figure of 3000 MΩ.km is nearby recovered at the end of the Post-LOCA test. This figure is remarkable high, considering the thermal ageing (336 h @150 °C), the radiation ageing (1.75 MGy), the two thermo-dynamic impulses (2 impulses @170 °C during 3 h, see fig. 9), the cooling down period of approx. 90 h and the Post-LOCA at 95 °C during approx. 720 h.

9. Conclusion

By monitoring especially the elongation at break of the cable materials and the insulation resistance of the cable during the type test, relevant mechanical and electrical data have been obtained.

These figures allow the NPP operator to evaluate the consumed life time, the actual status and the remaining life time of the cables installed in his system or equipment.

Furthermore, the fire behaviour of FRNH materials and cables have been demonstrated. These outstanding properties of the LSZH-FRNC-cables will be improved in the future by using nanocomposites [6, 7]. These compounds are presently under development and a stronger char formation on the surface of the cable jacket will still improve the performances during fire.

References

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Cable Aging and Fire Risk

International Conference on
Wire System Aging
April 23-25, 2002
Rockville, Maryland USA

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Sandia National Laboratories
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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company for the United States Department of Energy under contract DE-AC04-94AL85000

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Topics

- Five-minute tour of the USNRC/RES Fire Protection Research Program 1974-2002 (with a focus on cable-related studies)
- USNRC research on cable fire aging behavior
- Current perspectives and issues for fire risk analysis as related to cables

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USNRC/RES Fire Research 1974-1979

- Fire Protection Research initiated - late 1974
- 1975 Browns Ferry NPP fire put the focus squarely on cables
  - Fire behavior
  - Mitigation
- 1979 – Appendix R calls for defense in depth fire protection
  - Fire prevention
  - Fire intervention (e.g., detection, suppression, barriers)
  - Safe shutdown path free of fire damage
- Cables a key factor in implementation challenges

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RES Program 1979-1995

- 1979-82 – Research program focuses on verification of Appendix R provisions
- 1979-82 – First true fire PRA methods emerging
  - USNRC/RES-sponsored efforts at UCLA
- 1983-1986 – Fire protection research program focuses on PRA tools and data
- 1983-1990 – Early fire PRA applications
- 1988-89 – Fire Risk Scoping Study
- 1990-1995 – PRA applications take a prominent role in USNRC/RES programs
- 1990-95 – Fire Protection Program looks at fire aging (more later)

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1995-Present

- IPE and IPEEE risk studies
- Risk-informed regulatory approach emerges and is endorsed by USNRC
  - (e.g., NRR initiates risk-informed fire inspections)
- Fire Risk Research Program initiated and continues today - involves:
  - NRC staff efforts
  - Sandia National Laboratories
  - University of Maryland
  - Various private contractors
  - Cooperative research agreement with EPRI
  - International collaborations

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The Fire Aging Program and Cables

- Five focus areas – The Impact of Aging on:
  - Cable flammability NUREG/CR-5619 *
  - Cable thermal damage limits NUREG/CR-5546 *
  - Relay thermal damage limits (NUREG/CR-6220)
  - Penetration seals (SNL Letter Report)
  - Fire protection systems (SAND95-1361)
- For the two cable studies we tested:
  - XLPE/Neoprene - Rockbestos FIREWALL III
  - EPR/Hypalon - BIW Bostrad 7E
- Accelerated thermal aging applied (no radiation aging)

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Cable Flammability and Aging

- Basis: Four large-scale vertical cable tray fire tests using FMRC developed test configuration
- Three primary measures – all showed substantial decline with aging:
  - Rate of fire growth
  - Rate of heat release
  - Total heat release

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Cable Flammability and Aging (cont)

- Conclusion: Cable flammability was substantially reduced by accelerated thermal aging
- Conclusion should be relatively generic:
  - Aging is an oxidation process like fire
  - Aging should reduce the flammability of most insulation and jacketing materials

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Cable Thermal Damage Limits

- Basis: Air-oven tests
  - Various exposure temperatures 320-450C
  - Nominal step change
  - About 100 total test exposures each with two energized cable samples
- Primary measure: Time to electrical failure versus exposure temperature
  - Monitor electrical performance for up to 80 minutes
  - Measure conductor-conductor leakage currents
  - "Dead short" indicated by fuse blow

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Cable Thermal Damage Limits (cont)

- Results: Mixed
  - One cable products showed modestly higher damage threshold
  - Second cable showed lower threshold
  - Neither cable's threshold changed substantially (i.e., on the order of +/-20C)
- Conclusion: Damage threshold changed, but change not risk-significant, within uncertainty bounds.

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Cable Thermal Damage Limits (cont.)

- We also correlated fire damage thresholds to Equipment Qualification results for same cables
  - NUREG/CR-6095
- Very good correspondence between the IR degradation results in EQ test and fire damage thresholds
- Implication: High-temperature steam tests can provide thermal damage information applicable to fire analysis
- Ref: Fire and Materials 1st International Conf., Washington DC, Sept. 1992, (SAND92-1404C).

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Current Perspectives on Fire Risk

- Risk is a combination of two factors
  - Likelihood that an accident will occur
  - Consequences of the accident
- Fire risk is often found to be an important contributor to overall risk for nuclear power plants (e.g., the IPEEE studies)
- Fire PRAs weigh reliability and effectiveness of the defense in depth protections to assess residual risk

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Fire Risk and Electrical Cables

- Virtually every plant system is dependent on the continued operation of power, control, and/or instrument cables
- Cables have long been a focus of fire risk evaluation
  - Fuel and ignition source
  - Target for fire damage
  - Pinch-point for critical systems
- Current interest focusing on circuit analysis issues
  - Cable Failure Modes and Effects Analysis

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Cable Failure Modes and Effects Analysis

- Cables display different modes of failure
  - Shorts to external ground
  - Conductor to conductor shorts
    - Hot short (short to energized conductor)
    - Short to grounded conductor
    - Intra- or inter-cable
  - Open circuit – loss of continuity
- Cable failure can cause various circuit faults:
  - Loss of function
  - Spurious operation
  - Loss of indication
  - Erroneous instrument readings
- Each circuit fault may have unique risk implications

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Circuit Analysis – Work In Progress

- Need a process for circuit analysis quantification
  - Estimating cable failure mode likelihood
    - Recent testing by NRC (NUREG/CR in printing)
  - Mechanistic link between failure mode and circuit fault
  - Circuit fault likelihood
    - Recent industry tests and expert panel
- Overall risk analysis methods
  - Screening interactions
  - Interaction with plant response model
  - Interaction with Human Reliability Analysis
  - Demonstration applications and guidance

Sandia National Laboratories

Other Cable Fire Issues of Potential Interest

- Fire growth models for cables remain primitive
- Thermal damage models and criteria also remain primitive
- Performance of "fire-proof" cables uncertain
- Self-ignited cable fires still poorly understood

Sandia National Laboratories

Reducing Electrical System Wiring Fires

U.S. Consumer Product Safety Commission

International Conference on Wire System Aging

Fire Risk Assessment of Wire System Aging

Double Tree Hotel

Rockville, MD

April 23, 2002

About CPSC - Background

- Independent Federal regulatory agency, established in 1973 under the Consumer Product Safety Act
- Jurisdictional Authority for 5 Acts
  - Consumer Product Safety Act (CPSA)
  - Federal Hazardous Substances Act (FHSA)
  - Flammable Fabrics Act (FFA)
  - Poison Prevention Packaging Act of 1970 (PPPA)
  - Refrigerator Safety Act (RSA)
- 3 Commissioners, appointed by the President and approved by the Senate

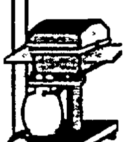
CPSC - Budget/Staffing

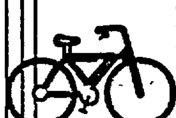
- Total Budget - $55 million in FY 2002
- About 480 staff
  - Headquarters (Bethesda, MD)
  - Field (throughout US)
  - Laboratory (Gaithersburg, MD)

CPSC - Jurisdiction


15,000 types of consumer products

- Electrical Appliances
- Combustion Appliances
- Furniture and Home Accessories
- Sports and Recreational Equipment
- Children's Toys
- Home Wiring
- Flammable Fabric, Materials, and Accessories
- Powered equipment and tools
- And more...








CPSC -Jurisdiction

Exceptions:

- Tobacco products
- Medical devices
- Food and drugs
- Automobiles
- Boats

- Aircraft
- Firearms
- Pesticides
- Cosmetics
- Workplace products

CPSC Functions

•Collect & Analyze Data

•Perform Applied Research

•Encourage Voluntary Standards

•Require Performance Safety Standards

•Require Safety Labeling

•Require Special Packaging

•Enforce regulations

•Recall Defective Products

•Ban Hazardous Products

•Inform Consumers

CPSC Data Sources

- National Electronic Injury Surveillance System
- Death Certificates
- In-Depth Investigation Reports
- Injury/Potential Injury File
  - Hotline/website reports
  - Newspaper accounts
  - Other sources
- National Fire Incident Reporting System (NFIRS)

CPSC Fire Loss Estimates

CPSC Epidemiology staff provides annual estimates of consumer product-related residential fire losses

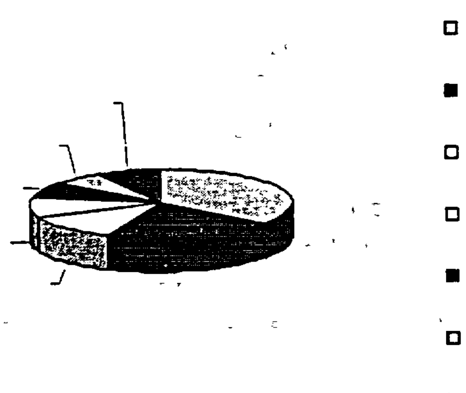
- National Fire Protection Association (NFPA) conducts an annual survey of fire departments and, from this, estimates national residential structure fire losses
  - Does not include details on causes of fire ignition or product involvement

CPSC Fire Loss Estimates

- U.S. Fire Administration's National Fire Incident Reporting System (NFIRS) compiles reports completed by participating fire departments
  - Reports include coding that describes fire cause and product involvement
- CPSC staff applies the proportions of the product-related fires from NFIRS against the NFPA national fire estimates to estimate total product-related fire losses.

Residential Electrical Distribution Fire Losses

38,800 Fires, 280 Deaths, 1,230 injuries and $680 million in property loss in 1998



CPSC History of Addressing Wiring Fires

Progressive effort since the Agency's inception

- In the late 70's, CPSC staff investigated problems with aluminum branch circuit wiring
  - Issued *Repairing Aluminum Wiring* pamphlet to advise consumers
- In 1987, CPSC staff conducted a special study of electrical wiring fires (149 in-depth cases)
  - Fires occurred in highest rate older homes
  - Improper modifications/installations also key factors

CPSC History of Addressing Wiring Fires

- Home Wiring Project focused on older homes
  - Push for re-inspection of electrical systems in existing residences
    - Adoption of NFPA 73 *Residential Electrical Maintenance Code for One- and Two-Family Dwellings*
  - Produced videotape demonstrations of incremental wiring repairs
    - Affordable steps to remove gross hazards
  - In 1994, sponsored an Underwriters Laboratories study of technology for detecting and monitoring conditions that could cause electrical wiring fires

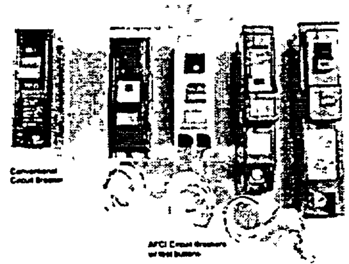
CPSC History of Addressing Wiring Fires

- UL study found that arc fault detection appears to be very promising, especially when added to an existing circuit protection device, e.g., a circuit breaker.
  - This can be further improved if combined with ground fault detection technology
- CPSC staff has had a longstanding involvement with the *National Electrical Code®,* including membership on Code-making panel 20 (now CMP-17)

Arc Fault Circuit Interrupters (AFCIs)

- By 1997, residential circuit breakers with arc fault were becoming commercially available

Figure 2



AFCIs

- CPSC staff submitted proposals for 1999 *NEC* to require AFCIs for all branch circuits
- Compromise position was requirement for circuits supplying power to bedroom receptacles to have AFCI protection; delayed effective date of Jan 2002
  - Adopted in 1999 *NEC*
- No significant change in requirements for AFCIs in 2002 *NEC*
- Breakers with combination AFCI and personnel ground fault protection available

Future

- Continue to support upgrades to the *NEC* through proposals for the 2005 Code
- Support AFCI technology for older homes
- Assess technology for distribution system components that could further reduce electrical wiring fires

BRE

INTERNATIONAL CONFERENCE ON WIRE SYSTEM AGING

TECHNICAL SESSION 2 - "FIRE RISK ASSESSMENT OF WIRE SYSTEM AGING"

Dealing with fire risk in aged cabling. Guidance from fire research in the UK

P.J. Fardell, Fire and Risk Sciences Division, Building Research Establishment, UK

FRS LPC

BRE

BUILDING RESEARCH ESTABLISHMENT? FIRE AND RISK SCIENCES?

- BRE was a formerly a UK government research laboratory, concerned with all aspects of the "built environment".
- BRE is now a private research and consultancy company.
- FRS was the "Fire Research Station".
- FRS is now the Fire and Risk Sciences division.
- FRS is concerned with all fire matters including buildings, structures, contents, industry and transport.

BRE

CABLE FIRES: FOUR STUDIES

- FIRE CHECK CONSULTANTS (SPI, USA) - 6 months - "Real-Scale" studies.
- PARTNERS IN TECHNOLOGY, PIT (DETR, 6 industrial partners, academia, technical advisors) - 3 years - General hazards of cables in hidden voids.
- PARTNERS IN INNOVATION, PII (DETR, 10 industrial partners) - l year - "Cables and the CPD reaction-to -fire requirements"
- THE "SEVEN DIALS" CABLE FIRE, LONDON

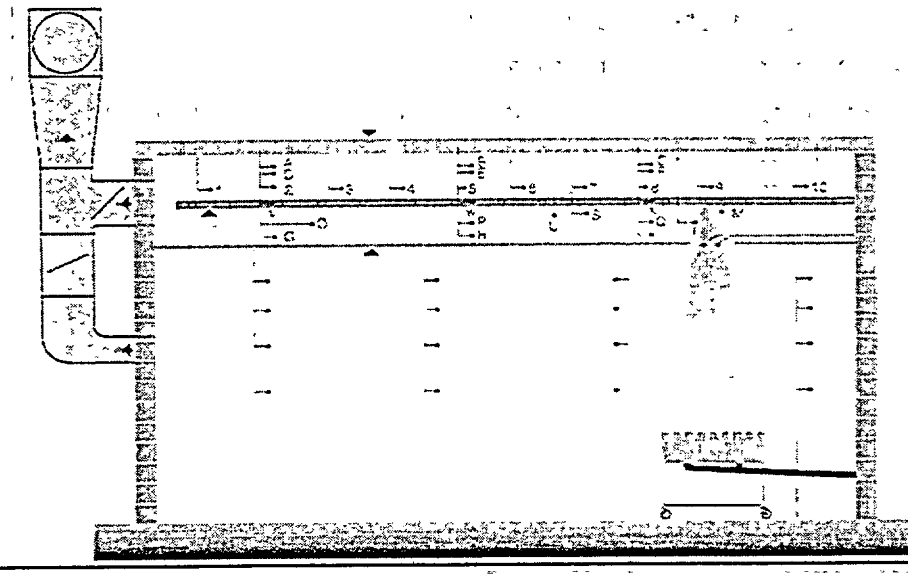
BRE

FIRE CHECK CONSULTANTS (SOCIETY OF PLASTICS INDUSTRY)

- Research for the Society of Plastics Industry (USA).
- 6 full scale tests planned, object:
  - to determine the effects of HVAC on cable flammability.
  - to determine the effectiveness of HVAC in clearing smoke.
  - To investigate potential differences between different cable materials.

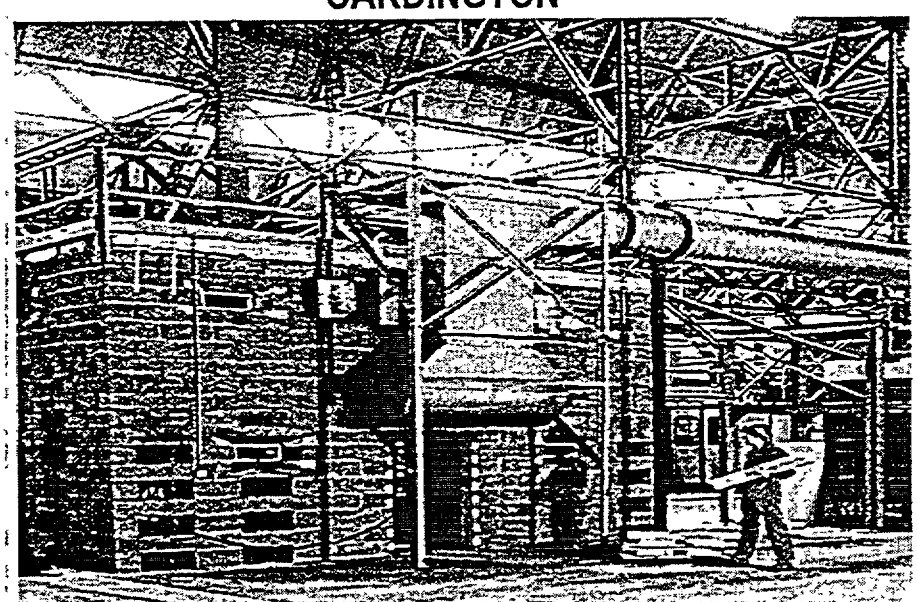
BRE

THE BRE REAL SCALE SCENARIO-BASED TEST RIG FOR CABLE FLAMMABILITY



BRE

PLENUM TEST RIG, CARDINGTON



BRE

CONCLUSIONS - FIRST 6 TESTS

- HVAC could spread fire and products around whole of building.
- Smoke clearance was possible but could lead to intense fires.
- Fire source (1MW for 45 minutes) was moderate - (c.f. later NIST office fires).
- Large differences between different cable materials - c.f. Standard test results.

BRE

3 Year "Partners in Technology" Research Programme

- Justified through:
  - Rapid increase in IT usage - great demand for new cabling.
  - New cables alongside old in hidden voids (floors, risers and plenums) - very high density and "fuel load".
  - Very large, poorly compartmented hidden spaces.
  - HVAC role of spaces - potential contamination/fire spread throughout building.

BRE

3 Year "Partners in Technology" Research Programme

- Very little fire detection/suppression in hidden voids.
- Testing/regulation regimes very varied (globally).
- Potential for a fire to spread undetected and unchecked with a large "fuel" load, over a wide area with possible spread of fire, smoke, toxic, irritant and corrosive gases around a building or industrial plant.

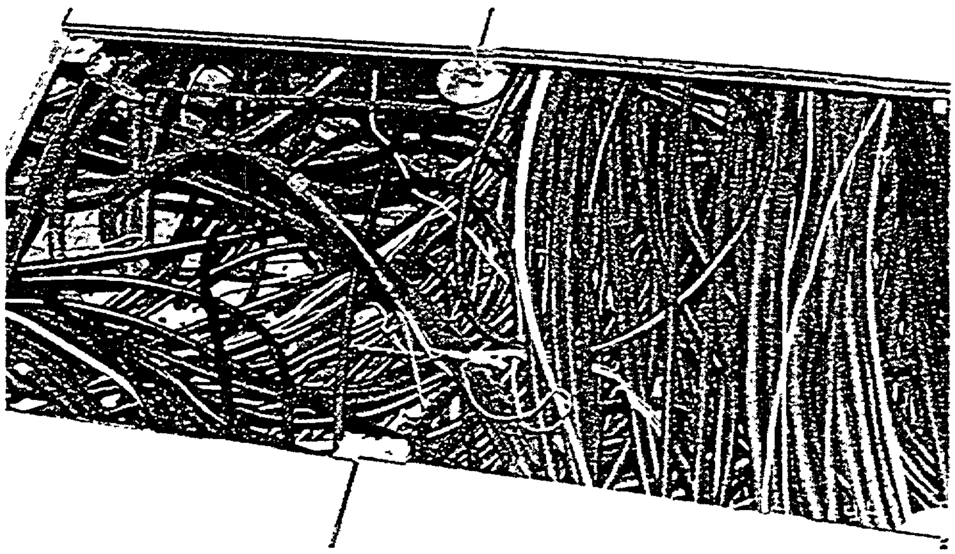
BRE

PARTNERS IN TECHNOLOGY - Study scheme

- Cable installation survey.
- "Real-scale" scenario-based test programme.
- "Small-scale" tests (cone calorimeter).
- Numerical modelling (zone and field).
- "Standard" test methods - how realistic?

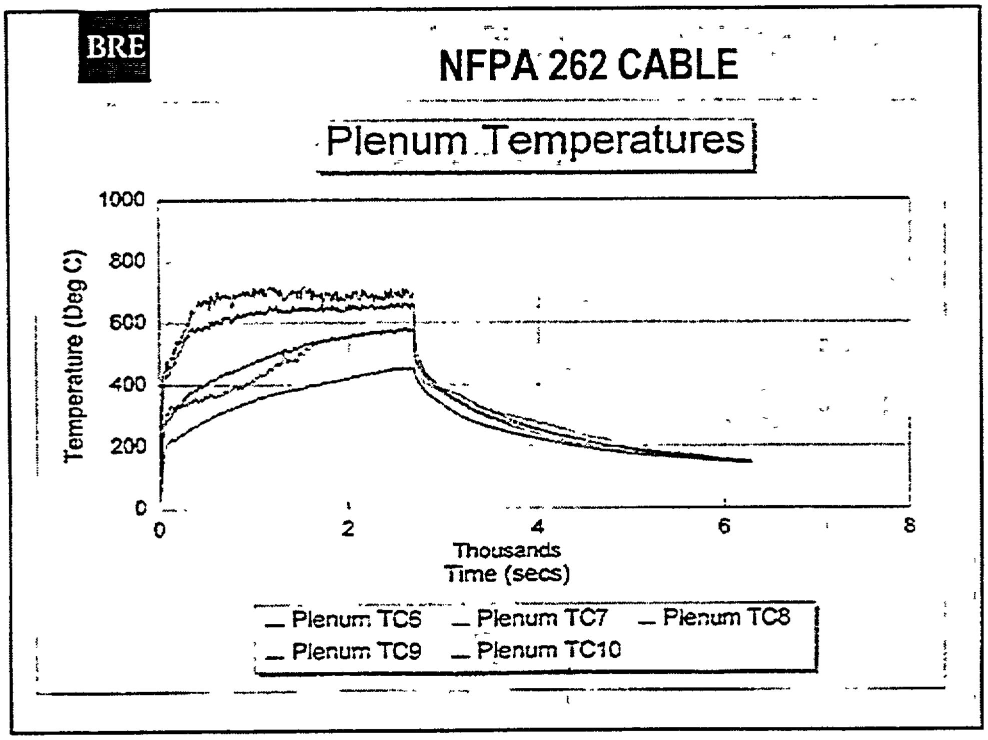
BRE

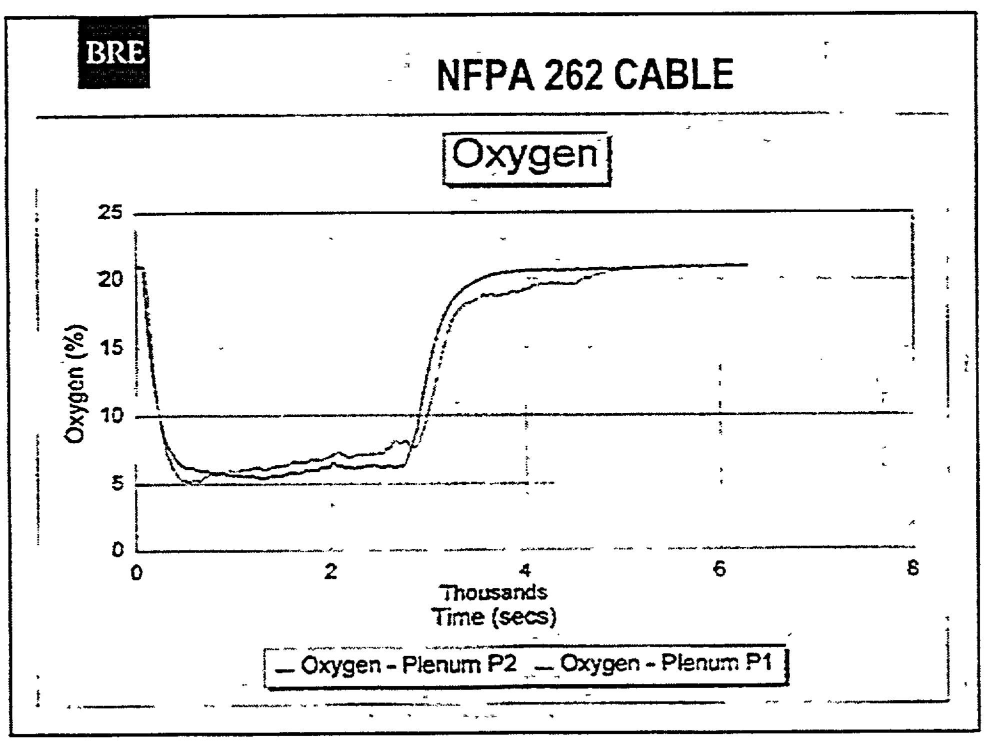
THE PROBLEM...



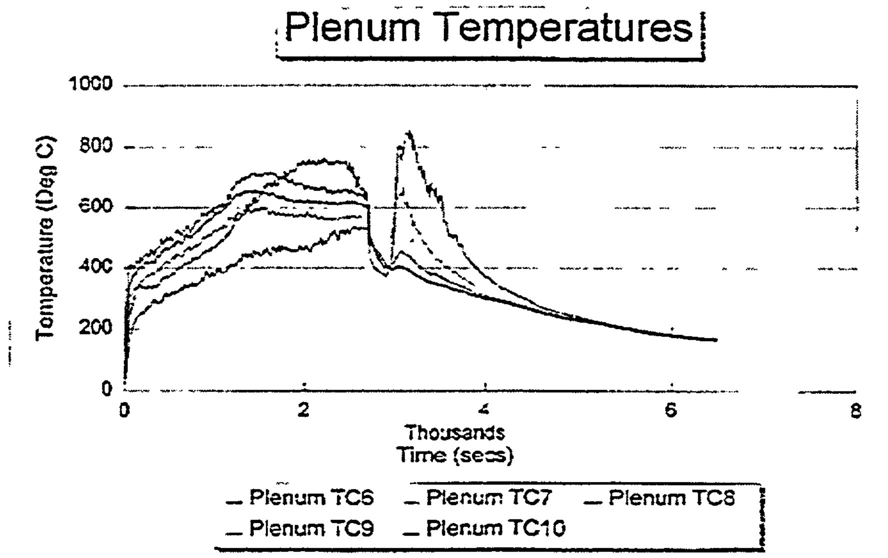
BRE

Fire spread along cable in plenum space

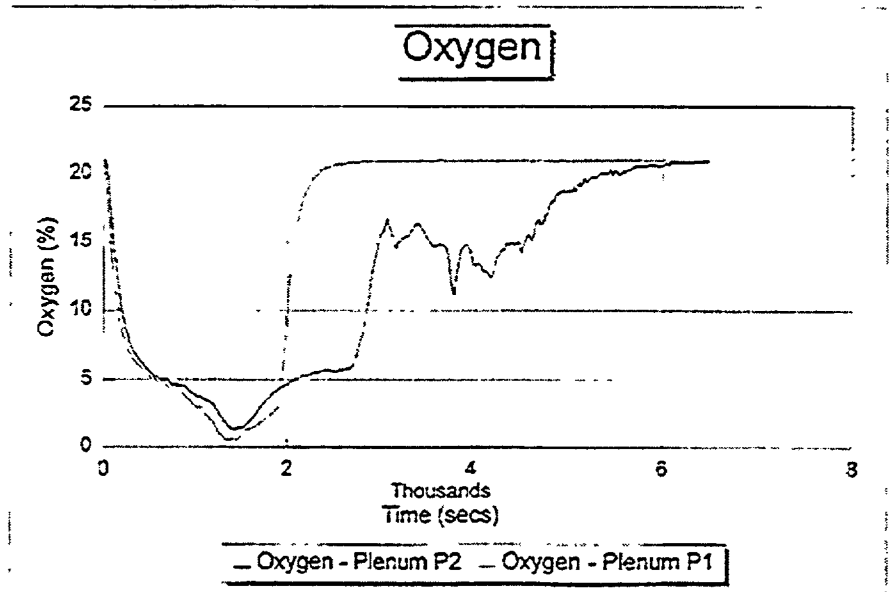

BRE
NFPA 262 CABLE
Plenum Temperatures
Temperature (Deg C)
1000
800
600
400
200
0
0
2
4
6
8
Thousands
Time (secs)
Plenum TC6
Plenum TC7
Plenum TC8
Plenum TC9
Plenum TC10


BRE
NFPA 262 CABLE
Oxygen
Oxygen (%)
25
20
15
10
5
0
0
2
4
6
8
Thousands
Time (secs)
Oxygen - Plenum P2
Oxygen - Plenum P1

prEN50266-2-4 (IEC 60332-3) CABLE

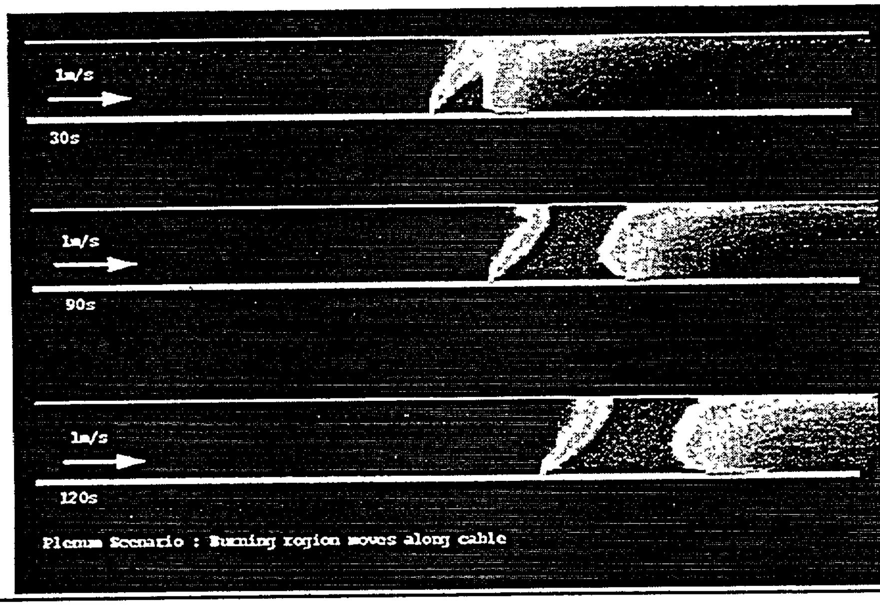


prEN50266-2-4 (IEC 60332-3) CABLE



BRE

CFD MODELLING - Spread away from source



BRE

SHOW PIT VIDEO

BRE

PARTNERS IN INNOVATION

- "CABLE FIRE TESTING AND THE CPD"

BRE

CLASSIFICATION SYSTEM

- 7 Classes "A1" (highest performance) "A2" "B", "C", "D", "E", "F" (lowest performance - no requirement).
- Highest performance - bomb calorimeter, prEN ISO 1182 and non-combustibility apparatus, prEN 1716.
- Lowest performance - small flame, prEN ISO 11925-2.
- Intermediate performers - SBI, prEN13823.

AIMS OF THE PII STUDY

- Characterise "harmonised" CPD RTF tests and existing and modified Standard cable fire tests for ability to meet CPD requirements.

- 6 tests chosen -
  - *FRS "real scale" plenum test rig*
  - *prEN13823 (Single Burning Item "SBI")*
  - *ISO 9705 (room corner test, "reference scenario" for SBI)*
  - *prEN50266-2-4 (IEC60332-3 vertical exposure)*
  - *prEN50289 (Horizontal Integrated Fire Test or "HIFT", a modified NFPA 262)*
  - *EN50268 (IEC61034 "3m³" test for smoke rating).*

AIMS OF THE PII STUDY

- Test commercially available cables with a wide spectrum of fire performance (i.e. as rated in Standard cable fire tests)
  - Nine cables tested
    - *IEC 60332/3C 4-pair UTP CAT 5*
    - *IEC 60332/3C 4-pair UTP CAT 5*
    - *IEC 60332/3C 4-pair STP CAT 7*
    - *CMP 4-pair UTP CAT 3*
    - *CMP 4-pair UTP CAT 3*
    - *CMP 4-pair UTP CAT 5*
    - *CMP 4-pair UTP CAT 5*
    - *CM 4-pair UTP CAT5*
    - *OFNP 12 core fibre optic*

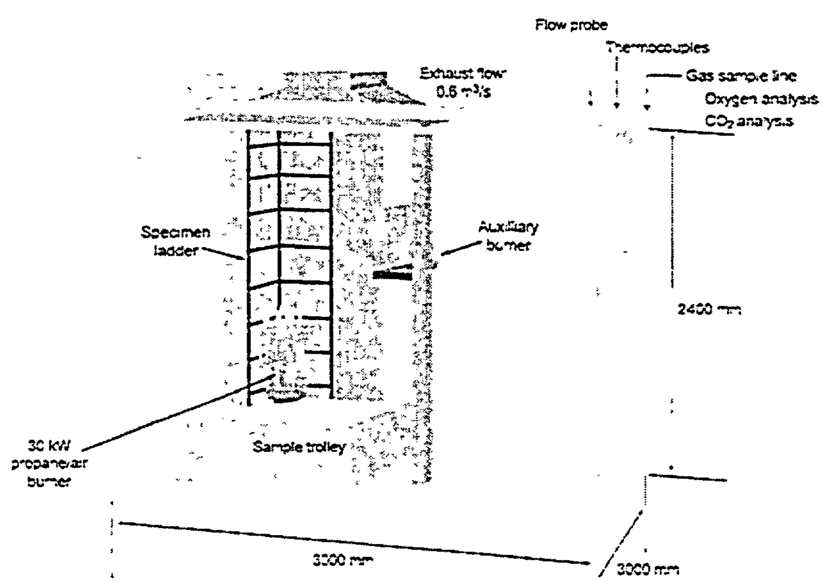
BRE

"HARMONISED" REACTION TO FIRE TEST REQUIREMENTS

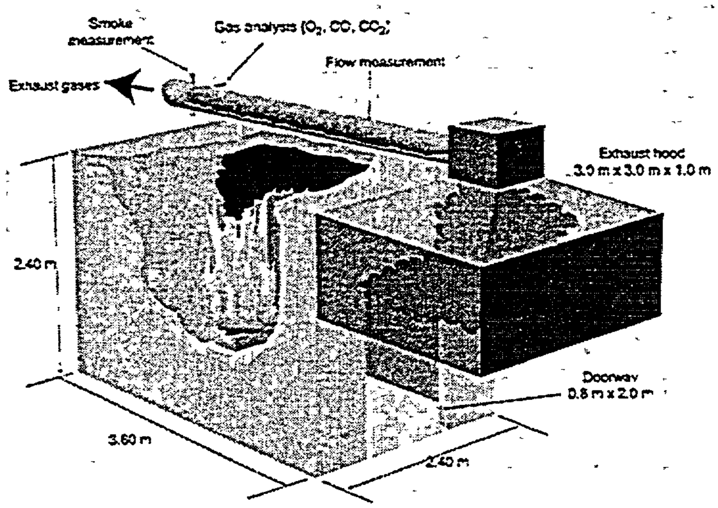
- Ignitability
- Flame spread
- Heat Release Rate
- Burning droplets
- Smoke
- Derived parameters
  - Fire Index Growth Rate - "FIGRA"
  - SMoke Index Growtn Rate - "SMOGRA"

BRE

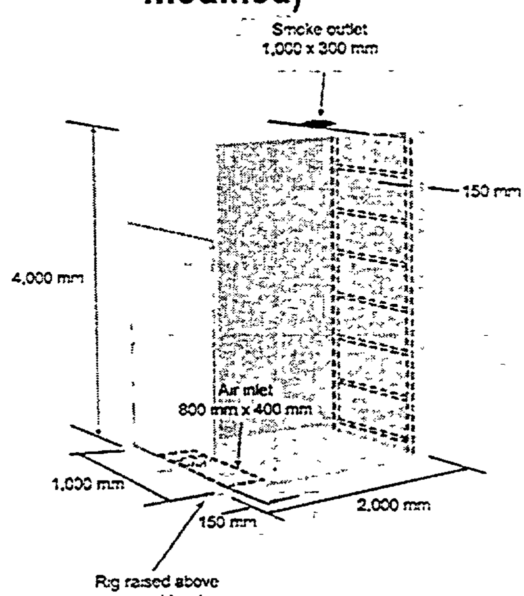
prEN 13823 "SBI"



ISO 9705 ROOM CORNER

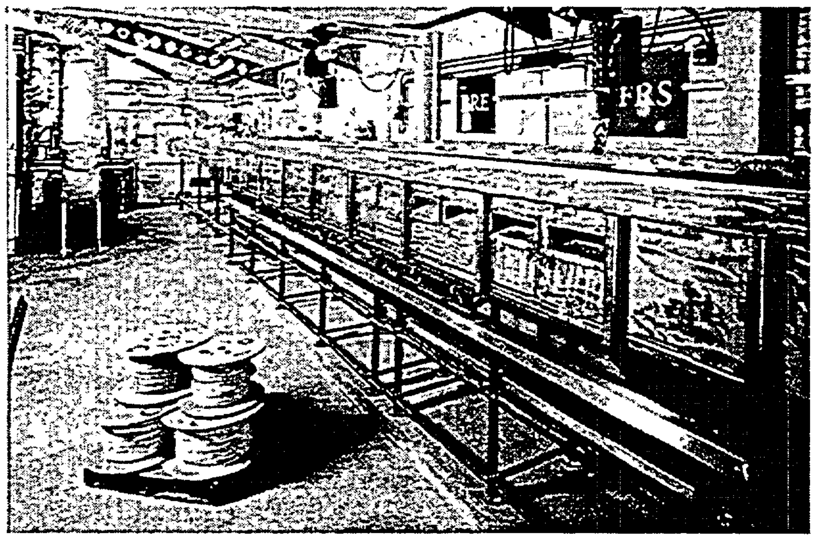


prEN 50266-2-4 (IEC 60332-3 modified)



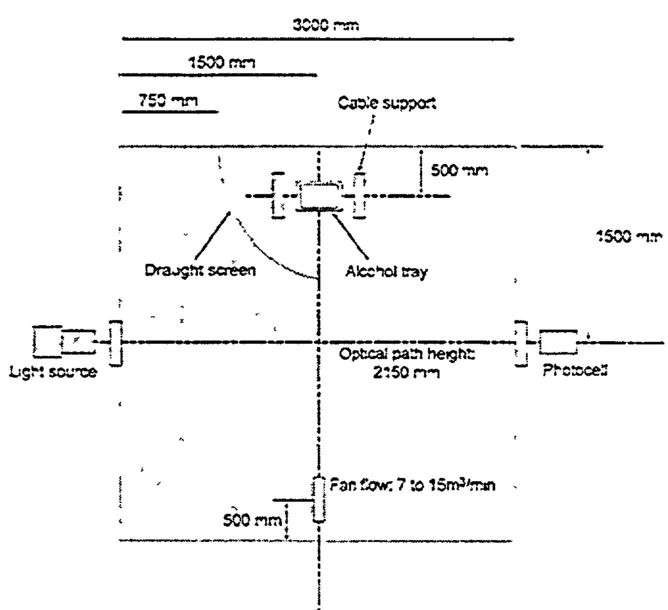
BRE

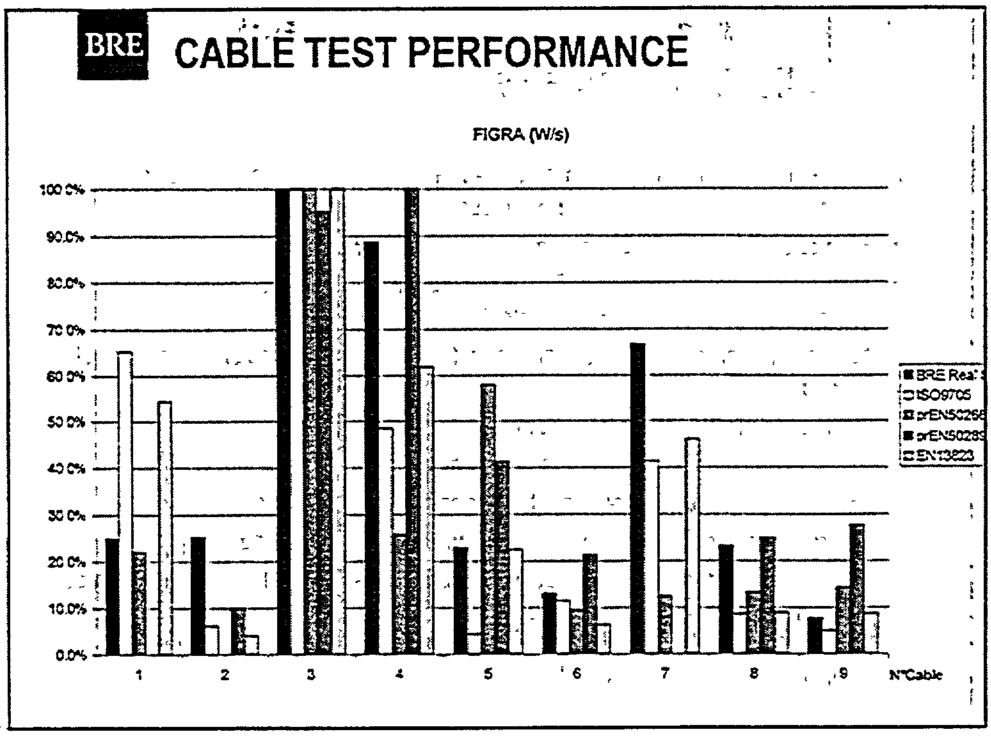
prEN50289-4-11 (HIFT)



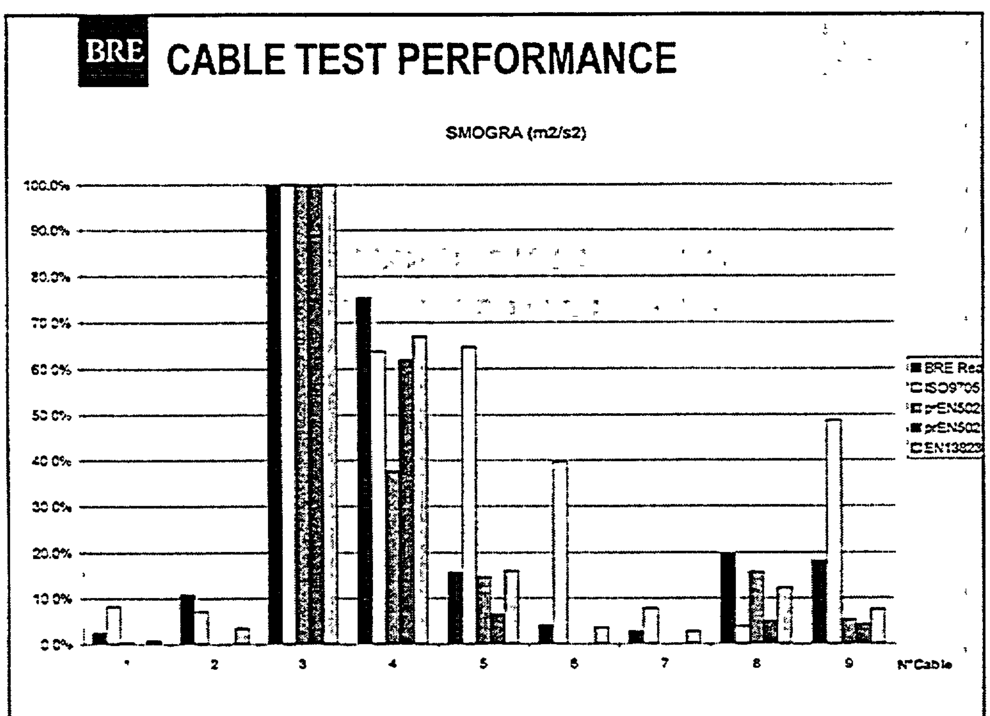
BRE

EN50268 (IEC 61064)





BRE
CABLE TEST PERFORMANCE
FIGRA (W/s)
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
1
2
3
4
5
6
7
8
9
N°Cable
ISO9705
EN13823



BRE
CABLE TEST PERFORMANCE
SMOGRA (m2/s2)
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
2
3
4
5
6
7
8
9
N°Cable
ISO9705

BRE

FINAL MESSAGES

- Cable installations are growing at a rapid rate - leading to rapidly increasing fire loads in buildings and industrial premises.
- High and low performance cables are often installed side by side.
- New hazards have been identified, including the risk of explosive ignition of cables in oxygen depleted fire environments.
- "Standard" test results and designations do not always give the best indication of hazard.
- New research is urgently needed in the fields of:
  - vitiated conditions (explosion hazards)
  - toxicity and corrosivity (e.g. cf. halogen/non halogen cables)
  - guidance documentation for specifiers, installers, users and fire fighters!
- "Communication cables don't just burst into flames - there will normally have to be another fire present. If there was ever a case for the application of performance - based testing and a fire safety engineered approach - as opposed to a simple "pass/fail" judgement - this is it".

BRE

CONCLUDING SESSION
"SEVEN DIALS" VIDEO

Appendix F: Papers and Presentations from Technical Session 3
Risk Significance of Wire System Aging

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Appendix F - Table of Contents

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A Scoping Study on the Core Damage Frequency Impact of Cable Failures Due to Harsh Environment in a PWR and a BWR

Pranab K. Samanta and Gerardo Martinez-Guridi
Brookhaven National Laboratory
Upton, NY 11973-5000

Abstract

The automatic and manual operation of safety systems in a nuclear power plant (NPP) rely on cables and related equipment, such as electrical penetration assemblies and terminations, for power, control, and instrumentation signals. During an accident that creates a harsh environment, the cables need to perform reliably to operate the electrical equipment to meet the system's performance requirements. The performance capability of cables during accidents is addressed through environmental qualification of electrical equipment. In this paper, we present a scoping study of the impact of cable failures on the NPP's risk using core damage frequency (CDF) as the risk measure.

We assess the impact of cable failures due to the harsh environment using the probabilistic risk assessment (PRA) model of the internal initiators in a plant. However, in the PRA of NPPs, the cable reliability in a harsh environment is typically assumed to remain unaffected. Also, typically, cables are not explicitly modeled in a PRA, and the effect of their failure on hardware and operator's actions is not directly addressed. We use existing PRA models to evaluate the impact of cable failures through the modeled component's and operator's actions. Several assumptions are made. Sensitivity analyses are conducted to assess the impact of failures of cables providing different functions inside the containment. The impact on CDF and the accident sequences that become dominant contributors when cables fail are studied. The relative CDF significance of cables providing different functions is obtained. A pressurized water reactor (PWR) plant, Surry Nuclear Power Station, and a boiling water reactor (BWR) plant, Peach Bottom Station, are studied.

1. INTRODUCTION

Electrical equipment used to perform a safety function in a nuclear power plant (NPP) must operate reliably under all service conditions, i.e., during normal operation as well as under harsh environments caused by accidents. The automatic and manual operation of safety systems rely on cables and related equipment, such as electrical penetration assemblies (EPAs) and terminations, for power, control, and instrumentation signals. For brevity, the word "cable" will be used to include cable connectors, splices, and penetrations. The performance of electrical equipment on demand to meet the system's performance requirements is addressed through environmental qualification (EQ) of electrical equipment.

To determine the ability of cables to perform during an accident, the U.S. Nuclear Regulatory Commission (USNRC) conducted tests to assess the validity of the current qualification methods.

This research, carried out at Brookhaven National Laboratory (BNL), focused on low-voltage electrical cables used for instrumentation and control applications in NPPs. The issues addressed are documented in NUREG/CR-6384 (Lofaro et al., April 1996) and NUREG/CR-6704, Vol. 1 and 2 (Lofaro et al., February 2001)..

Risk analyses of the effects of cable failures provide an integrated perspective to related issues that can be addressed in a risk-informed decision-making process. The number of cables in a NPP is substantial, and risk analyses can provide a risk-informed basis for decisions on cables throughout the operating life of a plant and also for the renewing licenses. A scoping study was undertaken to bring in risk perspective and to identify the specific issues that can be addressed in a risk-informed decision-making process (Samanta and Martinez-Guridi, 2002).

2. CABLES AFFECTED BY A HARSH ENVIRONMENT

The concern about cables primarily relates to their reliability in a harsh environment, i.e., whether they will perform their intended function under such conditions. The cables that may be exposed to harsh environments are qualified to withstand them, but with age and use, they may degrade increasing the likelihood of failures.

Cables can be exposed to harsh environments due to accidents at a plant. The accidents analyzed as part of the probabilistic risk assessment (PRA) models can be broadly categorized into two groups: (a) in-containment accidents and (b) accidents outside the containment. The former includes loss-of-coolant accidents (LOCAs) and main-steam-line break inside the containment; a high-energy line-break outside containment is an example of an accident outside the containment.

Here, we identify the cables that may be exposed to harsh environments. Simply, for in-containment accidents, the cables inside the containment can be exposed to harsh environments. Essentially, we focus on these cables. Since our interest is in conducting a PRA-based evaluation, we concentrate on cables that are included in the PRA model, i.e., the cables that support the actuation and operation of components modeled in the PRA. The operator's actions that depend on readings from instruments whose cables could be affected are also considered. A list was prepared for a PWR and a BWR plant of the cables that are included in the PRA model and may be exposed to a harsh environment in an in-containment accident.

2.1 Approach Used to Identify Cables Affected By Harsh Environments

The cables that may be affected by harsh environment are identified using the PRA models of a plant, the plant's system drawings, and the Regulatory Guide (RG) 1.97, "Instrumentation for Light-Water-Cooled Nuclear Power Plants to Assess Plant and Environs Conditions During and Following an Accident." The RG lists the variables that are measured and indicated in the control room. In many cases, cables are likely used inside the containment in measuring plant variables. Depending on the type of the accident, location of the break, and the location of the cables, the cables that are affected by the accident can be identified. System drawings are used to judge the cables that are inside the containment and hence may be exposed during an accident. Since our focus is on Level 1 PRA evaluations, we identify only the cables that can affect these evaluations. In other words, there are additional cables that are exposed to harsh environments and affect the risk of radioactive release and health consequences (Level 2 and 3 PRA evaluations), but presently, they are not identified.

The approach used to identify the cables that could be affected by harsh environment can be summarized as follows:

1. RG 1.97 is reviewed to identify the variables that are monitored and are potentially measured inside the containment. The variables that are incorporated in a typical Level 1 PRA analyses are selected. System and PRA models are reviewed, as described below, taking into account the variables identified.

2. The systems modeled in the PRA are examined to identify those portions that reside within the containment. Specifically, components within the system that are modeled in the PRA are reviewed to identify those within the containment. Within that list, those components that depend on cables for their operation or provide input for operation of other ones are identified. Each of these components is associated with cables that may be degraded by a harsh environment.

3. The instruments included in the PRA model that provide actuation signals in accidents which create a harsh environment are considered to identify their associated cables.

4. The operator errors modeled in the PRA are reviewed to identify those that depend on instrument readings. The cables that support the instruments' readings and are located within the containment are identified.

5. Since detailed cable drawings were not available, the drawings and information in the PRAs completed for the plant were used. For example, for the Surry plant, the information in the Surry Individual Plant Examination (VEPCO,1991), NUREG/CR-4550 study (Bertucio, 1990), and the WASH 1400 report (USNRC,1975) was used.

The PRAs and system drawings within the PRA are not necessarily good sources of information for identifying cables that can be affected by a harsh environment. Beyond a scoping study, cable drawings for the plants will be preferable for identifying cables that may be affected by a harsh environment.

2.2 Assumptions in Identifying the Cables Affected By Harsh Environment

As stated above, cable drawings or layouts in a plant were not used to identify the cables. Reviewing such drawings is time-consuming and was not undertaken in the scoping study. The approach used involves assumptions and can be summarized as follows:

1. The cables that can be identified through the hardware and human errors modeled in the Level 1 PRA are included; other cables are not considered. A detailed review of the cables in the containment might reveal some common links or interactions that may affect multiple components. However, such interactions cannot be identified without examining detailed cable layout drawings.

2. PRA Level 2 and 3 analyses will require the inclusion of additional cables related to containment systems.

3. Judgments are used to identify the types of cables that are involved. Typically, the motor-operated pumps and valves are associated with power, control, and instrumentation cables. Solenoid valves are associated with control and instrumentation cables; pressure and level transmitters are associated with instrumentation cables. We primarily focus on the instrument and control cables, but not the power cables because they are considered less vulnerable to harsh environments compared to the former group.

4. Judgments are made about the location of the components and the associated cables. Details of terminal boxes, penetrations, and splices were not available and are not discussed.

5. Individual components are assumed to have separate cables for their power, control, and instrumentation. Redundancy of the safety-system components is not affected by failure of any single cable. In our evaluation, a harsh environment may cause multiple cables to fail, thereby failing redundant components.

6. Operator's errors modeled in the PRA are reviewed to identify the instruments that operators need to carry out the required actions. Some additional instruments and the associated cables were identified through this process. This implies that in the PRA model, failure of those cables will affect the risk measure, e.g., the CDF, through its impact on the operator's actions.

7. Reactor trip function is assumed to take place very early before the onset of the harsh environment. The instrumentation associated with the trip function was not focused upon.

8. Regulatory Guide 1.97 classifies the cables used in NPPs. No attempt was made to include in our list all the cables included in the guide because of lack of information in relating the cables to the equipment modeled in the PRA. Also, the classification given in RG 1.97 was not used to assess their vulnerability to harsh environments.

3. CDF AND ACCIDENT SEQUENCE IMPACT OF CABLE FAILURES IN A PWR AND A BWR

The impact of cable failures in a PWR and a BWR is assessed in terms of core damage frequency (CDF) and the affected accident sequences. Accident sequences are identified that may become dominant contributors to the plant's CDF when cables fail.

3.1 Approach and Assumptions in the Scoping Evaluations

The scoping evaluation was conducted for the Surry Nuclear Power Station, Unit 1, a Westinghouse 3-Loop PWR, and Peach Bottom Station, Unit 2, a General Electric BWR-4. The Level 1 internal-event model is used to calculate the CDF contributions. The following summarizes the elements of the approach and the associated assumptions:

1. Data are not available to directly estimate the likelihood of cable failures under a harsh environment. For the scoping evaluation, the CDF impacts are obtained assuming that the cables fail in such conditions. No attempt was made to develop models that can estimate the likelihood of cable failures based on experimental evidence.

2. The cables identified to be affected by the harsh environment, based on their location inside the containment, are considered in defining the failed cables in the analysis. Details of splices, penetrations, and terminal boxes are not considered.

3. The failures of cables are assumed to cause the corresponding component to fail, e.g., the failure of cables associated with the containment-pressure channel will provide an erroneous reading of the containment's pressure. The failure of a control cable for a pump inside the containment will result in the pump's failure to perform its intended function. The impact of such failures then is assessed, using the PRA model to determine the resultant CDF.

4. The failures of cables are not directly modeled in a PRA, i.e., in PRA terminology, they are not separate basic events in the model; they are assumed to be part of the corresponding component which is modeled. In practice, considering that cable failures are unlikely, such contributions to the component's failures were neglected. In calculating the CDF impact of cable failures, the corresponding surrogate component was identified, and its failure was used to represent the failure of the cable. In representing the failures of multiple cables, corresponding multiple components and the common-cause failure events of the components are identified.

5. Cable failures also affect the operator's actions in a PRA model. The operator's actions modeled in the PRA are examined, and the probability of the failure of the operator to take the appropriate action is changed to reflect the impact of cable failures. Each of the operator's actions modeled is reviewed to identify the corresponding indication/readings that are used in deciding/conducting the actions. In this approach, for each cable failure, a set of corresponding operator's actions are identified. In assessing the impact of the cable failures, the probability of this set of operator's actions, along with the hardware failures is changed. For failure of multiple cables, similarly, a set of operator's actions are identified. The impact of cable failures on the human error probability (HEP) is uncertain. In many cases, an operator's action is based on information from multiple indications that depend on different cables. Typically, failure of a cable limits the information available to the operator. In this scoping study, no attempt is made to estimate the change in the HEP associated with the operator's action. Instead, sensitivity analyses are conducted by postulating that the probabilities are increased to 0.1.

6. Some operator's actions that are assumed to be executed very reliably in the PRA may be affected by the loss of indications in the control room due to cable failures. No review of the operating procedures was undertaken to identify such actions, additional to those modeled in the PRA, that may be adversely affected by cable failures.

7. The impact of cable failures are assessed by considering failures of different groups of cables. It is recognized that the zone of influence of the harsh environment caused by a particular accident is different from another, and also, the set of cables affected will vary

depending on the harshness of the accident. Resources and information were not available to assess the set of cables that may be affected in a particular accident. Different groups of cable failures were chosen, based on judgment, to represent the impact of failure of selective sets of cable. Also, groupings were made to represent failures of specific types of cables. Examples of such groups analyzed are cables associated with containment-pressure indication, those associated with pressurizer pressure, and those for recirculation spray pumps. Failures of combinations of cables involving control and instrumentation cables are possible, but are not analyzed at this time.

8. The progression in time of accidents causing a harsh environment can have an important influence on the CDF impact. These times are (a) the time needed for the harsh environment to develop in an accident, and (b) the time within which the components exposed to the harsh environment may need to operate, or the time needed by the operator to complete the actions that depend on instrument readings which may be affected by the harsh environment. If the operator can complete the necessary actions before the harsh environment has developed enough to damage the cables, i.e., the required information is unaffected, then the error probability remains the same as that in the PRA and the impact is negligible. In this scoping study, a reactor trip is considered to be unaffected. Otherwise, timing is not analyzed.

9. The analysis focused on accidents causing a harsh environment inside the containment; those outside it were not considered. The accidents that cause a harsh environment inside the containment were defined based on engineering judgment and available thermal-hydraulic analyses (Bustard et al., 1989). No specific analyses were conducted to define these accidents. Judgment on some accident sequences is difficult, particularly about the time available before the harsh conditions set in.

3.2 CDF and Accident Sequence Impact of Cable Failures in a PWR

The impact of cable failures on the CDF and accident sequences are assessed for the Surry Nuclear Power Station, Unit 1, using the Surry Individual Plant Examination (IPE) model implemented in the SAPHIRE code.

As discussed earlier, to obtain a scoping assessment of the impact of the cable failures in a harsh environment, a bounding evaluation is made considering failure of different combinations of the affected cables. The failures analyzed consist of the following:

1. Failure of instrument cables, and

2. Failure of control cables.

In each case, the cables involved are inside the containment, i.e., those that can be affected by harsh environment, and those that are modeled in some manner in the PRA.

In defining different combinations of cable failures, failures of cables associated with a particular type of measurement or a particular area where they may be located are focused upon. The selection of different cable failures is based on judgment, and not on any specific analyses of harsh environments following an accident. For the instrument cables, failures of containment-pressure channels, pressurizer-pressure channels, steam generator level transmitters, main steam pressure and differential pressure channels, and RCS cold leg temperature channels were analyzed. Each type of instrument cable is analyzed separately. The control cables analyzed were those associated with PORV and block valves, residual heat removal (RHR) pumps, and recirculation spray (RS) pumps.

Two evaluations are made for each case. First, only the hardware failure is addressed, assuming that despite the cable failures, the operator's actions are unaffected, i.e., the operator will perform as reliably as assessed in the PRA where cable failures are assumed not likely. While this scenario can be considered unlikely, it provides an insight for establishing a range on the impact of the cable failures. Second, the probability of the operator's actions being affected by the cable failures is increased to 0.1. Here, the impact on the operator actions is considered as limited only to those actions which require the instrument readings and control operations that are affected. The impact of this is uncertain. Hence, the probability of operator's action is increased to 0.1 for the sensitivity analyses, considering that other indications are available, and that the operator will rely on them. The error probability is increased because of the limitation on the available information due to the cable's failure.

3.3 Accident Sequences Causing Harsh Environment in a PWR

The following accident sequences are considered to cause a harsh environment inside the containment and are evaluated in obtaining the impact on CDF:

- Large, intermediate, and small LOCA inside the containment
- Transients with stuck-open power-operated relief valve (PORV)
- RCP seal LOCA
- Main steam line break inside the containment.

The contribution of anticipated transients without scram (ATWS) events are considered negligible. The CDF impact of cable failures is mainly dominated by small and intermediate LOCAs, as shown in the results presented below.

3.4 CDF and Accident Sequence Impact of Cable Failures in a BWR

The impact on the CDF and accident sequences of cable failures in a BWR are assessed based on an analysis of the Peach Bottom Station, Unit 2. The NUREG 1150 model of the Peach Bottom Station (NUREG/CR-4550, August 1989) implemented in the SAPHIRE code was used.

Similar to the PWR analysis, the scoping assessment of cable failures in a harsh environment for BWRs considered failures of different combinations of cables inside the primary containment. Similar to the PWR, failures of instrument- and control-cables were analyzed.

The cables that can be affected by a harsh environment in a BWR are minimal because very few components are located inside the primary containment, and very few measurements are carried out there. The components that can be affected in the Peach Bottom Station are motor-operated valve MV 18 of the shutdown cooling system, the solenoid-operated valves (SOVs) of the depressurization system, and the SOVs of the main steam isolation valves (MSIVs). The failure of the control cables of these valves are analyzed. The instrumentation measuring the reactor and drywell parameters that are used to actuate safety system components are located outside the primary containment, including the associated electrical cables. These parameters include reactor-vessel water level and pressure, drywell pressure, suppression pool water level. The cables associated with measuring the suppression-pool temperature are placed in a metal conduit outside the torus and are considered protected against harsh environment. The likelihood of failure of these cables due to a harsh environment is considered small.

3.5 Accident Sequences Causing Harsh Environment in a BWR

The following are the accident sequences affected by harsh environment in the Peach Bottom plant:

1. Large, intermediate, small, and small-small LOCAs. The contribution of large LOCA is relatively small.

2. Transients with failure of the suppression pool cooling, i.e., the sequences of the following transients that involve loss of suppression pool cooling: loss of offsite power transients (T1), transients with the power conversion system unavailable (T2), transients with power conversion system initially available (T3A) but subsequent loss of this system, and transients due to an inadvertent open relief valve in the primary system (T3C). These sequences are sometimes referred to as TW sequences. Transients due to an inadvertent open relief valve without the loss of suppression pool cooling is assumed not to cause a harsh environment; it is assumed that suppression pools are designed to handle such situations.

3. The ATWS sequence of concern is the one involving failure of reactor depressurization due to the failure of the safety relief valves. Such a sequence involves an ATWS followed by successful opening of safety relief valves, operation of standby liquid control system, and inhibition of ADS by the operator. But, the high pressure coolant injection fails and low pressure cooling cannot be accomplished due to the failure of the safety relief valves (from failure of cables due to a harsh environment). The contribution of this sequence, assuming failure of safety relief valves, remains around 1.0E-7and has negligible impact on our results.

4. RESULTS

Table 1 shows the results of the impact on CDF of different cable failures for the PWR plant, the Surry Power Station, with both the increased CDF when the failures are assumed and the increase in the CDF from the basecase. In each case, failure of all redundant cables is postulated. For example, failure of the containment's pressure channels signifies failure of all four of them. In each instance, sensitivity analyses are presented for the probability of failure of the affected operator's actions.

The failure at the Surry plant of some combinations of cables resulting in failure of the containment pressure indications, or failure of the inside recirculation spray pumps, can cause a sizable increase in the CDF. The failure of many other cables by themselves have negligible impacts on the CDF.

The scoping analysis of the cable's failures provides a perspective on the relative ranking of the cables in terms of their risk significance. The analysis, within its assumptions, shows the relative importance of instrument cables associated with the containment pressure measurement, and the control cables associated with the inside containment recirculation pumps. The cables associated with many other measurements, e.g., pressurizer pressure, main steam pressure, SG level detection, RCS cold leg temperature, by themselves, are not observed to be risk significant. The cables associated with the RHR pumps also have no impact on accident sequences causing a harsh environment inside the containment. In a general categorization, the results can be interpreted as showing that the instrument cables, as defined in the report, have a higher risk significance than control cables associated with the components inside the containment.

The scoping analysis also identified the accident sequences that become dominant contributors in case of cable failures in a harsh environment. These sequences are primarily LOCAs (large, intermediate, small) followed by failure of the recirculation spray system. In case of small LOCAs, the time available for the operator to initiate recirculation spray is longer than in large LOCAs (greater than 8 hours compared to 1 hour) and the probability of failure of the operator's action to initiate the recirculation spray will be lower. Such differences are not taken into consideration in this scoping study.

The results obtained for the Surry plant are plant-specific. The components and cables that are located inside the containment and affected by harsh environments vary from plant to plant. Some aspects of the Surry design are unique, e.g., failure of recirculation spray system in a LOCA causing core damage, location of RHR pumps inside the containment, location of normally closed hot leg recirculation motor-operated valves (MOVs) outside the containment, and contributed to the results presented here.

Table 2 shows the CDF results from our study of failures of cables inside the containment of a BWR plant, Peach Bottom Station. This analysis shows that the CDF impact of cable failure is sizable when ADS and non-ADS safety relief valves fail.

As stated earlier, relatively few of the cables that impact the safety analyses of a BWR are inside the primary containment. The primary concern is the failure of the relief valves that depressurize the reactor. The failure of the associated cables can increase the CDF to approximately 6E-5/yr (the increase in CDF is approximately 5E-5/yr). It is important to note that the increase in the CDF is from accident sequences that become dominant contributors due to the loss of the safety valves; otherwise, these sequences had a negligible contribution to the basecase CDF. As also noted earlier, the safety relief valves may degrade with age because of their location which exposes them to an adverse thermal environment during routine operation and so may make them more vulnerable to failure in a harsh environment.

The scoping analysis of this BWR plant shows that the impact on CDF for cable failures due to harsh environment has features that are expected to be common for BWR plants. The relief valves used to depressurize the reactor are similar, although their number may differ. The impact is due to failure of the relief valves and has minimal influence of the operator action error probability where the impact of the cable failures is uncertain. In that regard, generalization of the BWR results may be easier than those for a PWR.

5. SUMMARY

In this paper, we discuss a scoping study on the impact of cable failures due to harsh environment for a pressurized and a boiling water reactor. Using available PRA models, this study simulated cable failures in harsh environments during accidents to assess the impact on core damage frequency, considering both components and operator's actions that may be affected. The results provide useful insights on the effect of cable failures and identify selected cables that might warrant further studies. Some insights are plant-specific, whereas others may have generic implications for a type of reactor. As noted, this scoping study involved many assumptions and further detailed analyses addressing these assumptions will improve understanding of the cables' performance and their significance in accidents that create harsh environments.

Table 1 Internal Event CDF Impact of Failure of Instrumentation Cables in a PWR Plant: Surry Nuclear Power Station

Case	CDF(/yr) and Increase in CDF (/yr)[1]			
	Operator Actions Unaffected		Affected Operator Action Error Probability =0.1	
	CDF (/yr)	CDF Increase (/yr)	CDF (/yr)	CDF Increase (/yr)
Basecase	7.3E-5			
Failure of containment pressure channels	1.4E-4	6.7E-5	2.4E-3[1]	2.3E-3[2]
Failure of SG level transmitters	7.3E-5	1.0E-7	7.4E-5	1.0E-6
Failure of pressurizer pressure channels	Unchanged		7.3E-5	1.0E-7
Failure of main steam pressure channels	Unchanged		Unchanged	
Failure of RCS Cold leg temperature measurement	Unchanged		Unchanged	

[1] Cutset truncation at 1.0E-10.

[2] This result is dominated by small LOCA sequences where longer time is available for the operator to act with limitations in the available information due to cable failures. Detailed analysis of the error probability may lower the estimate from that assumed in this sensitivity analysis for such situations reducing the CDF impact.

Table 2 Internal Event CDF Impact of Failures of Instrument and Control Cables in a BWR Plant: Peach Bottom Station

Case	CDF(/yr) and Increase in CDF (/yr)			
	Operator Actions Unaffected		Affected Operator Action Error Probability = 0.1	
	CDF (/yr)	Increase in CDF (/yr)	CDF (/yr)	Increase in CDF(/yr)
Basecase	7.2E-6			
Failure of Control cables of ADS Valves	9.2E-6	2.0E-6	NA[1]	
Failure of Control Cables of ADS and non-ADS Relief Valves	5.8E-5	5.1E-5	NA[1]	
Failure of Control Cables for MOV MV18	1.2E-5	4.8E-6	NA[1]	
Failure of Instrument Cables[2] (failure of suppression pool temperature measurement)	Unchanged		NA[2]	NA[2]

[1] NA: Not Applicable

[2] The cables for measuring the suppression pool temperature are inside metal conduits outside the suppression pool. The likelihood of their failure due to harsh environment is considered small. Assuming an error probability of 0.1 for the operator's action is considered very conservative.

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Contribution of Cable Aging to the Risk of Nuclear Power Plant Operation

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Abstract

A method is given for estimating the contribution of cable aging to the risk of nuclear power plant operation. In this paper, the core damage frequency is used as a surrogate for risk. The method incorporates reliability physics models to estimate the probability of cable failure. The first step is a screening step, so that the more elaborate estimates of cable failure probability are based on the most risk important cables. Then the reliability physics models are used, and finally the results for the cable failure probabilities are input into the fault tree and event tree models, and the effect on the core damage frequency obtained.

Introduction

This paper presents a methodology for estimating the effects of cable aging on the risk from the operation of a nuclear power plant. The cables to be considered here are instrumentation and control cables in the containment of a nuclear power plant. The failures to be considered are those that occur after a loss of coolant accident (LOCA). Instrumentation and control (I & C) cables are considered more likely to fail to perform their function than power cables, under these circumstances, since small leakage currents may affect the function of instrumentation and control cables, while they may not affect the function of power cables. Failures after a loss of coolant accident are considered more important than possible random failures occurring during normal plant operation, since the harsh environment after a LOCA may fail cables associated with redundant trains of the same system, resulting in total system failure, while failures occurring during normal plant operation will likely be isolated failures (unless due to another common cause failure mechanism, such as fire). The current study considers only failures of cable insulation and does not consider failures of cable terminations or connectors. The emphasis will be on effects of cable aging on the core damage frequency, although much of the method is applicable to the determining of the effects of cable aging on other risk measures, such as expected offsite consequences. The estimation of the effects of cable aging on risk is important in order to (1) gain additional confidence that the risk from aging is acceptable, (2) to determine the most risk significant cables from the viewpoint of aging, and (3) to enable, if necessary, risk reduction measures such as environmental and condition monitoring of risk significant cables, with appropriate action taken depending on the condition and environment of the cables.

If, at some point in time, the probability of the cable failures, given a LOCA, were known, then the contribution of the cable failures to the core damage frequency could be estimated, using conventional fault tree and event tree analyses. However, the estimation of the probability of cable failure after a LOCA cannot be obtained directly from data, since little or no data are available under plant operating conditions. Hence, the use of reliability physics models, in conjunction with the results of accelerated aging experiments, is proposed. Prior work in the use of reliability physics models to estimate failure rates has been reported by Smith et al. (Ref. 1).

Because of the resource-intensive nature of the use of reliability physics models, the first step in the method is the use of screening methods to select those cables for which detailed reliability physics methods must be used; the effect on the risk of other cables will be neglected, or treated by bounding calculations. The screening is performed by the use of risk importance methods. After the cable failure probabilities, as a function of cable age are calculated, they are inserted into probabilistic risk analysis (PRA) calculations (event-tree/fault-tree calculations) to estimate the effect on the core damage frequency of the cables, as a function of plant age.

Screening Method

The cable failures of concern are those that occur after a LOCA; the LOCA causes a harsh environment in containment. Since the harsh environment has the potential to cause failure of cables in redundant trains, or in different systems performing the same safety function (such as decay heat removal from the reactor coolant system), it is not appropriate to use single component importance measures. Rather, one uses measures of importance where sets of cables are failed simultaneously.

Let X = Event that the I & C cables in redundant trains of some system are failed; include also cables in diverse systems performing the same function.

Consider:

$$I(t)=\sum_{E_I} f(E_I)(pr\{C|X,E_I\}-pr\{C|\bar{X},E_I\})pr\{X|E_I,t\},$$

where:

C = some consequence measure (take as core damage)

E_I = initiating event; $f(E_I)$ = frequency of E_I

t = cable age, assumed the same as plant age

I(t)= contribution to core damage frequency from event X, in the sense that the core damage frequency would be reduced by the amount I(t) if X never happened.

The importance measure I(t) will be used as a guide for screening. Take t at the end of plant life, and evaluate $pr\{C|X,E_I\}$ assuming that the cable failures X occur early in the accident. Evaluate the human error probabilities conservatively. If I(t) is small even if $pr\{X|E_I\}=1$, then the cable failures X can be screened out. In other words, if the (modified) Birnbaum importance

$$\sum_{E_I} f(E_I)(pr\{C|X,E_I\}-pr\{C|\bar{X},E_I\})$$

is small, then the cable failures X can be screened out.

If one cannot screen out on the basis of the Birnbaum importance, then screening may be attempted by showing that $pr\{X|E_I\}$ is small. This may be the case, for example, if the cable insulation temperature during normal operation is low compared to that assumed for the environmental qualification of the cables, and the effects of radiation are not greater for the cables than that assumed during environmental qualification. If the Arrhenius law is valid, then one has

$$e^{-\frac{E}{RT_1}}t_{f1}=e^{-\frac{E}{RT_2}}t_{f2}$$

where E is the activation energy, R is the molar gas constant, T_2 is the plant operating temperature (e.g., 90 deg. C) assumed for qualifying the cable, T_1 is the actual temperature for the cable insulation, and t_{f1}, t_{f2} are times to equivalent damage at the two different temperatures. If the cables are qualified for a time t_{f2} at temperature T_2, and the value of t_{f1} calculated from the above equation is large compared to the plant lifetime, then the cables will have experienced little aging compared to that assumed for their environmental qualification, and it is reasonable to conclude that the probability of cable failure is small.

Cable Failure Probabilities

The simple wear model described by Carfagno and Gibson (ref. 2) will be used. Here, the cable has an initial capacity h_0 which is degraded by the aging stressors consisting of the temperature T and the radiation dose rate D. The capacity h at time t is given, in this model, by $h=h_0-tR(T,D)$. When the resource level h falls below some critical value, then failure will occur for a given set of environmental conditions. Here, the environmental conditions of concern are those for a LOCA, including the humidity conditions of the LOCA. The environmental conditions of the LOCA are considered to be more or less fixed. This is a simplification, since some LOCAs may be more severe than others. Also, the focus in this method is on the degradation of the insulating material. Cable insulation may in fact be very brittle because of thermal and radiation aging, and yet not fail in a LOCA if the cable is not moved so that cracks develop in the cable insulation. In principle, this simplification could be removed if one knew enough about the location of the cables, and whether they were in conduits or cable trays, and if one was able to estimate the chances of cables cracking if they were moved. Note that this model does not assume that physically measured parameters, such as elongation at break, degrade linearly with time. Such physically measured parameters are functions, possibly non-linear, of h. If, for two different sets of variables (t, T, D), the same value of h is obtained, then one would expect equivalent degradation for the two different sets of variables, and the same value of the physically measured parameter, such as elongation at break. In this model, h_0 is a random variable with aleatory uncertainty. For R(T,0) one can frequently use an Arrhenius relationship, $R(T,0)=A\exp(-E/RT)$. On p. 79 of vol. 2 of ref. 3, one has the relationship $t_2=t_1/(1+kD^n)$, where t_1 is the time to some level of degradation at zero dose rate, and a given temperature, and t_2 is the time to the same level of degradation at the same temperature and the dose rate D. Here, k and n are empirical constants, with k possibly depending on temperature. For n=1 there is no dose rate effect; the effects of radiation depend only on the total dose received by the cable. The relationship is assumed valid for all degradation levels. This implies that $R(T,D)/R(T,0)=(1+kD^n)$, so that $R(T,D)=A\exp(-E/RT)(1+kD^n)$. The parameters E, k, and n have epistemic (state-of-knowledge) uncertainties.

To proceed further, one can take a capacity level h_1 during normal operation as a surrogate for cable failure. For example, one could possibly take an elongation at break of 50% absolute as corresponding to such a value of h_1. Then, if a LOCA occurs when the elongation at break is less than 50%, cable failure is assumed. In other words, although cable failure will not occur for an elongation at break of 50%, it is assumed that during the LOCA, the cable condition will deteriorate to the point of failure. If T_1, D_1 correspond to the temperature and dose rate during normal operation, and t_{f1} is defined by $h_1=h_0-t_{f1}R(T_1,D_1)$, then, in this model, if a LOCA occurs when the cable age is greater than t_{f1}, the cable will fail. Suppose now that, from accelerated aging experiments one can, for some other temperature and dose rate, T_2, D_2 obtain values for the time t_{f2} which corresponds to h_1. (In this example, this would correspond to values of t_{f2} at which the elongation at break was 50%.) Since h_0 is a random variable, t_{f2} is also a random variable. The values of t_{f1} and t_{f2} are related by $t_{f1}/t_{f2} = R(T_2,D_2)/R(T_1,D_1)$. Hence, if the values of t_{f2} obtained from the accelerated aging experiments can be fitted to some probability distribution, such as a Weibull distribution, one has the probability distribution for t_{f1}. One can then estimate the probability of cable failure if a LOCA occurs at some time t. This probability of cable failure incorporates the aleatory uncertainty. The epistemic uncertainty in the probability of cable failure enters by varying the parameters with epistemic uncertainty. One then gets a degree-of-belief distribution for the cable failure probability.

One can, with certain reasonable assumptions, extend the method to estimating the time during the LOCA at which failure occurs, provided one limits oneself to estimating the probability of cable failure before core damage. This is, of course, all that is needed if one wants to estimate the contribution to the core damage frequency of cable failure. In its essence, one assumes that aging during a LOCA is a form of accelerated aging. After the initiating event (the LOCA), but before core damage, the radiation dose would be low, since the reactor is shut down and the neutron and gamma dose is low. Coolant radioactivity levels are generally quite low (very few fuel failures), and so one would not expect high doses from this source either. The radiation dose of importance is that received before the LOCA. During this time intermediate degradation products are produced, and these decay out during the LOCA. This is discussed, for example, by Clough & Gillen (ref. 4). The reason for wanting to estimate the time during the LOCA at which failure occurs is that failures that occur later in the LOCA are less likely to result in core damage.

Event and Fault Tree Calculations

In order to obtain an estimate of the effect of the cable failures on the core damage frequency, one puts the probabilities of cable failures into the fault tree models. If it turns out that these failures have a significant contribution to the risk using conservative estimates of human error, then more refined estimates can be used. If one has found it necessary to estimate the probability of failure of the cables as a function of the time after the LOCA, then one can model this in the fault tree and event tree models. Results as a function of plant age are obtained by repeating the calculation at different values of the plant age.

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Risk Assessment for Aircraft Electrical Interconnect Subsystems (EIS)

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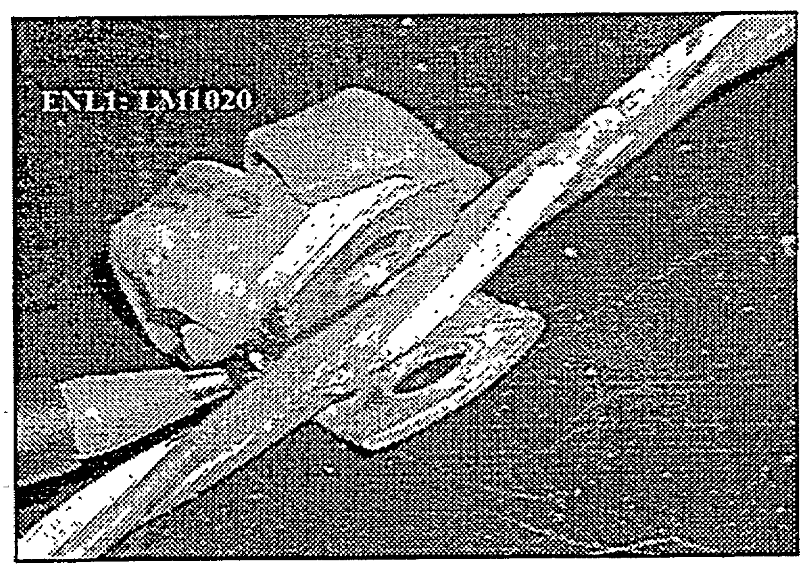

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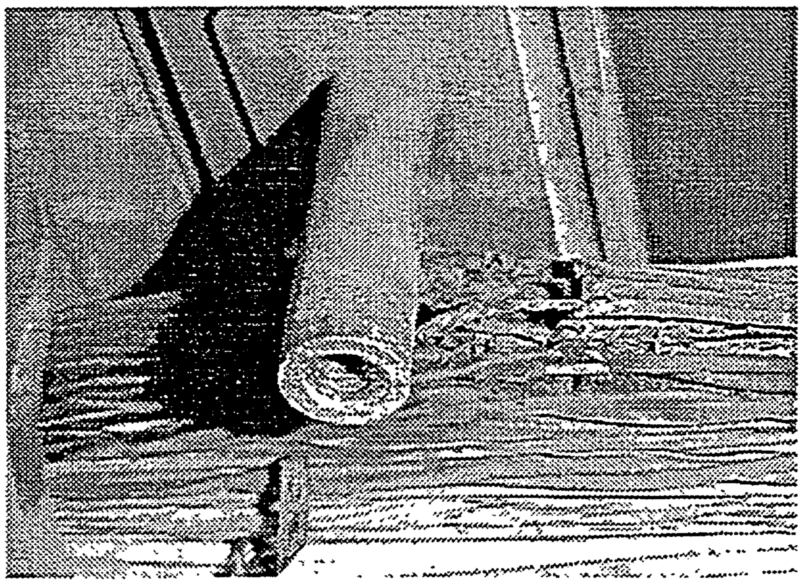

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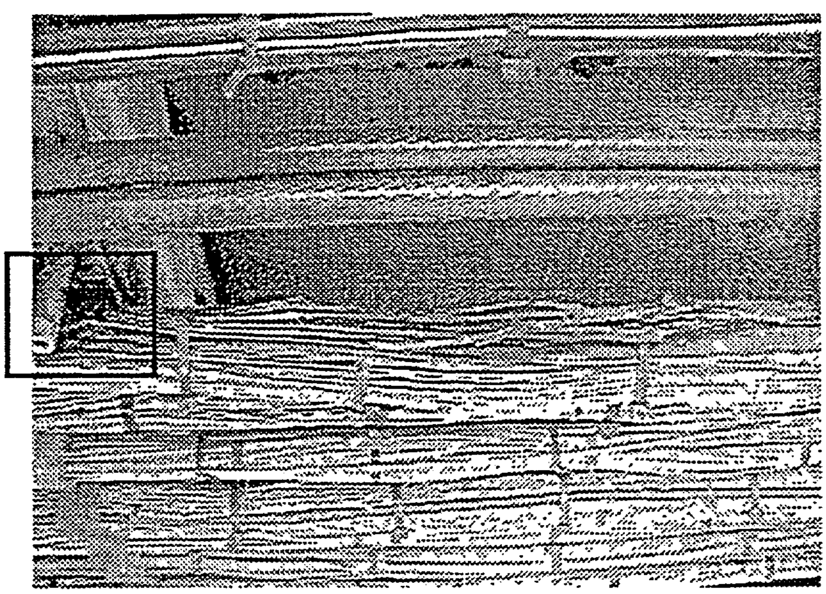

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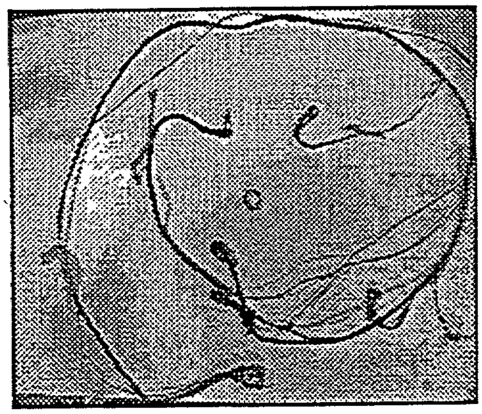
2 Insulation Breaches per 1,000 feet of Wire

Swamp or High Probability Areas = 15%



Small Trans.	⇨	80 Breaks
Narrow Body	⇨	159 Breaks
Hybrid	⇨	239 Breaks
Wide Body	⇨	318 Breaks

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"Smoke & Fire" - *Commercial*

Service Difficulty Report Data

First 10 Months of 1999

964 - Reported Events of Smoke or Fire

359 Unscheduled Landings

Approx. **50%*** - were Electrical Systems Related

*Some possibility of providing for a high temp event or ignition source. Figures are estimates and are not intended to infer overall safety of operations or practices

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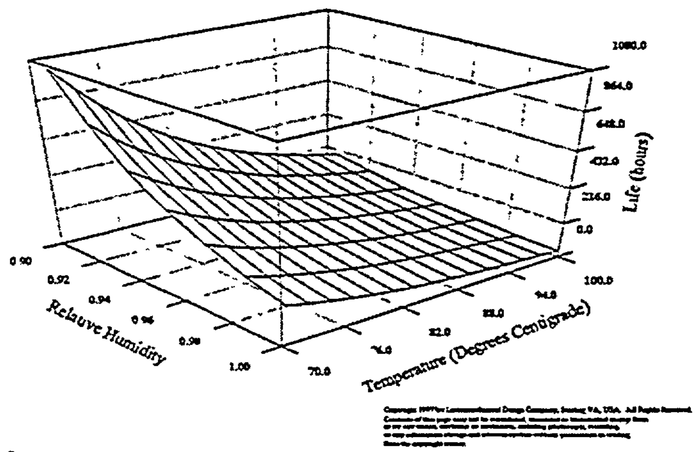
Wire Aging & Life Testing

Life plot corresponding to 1/2" bend radius (copyright)



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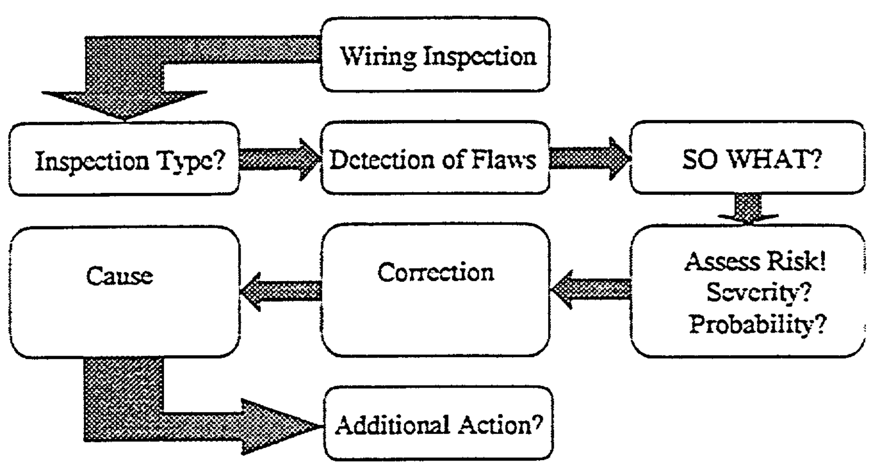
Process Flow Chart



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"Risk Analysis"

- Likelihood of Other Flaws ?
- Likelihood of Future Flaws Occurring ?
- Likelihood of Flaws Resulting in Problem ?
- Severity Potential of Problem (Arc or Noise) ?
- Likelihood of the above Occurring in "High Risk Area" ?

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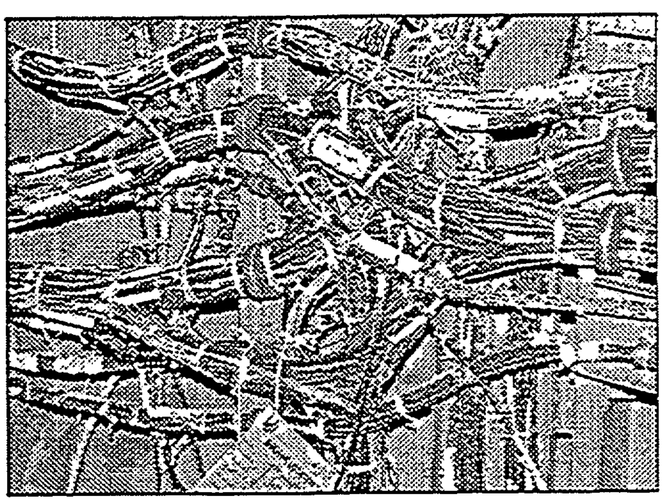
"Higher Risk Area" ?



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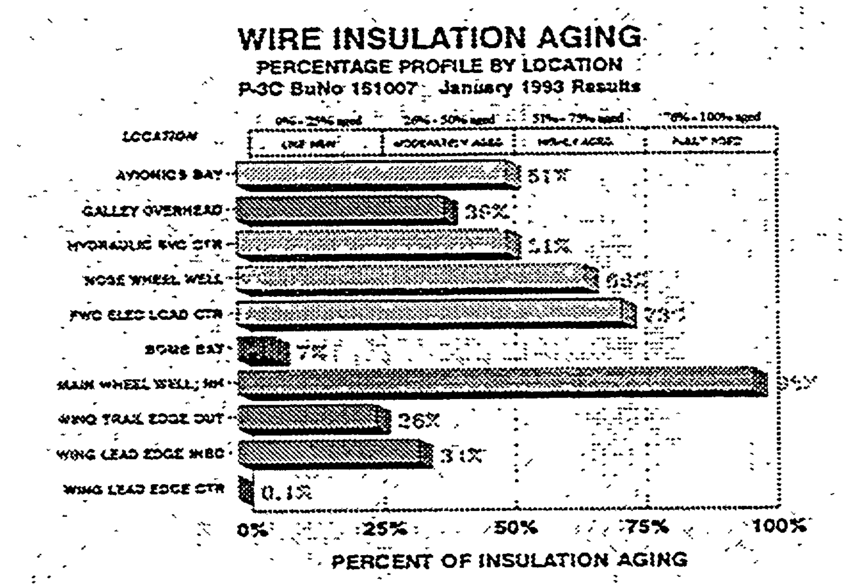

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Factors Matrix (affecting severity & likelihood)

Breach # 9, Avionics Bay

	Laboratory Rating	Field Notes
Wire Function (power or signal)	x	?
Wire Type	y	?
Wire Gauge	z	?
Circuit Protection	x	?
Bundle Size	y	?
Proximity to Critical Systems	z	?
⇒ Proximity to Ground Source	x	?
Average Humidity	y	?
Average Temp	z	?
Strain	x	?
Routing	y	?
Age of Aircraft or Wire	z	?
Proximity to Flammable Sources	x	?
Design	y	?
Voltage	z	?
Maintenance Frequency	x	?
⇒ Orientation of Wire	y	?
Contamination	z	?

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Risk Exposure Table

Severity \ Probability	Very Likely	Probable	Improbable
Catastrophic	6 High	5 High	4 Med
Critical	5 High	4 Med	3 Med
Marginal	4 Med	3 Med	2 Low
Negligible	3 Med	2 Low	1 Low

Functions of Risk Mngt. Attributed to Carnegie Mellon's Software Engineering Institute and their publication "Software Risk Evaluation (SRE) Method Description" V. 2.0, Dec 1999.

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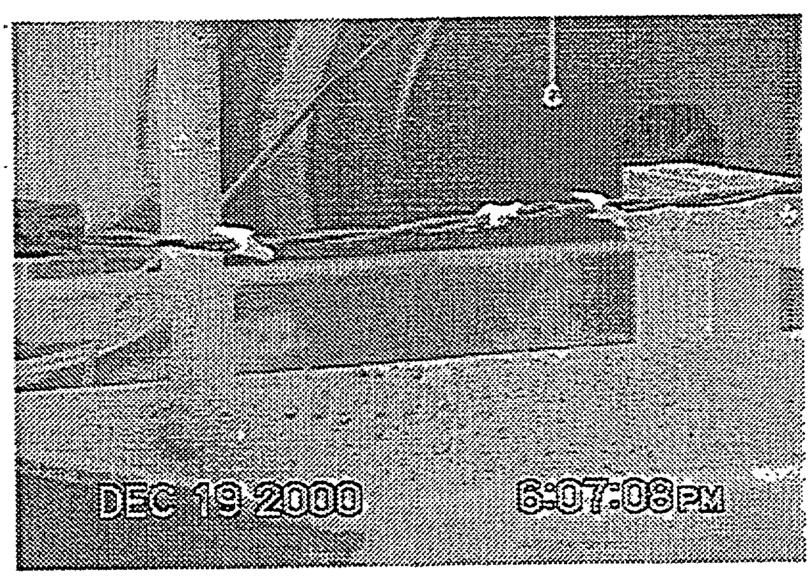

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Present FAA Efforts

Development of
Enhanced Risk Assessment Tools
for Aircraft Electrical Systems

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Enhanced Risk Assessment Tools for Aircraft Electrical Systems

- **Define Current Aviation Practices**
- **Benchmark Other Industries**
- **Identify Good Practices**
- **Develop, Refine, & Test Tools**

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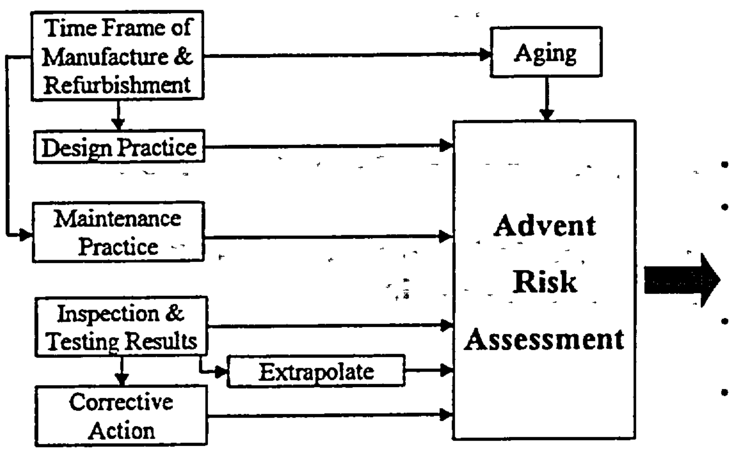
Overall Risk Assessment Process



Results

- Improved Safety
- Reduced Downtime/ Increased Reliability
- Prioritization of Resources
- Design Improvement Recommendations (short-term/long-term)

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Risk Assessment

- **Structured Presentation of Scenarios**
- **Each Scenario**
  - **- definition**
  - **- probability**
  - **- consequence**

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Nuclear Power Plant Application

- Develop Comprehensive Event Tree Model
- Quantify Failure Nodes on Event Trees Using Fault Tree Analysis

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Definitions

- Event Tree - a diagram that maps a scenario from an initiating event through combinations of system successes & failures to a result or consequence
- Fault Tree - a deductive logic model that defines all the combinations of failures that can result in an undesired outcome (e.g., system failure)

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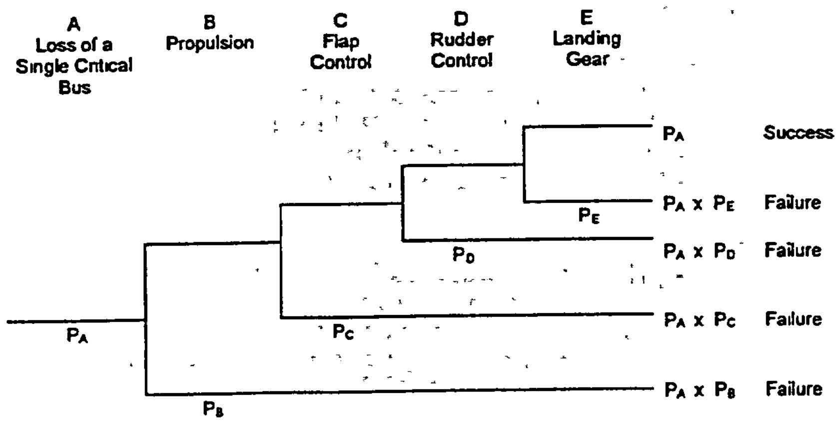
Example - Event Tree



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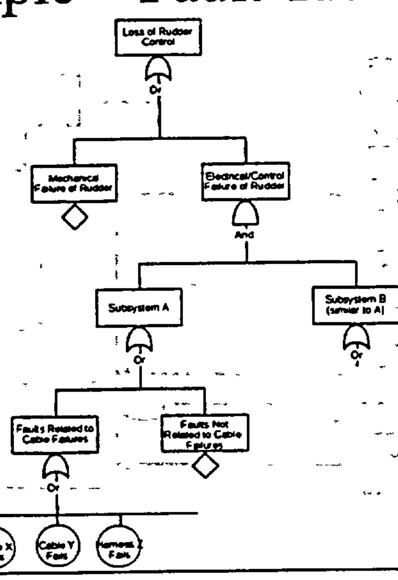
Example - Fault Tree



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Future Potential

- **May only utilize a portion of full-scope risk assessment**
- **Qualitative**
  - **- identify wire faults of concern**
  - **- define result of multiple faults**
  - **- improve future designs**
  - **- improve maintenance practices**
- **Quantitative**
  - **- prioritize problems by risk (probability & consequence)**
  - **- assign risk significance to as-found problem (input to corrective action)**
  - **- finite resource activity prioritization**

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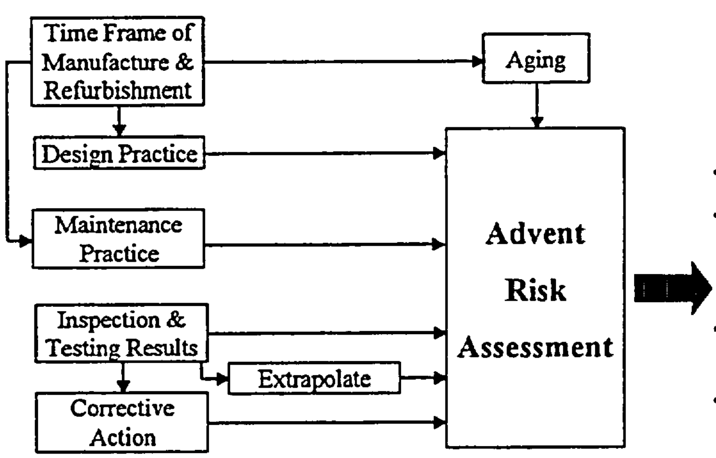
Overall Risk Assessment Process



<u>Results</u>

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- Design Improvement Recommendations (short-term/long-term)

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Component Importance Determination and Treatment Changes Using Risk Insights

2002 International Conference on Wire System Aging
Rockville, MD
April 23-25, 2002

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1

South Texas Project (STP) Overview

- South Texas Project is a two unit, four-loop Westinghouse PWR rated at 1250MWe each

  -Initial power generated-Unit 1 in 1988, Unit 2 in 1989
  -Each unit is physically separate-few common systems

- South Texas Project is located about 85 miles southwest of Houston, Texas - located near the Gulf of Mexico

- South Texas Project Nuclear Operating Company is co-owned by four power companies

2

Why a Risk-Informed Approach?

A risk-informed approach to safety-related activities:

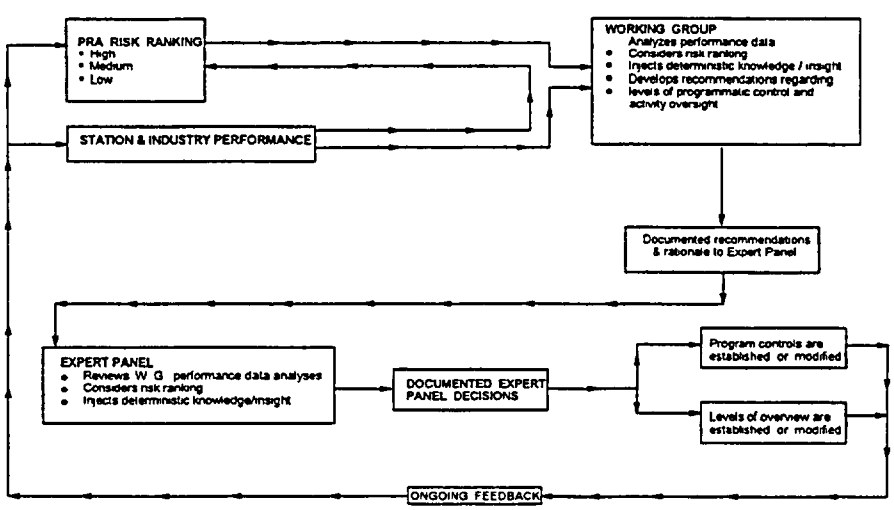
- Allows a documented basis for identifying what components are important (safety significant) and what components are not important (non-safety significant)

- Once identified, resources can be appropriately focused on the safety significant components

- This results in:
  - Reduced burden for the power plant
  - Reduced burden for the regulator
  - ***Improved*** overall safety

3

Importance Determination Flowchart



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Importance Determination Controls

- Decision-Making process is made up of two groups - a Working Group and an Expert Panel
  - both groups use experienced, qualified personnel
  - both groups use personnel from maintenance, operations, engineering, licensing, and quality organizations
- Procedures govern the component importance determination process
- Through this process, components are placed into one of four categories:
  - HSS - high safety significant
  - MSS - medium safety significant
  - LSS - low safety significant
  - NRS - not risk significant

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Categorization Results

- 32 systems (43,688 components) categorized to date
- Components have been categorized as follows:
  - HSS - 3%
  - MSS - 7%
  - LSS - 15%
  - NRS - 75%
- HSS/MSS components are safety significant (important)
- LSS/NRS components are not-safety-significant (least important)

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Results Broken Down Further

RISC - 1 Safety-Related, Safety Significant 4,104 (9.4%)	RISC - 2 Non-Safety Related, Safety Significant 374 (0.9%)
RISC - 3 Safety-Related, Not Safety Significant 12,611 (28.7%)	RISC - 4 Non-Safety Related, Not Safety Significant 26,599 (60.9%)

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Why is it okay to categorize components and treat them differently?

- Commercial practices have been demonstrated to be acceptable through improved power plant capability and reliability factors
- Safety-related/non-safety related component failure rates are generally the same
- It is expected that the least important components will continue to function when demanded
- Even if a safety-related Low or NRS component were to fail, it would result in little to no impact on safety

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Scope of the STP Exemption Request

- 10CFR Part 21 (Vendor Notification)
- 10CFR50.49 (Equipment Qualification)
- 10CFR50.55 (ASME / ISI, IST)
- 10CFR50.59 (Change Control)
- 10CFR50.65 (Maintenance Rule)
- Appendix B (Quality Assurance Program)
- Appendix J (Containment Leak-tightness)
- 10CFR Part 100 (Seismic)

9

50.49(b) and 50.55a(h) Insights

- Exemption granted for 50.49(b) and for 50.55a(h) to the extent that it imposes requirements of Sections 4.3, 4.4 of IEEE-279
- STP has the opportunity to adjust treatment on the least important safety-related, qualified components:
  - Cabling which supports safety significant SSCs will continue to satisfy regulatory requirements of 50 49(b) and 50.55a(h) - no exemption sought
  - Cabling which supports non-safety significant SSCs may be replaced with non-qualified cabling which satisfies the design functional requirements of the original design
  - An engineering evaluation would be performed to ensure that reasonable assurance exists that the replacement cable satisfies the design functional requirements under design basis conditions

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50.49(b) and 50.55a(h) Insights

- The exemption was granted by the NRC on August 3, 2001
- STP is in the early stages of implementing the exemption allowances - nothing has yet been removed from the EQ scope
- STP currently procures all cabling on site as safety-related, qualified cabling to eliminate co-mingling concerns
- Very little cable replacement is done at STP - most cabling issues are associated with new installation modifications
- STP does expect that cabling in harsh environments which supports non-safety significant end-point loads will utilize equivalent, non-qualified cabling for future modification installations

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Summary

- Importance determination (categorization) allows the importance of components to be recognized and treatment appropriately adjusted - not all safety-related components are equally important

- Opportunities exist to properly focus cable qualifications on the safety significant applications only

- Utilizing commercial equivalent cabling in non-safety significant applications will reduce burden while resulting in an overall neutral or beneficial safety impact

- STP will continue to pilot the implementation of this approach

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Appendix G: Papers and Presentations from Technical Session 4
Prognostics and Diagnostics for Installed Wire Systems

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Appendix G - Table of Contents

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