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Organisation de Coopération et de Développement Economiques
Organisation for Economic Co-operation and Development

11-Aug-2004

English - Or. English

NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

NEA/CSNI/R(2004)12
For Official Use

RESEARCH EFFORTS RELATED TO WIRE SYSTEM AGING IN NEA MEMBER COUNTRIES

English - Or. English

JT00168032

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971), New Zealand (29th May 1973), Mexico (18th May 1994), the Czech Republic (21st December 1995), Hungary (7th May 1996), Poland (22nd November 1996), Korea (12th December 1996) and the Slovak Republic (14 December 2000). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full member. NEA membership today consists of 28 OECD member countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The Committee on the Safety of Nuclear Installations (CSNI) of the OECD Nuclear Energy Agency (NEA) is an international committee made up of senior scientists and engineers. It was set up in 1973 to develop and co-ordinate the activities of the Nuclear Energy Agency concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations. The Committee's purpose is to foster international co-operation in nuclear safety among the OECD Member countries.

The CSNI constitutes a forum for the exchange of technical information and for collaboration between organizations, which can contribute, from their respective backgrounds in research, development, engineering or regulation, to these activities and to the definition of the programme of work. It also reviews the state of knowledge on selected topics on nuclear safety technology and safety assessment, including operating experience. It initiates and conducts programmes identified by these reviews and assessments in order to overcome discrepancies, develop improvements and reach international consensus on technical issues of common interest. It promotes the co-ordination of work in different Member countries including the establishment of co-operative research projects and assists in the feedback of the results to participating organizations. Full use is also made of traditional methods of co-operation, such as information exchanges, establishment of working groups, and organisation of conferences and specialist meetings.

The greater part of the CSNI's current programme is concerned with the technology of water reactors. The principal areas covered are operating experience and the human factor, reactor coolant system behaviour, various aspects of reactor component integrity, the phenomenology of radioactive releases in reactor accidents and their confinement, containment performance, risk assessment, and severe accidents. The Committee also studies the safety of the nuclear fuel cycle, conducts periodic surveys of the reactor safety research programmes and operates an international mechanism for exchanging reports on safety related nuclear power plant accidents.

In implementing its programme, the CSNI establishes co-operative mechanisms with NEA's Committee on Nuclear Regulatory Activities (CNRA), responsible for the activities of the Agency concerning the regulation, licensing and inspection of nuclear installations with regard to safety. It also co-operates with NEA's Committee on Radiation Protection and Public Health and NEA's Radioactive Waste Management Committee on matters of common interest.

FOREWORD

The December 2000 meeting of the NEA/Committee on the Safety of Nuclear Installations (CSNI) accepted a proposal to set up a Task Group to prepare a report describing research efforts related to the wire system aging in Member countries. International Organizations working on the topic contributed to this report.

There is a continued interest worldwide in the safety aspects of electrical wire (cable) system aging in national infrastructures, including operating nuclear power plants. Aging of a wire system, which includes cables, splices, terminations, connectors, 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 aging and safety, there are still a number of issues that remain unresolved and should be addressed. This report presents a preliminary list of those issues in several areas related to wire system aging and 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.

The complete list of CSNI reports, and the text of reports from 1993 onwards, is available on http://www.nea.fr/html/nsd/docs/

ACKNOWLEDGEMENT

Gratitude is expressed to the experts from the Member Countries who have contributed to the report, in particular to the chairman of the Task Group Dr Jitendra Vorah, USNRC.

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EXECUTIVE SUMMARY

Background

Nuclear facilities rely on electrical wire systems to perform a variety of functions for successful operation. Many of these functions directly support the safe operation of the facility; therefore, the continued reliability of wire systems, even as they age, is critical.

Wire systems can be a complex aggregate of different components, each having its own unique materials of construction and susceptibilities to failure. Basic to a wire system is the electrical wire itself; however, there are various other components that are necessary to make a wire system functional, such as splices, terminations, connectors and penetrations. The common requirement for each component is that they must function properly, when called upon, to achieve the objective of the wire system, which could be to transmit power to a load, or relay a signal to an instrument. In many applications wire systems play a critical role in performing safety functions and they must operate properly, sometimes in harsh environments.

A great deal of expertise and knowledge has been obtained related to the design and construction of wire systems, and how to optimize their performance. This is evidenced by the reliable performance demonstrated in the vast majority of wire systems currently installed. However, an area that has yet to be fully addressed is the impact of age degradation on the performance and reliability of wire systems after prolonged exposure to operating and environmental stressors.

To address the technical issues related to wire system aging and safety, the Working Group on Integrity of Components and Structures (IAGE), under the auspices of the Committee on the Safety of Nuclear Installations (CSNI), formed a special task group. The Task Group on Wire System Aging, also referred to as the Cable Task Group (CTG), was chartered with evaluating the current status of research in this area, identifying technical issues that remain unresolved and warrant additional research, and recommending research programs to address the outstanding issues.

Initial efforts by the CTG focused on the identification of issues related to wire system aging, and the review and evaluation of ongoing research to address these issues. This report documents the results of the initial efforts by the CTG and provides a preliminary list of issues related to wire system aging and safety that need to be addressed by future research efforts. It is the intention of the CTG that this list be expanded and modified as new issues are identified to obtain a comprehensive list of issues to be addressed by the research effort. Interested researchers can then use this list to identify collaborative research efforts in which they would be interested in participating. Collaborative research should then be performed to resolve these issues.

Conclusions

The initial efforts by the CTG resulted in the identification of a number of technical issues related to wire system aging and safety that are unresolved and warrant additional research. The preliminary list of technical issues is categorized into five subject areas, which are:

- Physical and Chemical Models of Wire System Aging
- Assessment of Fire Hazards due to Wire System Aging
- Risk Significance of Wire System Aging
- Prognostics and Diagnostics for Installed Wire Systems
- Environmental Qualification Practices for Wire Systems

The preliminary list of technical issues presented herein is based on a review of past and current work in these areas, as well as input obtained at the NRC International Conference on Wire System Aging, held in April 2002. The following general research topics related to wire system aging and safety were determined to warrant additional research:

Physical and Chemical Models

- Improvement of existing models used to predict the failure probability of aged cables and wire systems in the absence of empirical data, including additional testing of wire systems to obtain performance data for verifying existing models
- Development of new physical and chemical models to replace existing models, including the identification of limitations in current models and addressing changes in wire formulations
- Standardization of testing methods and condition monitoring techniques for the development and validation of physical and chemical models.

Fire Hazard

It is suggested that the fire-risk experts take the initiative to identify and prioritize the outstanding issues relevant to fire hazards, as they relate to wire system aging. The CTG, in conjunction with the fire-risk experts, should then identify the highest priority issues for collaborative research. The following fire hazard issues, as well as those in Table 2, are derived from the discussions that took place at the International Conference on Wire System Aging. They should be reviewed by the fire-risk experts and used to provide guidance to the CTG for future research.

- Development of improved models for predicting fire hazards, including fire growth and thermal damage models, as well as information on the factors affecting the frequency of self-initiating fires and the propagation of fires.
- Improving inputs to existing models to provide more accurate predictions, including performance testing of wire systems to obtain flammability and fire frequency data that can be used to determine the increase in fire hazards due to age related degradation
- Evaluation of the impact of aging on fire suppression and protection systems, including new fast acting circuit protective devices and “fire proof” cables

- 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.

Risk Significance

It is suggested that the aging-risk experts take the initiative to identify and prioritize the issues relevant to plant risk, as they relate to wire system aging. The CTG, in conjunction with the aging-risk experts, should then identify the highest priority issues for collaborative research. The following plant risk issues, as well as those in Table 3, are derived from the discussions that took place at the International Conference on Wire System Aging. They should be reviewed by the risk assessment experts and used to provide guidance to the CTG for future research.

- Continued studies to determine how aging of wire systems impacts plant risk, including determination of the relative importance of various wire systems, and the impact of aging on failure rates and reliability. Also, it would be beneficial to have a series of 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 probabilistic risk assessments (PRAs) and assure the accuracy of PRA results.

- Determination of how risk insights can best be used to more effectively manage wire system aging, including input to operator training programs, and optimization of inspection, maintenance, and replacement strategies

- Improvements to inputs for existing models to more accurately estimate plant risk due to wire system aging, including operational data acquisition to characterize failure rates, and the acceptability of currently used assumptions

- 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.

Prognostics and Diagnostics

- Continued development of new, 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

- The use of condition monitoring to predict remaining useful life, including the establishment of acceptance criteria, performance data acquisition, and 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

Environmental Qualification

- Evaluation of current practices for performing accelerated aging as part of the qualification testing, including acceleration factors and activation energies

- Evaluation of qualification test requirements to determine if improvements are needed, including the continued use of a time-based qualified life, the margins in test parameters, and the number of specimens tested

Specific issues within each of the general topics were identified, along with proposed collaborative research to address the issues, and are tabulated herein.

Specific Recommendations by the CTG

As a first priority to satisfy the near-term needs, it is recommended that resources be focused on collaborative research on the following topics: (1) prognostics and diagnostics and (2) environmental qualification. Research on the remaining topics identified in this report is recommended to satisfy long-term needs. Specific recommendations by the CTG are the following:

Prognostics and Diagnostics (near-term)

The CTG recommends that collaborative research in the area of prognostics and diagnostics of wire systems be pursued as one of the high priority short-term needs. Specific recommendations for collaborative research programs in this area are the following:

- Collaborative research is recommended for the development of an electrical diagnostics and condition monitoring method that can scan the entire length of an installed wire system and determine its current condition. In this regard, advanced electrical, optical, ultrasonic and aerospace technologies should be evaluated and developed for nuclear plant applications.

- Collaborative research is recommended to establish the correlation between wire system condition indicators and the functional performance of the wire system during design basis events.

Environmental Qualification (near-term)

The CTG recommends that collaborative research in the area of environmental qualification of wire systems be pursued as one of the high priority near-term needs. Specific recommendations for collaborative research programs in this area are the following:

- Collaborative research is recommended to provide a technical basis for developing and/or updating qualification methods and standards to reflect past operating experience and realistic plant operating conditions. Emphasis needs to be placed on a condition-based demonstration of ongoing qualification.

Physical and Chemical Models (long-term)

The CTG recommends that collaborative research in the area of physical and chemical model development for wire systems be pursued as one of the long-term needs. Specific recommendations for collaborative research programs in this area are the following:

- Collaborative research is recommended to establish the correlation between the physical, chemical, and electrical properties of the most widely used polymers in wire insulating systems for the current fleet of operating nuclear power plants. These polymers include cross-linked polyethylene (XLPE), Neoprene, ethylene propylene rubber (EPR), chlorosulfonated polyethylene (CSPE), ethylene propylene dienemonomer (EPDM), ethylene vinyl acetate (EVA), and polyvinylchloride (PVC).

- Collaborative research is recommended to provide technical bases for standardizing test methods, with emphasis placed on the understanding of electrical properties, measurement of parameters and indicators, and circuit performance.

- Collaborative research is recommended for the development of suitable models and methods for demonstrating ongoing qualification without the need to repeat DBE testing.

Fire Hazards and Plant Risk (long-term)

The CTG recommends that collaborative research in the area of fire hazards and plant risk related to aged wire systems be pursued as two of the long-term needs. However, input from the experts in these areas should be solicited prior to initiating any new collaborative research.

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ACRONYMS

BNL .... Brookhaven National Laboratory
BRE/FRS .... United Kingdom Building Research Establishment/Fire and Risk Sciences
CM .... Condition Monitoring
CSNI .... Committee on the Safety of Nuclear Installations
CSPE .... Chloro-sulfonated Polyethylene
CTG .... Cable Task Group
DBE .... Design Basis Event
DOE .... U.S. Department of Energy
DSC .... Differential Scanning Calorimeter
EDT .... Excited Dielectric Test
ENB Ethylene-5 Norbornene-2
EPDM .... Ethylene Propylene Dienemonomer
EPR .... Ethylene Propylene Rubber
EPRI .... Electric Power Research Institute
EVA .... Ethylene Vinyl Acetate
FTIR .... Fourier Transform Infrared
EQ .... Environmental Qualification
I&C .... Instrumentation and Control
IAEA .... International Atomic Energy Commission
IAGE .... Integrity of Components and Structures
IRSN .... France Institute for Radiological Protection and Nuclear Safety
IEC .... International Electrotechnical Commission
IEEE .... Institute of Electrical and Electronics Engineers
JAPEIC .... Japan Power Engineering and Inspection Corporation
MEMS .... Micro-Electromechanical Systems
METI .... Japanese Ministry of Economy, Trade and Industry
NASA .... National Aeronautics and Space Administration
NEPO .... Nuclear Plant Optimization
NMR .... Nuclear Magnetic Resonance
NRC .... U.S. Nuclear Regulatory Commission
OIT .... Oxidation Induction Time
OITP .... Oxidation Induction Temperature
PRA .... Probabilistic Risk Assessment
PVC .... Polyvinyl Chloride
PWR .... Pressurized Water Reactor
SNL .... Sandia National Laboratories
TDR .... Time Domain Reflectometry
XLPE .... Cross-Linked Polyethylene

INTRODUCTION

With the ever-increasing complexity of nuclear facilities, electrical systems have become ubiquitous and play an important role in safety. Integral to many electrical systems are wire systems. These wire systems not only link the various components internal to a device, but also connect different devices to each other. Wire systems are an integral part of all nuclear facilities and their continued reliable performance is critical.

Wire systems can be a complex aggregate of different components, each having its own unique materials of construction and susceptibilities to failure. Basic to a wire system is the electrical wire itself; however, there are various other components that are necessary to make a wire system functional, such as splices, terminations, connectors and penetrations. The common requirement for each component is that they must function properly when called upon to achieve the objective of the wire system, which could be to transmit power to a load, or relay a signal to an instrument.

In many applications, wire systems play a critical role in performing safety functions and they must operate properly, sometimes in harsh environments. For example, wire systems that are used in safety-related nuclear power plant applications must be qualified to ensure that they will be able to perform their function during and after a design basis accident, even after they have been in service for many years. Qualification standards have been developed by various organizations, such as the Institute of Electrical and Electronics Engineers (IEEE) and the International Electrotechnical Commission (IEC).

A great deal of expertise and knowledge has been obtained related to the design and construction of wire systems, and how to optimize their performance. This is evidenced by the reliable performance demonstrated in the vast majority of wire systems currently installed. However, an area that has yet to be fully addressed is the impact of age degradation on the performance and reliability of wire systems after prolonged exposure to operating and environmental stressors.

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. International efforts have been initiated and are continuing to address this issue. One such effort is described in the International Atomic Energy Agency's TECDOC-1188 [1], which provides an aging assessment of instrumentation and control cables in nuclear power plants. Similarly, IEC is actively involved in standardization activities and publications of IEC documents. For example, efforts are ongoing on IEC-TC 15E, "Guide for determining the effects of ionizing radiation on insulating materials- Part 5 Procedures for assessment of aging in service" (approved for FDIC circulation).

In the United States, significant research has been conducted over the past two decades by various institutions and organizations on aging related issues for cables. The U.S. Nuclear Regulatory Commission (NRC) continues to sponsor research in the area of long-term behaviour 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) also 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 IEEE in the U.S., relevant consensus standards are either being revised or new standards are being developed for wire systems. The IEEE has developed, and recently updated, its Standard 1205 [2], which provides guidance for assessing, monitoring, and mitigating aging effects on safety-related electrical equipment in nuclear power plants. The various industry groups and contractors continue to support the resolution of issues related to wire system safety.

Research is continuing in the area of prognostics and diagnostics to find new, effective, in situ techniques that can be used to monitor the condition of installed wire systems and predict their remaining useful life. Condition monitoring (CM) is accepted as one of the most powerful tools available to manage the effects of aging on wire systems and ensure that they are fit for continued service. However, a universally acceptable CM technique that can be used for all wire system applications has been elusive and is still not available.

In November 2000, the issue of wire system safety received national attention in the U.S. with the issuance of the White House Report on Wire System Safety [3]. This report concluded that wire system safety is an important public health and safety issue that transcends government agencies. One of the recommendations in this report is to encourage the use of collaborative research efforts to address any unresolved issues.

Even with the great deal of research already completed, there are a number of important issues that remain to be resolved. In April 2002 the NRC sponsored an International Conference on Wire System Aging [4]. At this conference, experts from around the world gathered to discuss issues that still need to be resolved and the collaborative research efforts that would be most effective to address these issues. 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.

To address the technical issues related to wire system aging and safety, the Working Group on Integrity of Components and Structures (IAGE), under the auspices of the Committee on the Safety of Nuclear Installations (CSNI), formed a special task group. The Task Group on Wire System Aging, also referred to as the Cable Task Group (CTG), was chartered with evaluating the current status of research in this area, identifying technical issues that remain unresolved and warrant additional research, and recommending research programs to address the outstanding issues. Appendix A provides a list of CTG members that contributed to this effort. Appendix B includes the specific terms of reference for the CTG.

Initial efforts by the CTG focused on the identification of issues related to wire system aging, and the review and evaluation of ongoing research to address these issues. This report documents the results of the initial efforts by the CTG and provides a preliminary list of issues related to wire system aging that need to be addressed by future research efforts. It is the intention of the CTG that this list be expanded and modified as new issues are identified to obtain a comprehensive list of issues to be addressed by the research. Interested researchers can then use this list to identify collaborative research efforts in which they would be interested in participating. Collaborative research should then be performed to resolve these issues.

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

- Physical and Chemical Models of Wire System Aging

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- Risk Significance of Wire System Aging
- Prognostics and Diagnostics for Installed Wire Systems
- Environmental Qualification Practices for Wire Systems

The preliminary list of technical issues presented herein is based on a review of past and current work in these areas, as well as input obtained at the NRC conference. The issues that remain unresolved and would benefit from additional research are listed and ranked as “High,” “Medium,” or “Low” based on their importance and potential contribution to current aging management practices. These rankings can be used as guidelines to assist in the selection of issues for research when limited resources are available. However, the issues listed in the areas of fire hazards assessment and risk assessment due to aging should first be reviewed by the respective experts in these areas prior to selecting any of these issues for research. Each area of interest is discussed in the following chapters.

PHYSICAL AND CHEMICAL MODELS OF WIRE SYSTEM AGING

Discussion

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. Several models currently exist, such as the Arrhenius model for predicting thermal degradation of polymers, and the equal-dose/equal-damage model for predicting degradation due to radiation exposure. However, each of these models has limitations that must be accounted for in their application in order to obtain useful results. The accuracy of these models depends on an understanding of how the various aging stressors interact and affect the physical and chemical structure of the materials of construction. The models have also limitations in their applications to real cables considering their construction (shielding, jacketing, armour, etc.)

Research in this area may prove beneficial in providing new or improved models for use as an alternative means of estimating future performance of wire systems and predicting remaining life. In this regard, standardization of testing methods and condition monitoring techniques is needed. The fulfilment of this need is recognized as a key element for the validation of physical and chemical models.

Issues to be addressed

Although models exist for predicting the degradation and performance of the polymeric materials commonly used to insulate wire systems as they age, these models have limitations that could impact their accuracy and usefulness when extrapolating data into regions representative of typical operating service conditions. Improvements to these models would be beneficial to provide more accurate and reliable predictions of the performance of wire system insulation as it ages. Alternatively, the development of new models for predicting insulation performance may be warranted.

Also, the current models tend to focus on the performance of one wire system component; the wire insulation. This is justifiable since aging of the insulation is known to be a major factor affecting the performance of wire systems subjected to age degradation. However, there are many other important components in a wire system; thus, there may be alternative models that provide a more representative performance prediction of the wire system as a whole. These models can only be identified through focused research.

The limitations in current models should be well defined so that they can be properly addressed in the application of these models. Further, performance data that can be used to validate or improve the models should be identified.

In addition, research to identify the most effective models for simulating and predicting service life of wire system components would be beneficial. This could include the identification of new, more accurate models for estimating accelerated aging requirements for qualification testing, and for predicting age degradation and performance.

In summary, the following research needs have been identified in the area of physical and chemical models of aged wire systems:

- Existing physical and chemical models need to be validated against performance data obtained from testing and field experience.

- Applicability and limitations of existing models (near-term) and development of new physical and chemical models (long-term), recognizing the fact that materials behave differently and that there is no model that is applicable to all materials.

- Standardization of testing methods and condition monitoring techniques for effective development and validation of suitable physical and chemical models.

Specific issues within these general topics that are unresolved and should be addressed are presented in Table 1.

Ongoing Research and Issues Being Addressed

In the U.S., research is being performed at the University of Michigan, in collaboration with Advent Engineering Services, to better understand the role of void formation in polymers as a contributor to the degradation of electrical properties for these materials. Previous work has confirmed that there are chemical changes in polymers over the long-term; however, there has been little work to correlate these changes to the microstructure and fracture mechanics of the material. Experimental evidence exists to suggest that voids or "virtual voids" form in polymers, and these voids are likely to promote the early onset of failure. Research is being performed to determine if a known mechanical model for metal failure due to voids can be applied to cable insulation polymer systems.

The research being performed at the University of Michigan related to the role of voids in polymer degradation addresses the issue of potential new models that can be used to predict wire system performance. If this research proves successful, models based on the void concentration in insulating materials may be developed to help understand and predict wire system performance.

At Sandia National Laboratories (SNL) in the U.S., work is continuing on the use of a "Time-Temperature Superposition" technique for modelling thermal degradation of polymers. This technique strives to improve on the Arrhenius model by using experimental data to generate scaling factors and obtain more accurate activation energy curves for polymer materials. The improved accuracy of the activation energy curves allows non-linear behaviour to be identified so that improved accuracy can be obtained in extrapolating thermal degradation data to the low temperatures representing typical operating conditions.

Research is also being performed at SNL on the use of an ultra-sensitive oxygen consumption technique to determine the linearity of activation energy curves in the commonly used low temperature extrapolation regions. Since most polymer degradation is due to oxidation, it is believed that measurements of oxygen consumption can be used to determine the material's activation energy. These measurements can be made at relatively low temperatures, approaching normal operating temperatures, thereby allowing the investigation of activation energy characteristics in the extrapolation region.

Also at SNL, research is ongoing to develop a "wear-out" approach for predicting the remaining life of polymer insulations. In this method, field samples that have been aged at typical service temperatures are taken and aged to failure at a higher wear-out temperature. When time-temperature superposition is valid, the remaining lifetime should be linearly related to the aging time prior to the temperature step. An advantage of the approach is that it has the potential for converting non-linear, non-predictive results to linear, predictive behaviour.

The research being performed at SNL addresses the issue of limitations in current models. The work on time-temperature superposition and ultra-sensitive oxygen consumption could provide a means to improve the accuracy of the currently accepted Arrhenius model for predicting thermal degradation of polymer insulation. The wear-out method of predicting remaining life of polymer insulation may also provide a model for more accurate estimation of remaining life.

To develop better models for use in predicting wire system age degradation and performance, it is important to elucidate the structural modifications induced in the various types of polymers used in cable insulating systems. To achieve this goal, the COMOR group and the University of Clermont-Ferrand in France carried out studies to evaluate the molecular modifications induced in ethylene propylene dienemonomer (EPDM) elastomers by gamma radiation. The results of this work provide insights into the mechanism for radiochemical degradation of an EPDM material based on ENB (ethylene-5-norbornene-2). A study of radiochemical aging of EPDM under inert atmospheres has identified the main routes of degradation. A study of radio-oxidation of EPDM has shown the consumption of the ENB termonomer, unsaturation, and the formation of carbonylated oxidation products.

In Sweden, a study is being performed to investigate methods for predicting the remaining life of aged Lipalon and Hypalon cables. The results will be available by the end of 2002 by Stockholm University.

In the Czech Republic, research at the Nuclear Research Institute REZ is being performed to identify the test procedures required for reliable simulation of cable ageing under normal and accident conditions in a nuclear power plant. The issues being considered are: simultaneous radiation/thermal homogeneous oxidation of the real cables (especially polyvinyl chloride (PVC) based cables); dose rate effects in PVC, cross-linked polyethylene (XLPE), ethylene propylene rubber (EPR), and ethylene vinyl acetate (EVA) based cables; and synergisms involving design basis event (DBE) and post-DBE conditions.

Based on a review of the ongoing research in member countries, the issues related to physical and chemical models that are being addressed are presented in Table 1 (column 3).

Additional Research Needed

While several of the issues related to physical and chemical models are being addressed to some degree by ongoing research, there remain several issues for which additional research is warranted. Additional work would be beneficial, as a supplement to ongoing research, to address the improvement and validation of current models. Also, additional work would be useful to identify more effective models for addressing the performance of wire systems as a whole. It is noted that standardization of testing methods and condition monitoring techniques are essential for the adequate development and validation of physical and chemical models.

In support of the development of suitable models, consideration should be given to the role of the characteristic conditions both during and after a DBE, such as the synergistic effects of temperature, radiation, humidity, and chemical sprays; the change in dose rates for both gamma and beta radiation; and the effects of low energy electrons on the degradation of polymer cable jackets. The reliable simulation of DBE and post-DBE conditions is important for predicting cable performance.

To address the remaining issues related to physical and chemical models, the potential collaborative research projects presented in Table 1 have been identified.

Table 1. Issues to address related to physical and chemical models of aged wire systems

Issue	Rank	Ongoing Research	Potential Collaborative Research
1. What are the limitations in current models for predicting wire system age degradation and performance?	High	– SNL research on Time-Temperature Superposition and ultra-sensitive oxygen consumption address limitations in Arrhenius model for thermal aging.	– Limitations of the equal-dose/equal-damage model for radiation exposure – Limitations of models using sequential versus simultaneous exposure of aging stressors – Limitation of models using gamma radiation to simulate degradation due to other radiation types
2. What testing and condition monitoring methods should be standardized for the development of reliable physical and chemical models?	High	– Past research by BNL, EPRI and others on condition monitoring techniques, such as the indenter, OIT, and IR, has demonstrated acceptable methods of performing these tests in a standardized manner.	– Identification of parameters which should be standardized for condition monitoring so as to realize reproducible and comparable results. – Additional research on electrical tests, such as dissipation factor/dielectric loss would be beneficial to determine a standardized method of performing these tests.
3. What performance data should be collected to validate and improve current failure models?	High	None identified	– Identification and demonstration of performance data monitoring to validate and/or improve current degradation models
4. What models/scenarios should be used for simulating and predicting service life of wire system components?	High	– SNL research on wear-out method addresses the prediction of wire remaining life.	– Development of models to predict the remaining life of other wire system components

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Issue	Rank	Ongoing Research	Potential Collaborative Research
5. Can better degradation models be developed for use in estimating accelerated aging requirements for qualification testing?	Medium	– Univ. of Michigan research on the role of voids in polymer degradation may provide a new model for predicting degradation.	– Identification of other new models that can provide improved prediction capabilities for the performance of aged wire system components
6. What additional models are needed, in addition to existing models, for predicting wire system age degradation and performance?	Medium	None identified	– Identification of new models needed to provide a more complete representation of wire system performance
7. What expertise is needed for the development of suitable models and their availability?	Medium	None identified	– Identification of expertise needed for the development of new models needed to provide a more complete representation of wire system performance

ASSESSMENT OF FIRE HAZARDS DUE TO WIRE SYSTEM AGING

NOTE: Aging leads to degradation of dielectric properties of cable insulation. To what extent this constitutes a significant fire hazard risk is not known by the cable aging experts. Therefore, fire experts should be consulted on this issue

Discussion

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, as well as propagate, and adversely impact the performance and/or reliability of safety-related equipment. Additives and protective sheaths are commonly used to reduce the vulnerability to fire. However, the additives can be depleted over time, and the sheaths can become degraded with age. Standards that are currently used to address the fire hazards of cables include IEEE Standards 323 [5] and 383 [6], as well as IEC Standards 60795-1-1 [7] and 60695-1-2 [8].

A significant amount of research has already been performed in the area of fire-risk assessment to address many of the important issues. In support of the U.S. NRC, Sandia National Laboratories has completed several research programs related to electrical cable fire hazards. In the SNL study on cable flammability, it was found that thermal aging substantially reduced flammability. This is attributed to the fact that aging is an oxidation process, similar to fire, and should reduce the flammability of most insulation materials.

In a study on the impact of aging on thermal damage limits, SNL found that damage thresholds for cables changed, but the changes were relatively small and were not considered risk significant. The fire damage thresholds were correlated to environmental qualification (EQ) results and a good correspondence for insulation resistance degradation was found between EQ tests and fire damage thresholds. This indicates that high temperature steam tests, such as those used in EQ testing, can provide thermal damage information applicable to fire analysis.

Research on cable fires has also been performed in the United Kingdom. At the Building Research Establishment/Fire and Risk Sciences (BRE/FRS), several studies were performed to investigate the mechanisms and factors affecting cable fires in buildings. Using a real scale test facility for studying cable fires, various scenarios were investigated to determine the impact of ventilation systems on cable flammability and the effectiveness of the ventilation systems for clearing smoke. It was found that ventilation systems could spread cable fires and fire products around an entire building. Also, ventilation systems could clear smoke; however, they could also intensify the fires by providing an increased oxygen supply.

BRE also performed studies to investigate the fire hazard due to cables installed in hidden spaces within ceilings and walls. It was found that, since very little detection or suppression equipment is located in hidden spaces, there is the potential for a fire to spread undetected and unchecked with a large fuel load over a wide area. BRE also studied the various fire tests currently being used to determine their effectiveness, as well as various commercially available cables to determine their fire performance. It was found that standard fire tests do not always give the best indication of a fire hazard.

While a significant amount of research has been performed in this area, a number of questions remain unanswered. Thus, the fire hazard related to aging of wire systems is an area that warrants additional research.

Issues to be addressed

Although much work has been performed in the area of fire hazard assessment, there are still areas that would benefit from further research. For example, fire growth models for cables, as well as thermal damage models, remain relatively primitive and research to develop more sophisticated models would be beneficial.

Also, the performance of "fire proof" cables, and the impact of age degradation on these cables, are still not well known and would benefit from additional research. Self-ignited cable fires are still poorly understood and research to provide a more in-depth understanding of the process and mechanisms of this phenomenon would be extremely useful for assessing risk.

Several of the technical issues that remain to be resolved in the area of fire hazard assessment are related to the factors that affect the initiation and propagation of fires. As wire systems age there is the possibility that the fire hazard factors will increase due to age degradation, and predicting this increase in risk requires an understanding of the contributing factors. Currently accepted installation practices can also influence the degradation rate of wire systems and should be evaluated to determine if improvements are needed.

Issues also remain regarding the effectiveness and benefits of circuit protective devices. Improvements have been made in the development of fast acting circuit breakers and arc fault circuit interrupters; however, their impact on fire hazard is largely unknown. Research to quantify the benefits of these devices would be beneficial.

Fire detection and suppression systems, both active and passive, are also susceptible to age degradation. The impact of this degradation on their performance and reliability is also unknown and should be investigated. For example, inadvertent actuation of fire suppression systems can cause damage to wire systems and, possibly, premature failure. Also, the actuation of fire suppression systems in response to an actual fire could damage nearby wiring circuits, and the vulnerability to this collateral damage could increase with the age of the wiring circuit. These are issues that would benefit from additional research.

While fire retardants are commonly added to insulation materials, these additives can be depleted with age, thus reducing the available protection from fire initiation and propagation. The impact of age depletion on the fire retardant capabilities of cables is an issue that has been studied in the past, but warrants further research. Also, the impact of these fire retardant additives on the degradation rate of the insulation has not been systematically researched and documented. Some of the additives could make the insulation more susceptible to other aging stressors, thus effectively accelerating the aging degradation rate of the insulation.

As new cable designs and constructions are developed, their vulnerability to fire initiation and propagation needs to be studied. Also, the tests used to determine the flammability of cables should be reviewed to determine if they are the most effective methods currently available, or if new methods need to be developed. For example, performance based testing and a fire safety engineered approach may be more appropriate for some types of cable instead of a simple pass/fail judgment based on a standard flammability test.

New research is also needed in the area of explosion hazards for certain types of cable installations. The toxicity and corrosivity of certain types of cables (e.g., halogen/non-halogen cables) should also be studied to provide a more thorough understanding of these mechanisms.

In addition, additional work would also be beneficial to develop guidance documentation for wire system designers, installers, users, and fire fighters to provide better information on how to mitigate the fire hazards for the various applications of wire systems.

In summary, the following general topics related to the fire hazard of aged wire systems were determined to warrant additional research:

- Development of improved models for predicting fire hazards, including fire growth and thermal damage models, as well as information on the factors affecting the frequency of self-initiating fires and the propagation of fires.

- Improving inputs to existing models to provide more accurate predictions, including performance testing of wire systems to obtain flammability and fire frequency data that can be used to determine the increase in fire hazards due to age related degradation

- Evaluation of the impact of aging on fire suppression and protection systems, including new fast acting circuit protective devices and “fire proof” cables

- 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.

Specific issues within these general topics that are unresolved and should be addressed are presented in Table 2. However, it is suggested that these issues be reviewed by the fire hazard experts prior to initiating any new research.

Ongoing Research and Issues Being Addressed

In the U.S., research is continuing at SNL on projects related to cable fire hazards. Currently, research is being performed to develop a process for circuit analysis quantification, whereby the likelihood of a particular cable failure mode can be estimated. This process would provide a mechanistic link between a failure mode and the circuit fault, as well as the circuit fault likelihood. In addition research is being performed to develop overall fire hazard analysis methods, including screening interactions, interactions with plant response models, and interactions with human reliability analysis.

The research at SNL addresses the issue of how to predict the probability of a wire system fire due to specific failure modes. By correlating these failure modes with the age-related failure mechanisms that cause them, this research could provide a new method for estimating the frequency and risk of fire hazards due to certain age-related failure mechanisms.

In the Czech Republic, tests are being conducted on the fire propagation properties of halogen free, DBE resistant cables that are constructed based on cross-linked polyolefins and optic cables.

Based on a review of the ongoing research in member countries, the issues related to fire hazard assessment that are being addressed are presented in Table 2.

Additional Research Needed

Prior to initiating any new research in the area of fire hazards, the solicitation of input from the fire-risk experts is suggested.

Comparing the unresolved issues related to fire hazard assessment in aged wire systems to the currently ongoing research, it is seen that additional new research may be needed to resolve the remaining issues. To address the remaining issues related to fire hazard assessment, the potential collaborative research projects presented in Table 2 have been identified. These proposed research programs should be evaluated and ranked by the fire-risk experts.

Table 2. Issues to address related to fire hazard assessment of aged wire systems

Potential Issue*	Tentative Rank*	Ongoing Research	Potential Collaborative Research
1. What are the limitation in existing fire growth models and what improvements can be made?	High?	None identified	– Determine the limitation in existing fire growth models and what improvements can be made.
2. What are the limitation in existing thermal damage models and what improvements can be made?	High?	None identified	– Determine the limitation in existing thermal damage models and what improvements can be made.
3. 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?	None identified	– Identification and prioritization of the factors affecting the frequency of self-initiating wire system fires, including the relative strengths of these factors and how they are affected by aging.
4. 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?	None identified	– Identification and prioritization of the factors affecting the propagation of wire system fires, including the relative strengths of these factors and how they are affected by aging.
5. How does aging affect the vulnerability of wire systems to fire induced damage?	High?	None identified	– Evaluation of the effect of aging on the vulnerability of wire systems to fire induced damage.
6. What is the best means of evaluating the effectiveness of fast-acting circuit protective devices for fire protection and mitigation?	High?	None identified	– Development of guidance on the best means of evaluating the effectiveness of fast-acting circuit protective devices for fire protection and mitigation.
7. What impact does aging have on the reliability of fire detection and suppression systems?	High?	None identified	– Evaluation of the impact of aging on the reliability of fire detection and suppression systems.

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Potential Issue*	Tentative Rank*	Ongoing Research	Potential Collaborative Research
8. What methods, tools, and data should be collected to predict the frequency of cable fires and their likelihood of propagation?	High?	– SNL research on a process for circuit analysis quantification could provide a method of estimating the frequency of cable fires due to certain age-related failure mechanisms.	– Development of guidance on the methods, tools, and data to be collected to predict the frequency of cable fires and their likelihood of propagation.
9. How does aging affect the fire retardant capabilities of “fire-proof” cables? How long will each of the common cable types survive in a fire as a function of age?	High?	None identified	– Evaluation of how aging affects the fire retardant capabilities of cables, including how long each of the common cable types will survive in a fire as a function of age.
10. 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?	None identified	– Evaluation of how the fire retardants added to cable insulation materials affect the aging degradation rate due to other stressors, such as temperature, radiation and humidity.
11. Is there any difference in the risk of fire hazard between cables qualified per IEEE-383-1974 and cables that are not qualified? How does this difference change with age?	Medium?	None identified	– Determination of whether there is a difference in the risk of fire hazard between cables qualified per IEEE-383-1974 and cables that are not qualified, including how this difference changes with age.
12. 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?	None identified	– Determine 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.

Potential Issue*	Tentative Rank*	Ongoing Research	Potential Collaborative Research
13. What effects do currently accepted installation techniques have on the risk of fire hazard for aged wire systems, such as locations where circuits are routed in close proximity (e.g., at the load end)?	Medium?	None identified	– Determine the effect of currently accepted installation techniques on the risk of fire hazard for aged wire systems, such as locations where circuits are routed in close proximity (e.g., at the load end).
14. How does aging affect the vulnerability of wire systems to damage induced by inadvertent actuation of fire suppression systems?	Medium?	None identified	– Determine how aging affects the vulnerability of wire systems to damage induced by inadvertent actuation of fire suppression systems.
15. 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?	None identified	– Determine the impact on risk from environmental stressors imposed in response to a fire, such as water spray or falling objects, including how these risks can be quantified and how these risks change with age.
16. What is the fire hazard impact related to new cable designs, such as fibre optic cable?	Medium?	None identified	– Evaluate new cable designs, such as fibre optic cable, to determine the fire hazard impact related to their use.
17. What are the limitations in currently accepted cable flame tests? What improvements can be made?	Medium?	None identified	– Review currently accepted cable flame tests to identify their limitations and what improvements can be made to them.

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RISK SIGNIFICANCE OF WIRE SYSTEM AGING

Note: Risk significance of wire systems is influenced by the changes in cable properties due to aging and may affect functionality of a wire system under design basis accident. Therefore, risk experts should be consulted on this issue

Discussion

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 (PRAs) may not accurately represent wire system performance later in life. Due to the increased use of 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.

At Brookhaven National Laboratory (BNL) in the U.S., a scoping study was performed to determine the impact of cable failures on nuclear power plant risk, using core damage frequency as the risk measure. Typically, in probabilistic risk analyses, a cable's reliability is assumed to remain unaffected by age. However, it is now known that this may not be accurate, since age degradation can adversely impact a cable's performance. It was found that decreases in reliability for some cables could lead to significant increases in plant risk. Further detailed analyses would improve the understanding of the contribution of cable aging to plant risk.

At the U.S. NRC, work was performed to develop a method for estimating the contribution of cable aging to the risk of nuclear power plant operation. In this method, physical and chemical models are used to estimate the probability of cable failure. These estimates of failure are then input into fault tree and event tree models to determine plant risk. By performing these calculations at various plant ages, plant risk as a function of age can be determined.

The use of risk assessments is becoming increasingly popular both in the regulatory arena, as well as for everyday operation and maintenance of facilities. At the South Texas Project nuclear power station in the U.S., PRAs are being used to categorize components based on their importance to plant risk. Those components that are the highest importance receive the most attention, while those that are of low importance receive little or no attention. This risk-based approach to maintenance, qualification, and inspection allows resources to be used more effectively.

Issues to be addressed

While significant advances have been made in the area of risk assessments, there remain a number of issues that would benefit from additional research. In the area of plant risk due to wire system aging, scoping studies have shown that certain wire systems can have a significant impact on plant risk if they fail. However, these studies evaluated only a limited number of plant systems and are based on a number of assumptions. This type of analysis needs to be performed on a wider scale to fully evaluate the significance of wire system failures for the range of nuclear plant designs that exist. If specific wire systems or components can be identified that contribute the most to plant risk, this would provide a valuable tool to use in optimizing resources for maintenance, inspection, and testing to reduce plant risk.

In addition, research would be useful to identify operational data that can be used to more accurately characterize the failure rate of wire system components, as well as their ability to withstand different levels of harsh environments.

The PRA analyses currently being performed include a number of assumptions related to component failure rates and reliability. Research into the acceptability of these assumptions would be useful to allow more accurate analyses to be developed.

Human factors research would also be beneficial to identify the types of training and information that should be provided to the operators to enable them to understand and deal with the potential impact of wire system aging. Also, the identification of approaches that can be used to assess human operator performance and response with respect to wire system failures that could limit expected indications and control information would be useful.

Other issues that should be addressed include the criteria that can be applied to better define the severity level of harsh environments, the impact on failure rate of installation techniques, and whether risk can be used as a criterion for post-accident performance duration during qualification testing.

In summary, the following general topics related to the risk significance of aged wire systems were determined to warrant coordination and interactions, as well as additional research:

- Continued studies to determine how aging of wire systems impacts plant risk, including determination of the relative importance of various wire systems, and the impact of aging on failure rates and reliability. Also, it would be beneficial to have a series of 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.

- Determination of how risk insights can best be used to more effectively manage wire system aging, including input to operator training programs, and optimization of inspection, maintenance, and replacement strategies

- Improvements to inputs for existing models to more accurately estimate plant risk due to wire system aging, including operational data acquisition to characterize failure rates, and the acceptability of currently used assumptions

- 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.

- Development of improved physical and chemical models suitable to address the phenomenological aspects of wire system aging for evaluating risk significance.

Specific issues within each general topic that are unresolved and should be addressed are presented in Table 3. However, it is suggested that theses issues be reviewed by the risk assessment experts prior to initiating any new research.

Ongoing Research and Issues Being Addressed

In the U.S., research on risk assessments related to wire systems is being sponsored by the NRC. A research program is being initiated to further investigate the importance of wire system aging on plant risk. This work will expand on the scoping studies performed previously, and will investigate the impact of age degradation on wire system failure rates and reliability. The results will then be used to evaluate the effect on plant risk for various scenarios of wire system degradation and failure rates. The importance of the various components in the wire systems will also be evaluated. This work addresses the issues related to the impact of wire system aging on plant risk, and the importance of various wire system components.

The Lectromechanical Design Co. and Advent Engineering Services in the U.S. are studying the risk associated with wire system failures in aircraft. In this work, typical wire system faults found in aircraft are being identified to characterize the type of age degradation experienced in these applications. Past operating events related to wire system faults are also being reviewed to extract information on age-related failures. This information is then being used to evaluate the risk to successful operation of the aircraft due to age degradation of selected wire systems. The result of this work will be the development of an overall risk assessment process that can be applied to aircraft to improve safety and reliability. This work could provide insights that are useful for nuclear power plant applications.

In the Czech Republic, the risk significance of cable systems in nuclear power plants is being assessed considering both operational and environmental conditions. The cable systems located in hot spot locations have undergone periodic inspections during which micro sampling was performed to obtain material specimens for oxidation induction time and temperature (OIT/OITP) measurements. The results of these tests are being used to estimate the remaining cable life.

Based on a review of the ongoing research in member countries, the issues related to risk significance that are being addressed are presented in Table 3.

Additional Research Needed

Ongoing research is addressing several of the issues of interest related to the risk significance of aged wire systems. However, there remain a number of issues that would benefit from additional research. To address the remaining issues related to risk significance of wire system aging, the potential collaborative research projects presented in Table 3 have been identified. However, prior to initiating new research in this area, it is suggested that input from the risk assessment experts be solicited.

Table 3. Issues to address related to risk significance of aged wire systems

Potential Issue*	Tentative Rank*	Ongoing Research	Potential Collaborative Research
1. What is the relative importance of the various wire systems in a plant in terms of their contribution to plant risk?	High?	– NRC research on plant risk due to wire system aging will address this issue for U.S. plant designs.	– Evaluation of wire system aging importance to plant risk for non-U.S. plant designs.
2. 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?	None identified	– Study to determine which of the components commonly found in a wire system are the most likely to have a failure rate affected by age degradation, and how this impacts the reliability of the wire system.
3. 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?	– Experience at the South Texas Project in the U.S. provides information useful to address this issue.	– Study to determine how inspection, maintenance, and replacement strategies can be most effectively optimized to manage the effects of wire system aging and mitigate potential increases in failure rate for nuclear plants.
4. 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?	None identified	– Study to determine 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.
5. What are acceptable assumptions in assessing the risk of wire system aging considering the limited information currently available?	High?	None identified	– Determine the acceptable assumptions for use in assessing the risk of wire system aging considering the limited information currently available.

* Risk assessment experts to evaluate/modify potential issues listed or add new issues, rank them, and recommend topics for collaborative research.

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Potential Issue*	Tentative Rank*	Ongoing Research	Potential Collaborative Research
6. 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?	None identified	– Identify the types of training and information that should be provided to human operators to enable them to understand and deal with the potential impact of wire system aging.
7. 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?	None identified	– Determine the approaches that can be used to assess human operator performance and response with respect to wire system failures that could limit expected indications and control information.
8. What is the impact of prolonged exposure to harsh environment on wire system performance and aging?	Medium?	None identified	– Evaluate the impact of prolonged exposure to harsh environment on wire system performance and aging.
9. What criteria can be applied to better define the severity level of harsh environments?	Medium*?	None identified	– Establish criteria that can be applied to better define the severity level of harsh environments.
10. 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?	None identified	– Determine the impact on failure rate of the various installation techniques for wire system components, such as conduits and cable trays, including the advantages and disadvantages of each.
11. Can risk be used as a criterion for determining post-accident performance duration for qualified wire systems?	Medium?	None identified	– Determine if risk can be used as a criterion for determining post-accident performance duration for qualified wire systems.

PROGNOSTICS AND DIAGNOSTICS FOR INSTALLED WIRE SYSTEMS

Discussion

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 [3] 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. Therefore, effective in situ condition monitoring techniques are considered an important aspect of managing aging of wire systems.

A great deal of research has been performed in the area of CM. For example, at Brookhaven National Laboratory in the U.S., several condition monitoring techniques have been studied, including ac impedance/dielectric loss, time domain reflectometry (TDR), oxidation induction time, and Fourier Transform Infrared (FTIR) Spectroscopy. The ac impedance/ dielectric loss technique measures the phase angle between an applied test voltage and the resulting current in a cable. Changes in the phase angle are then trended and can be correlated to degradation of the cable insulation. TDR uses the reflections of an input signal to the cable at impedance changes to locate potential defects. By measuring the time delay between the input signal and its reflection, the location of the impedance change can be determined. In the oxidation induction technique, a small sample of the cable insulation is heated in a calorimeter under controlled conditions and the time for oxidation to initiate is measured. This induction time is a function of the amount of antioxidant remaining in the material, and can be correlated to age degradation. Finally, FTIR examines the absorbance spectrum of an infrared light beam on the cable insulation. Peaks in the spectrum can be related to the various bonds formed as a result of oxidation, which is an indicator of degradation.

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. If successful, great benefits can be realized from research in this area.

Issues to be addressed

Prognostics and diagnostics is an important area for managing the effects of wire system aging, and there is continued interest in performing new research to develop new methods of monitoring wire system condition and predicting future performance. Although research is ongoing in this area, new research would be beneficial to provide new ideas for more effective techniques for in situ monitoring.

Related to the development of new CM techniques is the development of acceptance criteria that can be used to make decisions regarding the acceptability of currently installed wire system components. While a CM parameter may provide an indication of the aging degradation of a component, specific acceptance criteria are needed to determine if the current condition, which may include degradation from “hot spots” and localized anomalies, is acceptable for continued service.

In many cases, CM parameters provide a measure of the physical condition of the wire system component, such as material hardness. However, these measurements must be correlated to the electrical performance of the wire system to provide useful information on the acceptability of the wire system for continued service. Therefore, correlation of the physical properties to electrical properties is very important.

In summary, the following general topics related to prognostics and diagnostics of aged wire systems were determined to warrant additional research:

- Continued development of new, effective, in situ condition monitoring techniques for installed wire systems that can be used to determine the current condition of the wire system

- The use of condition monitoring to predict remaining useful life, including the establishment of acceptance criteria, performance data acquisition, and 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

- Conduct research to correlate condition indicators with the functional behaviour of wire systems under design basis event conditions.

Specific issues within each of these general topics that are unresolved and should be addressed are presented in Table 4.

Ongoing Research and Issues Being Addressed

In the United States, research is ongoing on a number of promising condition monitoring techniques for wire systems. At the National Aeronautics and Space Administration (NASA), development work is being performed using ultrasonic techniques to monitor electric wire insulation degradation. In this technique, two ultrasonic transducers are used to generate and receive an ultrasonic guided wave in the wire. The condition of the wire insulation, such as its stiffness, will affect the wave speed and amplitude of the guided wave. Therefore, a measurement of wave speed can be used to indicate the stiffness or condition of the wire insulation.

Another technique being investigated by NASA is lock-in thermography. In this technique an alternating current is passed through the wire to act as a thermal source to modulate the surface temperature of the wire. The surface temperature is then monitored using an infrared camera. Using appropriate processing techniques, the data provide amplitude and phase images of the wire surface temperature, which can be used to detect degraded areas of the wire insulation.

A third condition monitoring technique being studied at NASA involves the detection and location of degraded insulation by measuring the concentration of combustion by-products given off by the insulation either during arcing or current overloading. This is done through the use of micro-electromechanical systems (MEMS). MEMS sensors have the capability to detect the presence and concentration of specific chemical species. The presence of combustion products is used as an indicator of insulation damage resulting in arcing.

At the Sandia National Laboratories in the U.S., research is being performed on two promising condition monitoring techniques; the modulus profiler and Nuclear Magnetic Resonance (NMR) relaxation times. The modulus profiler measures the indentation of a small tip into the surface of a polymer sample. The degree of indentation at a constant load can be related to the modulus of the material, which can be correlated to age degradation. NMR relaxation times are a measure of the molecular dynamics of the polymer backbone chain. By soaking the polymer in a suitable solvent causing it to swell, the relaxation times can be determined and correlated to the degree of cross-linking in the polymer, which is a function of the age degradation.

Condition monitoring techniques being studied at EPRI in the U.S. are visual inspections and indenter testing. Visual inspections are used to examine accessible cables in nuclear power plants and provide a qualitative determination of their condition. Various physical properties are inspected, includingcolourr, cracking and degree of flexibility. These physical properties can be correlated to the degree of age degradation experienced by the cable. The indenter testing involves the use of a computerized probe, which is pressed into the insulation of the cable insulation. By measuring the force and displacement of the probe, the compressive modulus of the insulation can be determined. This can be trended and correlated with age degradation to provide a quantitative evaluation of the insulation condition.

In a joint effort by Boeing and Rockwell Scientific, the Broad Band Impedance technique is being studied as a means of monitoring electrical cables. In this technique, the impedance response of the cable is measured in both the shorted configuration and the open configuration. These measurements are then analyzed to extract information on the cable impedance, resistance, and dielectric function, which can then be related to the degree of degradation in the cable.

The Excited Dielectric Test (EDT) is a technique being studied by CM Technologies in the U.S. that combines TDR with dissipation factor measurements to determine the condition of a cable's insulation. In this technique, the cable is modelled as a parallel resistor/capacitor circuit and both dissipation factor measurements and TDR measurements are made. As the cable insulation degrades, its capacitance will also change, resulting in a corresponding change in impedance. Thus, the impedance measurements can be used as an indicator of cable insulation degradation.

Advent Engineering Services in the U.S. is performing research related to the use of micro-void detection techniques to determine the condition of cable insulation. Capacitance is used as a means of determining nominal micro-void content within the structure of the insulation. There reportedly is an age dependent relationship for insulation capacitance, and it is theorized that the capacitance is a function of the micro-void content of the material. Thus, it is possible that properly measured capacitance can be correlated to micro-void content and to a determination of remaining life of the insulation.

A technique for monitoring low-voltage cable insulation being studied by Hitachi, Ltd. in Japan involves the application of optical diagnosis for detecting degradation. In this technique, light sources of two wavelengths are used and the change in reflective absorbance between the two wavelengths is measured. Chemical kinetics is then used to predict the lifetime of the insulation. When the insulation darkens as a result of degradation, the reflective absorbance increases, indicating an increase in cross-linking density due to degradation.

Westinghouse Atom in Vasteras, Sweden has performed a number of measurements, which show that the dissipation of oxidation inhibitors can usually be established with good precision. They also show that the oxidation inhibitors can disappear before the dielectric behaviour of the cable insulation is affected. Thus, loss of oxidation inhibitors has proven to be an efficient condition indicator for cables that include oxidation inhibitors.

In Japan, the degradation diagnosis method of monitoring cables was developed and is being evaluated. This method correlates the velocity of ultrasonic waves in the surface layer of the cable insulation or jacket to values of elongation at break, which is a good indicator of degradation. Equipment for performing this test, which was developed by private nuclear power plant fabricators in Japan [9], is composed of a set of two ultrasonic probes that move to a pre-determined position and measures the ultrasonic velocity automatically in a sequential manner. The degradation diagnosis method has been applied to cables in some pressurized water reactor (PWR) plants in Japan beginning in 2000. [18]

At the Nuclear Research Institute REZ (Czech Republic), the condition monitoring techniques being studied are based on the measurement of OIT/OITP, and density. The indenter method, which measures compressive modulus of the insulating material, has also been developed.

Different CM techniques are being evaluated at Tecnatom in Spain. Ultrasonic testing has been applied to different types of cables at different stages of aging. Results obtained thus far have not been promising; however, the sample size evaluated is relatively small and may not be representative of all cable types. Mechanical indentation techniques are also being evaluated with positive results for some materials. Electrical monitoring of cables is also being performed on significant cable populations in various nuclear power plants during outages using a CM technique developed in the U.S. This technique, while very useful to identify circuit electrical condition, has thus far not provided consistent aging trends. Unesa has also developed specific tools for cable aging management within a generic software application for the management and extension of nuclear power plants in Spain.

At the OECD Halden Reactor Project in Norway, which is operated by the Institutt for Energiteknikk under the auspices of the OECD Nuclear Energy Agency, nuclear safety authorities, utilities, research institutes, and industry organizations from 20 countries are jointly sponsoring a research program on safety and reliability of nuclear power plants.

The research program proposed for the period 2003 to 2005 includes plans for investigating the applicability of empirical numerical techniques, developed at the Halden Project for on-line diagnostics of instrument and component failures and degradation, as well as for electrical testing of cables. If the results are encouraging, the program will include the development of a non-intrusive, whole length, electrical cable condition monitoring technique based on these signal-processing techniques.

Such a program will have to be based on collaboration with other organizations doing research in the field. The plan is to start with a review of current methods for on-line cable condition assessment, and a feasibility study of the possible use of the AI methods for signal processing and extraction of signal anomalies developed at Halden for enhancing these existing condition monitoring techniques.

Based on a review of the ongoing research in member countries, the issues related to prognostics and diagnostics that are being addressed are presented in Table 4.

Additional Research Needed

The issues remaining to be resolved related to prognostics and diagnostics of aged wire systems would benefit from collaborative research efforts. To address the remaining issues, the potential collaborative research projects presented in Table 4 have been identified.

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

Issue	Rank	Ongoing Research	Potential Collaborative Research
1. How can wire system defects be detected in the incipient state, and located prior to their impacting wire system performance or causing failure?	High	– Research being performed in the U.S. and Japan on new cable condition monitoring techniques addresses this issue.	– Develop other promising new condition monitoring techniques.
2. What types of models, analyses, and data trending are needed for determining the remaining service life of wire systems?	High	None identified	– Develop methods for analyzing and trending of data from various condition monitoring techniques or in situ performance data to predict remaining life of wire systems.
3. 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	– Research being performed in the U.S. and Japan on new cable condition monitoring techniques addresses this issue.	– Develop other promising new condition monitoring techniques.
4. 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	– Research being performed in the U.S. and Japan on new cable condition monitoring techniques addresses this issue.	– Determine how in situ wire system performance data be used to predict the future performance of the wire system and estimate its remaining life.
5. What acceptance criteria should be considered in determining if a wire system is fit for continued service and operability in a design basis accident?	High	None identified	– Develop acceptance criteria needed to judge a wire system fit for continued service in normal and accident condition. – Investigate the relationships between the condition (measured by appropriate condition indicators) of the wire system and its operability in a design basis accident.

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Issue	Rank	Ongoing Research	Potential Collaborative Research
6. How can the measurement of physical and chemical properties of a wire be correlated to the electrical properties of the wire?	High	None identified	– Develop an effective means of correlating measurable physical properties of a wire system to the electrical properties of the wire system such that the physical property measurements can be used as an indicator of the electrical condition of the wire system.

ENVIRONMENTAL QUALIFICATION OF WIRE SYSTEMS

Discussion

Depending on the application for which a wire system will be used, it may have to be qualified to provide some level of assurance that it will be able to perform its function, even after it has been in service for an extended period of time. The environmental qualification (EQ) process addresses the ability of the components to perform their safety function after prolonged exposure to environmental stressors, such as elevated temperature, humidity, or radiation. In addition, ongoing qualification is necessary to ensure that the component's condition and performance remain acceptable, and consequently the component remains qualified, throughout the plant's lifetime. Currently, qualification testing of electrical components in the U.S. is performed in accordance with IEEE Standards 323-1974 [5] and 383-1974 [6]. International standards for qualifying electrical equipment have also been developed, such as IEC Standard 60780 [10].

Qualification testing is an area in which a great deal of significant work has already been performed, and much knowledge has been gained. In the U.S., both Brookhaven National Laboratory and Sandia National Laboratory have performed research under the auspices of the NRC. This research investigated the accident performance of various types and constructions of cables commonly used in nuclear power plants. Accelerated aging techniques were investigated, along with condition monitoring methods for in situ use. A summary of this research is included in NUREG/CR-6384 [11] and NUREG/CR-6704 [12]. Experience shows that many uncertainties exist, and various hypotheses have been made, with regard to the applicability of environmental qualification for real plant situations.

EPRI has also studied issues related to the qualification of electric components extensively in the U.S. Various EPRI studies have been performed to address issues related to qualification, including maintaining and extending the qualification of currently installed equipment. A number of EPRI reports have been published on this topic [13, 14, 15].

In France, the Institute for Radiological Protection (IRSN) carried out studies to evaluate the temperature and dose rate effects, as well as the representativeness of accelerated aging conditions applied during the qualification tests. EPR/CSPE (Hypalon) insulated and halogen free cables were subjected to accelerated thermal and radiation aging, using different temperatures, doses, and dose rates, including very low dose rates (1 Gy/hr) over several years. It was observed that, for the Hypalon insulated cables, different degradation mechanisms were noted corresponding to the different temperatures and dose rates. The Halogen free cables were noted to be less sensitive to the high dose rate effects.

The IRSN studies also included the experimental determination of activation energies for several cable materials. Comparisons were then made of cable samples taken from a plant (after 7 years of operation) with samples aged artificially in the laboratory using the activation energies experimentally determined. There was good correlation between the natural and artificially aged Hypalon, however, naturally aged EPR insulated cables were more damaged than the artificially aged samples. It was concluded that there are limitations in using generic activation energies in thermal aging models, however there are also limitations in using experimentally determined values for the specific material being tested due to the range of temperatures used for the determination.

Research at IRSN also examined the performance of cables during design basis events (DBE) as it relates to margins in environmental qualification tests. It was found that, for Hypalon insulated cables, the performance during and after a DBE is dependent upon the pre-aging applied to the cable. Conversely, the DBE performance of EPR insulated cables is relatively independent of the pre-aging applied to the cables, and depends essentially on the temperature elevation during the DBE. Due to the non-representativeness of the qualification tests for Hypalon insulated cables, and the fact that the behaviour of the Hypalon insulated cables during and after a DBE depends upon the pre-aging applied, it is difficult to make a good prediction of the real behaviour of the cables during a DBE. It was concluded that supplementary aging management actions, such as including environmental monitoring and "ongoing" qualification of real cables, could be implemented to evaluate the behaviour of naturally aged cables, and to determine the margins of environmental qualification programs.

IRSN research also addressed aging indicators and relevant condition monitoring methods. Several non-destructive CM methods were studied, including oxygen consumption and oxidation induction time or temperature measurements. The correlation between electrical and mechanical properties, and oxidation of the polymers was analyzed. The results showed that the correlations between electrical and mechanical properties and oxygen consumption of polymers cannot be easily established.

Results from the IRSN research also found a synergistic effect between temperature and radiation on Hypalon, and more degradation on the polymers when thermal aging follows ionizing radiation. Qualification tests normally perform thermal aging before radiation aging. These tests must include sufficient margins to cover all of these phenomena. The behaviour of EPR/chlorosulfonated polyethylene (CSPE) insulated cables subjected to realistic accident conditions (total dose of 30kGy combined with thermodynamic profile) and to standard DBE conditions (total dose of 600kGy followed by thermodynamic profile) was studied. It was found that the cables subjected to the standard DBE were more damaged than the cables subjected to the realistic accident conditions, primarily due to the effects of the irradiation.

Issues to be addressed

Although much has been learned from the research already completed, several issues remain to be resolved in the area of environmental qualification that would benefit from collaborative research. In the area of accelerated aging for qualification, questions still remain regarding the limitations imposed by the use of high acceleration factors for aging the components prior to accident testing. Also, the impact of using generic activation energies in thermal aging models is still not completely understood. It is possible that new research could develop better models to provide more accurate estimates of age degradation due to service conditions that may include, in addition to thermal and radiation environments, humidity, vibration, and corrosive agents.

Questions still remain regarding the performance of the qualification testing, such as the optimum number of test specimens to include in a qualification test so that statistically significant results can be obtained and margins needed to compensate for uncertainties due to the limited number of test specimens. Also to be resolved is whether current qualification practices address all of the important aging stressors for a particular component.

In addition, the margins currently used in qualification tests should be examined based on current knowledge to determine if they provide a reasonable level of assurance of component performance during accident conditions, even after they have been in service for extended periods of time. The duration of the qualification test is another issue that should be examined to see if better criteria can be established for the test duration that would address a components importance to plant risk.

With regard to the currently accepted practice of establishing a time-based qualified life for components in qualification tests, the feasibility of using a condition-based qualified life should be investigated. This would allow a component to remain in service as long as its condition is still acceptable regardless of its time in service. It could also allow ongoing qualification without the need for repeating DBE testing.

Other issues to be resolved are related to whether variations in formulations between different brands or batches of components are significant in terms of qualification test results.

In summary, the following general topics related to environmental qualification of wire systems were determined to warrant additional research:

- Evaluation of current practices for performing accelerated aging as part of the qualification testing, including acceleration factors and activation energies

- Evaluation of qualification test requirements to determine if improvements are needed, including the continued use of a time-based qualified life, the margins in test parameters, and the number of specimens tested

- Evaluation of alternative methods to demonstrate ongoing qualification without a need to repeat DBE testing.

Specific issues in each of these general topics that remain unresolved and should be addressed are presented in Table 5.

Ongoing Research and Issues Being Addressed

Research is currently ongoing to study the qualification process and improve upon the methods currently being used. In the Czech Republic, research is being performed to investigate issues related to environmental qualification testing of cables. This research includes studies of the following subject areas:

- Synergistic effects of combined radiation and thermal aging,

- Uncertainties in the DBE simulations currently used for qualification testing,

- Application of non-destructive testing using a differential scanning calorimeter (DSC) for ongoing qualification of cables,

- Comparison of activation energies determined by DSC with those determined by conventional methods, and

- Homogeneity of radio-oxidation of polymers

The Japan Power Engineering and Inspection Corporation (JAPEIC) initiated the "Assessment of Cable Aging for Nuclear Power Plant (ACA)" project in FY-2002. This research is sponsored by the Ministry of Economy, Trade and Industry (METI) and has the following objectives:

1. Evaluate cable aging using samples aged with low acceleration, simultaneous aging conditions (low dose rate range of 1Gy/hr - 100Gy/hr and low temperature range of 80ºC - 100ºC), and

2. Reassess the methods used to evaluate the integrity of cables, as specified in IEEE Standard 383-1974 [6].

The details of this project were reported in a paper presented at the International Conference on Wire System Aging [4].

In Hungary, work is ongoing to perform in situ tests of safety-related cables operating in harsh environments in the nuclear power plants in PAKS. In conjunction with this program, there is a 5-year testing program is in process. The aim of this program is to perform forced aging tests of cables operating in normal service environments, and to determine the expected service life of the cables. The program will be finished in 2003 with a summary evaluation of the test results published upon completion.

Ongoing activities in Sweden include the investigation of the environmental conditions outside containment, affecting the ageing of safety-related components placed in exposed areas. One special issue being addressed is the influence on metallic parts (e.g. contacts), of corrosive atmospheres in cases of intermittently occurring peaks. Traditional methods based on continuous exposure significantly underestimate the effects (Ringhals Nuclear Power Plant).

In Germany, environmental qualification testing of aged nuclear power plant cables was initiated in 1979 [16]. From the beginning, representative samples of different cable types were stored at depository-sites in various plants. The depository-sites represent high stress zones, with high radiation dose rates and elevated temperature, giving a moderate acceleration factor for aging compared to other plant locations. Repeated LOCA-tests of these aged cable samples has shown that qualified 1E cables used for safety-related components are able to perform acceptably under such accident conditions even after 20 years of high load aging.

The ongoing qualification of electrical and I&C components in operating nuclear power plants in Germany is regulated by a safety standard developed by the Nuclear Safety Standards Commission (KTA) [17]. This standard requires that the functional chain of 1E components, necessary for plant operation and control in the event of a LOCA accident, must be identified and qualified. The environmental stressors for those components must be identified, and the LOCA qualification must be verified continuously.

Based on a review of the ongoing research in member countries, the issues related to environmental qualification testing that are being addressed are presented in Table 5.

Additional Research Needed

The issues that remain to be resolved in the area of environmental qualification testing of aged wire systems would benefit from collaborative research efforts. To address the remaining issues, the potential collaborative research projects presented in Table 5 have been identified.

Table 5. Issues to address related to environmental qualification testing of wire systems

Issue	Rank	Ongoing Research	Potential Collaborative Research
1. What are the limitations of using high acceleration factors for aging of wire system components in establishing qualified life?	High	– Research currently being performed in Japan on qualification practices addresses this issue.	– No new research proposed at this time.
2. What are the limitations in using generic activation energies in thermal aging models instead of experimentally determined values for the specific material being tested?	High	– Research currently being performed in the Czech Republic and Japan on qualification practices addresses this issue.	– Evaluate the limitations in using generic activation energies in thermal aging models instead of experimentally determined values for specific materials being used in U.S. plants.
3. Are better models needed for simulating the thermal and radiation aging of wire system components?	High	– Research currently being performed in the Czech Republic and Japan on qualification practices addresses this issue.	– Evaluate the adequacy of current models for simulating thermal and radiation aging of wire system components.
4. What is the optimum number of test specimens to include in a qualification test to provide statistically significant results?	High	None identified	– Determine the optimum number of test specimens to include in a qualification test to provide statistically significant results.
5. Are all of the important aging stressors accounted for in currently accepted environmental qualification tests?	High	– Research being performed by the U.S. NRC to evaluate aging and environmental qualification of electrical components addresses this issue.	– Continue research on the influence of other environmental parameters on aging than temperature and ionizing radiation, that is, humidity, corrosive atmosphere etc.
6. What alternative methods can be used to demonstrate continued qualification without repeating DBE tests?	High	– Ongoing research in Germany with the use of cable repositories for periodic condition monitoring addresses this issue.	– Establish a correlation between the condition indicators and DBE survivability.

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7. Are the margins currently used in qualification testing adequate to provide a reasonable level of assurance of component performance?	High	None identified	– Determine if the margins currently used in qualification testing are adequate to provide a reasonable level of assurance of component performance.
8. Are the variations in formulations between different brands, as well as different batches of components significant in terms of qualification test results?	Medium	– Research currently being performed in Japan on qualification practices addresses this issue.	– Determine if the variations in formulations between different brands, as well as different batches of components are significant in terms of qualification test results
9. Can the criteria for establishing the duration of accident testing be improved to provide a more relevant simulation of a component's importance to plant risk during accident conditions?	Medium	None identified	– Evaluate the criteria for establishing the duration of accident testing to see if they can be improved to provide a more relevant simulation of a component's importance to plant risk during accident conditions.
10. Can a condition-based qualified life realistically be used as a replacement to a time-based qualified life?	Medium	None identified	– Determine if a condition-based qualified life can realistically be used as a replacement to a time-based qualified life.
11. Would the performance of simultaneous accelerated aging, as opposed to the commonly accepted practice of sequential accelerated aging, provide any benefit in terms of qualification accuracy?	Medium	None identified	– Determine if the performance of simultaneous accelerated aging, as opposed to the commonly accepted practice of sequential accelerated aging, provides any benefit in terms of qualification accuracy.

RECOGNITION OF RECENT AND ONGOING EFFORTS BY OTHER ORGANIZATIONS

In response to the growing attention being received on aging of electrical wire systems and components in nuclear facilities, a number of activities have been initiated by various international professional societies to address this issue. The following summaries note several of the more significant efforts already completed or currently ongoing.

In the U.S., since 1998, the Department of Energy, together with the Electric Power Research Institute, have sponsored joint research programs to address the current technical needs of nuclear power plants. The Nuclear Energy Plant Optimization (NEPO) program focuses on research and development (R&D) of common interest to both industry and government as it relates to improving nuclear technology for the generation of electricity from currently operating nuclear power plants. The NEPO program includes short to medium-term R&D, to be conducted on a cooperatively funded public/private partnership basis, to meet the joint responsibilities of common interest to government and industry. A number of research projects funded under this program address aging issues related to electrical components, such as condition monitoring of installed cable systems.

The Institute of Electrical and Electronics Engineers has also recognized the need for guidance on management of aging in electrical components. In a continuing effort to provide relevant information, IEEE recently updated their guidance document IEEE Standard 1205-2000, “Guide for Assessing, Monitoring, and Mitigating Aging Effects on Class 1E Equipment Used in Nuclear Power Generating Stations” [2]. This guidance document provides an excellent resource for characterizing the aging degradation of electrical components, including common aging stressors and mechanisms, as well as potential condition monitoring techniques that can be used to monitor this degradation.

Internationally, in 2000 the International Atomic Energy Agency (IAEA) completed and published a guidance document on the assessment and management of aging of in-containment instrumentation and control (I&C) cables important to safety [1]. This document provides the results of a coordinated research project on the management of aging of in-containment I&C cables. Included is information on current methods for assessing and managing aging degradation in actual nuclear power plant environments, as well as a user’s perspective on the application of these methods. A great deal of useful information on the aging characteristics of various materials used in I&C systems, as well as guidance on how to manage and mitigate age degradation of these components is included in this document.

Work is also continuing at the OECD Halden Reactor Project in Norway in which nuclear safety authorities, utilities, research institutes, and industry organizations from 20 countries are jointly sponsoring a research program on safety and reliability of nuclear power plants. This research program is focusing on the applicability of empirical numerical techniques, developed at the Halden Project for on-line diagnostics of instrument and component failures and degradation, as well as for electrical testing of cables.

Most recently, the U.S. NRC, Office of Nuclear Regulatory Research sponsored the International Conference on Wire System Aging, which was held April 23-25, 2002 in Rockville Maryland. The purpose of this conference was to provide a forum for experts in wire system aging from around the world to come and discuss research they are currently performing related to this subject, as well as to identify technical issues that still need to be resolved in this area. The conference was very successful and the proceedings contain a number of interesting papers on this subject [4].

CONCLUSIONS ON ISSUES RELATED TO WIRE SYSTEM AGING AND SAFETY

With regard to the identification of issues related to wire system aging and safety, and those that should be addressed as part of a collaborative research effort, the CTG considered the following sources of information:

1. Review of U.S. Federal Programs for Wire System Safety, final report dated November 2000,

2. Proceedings of the International Conference on Wire System Aging, April 2002, and

3. Inputs provided by the members of the CSNI/IAGE Cable Task Group.

Based upon the information derived from the aforementioned sources, the following conclusions are drawn:

It is recognized that a great deal of research has been performed in the area of wire system aging and safety, and much knowledge is already available related to the phenomenological aspects of 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.

The five major categories of technical issues identified in this report are of continuing interest and should be addressed with collaborative research. However, there are several additional issues and sub-issues that should be considered in the overall program. A number of general research topics related to wire system aging and safety within each of the five categories have been identified. They are discussed below.

Physical and Chemical Models

- Improvement of existing models used to predict the failure probability of aged cables and wire systems in the absence of empirical data, including additional testing of wire systems to obtain performance data for verifying existing models

- Development of new physical and chemical models to replace existing models, including the identification of limitations in current models and addressing changes in wire formulations

- Standardization of testing methods and condition monitoring techniques for the development and validation of physical and chemical models.

Fire Hazard

It is recognized that expertise in this area resides with the fire-hazard experts. The CTG has the experience and expertise in the field of phenomenological aspects of insulation behaviour of polymeric materials associated with wire systems. Therefore, the two groups should work together and develop topics for collaborative research. It is suggested that the fire-hazard experts take the initiative to identify and prioritize the outstanding issues relevant to fire hazards, as they relate to wire system aging. The CTG, in conjunction with the fire-hazard experts, should then identify the highest priority issues for collaborative research. The following fire hazard issues, as well as those in Table 2, are derived from the discussions that took place at the International Conference on Wire System Aging. They should be reviewed by the fire-hazard experts and used to provide guidance to the CTG for future research.

- Development of improved models for predicting the frequency and potential risk of fire hazards, including fire growth and thermal damage models, as well as information on the factors affecting the frequency of self-initiating fires and the propagation of fires.

- Improving inputs to existing models to provide more accurate predictions, including performance testing of wire systems to obtain flammability and fire frequency data that can be used to determine the increase in risk from fire hazards due to age-related degradation

- Evaluation of the impact of aging on fire suppression and protection systems, including new fast acting circuit protective devices and “fire proof” cables

- 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.

Risk Significance

It is recognized that expertise in this area resides with the risk assessment experts. The CTG has the experience and expertise in the field of phenomenological aspects of insulation behaviour of polymeric materials associated with wire systems. Therefore, the two groups should work together and develop topics for collaborative research. It is suggested that the risk assessment experts take the initiative to identify and prioritize the issues relevant to plant risk, as they relate to wire system aging. The CTG, in conjunction with the risk assessment experts, should then identify the highest priority issues for collaborative research. The following plant risk issues, as well as those in Table 3, are derived from the discussions that took place at the International Conference on Wire System Aging. They should be reviewed by the risk assessment experts and used to provide guidance to the CTG for future research.

- Continued studies to determine how aging of wire systems impacts plant risk, including determination of the relative importance of various wire systems, and the impact of aging on failure rates and reliability. Also, it would be beneficial to have a series of 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.

- Determination of how risk insights can best be used to more effectively manage wire system aging, including input to operator training programs, and optimization of inspection, maintenance, and replacement strategies

- Improvements to inputs for existing models to more accurately estimate plant risk due to wire system aging, including operational data acquisition to characterize failure rates, and the acceptability of currently used assumptions

- 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.

Prognostics and Diagnostics

Continued development of new, 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.

The use of condition monitoring to predict remaining useful life, including the establishment of acceptance criteria, performance data acquisition, and 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

Environmental Qualification

- Evaluation of current practices for performing accelerated aging as part of the qualification testing, including acceleration factors and activation energies

- Evaluation of qualification test requirements to determine if improvements are needed, including the continued use of a time-based qualified life, the margins in test parameters, and the number of specimens tested

- The correlation of cable condition indicators with DBE survivability.

Each of these general topics is broken down into specific issues that can be addressed by a focused collaborative research effort. The specific issues are presented in this report, along with the proposed research effort to address the issue.

SUMMARY AND RECOMMENDATIONS FOR COLLABORATIVE RESEARCH

During the development of this report numerous suggestions were provided and recommendations made for collaborative research in all five areas of issues identified. Each suggestion provided was considered by the task group and prioritized according to its importance. Based upon the priority needs and availability of resources, recommendations for collaborative research were then categorized as "near-term" and "long-term" needs.

For the "near-term," collaborative research on issues related to Prognostics and Diagnostics, as well as Environmental Qualification is suggested. For the "long- term," collaborative research in all other areas with "high priority" is suggested. That is, in the areas of developing physical and chemical models, fire hazard assessment of wire system aging and determining risk significance of wire system aging. In general, it is recommended that collaborative research should be undertaken in all of the five areas identified in the report. However, in the areas of fire hazard assessment and plant risk, it is recommended that input from the experts in these areas be solicited prior to initiating any new collaborative research. These expert groups, in conjunction with the Cable Task Group, should develop guidelines, identify technical safety issues, and prioritize the issues for future collaborative research. The CTG recommends a joint meeting with the fire hazard and risk assessment experts during the first quarter of calendar year 2003, prior to the April 2003 IAGE meeting.

There was unanimous agreement to pursue collaborative research for the development of advanced prognostic and diagnostic methods that are effective for in situ measurements of cable conditions, as well as for determining the remaining useful life of installed cable systems in operating nuclear power plants. In this regard, it would be beneficial to conduct research that can relate the mechanical properties of the cable insulating materials with their electrical properties. In addition, it is agreed that standardization of testing methods and condition monitoring techniques is needed to facilitate the development and validation of suitable wire system models.

Collaborative research to establish the correlation of cable condition indicators with DBE survivability is recommended. Research elements should include:

- The selection of cable types and condition indicators, with emphasis placed on electrical properties, parameters, and indicators;
- Cable sampling;
- Simultaneous radiation/thermal accelerated aging with periodic cable condition monitoring;
- DBE and post DBE simulation to investigate the synergism between stressors;
- Elucidation of the role of low energy electrons on cable polymer degradation; and
- The definition of acceptance criteria for DBE survivability of the cables.

A collaborative approach to this research is recommended since it can provide for a more efficient use of research resources, as well as sharing of the extensive data that will be generated from the research and will be of mutual interest. An important element that must be considered for successfully performing collaborative research is the establishment of uniform criteria and test methods for performing the various CM techniques between the participating organizations. This will facilitate the comparison and sharing of results between all the participants.

In the environmental qualification area, it would be beneficial to conduct collaborative research and develop technical bases for the revision and/or development of new national and international standards. That is, develop standards that are more realistic, practical and reflect the operating experience of the past three decades.

It is recognized that ongoing qualification is necessary to ensure that the component's condition and performance remain acceptable, and consequently the component remains qualified, throughout the plant's lifetime. Standardized methods are needed for demonstrating ongoing qualification without the need to repeat DBE testing.

In summary, the Cable Task Group has identified and reviewed unresolved technical issues in five different areas related to aging of wire systems, and the following recommendations related to collaborative research on wire system aging are made for each area:

Prognostics and Diagnostics (near-term)

The CTG recommends that collaborative research in the area of prognostics and diagnostics of wire systems be pursued as one of the high priority short-term needs. Specific recommendations for collaborative research programs in this area are the following:

- Collaborative research is recommended for the development of an electrical diagnostics and condition monitoring method that can scan the entire length of an installed wire system and determine its current condition. In this regard, advanced electrical, optical, ultrasonic and aerospace technologies should be evaluated and developed for nuclear plant applications.

- Collaborative research is recommended to establish the correlation between wire system condition indicators and the functional performance of the wire system during design basis events.

Environmental Qualification (near-term)

The CTG recommends that collaborative research in the area of environmental qualification of wire systems be pursued as one of the high priority near-term needs. Specific recommendations for collaborative research programs in this area are the following:

- Collaborative research is recommended to provide a technical basis for developing and/or updating qualification methods and standards to reflect past operating experience and realistic plant operating conditions. Emphasis needs to be placed on a condition-based demonstration of ongoing qualification.

Physical and Chemical Models (long-term)

The CTG recommends that collaborative research in the area of physical and chemical model development for wire systems be pursued as one of the long-term needs. Specific recommendations for collaborative research programs in this area are the following:

- Collaborative research is recommended to establish the correlation between the physical, chemical, and electrical properties of the most widely used polymers in wire insulating systems for the current fleet of operating nuclear power plants. These polymers include XLPE, Neoprene, EPR, CSPE, EPDM, EVA, and PVC

- Collaborative research is recommended to provide technical bases for standardizing test methods, with emphasis placed on the understanding of electrical properties, measurement of parameters and indicators, and circuit performance.

- Collaborative research is recommended for the development of suitable models and methods for demonstrating ongoing qualification without the need to repeat DBE testing.

Fire Hazards and Plant Risk (long-term)

The CTG recommends that collaborative research in the area of fire hazards and plant risk related to aged wire systems be pursued as two of the long-term needs. However, input from the experts in these areas should be solicited prior to initiating any new collaborative research.

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APPENDIX B: IAGE CABLE TASK GROUP TERMS OF REFERENCE

AGENCE DE L'OCDE POUR L'ÉNERGIE NUCLÉAIRE

OECD NUCLEAR ENERGY AGENCY

Ref: nea/sec/WSA1 Issy-les-Moulineaux, November 24, 2001

Subject: Request for nomination to the Task Group on Wire System Aging

Dear Members,

The December 2000 meeting of the CSNI accepted a proposal to set up a Task Group to prepare a report describing research efforts related to the wire system aging in Member countries. This letter is to invite you to nominate a suitable expert to serve on the Task Group.

Background: There is a continued interest worldwide in safe operation of the current fleet of operating nuclear power plants through their original design life and for plant life extension considerations. From a technical perspective, the understanding and management of detrimental effects of aging in safety critical systems, structures and components (SSCs), and in SSCs important for reliable power production is of significant importance to plant operators and the regulatory agencies.

Electrical wire (cable) systems in operating nuclear power plants provide vital functions for information gathering and data transmission, signal processing and controls, and power transfers among the equipment within the electrical and I&C systems. Cables in the wire systems are long-lived passive components. They degrade over time, and they are not readily replaceable. There are hundreds of kilometers of instrumentation and control and power cables in a nuclear power plant, and currently there are no viable, non-intrusive, cost effective diagnostics and condition monitoring methods for installed wire systems. Premature or unanticipated aging of wire systems, which include cables, splices, terminations, and penetrations can result in loss of critical functions of the energized equipment by the system, or in loss of critical information relevant to the decision making process and operator actions, and compromise public health and safety.

A number of OECD countries have either completed research programs or new programs have been implemented for improved understanding of aging processes associated with the polymeric insulation materials involved in wire systems and for ways to determine residual or remaining service life of installed cable systems. Efforts are also under way to develop improved techniques for diagnostics and condition monitoring of wire system components. However, there are number of issues that require additional studies. For example, there exists technology gaps for prognostics and diagnostics, lack of knowledge and data on the treatment of cable aging in PRA/PSA, fire susceptibility of aged wire systems and fire propagation.

Therefore, exchange of technical information based on OECD Member countries research, development, engineering or regulation pertaining to the following topics would be of interest:

1. Reliability Physics Modeling of Key Elements of a wire System

2. Prognostics and Diagnostics for Installed Wire Systems

3. Risk Significance of Wire System Aging

4. Fire Risk Assessment of Wire System Aging

Mandate of the Task Group: The mandate of the CSNI/IAGE Task Group on Wire System Aging, consisting of experts on physical phenomena, will be to prepare a report describing research efforts related to the wire system aging in the member countries including the specific topics listed above. The Task Group will report to the IAGE Working Group and interface with the CSNI/WGRISK Working Group to gather inputs on points 3 and 4. This report will include conclusions and recommendations on issues that should be further pursued by the activities. The Task Group's activities and report should complement and build on the recent and on-going efforts by other organizations (e.g. IAEA).

To initiate this action, you are invited to nominate (by February 28th, attention: Eric Mathet) your national experts. Those experts will be invited to attend the meeting in May 2002 to establish the detailed program of work to fulfill their task. Note that the USNRC is planning to hold a workshop on this subject on April 23-25, 2002. The conclusions from this workshop will be used for plan the work of the Task Group.

We look forward to your nomination for this Task Group on Wire System Aging.

Yours sincerely,

Gianni Frescura
Nuclear Safety Division Head

CC: IAGE members
CSNI-PRG
Chairman and vice-chairs of CSNI/WGRISK - J.A. Murphy, J.M. Lanore, M.F. Venstag