FINAL REPORT

WORKSHOP ON MULTIFACTOR AGING MECHANISMS AND MODELS*

ONR R&T No. S 400018 SRD 01
Grant No. N 00014-92-J-1922

Prepared by

Dr. V.K. Agarwal

Moorhead State University

Moorhead, MN 56563

*Workshop was held on October 22, 1992, in Victoria, B.C., Canada with the joint sponsorship of EPRI, ONR and SDIO.

NOTICE

This report has been prepared by Dr. V.K. Agarwal of Moorhead State University, Moorhead, MN, summarizing the activities of the Workshop on Multifactor Aging Mechanisms and Models sponsored, in part, by the Office of Naval Research and the Strategis Defense Initiative Organization. Neither the organization named above, nor any person acting on behalf of them (a) makes any warranty, express or implied, with respect to the use of any information, apparatus, method, or process disclosed in this report or that such use may not infringe privately owned rights; or (b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this report.

Any opinions, findings and conclusions or recommendations expressed in this report do not necessarily reflect the views of workshop sponsors, members of the Technical Program Committee or Moorhead State University.

Table of Contents

SUMMARY

There have been considerable efforts to understand the aging and failure mechanisms of insulation in electrical systems. However, progress has been slow because of the complex nature of the subject particularly when dealing with multiple stresses e.g. electrical, thermal, mechanical, radiation, humidity and other environmental factors. When an insulating material is exposed to just one stress factor e.g. electric field, one must devise test(s) which are not only economical, efficient and practical but which take into account the nature of electric field (ac, dc and pulsed), duration and level of field strength, and field configurations. Any additional stress factor(s) make the matrix of measurements and the understanding of resulting degradation processes more complex, time consuming and expensive.

In an effort to assess our understanding, or the lack of it, of aging and degradation of electrical insulation, a one-day workshop was held on October 22, 1992 at Victoria, B.C., Canada immediately following the Conference on Electrical Insulation and Dielectric Phenomena. The workshop was jointly sponsored by the Electric Power Research Institute, the Office of Naval Research and the Strategic Defense Initiative Organization. The aim of the workshop was to promote intellectual interaction and exchange of ideas on aging and failure mechanisms of multistressed insulation in a variety of materials, components and systems.

As expected, the workshop was attended by sixty-five committed and interested scientists and engineers from academia, industry, research laboratories and users of electrical systems. Invited presenters and session chairpersons were experts in various aspects of multifactor aging. The summary of presentations is included in section III of this report. The presentations followed by a panel discussion session in which the audience and the presenters had time to discuss critical issues and the audience had opportunity for critique.

The questions raised during the discussion session included whether test guidelines or standards should be developed. It was suggested that the guidelines may well be the best approach. Arguments were also made for developing the non-destructive diagnostic procedures which should not cause aging. In this regard, PD technique, which provides detailed information on transient electrochemistry, was thought to be a good way to evaluate aging of materials.

The workshop was quite successful as a forum for intellectual discussion, scientific exchanges and the assessment of our understanding of a complex and critical subject of aging and failure mechanisms of multistressed insulation. In the post-workshop evaluation, when asked if the workshop was rewarding and effective, one participant wrote " . . . the format employed accomplished its mission in that it acquainted the members of the basic approaches currently active, it formulated broad guidelines for future direction and above all it generated an awareness of the need to understand the phenomena of aging." By and large the workshop participants were satisfied and felt that their expectations were met.

Section I

Introduction

The reliability and adequate service life of electrical equipment critically depends on how well the insulation material can withstand various stress factors e.g. electrical, mechanical, thermal and/or environmental while in use. This has motivated the manufacturers and users to evaluate aging and failure mechanisms of the insulation so that the service life of the system can be determined with reasonable accuracy. This has led to much debate among scientific and technical community to consider advanced methods of accelerated aging tests and to understand basic physical and chemical processes that govern aging for one or more stresses applied sequentially and/or simultaneously.

When one talks of "Aging" in the context of insulating materials, it is a qualitative measure of irreversible degradation due mainly to the multiple stresses the insulation undergoes while the equipment remains in service. Experience has shown that all insulating materials are prone to degradation under stresses applied or induced in service and that results into system failure. The degree and rate of degradation, however, depends on the physical and chemical properties of the material, the nature and duration of applied/induced stress(es) and material processing and treatment during manufacturing and subsequent use in equipment. The density of voids lead to significant material degradation.

Although researchers have debated on issues related to aging and degradation of insulating materials under multiple stresses for decades, progress has been slow. Many issues confronting researchers, manufacturers and users include what methodology and testing sequence are needed to examine the synergistic and interactive nature of stresses. How these tests can be made effective, efficient, reliable and economical and such that these tests do not cause additional aging? The tests should yield useful information for both short-term and long-term aging effects.

In recent years, the Multi-Factor Stress Committee of the Dielectric and Electrical Insulation Society has successfully developed an IEEE standard (1) which is intended to serve as a guide toward developing meaningful, efficient and simple tests for accelerated aging. This guide consists of relevant technical terms and their definitions, attempts to identify technical problems and helpful practical possibilities and recommends action(s) and procedure(s) that one may find useful while testing multistressed insulators. Furthermore, it discusses mechanisms of interaction between the factors influencing aging. The document is analogous to IEC 792 (2) which consists of test procedures and a bibliography.

In an attempt to assess the progress in the area of multistress aging, a bibliography was published by Agarwal (3). This consisted of over 400 citations covering multifactor, multistress, accelerated aging and degradation of insulators. The workshop on Multifactor Aging Mechanisms and Models discussed in the following sections is another significant step toward assessing our knowledge and understanding of a critical but complex area of "aging". The workshop provided an overview of several key subject areas within the framework of aging mechanisms and models.

Aging, as Brancato puts it (4), is an inescapable phenomenon affecting all living and most inert things. In that spirit, the utilities, industries and academia must continue toward better understanding of this inescapable and sometimes deadly phenomenon of aging/degradation of electrical insulation and systems. A critical state-of-the-art overview of aging will be covered in the IEEE Digest on Dielectrics due to appear in October 1993.

Section II

The Workshop and the Participants

The workshop on "Multifactor Aging Mechanisms and Models" was conceived during the regular meeting of the IEEE Technical Committee on Multifactor Stress (Committee S-32-7) held during the Conference on Electrical Insulation and Dielectric Phenomena (CEIDP) at Knoxville, TN in October 1991. The members of the Committee recognized that the complexities associated with aging and failure mechanisms and models in the context of electrical insulation and systems needed to be critically reviewed with broader participation of scientists and engineers from academia, industry, government, utilities, research laboratories and users of electrical systems. Subsequently, the workshop announcement (Appendix A) was mailed to IEEE membership soliciting applications for participation in the workshop.

The workshop, sponsored by the Electric Power Research Institute (EPRI), the Office of Naval Research (ONR) and the Strategic Defense Initiative Organization (SDIO) was held on October 22, 1992 at the Victoria Conference Center, Victoria, British Columbia, Canada.

In order to maximize and facilitate the participation of international scientific and technical community who generally attend the CEIDP and have significant interest in the area of multifactor aging, the workshop venue and dates were chosen to follow the CEIDP. This indeed led to bringing together 65 persons from 12 countries including the invited speakers (Appendix B).

The workshop planning and organization was led by Vijendra K. Agarwal of Moorhead State University, Moorhead, MN, USA, who is also the Chairperson of the Technical Committee S-32-7. The Technical Program Committee members for the workshop included the following, many of who had met in Washington, D.C. to deliberate on the workshop program and format, and the invited speakers.

Bruce S. Bernstein
Electric Power Research Institute

Emanuel L. Brancato
EPRI Consultant

Lynn L. Hatfield
Texas Tech University

Gabriel D. Roy
Office of Naval Research

Pete L. Rustan
Strategic Defense Initiative Organization

W.J. Sarjeant
SUNY Buffalo

The workshop participants were mostly registered with CEIDP registration. The workshop schedule (Appendix C) included two technical sessions before lunch in which the invited presenters provided an overview of the subject matter. Each session was chaired by an expert in the field. These sessions were summed up by an EPRI consultant Emanuel Brancato in his remarks during the luncheon. His message to the workshop participants was that the most probable path to a realizable prediction of insulation aging in a multistress situation is to understand the dynamics of aging mechanisms.

A dynamic afternoon included a panel discussion that comprised all of the speakers from morning sessions. Some of the very probing questions were raised by the audience, moderated by the session chairman and answered by one or more speakers. This led to a very lively and intellectual discussion on issues such as developing guides versus standards for multifactor stress aging, deterministic versus probabilistic approach for evaluating aging in materials and what kind of diagnostic tools must be developed.

Later in the final hours of the workshop, a brief overview on SDIO space insulation technologies was provided during the banquet. The keynote speaker Pete L. Rustan of SDIO was unable to attend due to some unavoidable engagements in Washington, D.C. and therefore the presentation was made by Matt Schor of W.J. Schafer & Associates, a consulting agency working with SDIO.

The workshop participants were also sent a questionnaire by mail to assess the workshop effectiveness. The summary of these workshop evaluations (based on 32 responses) is enclosed as Appendix D.

The workshop met most of its objectives and was well received and attended. However, a valid criticism raised by many participants and shared by the organizing committee members is that we followed 80/20 rule i.e. 80% of the work in 20% of the time. The one-day workshop became somewhat hectic and allowed less than adequate interaction and exchange opportunities, particularly when dealing with a subject as complex as aging and failure under a multistress environment.

The workshop summary prepared by the chairman Agarwal was published in IEEE Electrical Insulation Magazine (Jan/Feb 1993), Vol. 9 no. 1 (Appendix E). One of the committee members, Jim Sarjeant, had prepared a more detailed workshop report which appeared in the informal workshop proceedings.

Section III

Summaries of Individual Presentations

Some General Observations on the Multi-Factor Functional Evaluation of Electrical Insulation Systems (Andreas Kelen, Vasteras, Sweden)

The opening speaker discussed the framework of multifactor (MF) aging in the context of electrical insulation systems (EIS) from a historical perspective. Starting with general observations on MF aging and testing he outlined the efforts of the International Electrotechnical Commission (IEC) since 1967 when a technical committee TC 63 was created. The major goals of this committee were to develop guidelines for material qualification for designated EIS performance by realistic test methods. The committee's deliberations included the term "Factor of Influence" which included T-E-A-M scheme (Thermal, Electrical, Ambient and Mechanical). The committee introduced the concept of "interaction" among stresses that may be direct and/or indirect. This led to the publication of IEC 792-1 (The multifactor functional testing of EIS: Test Procedures) in 1984 and a bibliography on MF testing which is likely to be published soon (2).

This speaker stressed the fact that two sets of experiments are necessary for developing a better understanding of MF aging mechanisms. One requiring sequential application of stresses and another with simultaneous stresses. All the evidence to date suggests that sequential stress testing leads to indirect interactions i.e. one stress changes the conditions of the insulation which can be characterized prior to subsequent changes due to other stresses. However, the simultaneous stress testing, which amounts to direct interactions, is far more complex.

In Kelen's view the emphasis should be placed on developing non-comparative evaluation methods which should be based on detailed inventory of service and/or operating conditions rather than on the material or the system. The future work on MF aging must also focus on material modifications at a molecular level.

Multi-Stress Aging of High Density Polymer Film Capacitors (C.W. Reed and S.J. Rzad, GE Corporate Research and Development Schenectady, NY)

The focus of this presentation was high energy density (HED) capacitors which typically operate at about 10 KV/mil which is quite close to the breakdown voltage of the insulating polymer film. These polymer films have specific energy densities ranging from 0.1 to 2 J/g and future expectations are to reach 10-30 J/g. However, this will impose further limits on their breakdown strength and will necessitate a careful selection of polymer film, impregnating fluid and capacitor design.

The presentation included a discussion on a variety of known amorphous thermoplastic films with dielectric constant ranging from 2-3. Several polycrystalline materials with dielectric constants from 10-20 and high losses may be acceptable for limited life designs. Many liquid impregnants in use include mineral oils, esters, synthetic hydrocarbons, fluorocarbons which vary significantly in dielectric constant and viscosities and thus require proper match with the dielectric properties of the polymer film.

Among various capacitor designs, the self supported films/foils, metallized film and monolithic designs were discussed. In discussing some examples, capacitors with 3 sheets of 16μm films with different fluids showed dramatic improvements for some combinations. Some of the work done at GE on life test for one year exhibited a smooth flattening of aging curve with time if fluids with large dielectric constant were used. It was also found that the thickness of the fluid had significant influence on the corona inception voltage (CIV). On the other hand, some laminate structures tested in France show that the capacitors aged at 1.6 MV/cm, the CIV was at $\approx$4 MV/cm for 1800 hours. These laminates did not show any intrinsic aging when tested to breakdown and no perceptible influence due to added water and a salt material.

In discussing polymer chemistry as one of the factors causing aging, he suggested that electrostatic forces permit cavitation so that the bubbles arise which have very low withstand fields. In addition, the fluids may change chemistry and become semiconducting.

With regard to temperature effects, very often there are electromechanical effects that will influence life of the capacitor. Interaction of fluid film may give rise to dimensional changes as a result of thermal heating, vacuum impregnation and impregnation. In fact, the swelling during impregnation can cause mechanical stress which effects tan δ, morphology and breakdown fields. The swelling is very sensitive to polymer crystallinity.

Tentered film with much less swelling are different (better) because of morphology differences. Measurements have shown decreasing tan δ as impurities leach out of the films. Thus multiple impregnation may be valuable for capacitors.

Aging Considerations for Insulators in Space and Aging by Recombination - Induced Defect Migration (A.R. Frederickson, USAF Philips Laboratory,Hanscom AFB, MA)

This speaker concentrated on radiation fields as an aging factor which leads to streamer initiation in insulation. The plasma in the streamer conducts the electric current but it may be quenched by the build-up of pressure.

For partial transit streamers, adding an external field then can force the streamer to propagate all the way through the insulation. This moves the charge centroid further into the capacitor so that large fields exist than at the streamer end, forcing propagation of the streamer heads. The impregnating fluids could be used to leak off radiation charging if their conductivity permitted field relaxation at a rate lower than radiation pumping of the charge.

In space tests of dielectrics in vacuum they found 100 volts across electrodes would fully arc across parallel electrodes, triggering from a weak plasma injected from the sides of the plates. Such plasmas at few kilovolts will move over 1 meter and short out these 100 volt difference plates.

Space radiation can cause insulator pulsing and these pulses lead to breakdown. Therefore, worst breakdown rate could be expected in space for insulators at applied bias with normal safety margins. Measurements have shown that the pulsing rates were far higher for variable flux rate than for a constant flux radiation rate. It was noted that the flux varied from 0.05 to 5.0 x 10" electrons per orbit.

In discussing experimental data on various insulation, it was suggested that PTFE becomes conductive from radiation aging but will eliminate pulsing if preradiated. Fiberglass PTFE gave pulses under intense space radiation in vacuum which may be related to outgassing of fluorine radicals. FEP teflon with very few defects maintained insulation integrity very well.

On the other hand, fiberglass filled FEP produced many pulses and continue to pulse. Over several weeks at a resistivity of $\approx 10^{18}$ Ω-cm, V_{bd} was found to reach PD magnitudes.

The space data collected over 14 months with 2mm of aluminum shielding, fewer pulses were observed. The flux per pulse decreased substantially over weeks of time. Unfortunately, no more data will be available as the satellite died.

For solar cell glass covers, radiation may cause defect motion and increase in field stress levels resulting in the possibility of breakdowns. Defects are moved by the radiation flux - over several years - even with no externally applied electric fields.

This speaker stressed the fact that insulator aging in an actual space environment is far more complex to investigate and, indeed, to understand than in the ground based systems.

Modeling the Effects of Combined Radiation - Thermal - Oxygen Environments on the Degradation of Polymers (Kenneth T. Gillen and Roger L. Clough, Sandia National Laboratories, Albuquerque, NM)

According to this speaker, radiation-induced damage to polymeric materials in oxygen environments strongly depended on both dose rate and temperature. According to him, radiation-induced damage to polymeric materials in oxygen-containing environments strongly depends on both dose rate and temperature. He suggested that we must first understand/eliminate "physical" dose-rate effects followed by the true "chemical" effects. In other words, their approach first used a time-temperature superposition approach to make thermal-environment lifetime predictions and then generalized it to combine radiation-thermal environments. He discussed the success of their approach in predicting long-term (7-12 years) aging of numerous cable jacketing and insulation materials that were naturally aged in nuclear power plants.

An approach to understanding accelerated aging include a two step process; first one should understand and eliminate diffusion limit of oxidation and then model the homogenous chemical effects i.e. using generalized Arrhenius approach to time-temperature-dose rate.

In their work, they first plotted fractional elongation versus temperature and found excellent fit with very little scatter. Then they added radiation and the data was plotted as a function of dose for a certain amount of damage e.g. some specific fractional change in elongation. Under isodose conditions they thus determined a relation between time (life) and temperature. In their work, the radiation aging test data approached thermal aging data as the dose rate from radiation decreased. In general, they were able to determine the kinetic chemical steps causing the degradation and theoretical curves agreed well with experimental curves.

Multi-Factor Aging of Insulation Systems for Power Cables (John Densley, Ontario Hydro Research, Toronto, Canada)

The influence of various aging stresses e.g. electrical, thermal, mechanical and environmental factors in power cables was the focus of this presentation. He characterized intrinsic thermal aging which changes the properties of the material itself e.g. depolymerisation at high temperatures and suggested it to be a complex path to failure. The extrinsic aging, on the other hand, is the stress interaction with defects and contaminants. He observed that the extrinsic aging dominates the extruded cables.

In presenting elaborate flow charts for extrinsic electrical and thermal aging, and intrinsic thermal aging of practical insulation systems, he showed the need to consider interactive multistress aging factors. Among thermal stress factors, one must consider maximum and minimum temperature, temperature gradient and temperature cycling. Electrical stress effects should include the frequency for accelerated aging tests, transients, partial discharges, current and charge injection.

In studying environmental aging, it is important to consider the atmosphere (e.g. O_2, SF_6), lubricants, humidity, corrosive chemicals and exposure to radiation. The mechanical stress factors include tension, bending, compression, shear and torsion of material.

This presentation stressed that the life and aging of the cable insulation is determined by contaminants and defects and the aging model must account for them. The defects to be considered include cavities at shield and/or due to shrinkage or gas formation in insulation, loosely bound solid particles, protrusions and splinters during manufacturing. He favored the inverse power law model for accelerated aging ($V^n t$ = constant) with n = 8 to 12 i.e. increasing n with decreasing density of defects, and n = 4 for aging due to water trees.

A important question raised was "do we have a valid accelerated aging test?" Such tests need to be developed which should not cause additional aging, should test complete systems and should account for the weak links (interfaces at joints) in insulation systems. These tests should be reliable and simple for periodic field testing.

A Practical Application of a Three stress Multifactor Fundamentally Based Aging Relation (A.M. Bruning, Lectromechanical Design Co., Herndon, VA)

Bruning discussed the aging of aircraft wiring which was covered with polyimide insulation - a simple linear rigid polymer. Their work included measuring the elongation to break (breaking strain) as a function of moisture and temperature. In modeling their observation, reference was made to Crine's model for aging which is based on Gibb's free energy (discussed later). It was also suggested that the strain in the insulation while wrapped around the wire limits the life.

Having measured the breaking strain, they were able to work backwards to establish a predictable time-to-failure for the insulation. It was also suggested that the electrical aging was not a significant factor in the insulation failure of aircraft wire rather it was due to microcracks due to salt, air and water. In the final analysis, it was suggested that the relative humidity was the significant factor in determining the insulation life i.e. below 70% relative humidity, the life was predicted to be nearly infinite.

Applications of the Rate Theory to the Understanding of Various Dielectric Aging Mechanisms (Jean-Pierre Crine, IREQ, Cables and Isolants, Varennes, Quebec, Canada)

This paper included several applications of the rate theory in the context of electro-thermal aging mechanisms of the extruded dielectric cables. He emphasized the importance of Gibbs free energy in modeling the aging mechanisms and not the apparent activation energy. It was suggested that one should include the thermodynamic transitions as temperature decreases while dealing with thermal aging. These transitions can be determined by the DSC.

Aging of cable insulation, according to Crine, begins long before diagnostics can locate it. The proposed model predicts the formation of submicrocavities ($\approx$ 100 A° size) due to fatigue at fields higher than 10-20 kV/mm. These cavities are believed to be formed by bond breaking at fields > 10kV/mm so that free radicals do form capable of additional electromechanical activity. The size of the microcavities increases above 20 kV/mm and none were observed below this stress level.

In the case of mechanical aging of polymers an exponential regime was found at high stresses and a tail at low stresses that is very similar to electrical aging. In a plot of log of time-to-breakdown versus mechanical stress, one finds a plateau stress for nearly infinite life.

A Pathway to Multifactor Aging
(Emanuel L. Brancato, EPRI Consultant, Clarksville, MD)

This presentation summed up the morning session by reviewing the history of thermal and electrical aging relations and their apparent limitations. He reiterated the work of previous speakers, namely Crine and Bruning, et al., and emphasized that all aspects of aging may be "chemical" in nature. If these chemical changes can be further quantified and identified, one can hope for a general model for multifactor aging. He reminded everyone that the most probable path to a realizable prediction of insulation aging in a multistress situation is to understand the dynamics of aging mechanisms.

His recommendations included that the mechanisms of electrical and mechanical aging should be conclusively determined and Crine's approach to aging must be further assessed through experiments. Furthermore, the sensitivity of PD diagnostics must be improved to validate the presence or absence of a Corona Inception Voltage in so far as affecting the aging life of the insulation.

Section IV

CONCLUSIONS/RECOMMENDATIONS

The workshop was not designed to provide solutions to any specific issues related to multifactor aging and therefore no significant and conclusive recommendations were to be expected. Nevertheless, the workshop succeeded in providing a greater insight, and probably an overview, to what we do and do not know about aging in electrical insulation. From the post-workshop eveluations, it is clear that the workshop participants came with different expectations some of which were met and others not. One of their suggestions was a more "narrower" focus of the workshop rather than a broader overview that was planned.

Another important finding from the post-workshop evaluations (Appendix D) relates to what other workshops should possibly be conducted in the future. These suggestions included workshops on material or system specific aging issues, e.g. conduction and space change accumulation in polymeric insulation, electrical insulation under varying climatic conditions (indoor and outdoor), space charge distribution in solids, high energy density dielectrics and capacitors, charge injection in dc cables, measurement techniques, good operating practices, pulsed HV systems, and diagnostic techniques for specific types of equipment. Several participants suggested critical need for more active international cooperation and ongoing discussion in this area. In fact, several European scientists have expressed interest in working with the Multifactor Stress Committee and discuss avenues of cooperation.

Furthermore, based on the panel discussion, the following comments provide good food for thought and future developments/action.

1. Future development of multifactor aging procedures must specify both the system and service environment.

2. A deterministic thinking along the approach of Crine has a chance of providing far more reliable products.

3. Standards are very difficult to use to improve system design and therefore the guidelines may well be the best approach.

4. Understanding of the electrophysical processes of aging are needed to be developed in a rational way; an automatic consequence of this approach will be a knowledge of the projected design life with high reliability.

5. Absolute noncomparative testing will be needed for the evaluation of new insulation systems, with a strong emphasis upon the intended service conditions.

6. One must look at the diagnostic tools in the context of the service environment. The more precisely we want to measure, the more expensive will be the test equipment.

7. A nondestructive procedure to understand the performance of the dielectric should be developed. That is to say, the diagnostics should not age the material. The detection system is needed in some routine way to indicate the beginning of a life-limiting time in the history of a material within a system.

8. PD contains very detailed transient electrochemistry information and possibly represent the simplified technique to evaluate aging in the material.

Section V

References

1. IEEE Guide for Multifactor Stress Functional Testing of Electrical Insulation Systems (IEEE Std. 1064-1991)

2. The Multifactor Functional Testing of Electrical Insulation Systems (IEC 792)
   Part 1: Test Procedures (1984)
   Part 2: Bibliography (1993, in print)

3. V.K. Agarwal, "Aging of Multistressed Polymeric Insulators," IEEE Transactions on Electrical Insulation, Vol. 24 pp 741-764 (1989)

4. E.L. Brancato, "The Problems of Accelerated Aging" IEEE Electrical Insulation Magazine, Vol. 2, pp 50-51, March 1986

Appendix A

WORKSHOP ON MULTIFACTOR AGING MECHANISMS AND MODELS

SPONSORS: **Strategic Defense Initiative Organization and Electric Power Research Institute**

WHEN: **October 21-22, 1992**

A workshop on the above topic is planned to follow immediately after the CEIDP at Victoria, B.C., Canada. The workshop is aimed at bringing together the interested scientific and technical community to promote intellectual interaction and exchange on the complexities associated with aging and failure mechanisms of multistressed insulation in a variety of materials, components and systems.

The major focus of the workshop is on fundamentals of insulation aging due to multiple stresses in earth and space environments. The multiple stresses include electrical, thermal, mechanical and radiation effects that lead to insulation degradation and the loss of life in equipments such as capacitors, cables, transformers, switchgear, and rotating machines.

The workshop should be of interest to persons concerned with AGING MECHANISMS AND MODELS. If you are interested, send the lower portion of this announcement to:

Dr. Vijendra Agarwal
Department of Physics
Moorhead State University
Moorhead, MN 56563, USA

TEL: (218) 236-2451
FAX: (218) 236-2168

Please mail your request for attending the workshop as soon as possible but no later than Friday, January 24, 1992.

....

MULTIFACTOR AGING MECHANISMS AND MODELS

I am interested in attending the workshop which follows immediately after the CEIDP.

NAME: ______________________________

MAILING ADDRESS: ______________________________

____

____

Telephone: ____________________ FAX: ______________________

Please provide a brief description of your interest in Multifactor Aging and Mechanisms (Use additional pages, if necessary)

Appendix B

Workshop on Multifactor Aging Mechanisms and Models

Victoria, B.C., Canada, October 22, 1992

List of Participants

Agarwal, Vijendra
Physics Dept.
Moorhead State University
Moorhead, MN 56563
Tel (218) 236-2451

Arens, Ingo
ESTEC, Dept. XPC
PO Box 299, NL-2200 AG
Noordwijk, Netherlands
Tel +31-1719-83523

Bamji, Soli
National Research Council
INMS Bldg. M-50
Montreal Rd.
Ottawa, Ontario
K1A 0R6
Tel (613) 990-4021

Banford, Hamish
SURRC
Birniehill
East Kilbride, Glasgow
G75 0QU Scotland
Tel 011-44-3552-72534/72897
Fax 011-44-3552-72005

Barker, R.E., Jr.
Materials Science Dept.
University of Virginia
Charlottesville, VA 22903-2442
Tel (804) 982-5655
Fax (804) 982-5660

Bezille, Jose
Alcatel Cable
536 Quai de la Loire
62225 Calais France
Tel (33) 21-46-70-03

Bialek, Tom
Raychem Corp.
300 Constitution Dr.
Menlo Park, CA 94025-1164
Tel (415) 361-2022

Bosche, E.E.
Dow Chemical Co.
2301 Brazosport Blvd
Bldg B-2405
Freeport, TX 77541
Tel (409) 238-5858

Brancato, Emanuel
Consultant
7370 Hallmark Rd.
Clarksville, MD 21029
Tel (301) 953-3039

Braun, Jean-Marie
Ontario Hydro
800 Kipling Ave, KR 151
Toronto, Ontario
M8Z 5S4
Tel (416) 207-6874

Brotzman, Richard
TPL Inc.
3754 Hawkins NE
Albuquerque, NM 87109
Tel (505) 345-5668

Bruning, Armin
Lectromechanical Design Co.
13510 Glendundee Dr.
Herndon, VA 22071
Tel (703) 481-1233

Budenstein, Paul
US Army Missile Command
AMSMI-RD-WS-LS
Redstone Arsenal, AL 35898-5248
Tel (205) 876-4608

Bulinski, Alexander
National Research Council Canada
Montreal Rd., Bldg. M-50
Ottawa, Ontario
K1A 0R8
Tel (613) 990-4020
Fax (613) 952-9366

Buttram, Malcolm
Sandia National Labs
Dept. 1248
Albuquerque, NM 87185-5800
Tel (505) 845-7117

Campbell, Francis J.
Code 4654
Naval Research Lab
Washinton, D.C. 20375
Tel (202) 767-2414

Charlson, Elaine
Dept. of Electrical & Computer Engineering
225 Engineering Bldg. W
Columbia, MO 65211
Tel (314) 882-3480

Cherukupalli, Sudhakar
Power Tech Labs
12388 88th Ave
Surrey, B.C., Canada
V3N 7R7
Tel (604) 590-7492

Crine, Jean-Pierre
IREQ
PO Box 1000
Varennes, Quebec
J3X 1S1
Tel (514) 652-8394

Densley, John
Ontario Hydro
800 Kipling Ave., KR 151
Toronto, Ontario
M8Z 5S4
Tel (416) 207-6290

Epstein, Mike
Battelle Memorial Institute
505 King Ave.
Columbus, OH 43201
Tel (614) 424-5512

Fleming, Robert
Monash University
Dept. of Physics
Clayton, Victoria 3168
Australia
Tel 61-3-565-3672

Frederickson, A. Robb
USAF Philips Laboratory
PL-GPSP
Hanscom AFB, MA 01731-5000
Tel (617) 377-3211

Gillen, Ken
Sandia National Labs
Organization 1812
Albuquerque, NM 87185
Tel (505) 844-7494

Grzybowski, Stanislaw
Mississippi State University
Electrical & Computer Eng. Dept.
PO Drawer EE
Mississippi State, MS 39762
Tel (601) 325-2148

Hatfield, Lynn
Physics Department
Texas Tech University
Lubbock, TX 79409-1051
Tel (806) 742-3767

Heydon, Rodney
CSIRO Division of Applied Physics
National Measurement Lab
Bradfield Rd.
West Lindfield, Sydney NSW 2070
Australia
Fax (02) 413-7383

James, D. Randy
Oak Ridge Nat'l Lab
Power Systems Tech
PO Box 2008
Oak Ridge, TN 37831-6070
Tel (615) 574-0266

Janah, Hakim
Alcatel Cable
536 Quai de la Loire
62225 Calais, France
Tel (33) 21-46-70-55

Johnson, G. Edward
AT&T Bell Labs
RM 7D-214
Murray Hill, NJ 07974
Tel (908) 582-2585

Jow, T. Richard
US Army Electronics
Technology & Devices Laboratory
SLCET-PR
Fort Monmouth, NJ 07703-5601
Tel (908) 544-3630

Kelen, Andreas
International I.E. Consulting
572011
Vasteras, Sweden
Tel 46-21-13788

Konig, Dieter
Techn. Univ. of Darmstadt
High Voltage Laboratory, FB 17
Landgraf-Georg-Str. 4
D-6100 Darmstadt, Germany
Tel (06151) 16-2168

Kosaki, Masamitsu
Dept. of Elec.& Elecns. Eng.
Toyohashi Univ. of Technology
Toyohashi Japan 441
Tel +81-532-47-0111 x505
Fax +81-532-48-3422

Lee, Min Jea
Heavy Duty Electric
PO Box 268
Goldsboro, NC 27530
Tel (919) 734-8900

Lemm, Art
Cooper Power Systems
11131 Adams Rd.
Franksville, WI 53126
Tel (414) 835-3368

Lewis, T.J.
School of Electronic Eng. Science
U.C.N.W. Dean Street
Bangor, Gwynedd UK
Tel 2488 351151

Montanari, Gian Carlo
Istituto di Elettrotecnica Industriale
Viale Risorgimento 2
40136 Bologna, Italy
Tel +39-51-6443471

Ohki, Yoshimichi
Waseda University
Dept. of Electrical Engineering
3-4-1 Ohkubo, Shinjuku-ku
Tokyo 169 Japan
Tel +81-3-3204-1258

Orton, Harry
Power Tech Labs Inc.
12388 88th Ave
Surrey, B.C., Canada
V3W 7R7
Tel (604) 590-7490

Pace, Marshall
University of Tennessee
411 Ferris Hall
Knoxville, TN 37996-2100
Tel (615) 974-5419

Parpal, Jean-Luc
IREQ
1800 Montee Ste-Julie
Varennes, Quebec
J3X 1S1
Tel (514) 652-8473

Reed, Clive W.
GE Corporate R&D
KI-3B20
Schenectady, NY 12301
Tel (518) 387-6039

Reher, H.
Dept. 00115
ERNO Raumfahrttechnik GmbH
OQ115, PO Box 105909
Hunefeldstrasse 1-5
D-2800 Bremen 1
Germany
Tel 49-421-539-4301

Ryder, Dennis M.
University of Brighton
Lewes Rd.
Moulescoomb
Brighton, BN2 4GJ
E. Sussex, England
Tel 0273-642225

Ryu, Boo-Hyung
Inspec. Dept. III, NRI Div.
Korea Inst. of Nuclear Safety
Daiduk PO Box 16
Taejon, 305-606 Korea
Tel +82-042-861-2529

Saha, Tapan Kumar
University of Queensland
Dept of Electrical Eng.
St. Lucia, QLD-4072
Australia
Tel 61-(07) 365-3988
Fax 61-7-365-4999

Sarjeant, W.J.
312 Bonner ECE
SUNY-Buffalo
Buffalo, NY 14260
Tel (716) 645-3117

Schor, Matt
W.J. Schafer & Assoc.
1901 N. Fort Myer Dr.
Suite 800
Arlington, VA 22209
Tel (703) 558-7900

Srinivas, M.B.
Dept of High Voltage Eng.
Indian Institute of Science
Bangalore 560 012 India
Tel 344411

Tanaka, John
U Conn - Honors
U-147 Wood Hall, Rm. 113
241 Glenbrook Road
Storrs, CT 06269-2147
Tel (203) 486-4223

Turner, Noel H.
Code 6170, Surface Chemisrty
4555 Overlook Avenue
Washington, D.C. 20375-5000
Tel (202) 767-2329

Wootton, Roy
Westinghouse STC
1310 Beulah Road
Pittsburgh, PA 15235-5098
Tel (412) 256-2108
Fax (412) 256-1222

Starr, Wendell
25,700 Deerfield Dr.
Los Altos Hills, CA 94022
Tel (415) 941-5922

Eric B. Forsyth
Bldg 911
Brookhaven National Laboratory
Upton, NY 11973
Tel (516) 282-4676
Fax (516) 282-2588

Nagao, Masayuki
Toyohashi University of Technology
Tempaku, Toyohashi, 441 Japan
Tel +81-532-47-0111 (ex. 506)
Fax +81-532-48-7634
E-mail: nagao @ tut.ac.jp

Winslow, John W.
103-101 JPL/Caltech
4800 Oak Grove Drive
Pasadena, CA 91109
Tel (818) 354-2150

Le Gressus, Claude
Centre d'Etudes de Bruyeres le Chatel
BP 12 - 91680 Bruyeres le Chatel. France

DeReggi, Aime S.
Bldg 224 Room B320
National Institute of Standards and Technology
Gaithersburg, MD 20899
Tel (301) 975-6739

Clavreul, Regine
EDF/DER
CIMA
77250 Moret sur LOING-FRANCE
Tel 60-70-60-34

Markiewiiz, Andrew
School of applied Science
Monash University College Eippsliemt
Churchill, Victoria, Australia 3842
Tel 61-051-226476

Gordon, Lloyd B.
University of Texas at Arlington
Box 19016
Arlington, Texas 76019
Tel (817) 794-5100

Cyoam, Peter J.
Army Research Laboratory
Electronic and Power Sou...es Directorate
Mail Stop SLCET-PR
Fort Monmouth, NJ 07703-5601
Tel (908) 544-4920

Marsden, Harold
1021 Main Campus Drive
Raleigh, NC 27606
ABB - TTI
Tel (919) 515-6000

Frontzek, Fraur R.
Landgraf-Georg Str. 4
6100 Darmstadt/Germany
High Voltage Lab / FB17
Technical Universit of Darmstadt
Tel (49) 6151 162529

Fouracre, R.A.
University of Strathclyde
204 George Street
GLASGOW G11XW
SCOTLAND
Tel 011-44-41-552-4400

Appendix C

WORKSHOP ON MULTIFACTOR AGING MECHANISMS AND MODELS

Workshop Schedule

AM	7:00-8:00	Breakfast and Networking with Colleagues
	8:00-8:10	Welcome by Workshop Chairman
	8:10-10:10	Session 1: Multifactor Aging Mechanisms Chairman: Lynn L. Hatfield, Texas Tech University
	10:10-10:40	Coffee Break
	10:40-12:10	Session 2: Multifactor Aging Models Chairman: Gabriel D. Roy, Office of Naval Research*
PM	12:15-2:00	Luncheon

Keynote Speaker: **Emanuel L. Brancato, EPRI Consultant**
Title: **A Pathway to Multifactor Aging**

	2:00-3:30	Panel Discussion Chairman: John A. Tanaka, University of Connecticut
	3:30-4:00	Coffee Break
	4:00-5:00	Summary/Conclusions Chairman: W.J. Sarjeant, SUNY Buffalo
	6:00-7:00	Cash Bar
	7:00-9:00	Banquet

Keynote Speaker**: **Pete L. Rustan, Strategic Defense Initiative Organization**
Title: **SDIO Space Insulation Technologies**

*Chaired by Paul Budenstein (U.S. Army Missile Command)

**Presentation given by Matt Schor (W.J. Schafer & Associates)

Appendix D

Workshop on Multifactor Aging Mechanisms and Models
(Held at Victoria, B.C., October 22, 1993)

Summary of Post-Workshop Evaluations

Note: Each participants' evaluation was assigned a number (1-32) and that number was used consistently throughout the tabulation.

Scale: 1-5 (poor to excellent)

I. The communication/ correspondence prior to the workshop was effective.
4.0

II. The abstract booklet was useful.
3.9

III. The meals and facilities were satisfactory/adequate. 4.6

IV. The invited talks were of high quality 4.2 and relevant 4.1.

V. The discussion session was meaningful 3.6 and focused 3.3.

VI. I had come to the workshop with the following expectations. Please indicate if your expectations were met or not.

1. Multifactor aging of cable used in Nuclear Power Plant - Partly met.
-Radiation and Thermal Aging on Electronic Components and Parts-not met.
2. My expectation for the workshop did not include solutions, but a disclosure of the thoughts and work of those who are presently entrained on a "basic" path towards the treatment of multifactor aging dilemma. Frederickson, Gillen, Bruning, and Crine did reveal, at this meeting, approaches or models that were directed by, or were based on physical or chemical interpretation. Thus the workshop succeeded in providing an insight to what is being done in the subject of multifactor aging.
3. -to learn something concerning aging of wires/cables.
-prediction methods (lifetime).
-application/problems in space.
4. Not.
5. Yes, my expectations were met.
6. a. The major factors involved in aging would become clear. b. The essential steps to be taken for progress to be made would emerge. While individually we came to conclusions on these two points, no consensus of the whole meeting was made.
7. My expectation was to discuss about aging models and mechanisms. It was not met at the workshop. There are still some fundamental points to be clarified, for people involved in these topics, such as definition of aging, definition of stress, etc.
8. I expected discussion of our familiar lines and was agreeably surprised to meet colleagues from organizations

that were new to me. Some of their contributions introduced new aspects. The workshop, therefore, was very instructive.
9. I expected what I saw.
10. I thought we would identify funding sources. I don't think we did.
11. Fundamental aspects of polymer physics and interfaces in dielectrics were not addressed.
12. Brief introduction of attendants background.
13. Since my knowledge of the field was limited, all of the presentations offered me quite an insight to this area.
14. I had come to the workshop expecting a thorough discussion on existing models (their usefulness and their drawbacks). Unfortunately the workshop was bogged down by one or two side issues. Therefore I would say that my expectations were not met.
15. My expectations were not very high since the subject is very complex. However, they were only partially met. Too many talks were focused on one specific aspect of aging and completely miss the point of multifactor mechanisms and models as well as potential synergistic effect.
16. Some expectation of an indication of funding available on specified research topics from e.g. EPRI (not met).
17. I came for guidance and discussion on the methodology of multifactor and modeling and its relevance to the real world. Also came to learn about future directions for development in the field. My expectations were met in part.
18. Yes.
19. I was hoping to be able to focus on an action item list to structure my research goals. I am not sure I was able to come up with one.
20. No comments listed.
21. I thought the speakers were well chosen when the program was sent prior to the workshop. They each had an interesting story, with results being reported on long term studies of different nature. My expectations were exceeded.
22. Foundation of theory O.K. Application on large variety of endurance data? Compilation of model parameters for more materials and applications? More test data evaluated?
23. No comments listed.
24. A relationship between depolymerization of paper and tensile strength (or "usability") has been proposed (or demonstrated) and I was looking for an expansion of this definition to other materials or structures. I was not prepared for so much theoretical (even though I believe the theories).
25. I came with an open mind and generally found the workshop useful.
26. To get an overview. The workshop was excellent for my purposes. This is a difficult subject!
27. To interchange ideas on multistress aging from various disciplines i.e. from experts from different equipment backgrounds (power equipment, low voltage equipment, etc.) and different subjects (physical, chemical, etc.). In general, my expectations were met but some presentations were too specific. J. Tanaka did an excellent job of generating discussion. However, I think the focus of the workshop should have been better defined at the outset.
28. I wanted to get good background

information as well as some of the latest research results. I think the workshop was highly successful in this respect. The summary by Jim Sarjeant was also good.

29. I am reasonably new to the field and hoped to gain some insight into what has been done and what is currently going on. That expectation was more than adequately fulfilled. I have a much better feel for the total picture and how our work and the pace of our work measures up to what others in the field are doing. Thank you!

30. I expected some specific objectives to be identified at the start. Multifactor aging is so complicated that almost every facet is open ended. Specific objectives (i.e. directions) needed to be given, but weren't.

31. Most interested in learning what others feel is important state-of-the-art issue for ageing in space and/or radiation. I think I now know where most minds are situated across the spectrum of ageing phenomena. It was very good for me!

32. Expectations: Want to get informed about the level of discussion, topics, open questions and planned future activities in this field - from the standpoint as an European University Professor and candidate for the Chairmanship of IEC TC 15. - Expectations were mainly met.

VII. The workshop may have been more effective and rewarding had we done things the following way.

1. If the workshop will be co-sponsoring and cooperate with US NRC, BNL and IEEE NPSS, may be more effective.

2. While there are "n" number of different ways the workshop could have been planned, I believe that the format employed accomplished its mission in that it acquainted the members of the basic approaches currently active, it formulated broad guidance for future direction, and above all it generated an awareness of the need to understand the phenomena of aging.

3. No comments listed.

4. Fundamental basis related to the space charge physics and related phenomena (breakdown, ageing) should be added.

5. No comments listed.

6. We needed much more time at the end to summarize the various themes. Although this was attempted at dinner, the atmosphere was not ideal for it.

7. Perhaps the organizer overestimated the average knowledge of the topic. Therefore, too many subjects were discussed at the workshop, without the needed deepening.

8. The most important desire, the distribution of copies of all lecturer's overhead transparencies was met. Simultaneous distribution of Professor Sarjeant's summary of the discussions would be highly appreciated.

9. The workshop should be longer and the presentations and discussions should be rather limited to some materials and devices.

10. We needed Bernstein and Rustan.

11. It was a diverse group - hard to change format.

12. No comments listed.

13. Some of the speakers had a very empirical approach, and some more basic information as to what was being presented would have been better in

my opinion.
14. 1) A discussion on papers presented in the morning session (A couple of important questions on each paper would have sufficed).
2) It should have focused more on existing models (physical as well as empirical) pertaining to Multifactor aging.
15. Reduce the number of invited talks and be sure that they will be on the proposed topic. Increase the time for questions after talks and of the forum.
16. Format was fine.
17. I think the basic format was O.K. However, the panel session was a bit cumbersome.
18. I thought it was an especially well done workshop and I was glad to be able to participate.
19. A brief period following the presentations and panel might have been used for groups (4-6 people) to come up with specific research projects.
20. More time for each speaker. Printed proceedings prior to presentations.
21. In a number of cases too many graphs flew by in too little time and too little discussion. I did not think the workshop's function was to arrive at some sort of a standard on multifactor aging, but rather to show methodologies for difficult situations-emphasizing both problem areas and rationales for success.
22. Earlier availability of presentation material. More time for questions.
23. No comments listed.
24. The objective may be more achievable if the workshop were to be used for the presentation/identification of aging characteristics and how they might be evaluated; as well as how an aging characteristic relates to the "age" of a device or structure. Empirical data and field observations could have been compiled and presented at the workshop. Some of the presenters were well qualified to incorporate this information into their ideas/theories and to evaluate the resulting hypotheses.
25. There was a tendency to regard the workshop as an opening to set standards or, at least, suggest them. I thought this was inappropriate. Should have been more on testing methods.
26. No comments listed.
27. The focus of the workshop should have been well defined in terms of what were the goals. I was not sure of the goals except to generate discussion. The discussion was better than usual, with input from many persons. Perhaps in the future we should consider each type of insulation system separately rather than attempt to discuss them all together.
28. No comments listed.
29. No comments listed.
30. Identified specific objectives at the start e.g. Objective 1: What research program is likely to be most productive in furthering basic scientific understanding of multi-factor aging interactions? Objective 2: Taking as an example a particular practical insulation system e.g. an oil/paper source transformer. What research program is likely to be most productive in identifying the multi-factor aging conditions which presently limit life in-service?
31. We should have focused on ageing specific environments for state of the art cases. We tended to wander "back" to old issues, small details, and

general theories whose impacts are generally known. We lost touch with the specific issues at hand.

32. Maybe.

VIII. Please suggest topic(s) for similar workshop(s) in the future with a brief rationale or any other comments/ criticism/suggestions.

1. No comments listed.
2. a) It is not possible to suggest a topic for a future workshop until new material has been gathered. To this end, I suggest that you IEEE Multifactor Committee, jointly with Dr. Laghari's IEEE Radiation Effects Committee, collect from the literature, and from ongoing work, basic information relevant to environment or stress related aging. b) Round-robin examination should be started of proposed approaches on aging, such as Crine's. c) Metallurgy literature should be examined for aging phenomena that might be applicable to organic materials.
Following sufficient progress, a second workshop could be implemented to examine the findings of these committees and to generate, from these findings, research proposals to carry out needed work. Of course, the workshop would also act as a forum for ongoing research activity on aging phenomena.
3. Talks concerning lifetime prediction of cables/wires, harness in space application.
4. a. Discussion of fundamental basis
b. Characterization: What to Measure?
c. Technology
d. Round Robin
5. Diagnostic Methods of Dielectric Insulations.
6. In almost all dielectric/insulation applications, the interfaces between electrodes and dielectric play a major part (largely misunderstood role). There is need to bring together the various approaches to the problem in an interdisciplinary way. Increasing stress levels, alien environments and miniaturisation will accent this.
7. Same topic, but with more concentrated, more strict development (it also depends on session organizer)
8. 1) Partial Discharges and Insulation Ageing - an area of interesting progress. 2) Electrical Insulation Under Varying Climatic Conditions - both outdoor and indoor climates pose various problems of stressing and degradation of electrical insulation.
9. Workshop on aging phenomena in selected devices with the idea that some conclusions will be reached.
10. No comments listed.
11. High-Energy Density Dielectrics and Capacitors,
12. a. Tan δ at high temperature and high field.
b. Space change distribution in solid.
13. The deadline was way too early. I realize that you had space problems, and maybe trying to find facilities that are "too large" would be the best approach. On site copies of the presented view graphs would have been useful also.
14. Failure mechanisms and models pertaining to a particular insulating system (such an approach would help in discussing rigorously problems related to any particular insulating system).
15. "Conduction and space charge accumulation in polymeric insulation" This topic is important to understand the effect of DC testing of cables and

also for dielectric relaxation measurements for the diagnostic of aging in polymeric insulation.

16. Perhaps a workshop could be held after, say, every other CEIDP. One topic would be charge injection into DC Cables.

17. A teach-in on measurement techniques?

18. The influence of the micro structure of solid insulation materials on their electrical breakdown strength functions of temperature, pressure and dimensions.

19. No comments listed.

20. No comments listed.

21. As a user of various pieces of equipment, I have often unconsciously abused the equipment by thoughtless acts - setting a piece down too hard, allowing dust to accumulate, twisting wires, dropping cables, etc. Manufacturers can help consumers by alerting them to good operating practices, practices that are sensitive to multifactor aging effects.

22. The topic is not yet exhausted.

23. No comments listed.

24. No comments listed.

25. Although the emphasis was on utility applications, my own work is often oriented to one of a kind pulsed HV. A workshop on theory and practical applications of pulsed HV devices would be interesting to me personally.

26. Now I would like to see several more specialized workshops on various sub-topics of this one.

27. Diagnostic techniques for power equipment (techniques to monitor ageing, predict remaining life). This should be done testing specific types of equipment e.g. machines(large/small), capacitors, transformers, cables (high/low voltage).

28. No comments listed.

29. No comments listed.

30. No comments listed.

31. I thought that this workshop was motivated to help "funded" programs. As studies from these "funded" programs become published, a workshop may be convened to comment on the work, and to suggest further works.

32. Reports should be presented which inform about what is going on worldwide in the field of Multifactor Aging . . in the International Institutions such as CIGRE, IEC as well as National Research Labs and Technical Universities.
The information of joint International Working Group should be prepared which focus their work on a common subject to be selected. Thus, doubling of work could be avoided and application for financial support strengthened.

APPENDIX E

Reprinted from
IEEE Electrial
Insulation Magazine
(Jan./Feb. 1993)
Vol. 9, No. 1

Multifactor Ageing Workshop Held in Victoria

A workshop on "Multifactor Ageing: Mechanisms and Models," was held on Oct. 22 at the Victoria Conference Center, Victoria, B.C., Canada. The workshop, the first of its kind, was sponsored by the Electric Power Research institute, the Strategic Defense Initiative Organization and the Office of Naval Research. The workshop was successful in bringing together 65 persons from 12 countries who were interested in the subject matter and who, indeed, engaged in intellectual interaction and exchange about the very complex subject of ageing and failure mechanisms of multistressed insulation.

The idea for the workshop was conceived during the Multifactor Stress Committee meeting held during the 1991 CEIDP. The technical program committee for the workshop included Vijendra Agarwal, Bruce S. Bernstein, Emanuel L. Brancato, Lynn L. Hatfield, Gabriel D. Roy, Pete L. Rustan, and W.J. Sarjeant.

The workshop featured a number of invited speakers in the morning who provided an overview of the subject matter. The opening speaker, Andreas Kelen of Sweden, discussed the framework of multifactor ageing and testing from a historical perspective and how the subject has progressed through the years. This was followed by multifactor stress ageing of high energy density polymer film capacitors by Clive Reed of General Electric. He emphasized that the main factors that may account for differing ageing mechanisms in capacitors include the polymer chemistry, corrosion, nature and properties of impregnant, capacitor design and the uniformity of electric stress. He suggested that the intrinsic ageing of materials is rather mysterious and not well understood.

Ron Fredrickson of USAF/Philips Laboratory provided an overview of ageing in space environment, particularly, how radiation fields cause initiation of streamers in insulation materials. He further elaborated on insulator pulsing caused by space radiation, which, in turn, initiates breakdown. He also discussed results on several insulating materials exposed to the space environment, including glass covers used for solar cells. The message was loud and clear that insulator ageing in an actual space environment is presumably more complex to investigate and understand than in ground-based systems.

Continuing with the effect of radiation but combined with thermal and oxygen environments, Ken Gillen of Sandia National Labs discussed their approach. According to him, radiation-induced damage to polymeric materials in oxygen-containing environments strongly depends on both dose rate and temperature. He suggested that we must first understand/eliminate "physical" dose-rate effects followed by the true "chemical" effects. In other words, their approach first used a time-temperature superposition approach to make thermal-environment lifetime predictions and then generalized it to combine radiation-thermal environments. He discussed the success of their approach in predicting long-term (7 to 12 years) ageing of numerous cable jacketing and insulation materials that were naturally aged in nuclear power plants.

John Densley of Ontario Hydro concentrated on the influence of various ageing stressed, i.e., electrical, thermal, mechanical and environmental factors in power cables. He suggested that the intrinsic thermal ageing, e.g., depolymerization at high temperatures, is a complex path to failure. He also discussed several multistress ageing models and their applicability in the context of cable insulation. He further suggested that the key elements that determine the type and rate of ageing, and ultimately the life of insulation systems, are the number, location, size and type of contaminants, defects and imperfections and the way they interact with applied stresses.

The ageing of aircraft wiring covered with polyimide insulation was the topic of discussion by Armin Bruning of Lectromechanical Design Co. Three significant parameters considered in this work included the chemical reaction of water and the polyimide, deterioration due to temperature gradient, and the reaction rate because of mechanical strain applied to the molecular structure. In the final analysis of this presentation, it was suggested that the insulation life is nearly infinite below 70% relative humidity.

Jean-Pierre Crine of IREQ discussed several applications of the rate theory in the context of electro-thermal ageing mechanisms of extruded dielectric cables. This presentation emphasized the importance of Gibbs free energy in modelling the ageing mechanisms and not the apparent activation energy. It was suggested that one should include the thermodynamic transitions as temperature decreases while dealing with thermal ageing. The proposed model predicts that submicrocavities (~100A' size) are formed due to fatigue at fields higher than 10-20 kV/mm. These cavities are believed to be formed by bond breaking that leads to free radical formation and thus the ongoing electrochemistry and energy of cohesion of the material become determining factors for dielectric ageing.

Emanual Brancato, an EPRI consultant, summed up the morning session by reviewing the history of thermal and electrical ageing relations and their apparent limitations. In this presentation, he reiterated the work of previous speakers, namely Crine and Bruning, et al., and emphasized that all aspects of ageing may be "chemical" in nature. If these chemical changes can be further quantified and identified, one can hope for a general model for multifactor ageing. He reminded everyone that the most probable path to a realizable prediction of insulation ageing in a multistress situation is to understand the dynamics of ageing mechanisms.

While the individual presentations filled the morning hours, a much more dynamic afternoon included a panel discussion that comprised all of the speakers. The session chairman, John Tanaka of the University of Connecticut, raised some very probing questions that led to an intellectual discussion among workshop participants and speakers. The question of developing guides versus standards for multifactor stress ageing was discussed. In the final analysis, it was suggested that guidelines may well be the best approach.

With regard to diagnostic tools, it was suggested that nondestructive procedures be developed that should not age material. In this context, PD technique, which provides very detailed transient electrochemistry information, was suggested to be the simplest way to evaluate ageing in materials. Once again, a deterministic approach along the line of Crine's work was suggested to be the way to proceed.

In the final hours of the workshop, a brief overview on SDIO space insulation technologies was provided by Matt Schor of W.J. Schafer & Associates. He discussed various phases of the experiments called SPEAR (Space Power Experiments Aboard Rockets). SPEAR I and II have led to the validity of the space vacuum insulation technology in an LEO environment. Systems with 100kV and 150kA were successfully tested in vacuum chambers without significant breakdown. The SPEAR III program is in progress, which is expected to provide information on spacecraft charging as a function of altitude and geomagnetic field orientation. This also will test the effect of grounding techniques on the operation of solar cells.

No formal workshop proceedings are being planned; however, a collection of notes furnished by various speakers and a summary report prepared by Jim Sarjeant will be made available to the workshop participants, if they so desire.

For questions about the workshop, readers should get in touch with the workshop chairperson, Dr. Vijendra Agarwal, Department of Physics, Moorhead State University, Moorhead, MN 56563, U.S.A. Telephone: 218-236-2451, Fax: 218-236-2168.

—*Vijendra Agarwal*

DEIS Technical Activities

This is the fourth, and last, in the series of contributions that profile the work of the society's technical committees. In this issue, Committees S-32-10, S-32-11 and S-32-12 are covered. Although the subjects of concern to these groups are very different, they are all striving to assemble an informed scientific understanding and establish a position on matters of importance to the insulation community. In some cases (such as S-32-12) this takes the form of preparing an IEEE guide and, in instances where the area is less well-defined or is fast evolving, position papers are assembled.

As in previous articles in this series, the broad objectives of these committees are summarized and the name and telephone number of the chairmen is given so that those who are looking for more information, or who would, perhaps, wish to participate, may make contact.

Committee S-32-10, Failure Mechanisms (Chair: Tom Bialek, Tel. 415/361-2022.)

This committee was initially chaired by Dr. John Densley. When it started, the committee's main objective was to collect information regarding fundamental studies of the failure mechanisms of insulating materials and systems. The information was to be reviewed and a position paper was to be published to provide the most up-to-date information on possible mechanisms of failure. The different modes of failure under various condition would be outlined and suggestions about areas needing further research would be published. However, due to the difficulty in covering all failure mechanisms of all insulating systems in one paper, specific classes of insulating materials and systems now will be covered separately.

The objectives of the committee can be summarized as follows: (a) Provide a forum for discussing the mechanisms of failure of insulating materials and systems. (b) Prepare state-of-the-art reviews of the failure mechanisms of specific insulating systems, which will be oriented toward equipment users.

The committee was initially focused on the failure mechanisms of polymeric cable insulation systems. A position paper was drafted examining in detail the different mechanisms. Unfortunately, the paper was never completed. After the transfer of the chairmanship, a new effort was initiated to complete this work and publish a position paper. The committee agreed that mechanisms will be discussed in some length and this section will be followed by a discussion of the impact and importance of the research of failure mechanisms and the recent advances in polymeric cable insulation systems from various perspectives. A user orientation is the objective of this paper in order to disseminate information to those who may not be conversant with the literature. Once this paper has been completed, another system or material will be chosen by the committee. Work has begun on this position paper, and it is expected to be available for publication in early 1994.

As with most committees, volunteers are needed, especially from the equipment user and manufacturer groups. If anyone is interested, they should contact the chairman directly. it is expected that the committee membership will change depending on which insulation system or material is being discussed.

Committee S-32-11, Gaseous Dielectrics (Chair: Dr. Richard J. Van Brunt, Tel. 301-975-2425).

The objectives of this technical committee are: (1) Collect information about research on gaseous dielectrics. (2) Inform members about progress of research. (3) Create an international forum for exchange of ideas. (4) Identify and suggest future needs for research. (5) Formulate and/or suggest standards and guidelines. (6) Sponsor and/or organize special sessions at technical and scientific conferences.

The present committee chairperson is aided by the committee secretary, Phil Bolin of Mitsubishi Electric. A working group was formed in 1990, chaired by Jim Pachot of BPA, to deal