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INDUSTRY APPROACH TO AGING ASSESSMENT UPDATED

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ABSTRACT

The service life of nuclear power plant equipment may include operation beyond design or qualified life. A technical basis is necessary to demonstrate that critical equipment is capable of continued safe operation for any renewed license term. Such a technical basis is also useful in addressing initial license term age-related failures and maintenance issues. Early approaches for assessing aging developed for Environmental Qualification Programs in the 1980s were incorporated into the Institute of Electrical and Electronic Engineers' IEEE Std. 1205-1993. However, subsequently, a number of events (including the Maintenance Renewal Rule, the new License Renewal Rule, and initial Plant Owner submittals of License Renewal applications) have resulted in improved techniques. Concerted industry efforts allowed improved aging management approaches, which focus on addressing aging effects rather than attempting to identify and mitigate every possible aging mechanism. IEEE's Nuclear Power Engineering Committee recognized the need to capture these improved approaches. A two-and-a-half year effort of Working Group 3.4 culminating in IEEE Std. 1205-2000 is the consensus of representatives from the two lead license renewal plants (Calvert Cliffs and Oconee), the Nuclear Regulatory Commission, a national lab, other utilities, and multiple engineering/consulting firms. This paper will summarize the new information and approaches now available.

1. INTRODUCTION

Over the past five years a new industry approach for performing aging assessments has developed, evolved, and was piloted for license renewal. More recently this new approach has taken the form of an industry standard, specifically a Year 2000 revision of IEEE Standard 1205 *Guide for Assessing, Monitoring, and Mitigating Aging Effects on Class 1E Equipment Used in Nuclear Generating Stations*. Since 1993, IEEE 1205 has provided guidelines for assessing, monitoring, and mitigating aging degradation effects on safety-related electrical equipment. Its purpose has been to supplement existing IEEE nuclear standards in assessing aging effects. For example, this guide was intended to be used to supplement or assist the use of IEEE Std. 323 *Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations*.

Aging assessments may be pursued in response to a variety of factors: e.g., regulatory guidance, approaching obsolescence, reduced availability or reliability, or for life extension. Monitoring and/or mitigating the aging of some equipment may often cost less than its replacement. Aging management consists of assessing, monitoring, and mitigating the effects of aging.

At the time of original issue of IEEE Std. 1205 the industry focus for assessing and mitigating aging degradation was on identifying and addressing all possible aging mechanisms. This approach derived from the rigorous aging analyses performed in support of earlier environmental qualification (EQ) programs. In 1991 10 CFR 50.65 (Maintenance Rule) was published. In 1995 10 CFR 54 (License Renewal Rule) was amended. As a result of these two regulation changes and industry interactions in response [e.g., NEI 95-10 (Revision 1)], the emphasis for addressing aging degradation shifted from identifying aging mechanisms to identifying aging effects.

In 1997 The Nuclear Power Engineering Committee of IEEE's Power Engineering Society authorized its Working Group 3.4 to revise IEEE Std. 1205 to incorporate industry feedback and to bring the approaches discussed in the Guide into closer conformance with present industry philosophy. As a result, the following notable changes to the Guide were adopted:

- Update of the aging assessment, monitoring and mitigation process for consistency with current industry philosophy and to better show and integrate the relationships between the process steps and updated corresponding guidance discussions;
- New guidance, bases, and limitations for performing Arrhenius and radiation dose age modeling when assessing remaining equipment life;
- New Annex C on Condition Monitoring approaches;
- Update of the example assessments in the guide's Annex D for consistency with the revised Clause 6 and added two new examples on electric cable and electric penetrations; and
- New Annex E on attributes of an effective aging management program.

This paper will summarize these changes.

2. OVERVIEW OF THE IMPROVED AGING ASSESSMENT PROCESS

Equipment and its constituent materials age in response to stressors and as a result of aging mechanisms. A stressor is an agent or stimulus that stems from fabrication or preservice and service conditions and can produce immediate degradation or aging degradation of a system, structure, or component. There are two types of stressors: environmental and operational. The aging degradation of electrical equipment will usually be a function of the duration, range and intensity of stressors experienced by the equipment.

An aging mechanism is a specific process that gradually changes the characteristics of a system, structure, or component with time or use. A significant aging mechanism is one which, if in the normal and abnormal service environment, causes degradation during the installed life of the equipment that progressively and appreciably renders the equipment vulnerable to failure to perform its safety function(s) during design basis event conditions.

IEEE Std. 1205 includes numerous examples of stressors, aging mechanisms and resulting aging effects in its Annex A in the form of Tables for different types of materials (polymers, lubricants, and metals).

As alluded earlier, the new industry philosophy was a shift from attempting to identify and address all possible aging mechanisms to evaluating and mitigating known, significant aging effects where "significant" was defined as those effects that could detrimentally hinder or prevent the intended equipment function.

Figure 1 below provides an overview of the multi-phase process of assessing, monitoring, and mitigating aging effects.

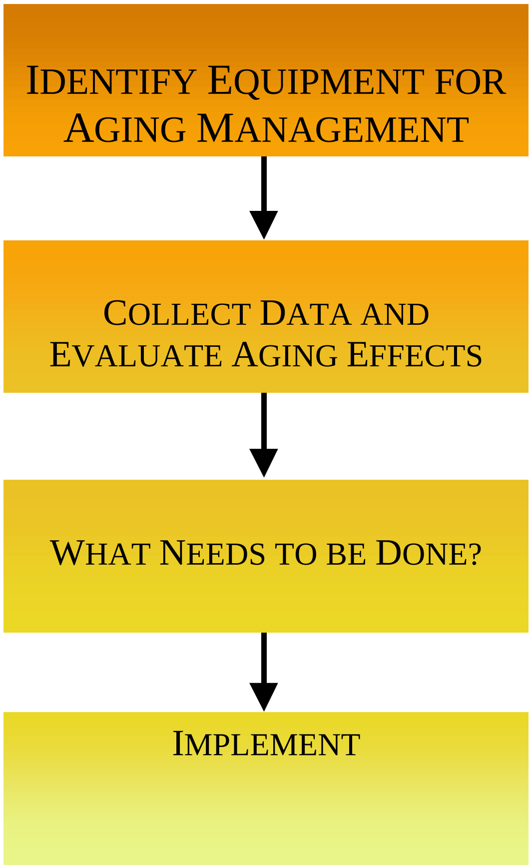

Fig. 1 Overview of Assessing, Monitoring, and Mitigating Aging Effects

First, the "universe" of equipment to be evaluated must be established. This list could be electrical equipment within the scope of license renewal, or a recently failed item or group of equipment (where the potential for a maintenance preventable second failure exists), or an Environmental Qualification (EQ) Program equipment item with a qualified life believed to be overly conservative.

Next, known aging effects need to be evaluated. Working Group 3.4 recognized that aging evaluation work efforts already completed for similar type and application EQ Program equipment should be considered to avoid possible duplication of earlier work. Otherwise it is necessary to research and document evaluation boundaries, intended function, locations, service conditions, materials, and known aging effects for assessment. The guide includes five steps (Colaianni and Horvath, 2000) for performing the aging assessment including use of thermal and radiation aging models and condition monitoring considerations. This paper discusses the thermal and radiation aging models and condition monitoring in more detail in Sections 3 and 4, respectively.

Third, based on the results of the aging effects assessment one or more of the following options is selected for subsequent aging mitigation: maintenance, replacement, refurbishment, redesign of equipment, adjustments in operating environments and practices that reduce stresses, environmental and operational stress monitoring, inspection, surveillance, and trending. If the equipment being evaluated is part of the station's EQ program, IEEE Std. 323 should be followed and the corresponding Program documentation may require an update.

3. THERMAL AND RADIATION AGING MODELS

Two aging stressor models (thermal and radiation) are described in the IEEE Std. 1205-2000 and summarized below.

3.1 Thermal Aging Model

Thermal aging has been and is continuing to be assessed using the Arrhenius model. It has been described elsewhere such as in Carfagno (1980) and Nelson (1990). Many instances of non-conservative use of this model have been identified in recent years in order to justify additional equipment life. For this reason, IEEE Std. 1205 now offers a more complete compilation of ways to more appropriately use the model by observing its many limitations and assumptions and thereby avoid past pitfalls.

The model establishes aging degradation as a function of temperature and allows an estimation of thermal life or a given temperature. It is also used to relate remaining life at one temperature to remaining life at another temperature. Alternatively, it can be used to determine a maximum continuous temperature for a specific length of time.

Thermal aging is a chemical reaction and such reactions are a function of temperature. The reaction rate (dg/dt) according to the Arrhenius model (Carfagno, 1980 and Nelson, 1990) is:

$$\mathrm{dg/dt} = \mathrm{A}\ \exp\,(-\phi/\mathrm{kT}) \qquad (1)$$

Neglecting the effect of depletion of the reactants on the reaction rate to solve this differential equation gives:

$$t = B\ \exp\,[\phi/kT] \qquad (2)$$

Equivalent degradation can be applied to the Arrhenius relationship to allow calculation of a lifetime t_a at an actual (or expected) installed temperature T_a given a different test temperature T_b and a test period t_b.

$$t_a / t_b = \exp [(\phi / k) \ (1/T_a - 1/T_b)] \tag{3}$$

Equation 3 can be used in conjunction with appropriate testing results (to a marginal degradation condition) at a higher temperature to theoretically derive a maximum continuous use lower temperature for a longer specified period of time.

Alternatively, Equation 3 is used in the guide to newly derive an approach for approximating remaining life given a known exposure temperature history and a conservative expected future temperature. To facilitate such a determination, a series of *i* discrete "time at temperature" intervals can be used to derive an equivalent Arrhenius weighted average temperature T_n for the entire period of time t_n as follows:

$$\begin{aligned} g(t_n) &= A\ t_n\ [\exp(-\phi/k\ T_n)\ ] \\ &= A\ [\ t_1 \exp(-\phi/k\ T_1) + t_2 \exp(-\phi/kT_2) + \ldots + t_I \exp(-\phi/kT_3)] \end{aligned} \tag{4}$$

$$T_n = (\phi/k) / \ln \{t_n / [\ \Sigma\ t_i \exp(-\phi/(kT_i))]\} \tag{5}$$

Where T_i is the temperature for time interval t_i and the summation is over all *i* discrete intervals.

Arrhenius thermal age modeling has the following assumptions, sensitivities and limitations, which must be considered to assure appropriate results are derived:

1) A single stressor type, i.e., thermal aging is assumed at work throughout the life of the material. [Radiation exposure degradation and other forms of aging would need to be addressed separately.]
2) One dominating chemical reaction corresponding to one dominating aging mechanism causing the identified aging effect (e.g., corrosion, embrittlement, etc.) is assumed. [Test temperatures should be selected to assure that the dominant aging reaction at the test conditions is also dominant and equivalent at the installed service condition temperature.]
3) The coefficient *A* is assumed to be independent of temperature. According to gaseous reaction theory, *A* increases at approximately the square root of temperature.

   NOTE: It is square root dependent when both reactants are gases; for solid material aging, only one of the reactants (oxygen) is normally gaseous and *A* would be less temperature dependent. This assumption could cause the reaction rate or amount of reactions to be calculated lower than actual but the error is small – less than 5% for typical ambient and test temperatures and this error would be offset by other conservative assumptions.

4) The activation energy is considered to be constant with temperature and time. [The selected activation energy should be at the conservative end of the range of possible activation energies.]

5) The above derived expressions are very sensitive to the accuracy of the selected activation energy. Because the activation energy is often available in only one or two significant digits, it should be selected carefully and the expression results interpreted judiciously. [That is, calculated results with accuracy beyond one or two significant digits are not considered credible.]

6) The reaction rate is assumed to be not affected by depletion of the reactant concentration or in other words the end of life (amount of degradation) is selected to be before depletion effects are noticeable.

   NOTE: This assumption is conservative because reactant depletion reduces the aging reaction rate, which would give a longer predicted life given a life endpoint based on the same amount of degradation.

7) Equation 3 assumes the same amount of degradation damage when converting from one set of time at temperature conditions to another set of conditions. [This amount of damage does not necessarily represent an end of life condition.]

Because of the limitations and assumptions stated above, the Arrhenius model for thermal aging should be considered to provide only an approximation of the lifetime of the equipment. When feasible, condition monitoring or other means should be considered to validate remaining or residual life of equipment.

3.2 Radiation aging model

Unlike thermal exposure, the radiation dosage or amount of energy deposited affecting a material’s integrity and operability linearly increases with time for a constant field or dose rate. A conventional model for radiation aging assumes that material damage is directly related to the amount of energy deposited as a result of exposure in an ionizing radiation field. This model also assumes a principle of equivalent damage exists. This principle states that the amount of material damage resulting from exposure to a constant radiation dose rate field and a given duration is equivalent to that same exposure from any other combination of dose rates and exposure durations. The total integrated dose is the time integral of the dose rate as a function of time over the total exposure duration.

The value of total integrated dose that begins to detrimentally affect the material’s functionality and, thereby, the equipment’s ability to perform its safety function can be determined by test and has been tabulated for many materials. Therefore, an assessment of the effects of radiation aging would be a determination of remaining life to achievement of a detrimental-to-function dose at the expected service condition dose rate.

4. NEW ANNEX DETAILS STATE OF THE ART CONDITION MONITORING

Condition monitoring is the observation, measurement, or trending of condition indicators with respect to some independent parameter (usually time or cycles) to indicate the current and future ability to function within acceptance criteria. IEEE Std. 1205 in its annex C offers for the first time in an IEEE standard, a list of state of the art condition monitoring techniques that may be used to support aging assessment and mitigation. Much study and experimentation in this area has been conducted and continues to occur. Because the technology for condition monitoring is continuing to be developed, it is anticipated that this annex will be updated as IEEE Std. 1205 is periodically updated.

A valid aging trendable parameter or property (also called a condition indicator) needs to be identified in order for condition monitoring to be effective. Selection of the trendable parameter or property should consider practicality and ease of the test measurement, destructive / intrusive vs. nondestructive / non intrusive nature of the method, as well as sensitivity to aging.

Ideally, the property or parameter would also have relatively uniform changes with age, changes with age large enough in magnitude to establish differences in the degree of aging, ability to be tested or measured, reproducible results and confidence in establishing intervals of time between testing that assure continued functionality (as defined by the acceptance criteria) during the entire duration of this interval (and during the post-accident operating time for EQ equipment).

An appropriate aging trendable parameter can be determined based on type of equipment or weak link part or both. An example of equipment type is the rotating machinery where a useful trendable parameter might be vibration or lubricant wear product concentration. An example of a potentially limiting part is the electric insulation where a parameter such as hardness, dielectric strength, or tensile strength could be used for condition monitoring. Table C3-1 of the guide summarizes candidate condition monitoring methods for six basic equipment types: rotating machinery, motor operated valves, heat emitters (e.g., bearings, fuses, normally energized solenoid valves, or motors), pressure retaining components (e.g., pressure transmitters), motor/generator electric insulation systems, and electric cable insulation.

A comprehensive list of 24 condition monitoring techniques including 12 specifically for cable insulation condition monitoring is provided. Cable insulation techniques including the indenter, partial discharge, void size/density correlation, and oxidation induction time are described. 26 bibliographic references are cited.

5. UPDATE OF EXAMPLE ASSESSMENTS

The earlier version of IEEE Std. 1205 offered detailed aging assessment examples for the reactor protection system, emergency diesel generator, and motor control center. These sample assessments were updated to shift the focus from identifying aging mechanisms to addressing and evaluating aging effects. In addition, two new sample assessments were added to the 2000 version: one on insulated cable and one on electrical penetration assemblies. A separate paper (Colaianni and Horvath, 2000) has been prepared summarizing the new annex on performing a sample electric cable insulation aging assessment.

6. ESSENTIAL ATTRIBUTES OF AN AGING MANAGEMENT PROGRAM

An effective aging management program must define its purpose and scope, describe the aging effects to be managed and the actions, methods, or techniques, to manage the aging effects. If inspections are to be performed, sample sizes and frequencies need to be established. Measurable threshold values or identifiable criteria that can be used (1) to determine acceptability of the current physical configuration and (2) to trigger appropriate actions prior to a loss of equipment safety function must be defined. These and other essential attributes of an effective aging management program are now described in the new annex E of IEEE Std. 1205-2000.

7. CONCLUSIONS

In summary, the newly issued IEEE Std. 1205-2000 now offers a standardized approach for performing aging assessments based on an industry consensus, which takes advantage of recent industry lessons learned gained from achieving the first two successful license renewals. The new guide may also be used to perform aging assessments for other reasons such as to address maintenance preventable failures and EQ Program issues. In addition to a providing a more effective approach the guide contains new guidance on use of Arrhenius, performing radiation aging evaluations, and successful elements of a successful aging management program as well as updated assessment examples for five types of electrical equipment.

NOMENCLATURE

CFR	United States Code of Federal Regulations
IEEE	Institute of Electrical and Electronic Engineers
NEI	Nuclear Energy Institute
PES NPEC	Power Engineering Society Nuclear Power Engineering Committee
t	is the time to reach a specified end-of-qualified life condition or lifetime
A	is a constant of proportionality
B	is a constant [related to the amount of degradation that will have occurred at end of time t or $B = g(t)/A$ where g(t) is the amount of reactions occurring through time t].
ϕ	is the activation energy (in units of electron volts eV) for a chemical reaction of concern and indicative of aging susceptibility.
k	is the Boltzmann's constant (0.817×10^{-4} eV/K).
T	is the absolute temperature (K) of the service condition.

Subscripts

a	actual or expected condition

b test condition

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REFERENCES

IEEE Std. 1205-2000 *Guide for assessing, monitoring, and mitigating aging effects on Class 1E equipment used in nuclear power generating stations*.

NEI 95-10 (Revision 1) *Industry guideline for implementing the requirements of 10 CFR Part 54 — the license renewal rule*

Carfagno, S.P. *A review of equipment aging theory and technology*, Electric Power Research Institute, EPRI Report NP-1558, September 1980.

Colaianni, R.P. and Horvath, D.A., *IEEE Std. 1205-2000 incorporates new guidance for electric cable aging management and assessments*, NUPIC&HMIT 2000.

Nelson, W. 1990. *Accelerated testing statistical models, test plans, and data analysis*, Wiley Interscience, New York, pp. 75-79.