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Aging-Seismic Correlation Study on Class 1E Equipment

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ABSTRACT

This paper presents a new method of analysis for evaluating the effect of aging in electrical equipment on the seismic capacity. The method is based on the probability of mechanical failure of weak link materials which may be subjected to a load during an earthquake. It is shown that aging-seismic correlation is related to: number of age-degradable weak link components, rate of degradation in weak link components, the seismic stresses on the components and component material failure. Before conducting the Probabilistic Failure Analysis, preliminary screening for equipment with potential aging-seismic correlation is performed.

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EXECUTIVE SUMMARY

The purpose of this work is to develop a methodology for screening electrical equipment into various categories; the equipment will fall into groups that range between those in which no correlation between aging and seismic capacity exists and those in which a significant correlation exists.

The basis of the methodology for evaluating potential aging seismic correlation is the premise that equipment will fail during a seismic test when a "weak link" in the equipment mechanically fails by yielding or breaking. The probability of failure is calculated by using a normal probability function to define the relationship of the stress applied to the weak link and its frequency (or probability) of failing. If the weak links are fabricated from materials (e.g., elastomers, plastics) which degrade in strength with time and which may bear high loads during a seismic test, then a significant increase in the probability of failure with age may exist.

For equipment which contains only one weak link, the aging-seismic correlation is simply related to the increase in the probability of failure with the age of the weak link (see Figure 2-4). In equipment having many weak links, the probability of the equipment failing is related in a more complex way to the failure probabilities of these components.

A basic assumption of the methodology suggested in this paper is that the only failure mode for which an aging-seismic correlation exists is the mechanical failure of the weak link component. This excludes, for example, the movement of dust or dirt resulting in a poor electrical contact or a small electrical component (e.g., relay, circuit breaker) being damaged by a falling object.

Before a methodical analysis for the presence of aging-seismic correlation is conducted, a preliminary screening can be performed (see Figure 2-1). For equipment for which an aging-seismic correlation is found, the following additional analyses are performed to further assess the correlation:

- Weak Link Analysis (WLA) of the equipment to identify those components made from materials in which significant age related degradation may occur.
- Failure Modes and Effects Analysis (FMEA) to define the failure mode in the equipment. Only those failure modes which have age degradable material will be of interest.
- Probabilistic Failure Analysis (PFA) of the components and system based on the ultimate strength of the

component and the total stress (from normal operation plus seismic loading) on the component.

The methodology proposed in this paper for screening and assessing the aging-seismic correlation in electrical equipment was carried out in a preliminary fashion for batteries and motors using engineering approximations when data was not available. These examples showed that the aging-seismic correlation is related to:

- Number of age-degradable weak link components.
- Rate of degradation in weak link components.
- Seismic stresses on weak link components.
- Failure strength of weak link components.

The probabilistic approach to evaluating the effects of aging and seismic stresses on the operability of safety related equipment is considered more realistic than the presently used deterministic approach. Another advantage in using the probabilistic method is that the results can be used in determining the effects of aging on the probability of the system being able to perform its safety functions; an item which should be considered when completing a Probabilistic Risk Analysis.

1.0 INTRODUCTION

The question of the effects of aging on the seismic capacity of safety related electrical equipment has been the subject of two experimentally oriented programs sponsored by Westinghouse (1-1)* and EPRI (1-2). These programs have been initiated to test large numbers of electrical components (by aging and seismically testing them) to reveal any age-related seismic correlation. In these studies, analytical techniques were used to screen the components for potential aging-seismic correlation or to predict potential correlation.

In the Westinghouse component aging program, 300 electrical and electronic components representative of those found in a mild environment have been scheduled to be artificially aged for five, ten and 20 years and then seismically tested as part of a qualification program. It is hoped that the components, such as transistors, relays and silicon controlled rectifiers, will be qualified for a 20 year life. Of the 100 components which have already been aged for five years and tested, no failures have occurred.

The EPRI sponsored age-sensitivity program being conducted by Wyle Laboratories addresses the question of aging-seismic correlation in a generic way. Approximately 2000 items (resistors, diodes, integrated circuits, transistors, optical couplers, capacitors, and terminal blocks as well as their interfacing hardware) were divided into sample groups of 20 to 228 items, each group consisting of one component type. Further division of each group into unaged, thermally aged, cycle aged, and thermally/cycle aged categories were performed. All the components were subsequently subjected to six increasingly severe seismic spectra on a biaxial shake table. From the preliminary test results, it has been concluded that no difference exists in the seismic performance of the aged and unaged groups of components.

Both the Westinghouse and EPRI sponsored equipment qualification programs are focused on relatively small components and do not examine larger equipment such as motor operated valves, batteries, or pump motors. These programs do not consider part interfaces such as lead wires and structural supports which are not present

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* Underlined numbers are the references listed in Section 5.

during component tests. Other uncertainties not included are operational environmental stresses (e.g., temperature, vibration, humidity) which may exist in the equipment housing but are not considered in the Westinghouse of EPRI programs.

In both of these programs, no attempt has been made to analyze the potential aging-seismic correlation in generic equipment types. The purpose of this screening would be to eliminate the equipment items which can be shown by analysis not to have an aging-seismic correlation.

It is the purpose of this work to examine utilizing an analytical approach for the effect of aging on the seismic capacity of electrical equipment. The fundamental basis of this approach is that equipment will fail when a weak link mechanically fails, and the probability of the weak link failing can be calculated by using a probability function (e.g., a normal probability distribution function) of the stress applied to it and its breaking strength. This concept can be easily understood if the failure frequency of simple tensile specimens is assumed to have a shape (on a plot of tensile stress vs. frequency of failure) similar to that of a normal probability distribution. If the tensile specimens were made from an age-degradable material such as a rubber or plastic, it would be expected that as the strength of the material decreases, the specimens would fail at lower stresses which would move the mean of the distribution to the lower stresses. If this material was a critical component in a piece of equipment such that its failure would result in the equipment failing, then the probability of the equipment failing would also increase as the material ages if the stresses on the material remain unchanged. If many weak links were identified in the equipment, then the probability of the equipment failing is related in a more complex way to the failure probabilities of all the weak links. This methodology is discussed in more detail later in this report.

It is important to understand that a basic assumption in the methodology presented in this report is that the only failure mode for which an aging-seismic correlation exists is the mechanical failure of the weak link component. This excludes, for example, the movement of dust or dirt resulting in a poor electrical contact or a small electrical component (e.g., relay, circuit breaker, switch) being damaged by a falling object. In a nuclear generating station where the highest standards of cleanliness and preventive maintenance are maintained, and where so much attention is given to seismic design and engineering in the plant, it is felt that this assumption is valid.

The first step in the study reported here is the development of a preliminary set of criteria for screening electrical equipment for potential aging-seismic correlation. These criteria are concerned with three different aging mechanisms (environmental, wear, and cyclic). They determine if any components in the equipment degrade by aging and cause a loss in the ability of the equipment to perform its safety-related function. For example, if operational or cyclic loads on weak link components in the equipment from vibration or shock exceed those loads predicted from a seismic test, then premature failure (failure before the seismic event) would probably occur and the aging-seismic correlation would not be expected to be strong. Another consideration is if the seismically-induced failure of a component which is not critical to the equipment operability affects the load path in the equipment resulting in a significant loading on a critical component with the possibility of its failure. Seismically induced loads may also cause equipment failure by reconfiguring the equipment by activating switches, disabling the trip latch or deforming a structural member (e.g., valve stem, or yoke). Reconfiguration may be initiated by degradation of the structural integrity of a supporting member. This is another consideration in screening equipment for aging-seismic correlation.

Following a discussion on the criteria for screening the equipment for potential aging-seismic correlation, Weak Link Analysis (WLA) and Failure Modes and Effects Analysis (FMEA) are considered.

These analyses are performed to evaluate the sensitivity of seismic capacity to aging. The WLA is conducted to identify weak link materials which can degrade with age and are critical for the equipment to carry out its safety-related function. A FMEA is performed on each equipment item to identify the aging mechanism in the weak links, the failure mechanism, failure mode, and an assessment of whether or not there is age sensitivity in the seismic capacity of the equipment.

The Probabilistic Failure Analysis (PFA) methodology is presented in Section 2.4. PFA is used as a tool for determining the cumulative failure probability of equipment when given a known weak link part, the applied seismic loads on the weak link components, the weak link material breaking strengths, the uncertainty (standard deviation) in the breaking strengths and an assumed failure probability distribution (such as the Gaussian distribution), for the weak link.

A simple example of the failure probability concept can be illustrated by considering one weak link component in a piece of equipment. For example a battery case cover made from polycarbonate and having an ultimate breaking strength of 12,000 psi may be loaded to 12,000 psi. If this component fails, failure of the battery would be expected to occur. If the load on the battery case cover is 12,000 psi, then the cumulative probability of failure (probability of failing at that load assuming a Gaussian failure probability distribution) is 50%. To determine the cumulative probability of failure of the battery, the failure probabilities of all the critical components, including the cover, must be determined. An assumption is then made that in a series system of failure modes, battery failure will occur if any one component fails.

The PFA concept assumes that in any piece of equipment there are parts which, if they fail, will cause the equipment to fail. It is further assumed that there is a probability of this part failing when it is subjected to a load. The failure probability can be determined from considering the area under a failure frequency vs. stress curve (which in this report is assumed to be a normal probability curve). The mean of the distribution defined by the curve is the breaking strength and the standard deviation is assumed to be 20 per cent of the breaking strength. If the part is made from an age-degradable material, then the breaking strength (or mean) will likely decrease (or shift to the left) so that the probability of its failing under the same load it had before it degraded is increased. If the equipment is simple (e.g., terminal block) and has only one weak link, then the probability of equipment failure is the probability of the failure of that weak link. However, if there is more than one weak link then the probability of the equipment failing is a more complex function of the number of weak links and the failure probabilities of each one.

In Section 3.0 of this report, use of the PFA on selected equipment using experimentally obtained and assumed values for applied seismic loads, breaking strength uncertainties, and rate of aging is demonstrated. Conclusions should not be drawn from the failure probabilities calculated here for equipment. These calculations should be used only to better understand the relationships of the variables to the seismic capacity as screening tools and for relative comparisons. For example, it becomes clear rather quickly that the larger the number of age degradable weak link components in the equipment and the more rapid their rate of degradation, the more sensitive the seismic capacity is to age.

The last section in this report is a summary which discusses the results and highlights areas where further work is recommended.

2.0 GENERAL METHODOLOGY FOR EVALUATING SEISMIC AGING CORRELATION

To methodically evaluate the aging-seismic correlation in equipment, several sequential analyses are performed. These include:

- Preliminary Screening Evaluation to eliminate equipment in which no aging-seismic correlation would be expected.
- Weak Link Analysis (WLA) of equipment to identify those components made from material in which significant age-related degradation may occur.
- Failure Modes and Effects Analysis (FMEA) to define the failure modes in the equipment. Only those failure modes which have age degradable material will be of interest.
- Probabilistic Failure Analysis (PFA) of the components and the system based on the ultimate strength of the component and the total stress (from normal operation plus seismic loading) on the component.

The Preliminary Screening Evaluation is performed to make an initial assessment of potential aging-seismic correlation in equipment by evaluating certain critical conditions that are necessary for aging seismic correlation to occur. These include whether or not there are age-degradable components in the equipment and whether the normal operating stresses exceed the seismic stresses.

After the preliminary screening, a Weak Link Analysis and Failure Modes and Effects Analysis are performed on the screened equipment to identify failure modes through components which may be subject to age-related degradation. It is only these failure modes which are of interest in evaluating aging-seismic correlation.

The last phase of the evaluation is to establish a common basis (e.g., probability) for comparing the effects of aging on the seismic capacity of the equipment. This is done by determining the probability of the equipment failing under specified seismic loads and considering the effects of aging. The Probabilistic Failure Analysis is performed by comparing the calculated stresses on the weak link components with the ultimate failure criteria (e.g. breaking strengths, and yield strengths) to calculate the probabilities of failure. The effects of aging on the material property, used for the failure criteria are obtained from test data such as accelerated aging tests and radiation exposure tests.

PFA applicability may be extended by differentiating it with respect to time to obtain the sensitivity of the failure probability with equipment age. An approximation to this is to determine the failure probabilities at two or more temperatures or times which are representative of those values the equipment weak links may be exposed to. The slope of the curve is the sensitivity of the failure probability of the equipment to these parameters. The approximation is easier to perform and adequate for most applications and may be useful for indicating trends and "precipitous" tendencies.

2.1 Criteria for Screening Equipment with Aging-Seismic Correlation

A methodical way of determining the effect of aging on the seismic capacity of equipment is shown in Figure 2-1. The decision tree in Figure 2-1 shows the responses to a series of questions on the potential aging-seismic correlation in the equipment. The first question concerning the equipment is whether or not there are age-degradable components which are critical to the operation of the equipment. If the answer is yes, than the type of aging (wear aging, environmental aging, and cyclic aging) must be considered. Knowing the type of aging is necessary to evaluate the possible correlation of the age of the equipment with its seismic capacity. For example, in a motor that drives a pump, the vibration of the motor might exceed the load it experiences during a seismic test so that little to no aging-seismic correlation would be expected. Parts that are made from materials which can thermally degrade (environmental aging), may not age significantly if the time-temperature conditions they are exposed to are not higher than what they were designed for.

To demonstrate how the decision analysis tree may be used, a battery will be evaluated.

ARE THERE CRITICAL COMPONENTS THAT
CAN DEGRADE BY AGING?

Yes! They are the polycarbonate case and cover, positive and negative plates, microporous separators, electrolyte and vent caps. The polycarbonate parts may thermally degrade with time and become embrittled.

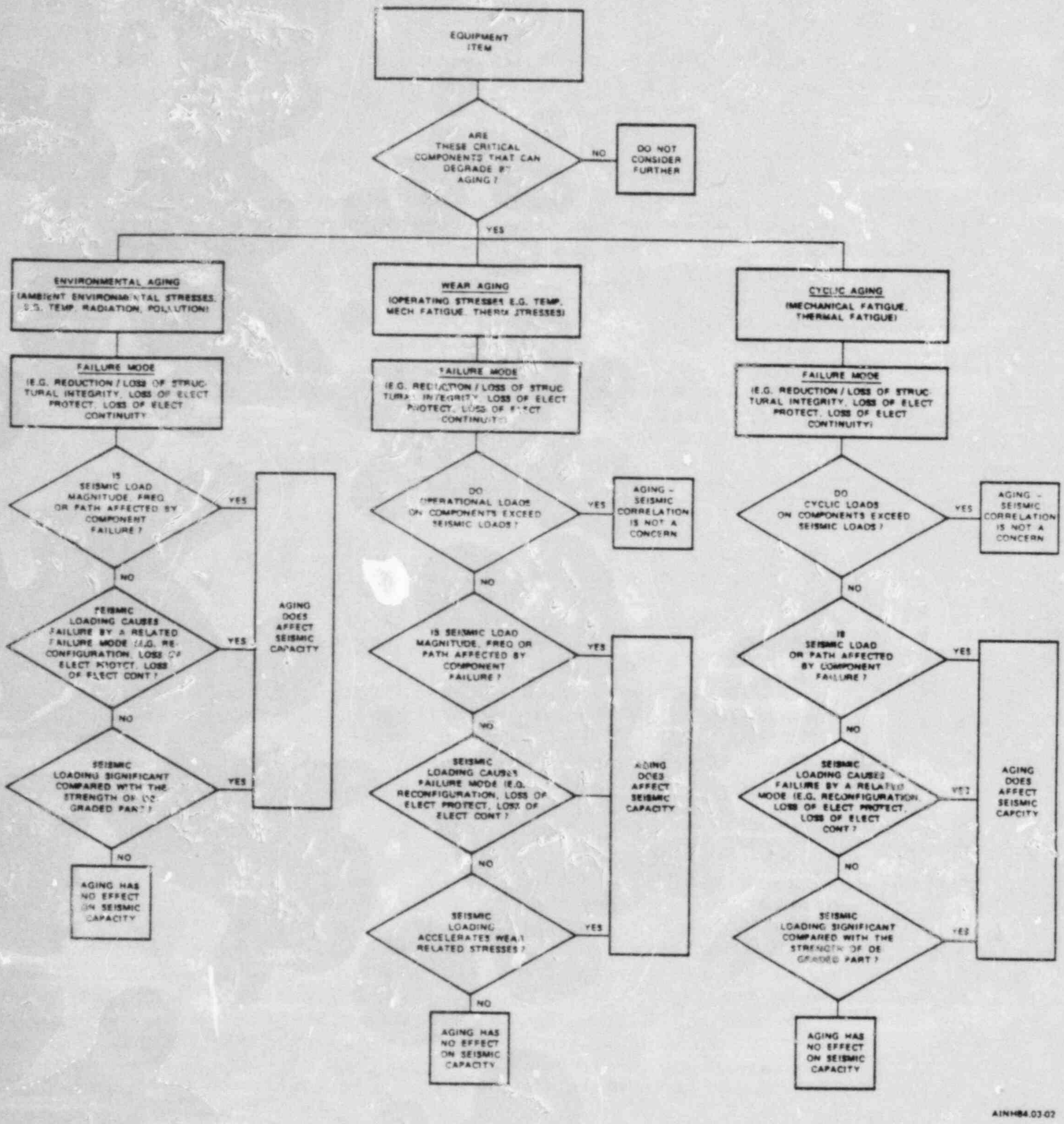

Figure 2-1. Preliminary criteria for screening equipment that may require aging before seismic testing

The positive and negative plates are composed of two components: a cast lead grid and the active material (PbO_2 for the positive plate and Pb for the negative plate). The plates may degrade in several ways. Corrosion of the lead alloy (lead-calcium or lead-antimony) grid of the positive plate can result in its swelling, becoming stressed until cracking occurs and separation of the active material from the grid results so that the plate can no longer store and discharge electricity.

Upon the discharge reaction, Pb (on the negative plate) and PbO_2 (on the positive plate) react with the sulphuric acid in the electrolyte to form $PbSO_4$. The $PbSO_4$ crystals can fill the pores between the grains of active material on the positive and negative plates so that the surface of the active material exposed to the electrolyte is reduced. This may reduce the capacity of the plates below the acceptable level (approximately 80% of the rated capacity per IEEE 535-1979) (2-1).

Another way aging of the plates can occur is by "poisoning" of the negative plates from the absorption of antimony (Sb) metal on the active surface. The deposited antimony acts as a catalyst for the formation of $PbSO_4$ and H_2 from the lead. The H_2 is evolved more easily from the Sb metal surface than the Pb surface. The Sb is released into the electrolyte from the grid (which supports the active material) as grid corrosion proceeds. The Sb can be transported in the electrolyte to the active material as the species $Sb(SO_4)_2^-$, $SBOSO_4^-$ and $Sb_3O_9^{-3}$ (2-2). Low Sb concentrations relative to those which are found in the positive plate active material can significantly decrease the voltages achieved by the negative plate.

Battery failure may occur through loss of the active material on the positive plates. The active material is often a porous, granular cohesive mass which is fixed to the lead alloy grid. When the battery is charged, the Pb in the active material is oxidized to PbO_2 which has a density of 9.3g/cc*. Upon discharge, this reacts with the H_2SO_4 in the electrolyte to form $PbSO_4$ with a density of 6.3g/cc which has a 48% larger specific volume (cc/g) than the parent material which deposits on

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* The new positive plate has β-PbO_2 (ρ = 9.3 g/cc) as the active material. With age, the relative amount of PbO_2 (ρ = 9.9 g/cc) increases.

the plate. The large change in specific volume of the active material upon cycling, weakens the material so that a shock administered to the battery could cause the material to fall out of the grid.

FOR ENVIRONMENTAL AGING OF THE BATTERY WHAT ARE THE FAILURE MODES?

The failure modes in a battery that can occur from aging are (<u>2-3</u>, <u>2-4</u>):

- Destruction of the positive grid from corrosion causing it to thin, leading to its structural weakening and increasing in electrical resistance. The weakened grids may eventually crack and cause the capacity of the battery to drop below its rated value.
- Cracking of the battery case and/or cover from the stresses created inside the battery from the swelling of the positive grids leading to loss of electrolyte and/or a fire.
- Sludging (loss of weight) of the active positive material by the shedding of $PbSO_4$ which is formed from the PbO_2 active material. Loss of the active material can reduce the capacity of the battery below its rated value.
- Sulfation and leading of the negative plate in which a hard layer of $PbSO_4$ and/or Pb forms on the surface of the negative plate and reduces the surface area of the active material. Reduction in surface area can reduce the capacity of the battery below its rated value.
- Breach of separator may lead to the growth of dendrites between the plates causing a short circuit and reducing the capacity of the battery below its rated value.

The failure modes discussed above are not only the result of environmental aging but of a combination of environmental aging and cyclic aging (e.g., charge-discharge cycle).

IS SEISMIC LOAD MAGNITUDE, FREQUENCY OR PATH AFFECTED BY COMPONENT FAILURE?

Yes! For example, the assumption made in analyzing the seismic loading stresses on the battery is that the lead plates are supported on the cell floor and the battery is rigid (i.e., no resonant frequencies occur at, or below 33 Hz).

If failure of the lead plates or of the support system occurs so that a major portion of the load exerted by the plates becomes supported by the cell cover and cell walls, it is expected that the assumption of rigidity may not be valid because of plate oscillation. If the battery is not rigid, than resonances could occur which may amplify the stress on supporting components.

DOES SEISMIC LOADING CAUSE FAILURE BY A RELATED FAILURE MODE (E.G. RECONFIGURATION, LOSS OF ELECTRICAL PROTECTION, LOSS OF ELECTRICAL CONTINUITY)?

Seismic loading of the battery may cause battery failure by inducing failure in a component that has been degraded by aging. For example, thermally aging a battery may cause degradation in the battery case which reduces the breaking strength. Seismically loading the battery case with an applied stress may cause the case to fail by cracking. The seismic failure of the battery case is related to its thermal aging. The failure modes for a battery which can be initiated by seismic testing and are influenced by aging are provided below:

- Cracking of battery case and/or cover leading to loss of electrolyte and failure of the battery to take a charge or discharge.
- Breakage of plates resulting in a reduction of capacity below the rated value.
- Loss of active material from the positive plate resulting in a reduction of capacity below the rated value.
- Deposition of "moss" (a material containing PbO_2, $PbSO_4$, Pb) on the bottom of the cell which accumulates to a high enough level to electrically short circuit the plates.
- Tearing of the rubber separators from the relative motion of the broken plates with respect to each other.

IS THE SEISMIC LOADING SIGNIFICANT COMPARED WITH THE STRENGTH OF THE DEGRADED COMPONENT?

The answer to this question depends on several factors. As the number of weak link parts increase and the seismic stresses on each part increase, the probability of equipment failure also increases. For equipment with a large number of weak link components, the failure probability can be high even though the loads on the components are low and the individual failure probabilities are small. For example, if there are six weak link components each having a probability of failure of 0.2, then the probability of any one of these components failing resulting in failure of the equipment is 0.74.

2.2 Weak Link Analysis

A WLA is performed to identify those components which will have significant degradation during the working life of the part and which may lead to equipment failure. This analysis entails the use of engineering drawings, materials lists, manufacturer's catalogs and any other references which may describe the materials of fabrication or design. The amount of significant degradation which may occur can be estimated by extrapolating accelerated test data to the environmental stresses representative of those on the part.

Age related degradation may occur through the embrittlement or softening of polymeric materials, corrosion of metals, fatigue of metals and plastics, erosion and the embrittlement of metals (e.g., by recrystallization). The amount of aging that occurs in these materials is related to many parameters including temperature, atmosphere, material property [e.g., grain size for metal recrystallization and composition for polymeric degradation]). An extensive review of the effects of radiation on organic materials is given in References 2-5 and 2-6.

For example, when temperature is the primary stress that influences aging (e.g., in the degradation of polymers), the accelerated aging data for the material of interest which is ordinarily obtained at high temperatures, above the normal operating range, may be extrapolated to the temperatures of interest on a ln (time to failure) vs. 1/T(°K) plot to linearize the data as shown in Figure 2-2. In Figure 2-2, a_T is the acceleration shift factor which is the reciprocal of the time to reach a given failure criterion. The effect of using a_T in place of time is to change the sign of the slope of the curve unless the direction in which the temperature increases on the X axis is also reversed. The slope of the line $(-E_{Act}/k)$ determines the acceleration factor which is used to determine the accelerated test temperature and time necessary to achieve the equivalent degradation over the life of the equipment under plant ambient temperatures. In the expression for the slope given above, E_{Act} is the activation energy for the degradation process in electron volts per atom and k is Boltzmann's Constant (0.8617 X 10^{-4}eV/°K-atom). The activation energy is related to the degradation rate and can be used to identify those components which would be expected to degrade and fail most rapidly.

Some degradation processes are not thermally activated and therefore are not strongly related to temperature. These include fatigue and erosion. By comparing the number of cycles a part is expected to experience with the fatigue life (number of cycles corresponding to mean failure time) of the material, the life remaining can be estimated and used to predict which parts will fail by fatigue most rapidly. The rate of loss of material by erosion, over its expected life, can be used to estimate if the structural integrity of a part may be threatened.

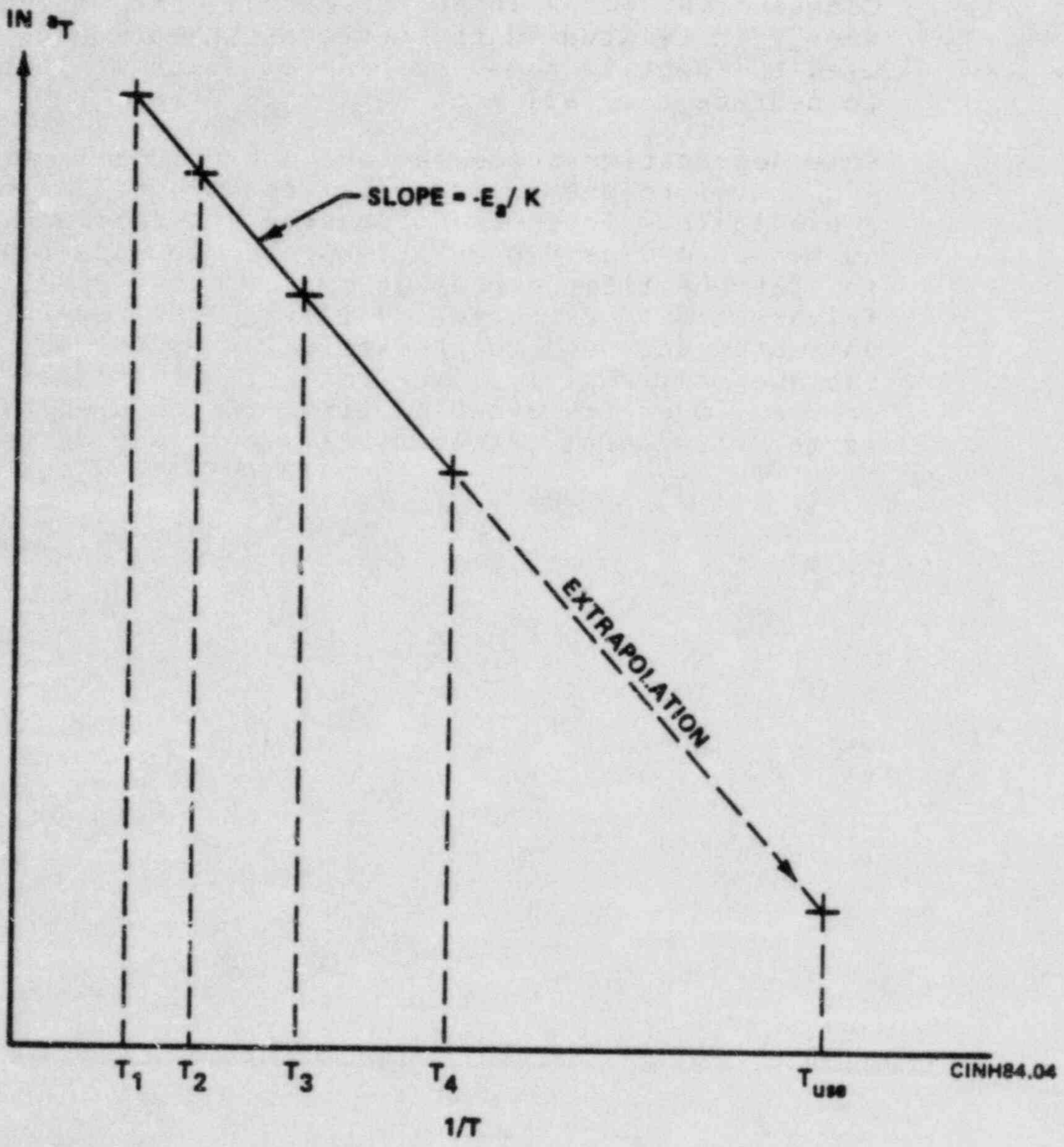


Figure 2-2. Arrhenius plot of ln of the thermal shift factor, a_T, vs. inverse temperature ($°K^{-1}$) for 4 temperatures, T_1, T_2, T_3, and T_4. The resulting straight line behavior is extrapolated to the temperature of interest, T_{use} (2-7).

2.3 Failure Modes and Effects Analysis

An abbreviated discussion of the purposes and procedures for carrying out a Failure Modes and Effects Analysis is given in paragraph 4 of IEEE 352-1975 (2-8). Many of the elements of this discussion can be applied to evaluating potential aging-seismic correlation. In this report, the FMEA is used to:

(a) identify age-degradable materials that are critical to the safety-related function of the equipment. Not all parts that are made from materials having significant age-related degradation are functionally necessary.

(b) determine the failure modes caused by mechanical failure of weak link parts.

The FMEA is used to systematically determine whether the age-degradable materials identified in the WLA are weak links - that the failure of the degradable materials will cause the equipment to fail. In performing an FMEA the question which must be repeatedly asked throughout the analysis is "could that failure occur?" and not "will it occur?" The probability of occurrence is not the concern in this analysis and the least likely and most likely failure modes are not distinguished.

To conduct a thorough FMEA, the analyst should have some first hand experience with the operation of the part or seek the experience of others. This is necessary because it is nearly impossible to anticipate all the failure modes which may occur in a piece of equipment from only the inspection of drawings, schematics, manufacturer's literature and pictures.

An alternative to performing a FMEA is to physically test the equipment by stressing it to failure and diagnosing the failure mode. For example, the equipment could be thermally aged, vibrated, or cycled until it failed to function and selected parameters could be monitored during the test.

The advantages of testing are:

- Test results can show failure modes not previously considered.
- Test results may identify the more probable or dominant failure modes.

- Test data and post failure inspection of the equipment can provide a more accurate picture of the failure mechanism than possible by analysis alone.

The disadvantage of testing is that it is nearly impossible to test equipment for all possible failure modes within reasonable cost and time constraints. However, it is felt that some testing to failure be performed or the failure data for equipment be evaluated, if it is desired to take the FMEA out of the purely speculative realm.

In this report a FMEA was performed on 18 safety-related, generic, electrical equipment items; the resultant data is presented in Table 2-1. The items are representative of those evaluated by a utility in an equipment qualification program. The failure modes considered were only those involving age-degradable materials.

Table 2-1

FAILURE MODES AND EFFECTS ANALYSIS FOR ELECTRICAL EQUIPMENT

EQUIPMENT	AGE DEGRADABLE COMPONENT	AGING MECHANISM	FAILURE MECHANISM	FAILURE MODE	SEISMIC-AGING CORRELATION
Batteries	Polycarbonate Container	o Thermal degradation causing embrittlement of container	o Cracking of container leading to loss of electrolyte	o Failure of battery to discharge or take a charge	o Crack growth promoted by seismic testing
	Lead (-)/ Lead Oxide (+) Plates	o Shrinking & loss of integrity of PbO_2 in + plate	o Shrinking of PbO_2 away from grid causing electrical isolation of active material or o Loss of PbO_2	o Cell fails to discharge or take a charge or o Reduction in capacity of cell o Increase in internal resistance leading to increased heating & evaporation of electrolyte	o Loss of PbO_2 in + plate and accumulation of $PbSO_4$, Pb, PbO_2 on bottom of cell promoted by seismic testing
		o "Swelling" of + plates from corrosion	o Expansion of + plates stresses polycarbonate case to failure	o Loss of electrolyte causes failure of battery to discharge or take a charge	o Crack growth in battery cover is promoted by seismic testing
	Microporous Separators	o Cracking/separation of material	o Build-up of material to bridge + & - plates	o Electrical shorting of plates causing cell failure	o Crack growth in separators promoted by seismic testing
	Molded Plastics Cell Cover	o Thermal degradation causing embrittlement of plastic container	o Collapse of cover resulting in plates contacting each other	o Electrical shorting of plates causing cell failure	o Crack growth in cell cover promoted by sesimic testing
	Electrolyte (Water, sulfuric acid)	o Evaporation of water	o Loss of electrolyte	o Failure of electrochemical reactions to occur causing failure of cell to discharge or take a charge	o No seismic-aging correlation
	Lead Posts	o Corrosion of material between lead post and terminal clamps	o Build-up of lead sulfate layer at post-clamp interface creating a high resistance path	o Failure of cell to discharge or take a charge	o No seismic-aging correlation
	Vent Caps (Plugs)	o Thermal degradation causing embrittlement	o Blockage of vent holes	o Build-up of H_2 pressure causes battery case to burst	o Seismic loads applied to battery case under stress may accelerate failure of case
		o Build-up of dirt in vent holes	o Blockage of vent holes	o Build-up of H_2 pressure causes battery case to burst	o Seismic loads applied to battery case under stress may accelerate failure of case

Table 2-1 (Continued)

FAILURE MODES AND EFFECTS ANALYSIS FOR ELECTRICAL EQUIPMENT

EQUIPMENT	AGE DEGRADABLE COMPONENT	AGING MECHANISM	FAILURE MECHANISM	FAILURE MODE	SEISMIC-AGING CORRELATION
Battery Charger	Circuit Breakers and Switches	o See Circuit Breakers	o See Circuit Breakers	o Failure in closed position may cause failure of critical component from line surge	o Seismic-aging correlation for some failure mechanisms
				o Failure in open position may cause loss of power	o Seismic-aging correlation for some failure mechanisms
	Electromechanical Relays	o See Protective Relays	o See Protective Relays	o Failure of ac power failure alarm in normal (closed) position may cause loss of circuit protection	o Chattering may be correlated with age of relay
	Magnetic Components	o See Transformer	o See Transformer	o Failure of battery charger to deliver charge	o Seismic loading may accelerate failure of leads and terminal contacts
	Wire and Cables	o See Cables	o See Cables	o Failure of charger to receive ac power or deliver dc power	o Seismic response of cable trays may cause bending and/or tensile stresses to occur in insulation causing cracks
	Terminal Blocks	o See Terminal Block	o See Terminal Block	o Will not result in charger failure	o No seismic-aging correlation
	Connections (solder and compression types)	o Fatigue of wire at terminal connection	o Failure of terminal wire connection will create open circuit	o Failure of charger to receive ac power or deliver dc power	o No seismic-aging correlation
	dc electrolytic capacitors	o Evaporation of electrolyte from heat generated by internal stresses (ripple currents, current pulses, over voltages, surge voltages) & high ambient temperature	o Loss of electrolyte causes failure of capacitor to store charge o Failure of lead at bond.	o Failure of capacitor may cause failure of charger to operate at its stated values	o Failure of lead to capacitor during seismic testing may be correlated with aging
	ac oil filled capacitors	o Thermal degradation of oil causing loss of dielectric strength and formation of gasses	o Dielectric breakdown of of oil dielectric o Failure of lead at bond.	o Failure can cause damage to solid state components (e.g., rectifiers) if a line transient occurs	o Failure of lead to capacitor during seismic testing may be correlated with aging.

Table 2-1 (Continued)

FAILURE MODES AND EFFECTS ANALYSIS FOR ELECTRICAL EQUIPMENT

EQUIPMENT	AGE DEGRADABLE COMPONENT	AGING MECHANISM	FAILURE MECHANISM	FAILURE MODE	SEISMIC-AGING CORRELATION
	Circuit board assemblies	o Corrosion of terminals and/or printed circuits	o Corrosion of thin metallic layer causes open circuit	o Failure of circuit board assys. can cause loss of control and protection functions of charger or failure of charger	o Seismic loading may promote the failure of terminal connections or printed circuits in severly corroded areas
		o Non uniform temperature distibution creates thermal stresses	o Warping and buckling leading to cracked circuit lines	o Failure of circuit board assys. can cause loss of control and protection functions of charger or failure of charger	o Seismic shock and vibration may accelerate cracking in terminal board
		o Silver migration by thermal diffusion	o Shorting of circuit lines	o Failure could result in failure of power & control semiconductors and SCRs causing failure of charger	o No seismic-aging correlation
	Organic Insulating Materials	o Thermal degradation causing embrittlement	o Cracking of insulation causes failure of electrical protection	o Loss of electrical protection may cause failure of charger to deliver charge	o Seismic loading may cause cracking in embrittled electrical insulation
	Surge Suppressors		o Short circuiting leading to melting of terminals and an open circuit	Failure could result in failure of power & control semiconductors and SCR's causing failure of charger	o No seismic-aging correlation
Transformers	Varnish on core assembly	o Thermal degradation causing embrittlement	o Cracking of insulation leading to low resistance leakage paths or dielectric failure	o Cracking may cause electrical shorting between turns or open circuit causing transformers not to function properly	o No seismic-aging correlation. Normal vibration from electromagnetic forces during operation may make significant contribution to mechanical fatigue above seismic testing
	Insulating Bobbin	o Thermal degradation causing embrittlement	o Cracking of insulation leading to low resistance leakage paths or dielectric failure	o Cracking may cause electrical shorting between turns or open circuit causing transformers not to function properly	o No seismic-aging correlation. Normal vibration from electromagnetic forces during operation may make significant contribution to mechanical fatigue above seismic testing

Table 2-1 (Continued)

FAILURE MODES AND EFFECTS ANALYSIS FOR ELECTRICAL EQUIPMENT

EQUIPMENT	AGE DEGRADABLE COMPONENT	AGING MECHANISM	FAILURE MECHANISM	FAILURE MODE	SEISMIC-AGING CORRELATION
	Interturn Insulation	o Thermal degradation causing embrittlement	o Cracking of insulation leading to low resistance leakage paths or dielectric failure	o Cracking may cause electrical shorting between turns or open circuits causing transformers not to function properly	o No seismic-aging correlation. Normal vibration from electromagnetic forces during operation may make significant contribution to mechanical fatigue above seismic testing
	Interlayer Insulation	o Thermal degradation causing embrittlement	o Cracking of insulation leading to low resistance leakage paths or dielectric failure	o Cracking may cause electrical shorting between turns or open circuit causing transformers not to function properly	o No seismic-aging correlation. Normal vibration from electromagnetic forces during operation may make significant contribution to mechanical fatigue above seismic testing
	Body Insulation	o Thermal degradation causing embrittlement	o Cracking of insulation leading to low resistance leakage paths or dielectric failure	o Cracking may cause leakage from primary or secondary windings causing transformer not to function properly or operate	o No seismic-aging correlation. Normal vibration from electromagnetic forces during operation may make significant contribution to mechanical fatigue above seismic testing
	Terminal Leads	o Thermal degradation causing embrittlement	o Cracking of insulation leading to low resistance leakage paths or dielectric failure	o Shorting of lead wire causes failure of transformer not to function properly or operate	o No seismic-aging correlation. Normal vibration from electromagnetic forces during operation may make significant contribution to mechanical fatigue above seismic testing
			o Embrittlement of lead wire insulation may promote its being pulled away from the terminal, exposing the conductor,resulting in a short	o Shorting of lead wire causes failure of transformer not to function properly or operate.	o Seismic vibration and shock may accelerate the failure of terminal leads & contacts
		o Vibration of contact terminals	o Contact terminals loosen from vibration, eliminating the gas-tight seal. Corrosion of conductor & terminals occurs	o Loss of electrical continuity causes failure of transformer to operate	o Seismic vibration and shock may accelerate the failure of terminal leads & contacts

Table 2-1 (Continued)

FAILURE MODES AND EFFECTS ANALYSIS FOR ELECTRICAL EQUIPMENT

EQUIPMENT	AGE DEGRADABLE COMPONENT	AGING MECHANISM	FAILURE MECHANISM	FAILURE MODE	SEISMIC-AGING CORRELATION
		o Vibration of contact terminals causing bending fatigue of wire leads	o Bending fatigue of wire leads to fatigue limit (failure)	o Loss of electrical continuity of leads causing failure of transformer to operate	o Seismic vibration and shock may accelerate the failure of terminal leads & contacts
Cables	Insulation	o Thermal degradation causing embrittlement	o Cracking of insulation leading to low resistance leakage paths, dielectric failure, short circuit, cross-talk, noise or galvanic currents	o Failure of cable to transmit power or signal	o Seismic response of cable tray may cause bending and/or tensile stresses to occur in insulation causing cracks in insulation
	Terminals	o Corrosion [illegible] metal terminals	o Build-up of non-conductive corrosive product destroys electrical continuity	o Failure of power or signal to reach load	o No Seismic-aging correlation
		o Loosening of terminals from thermal cycling	o Separation of leads from terminals	o Failure of power or signal to reach load	o Seismic vibration and shock may accelerate the separation of leads from terminals
Penetrations	Cast Epoxy Seal	o Thermal degradation of polymeric resin causing loss of structural integrity	o Seal looses structural integrity and does not electrically insulate embedded leads and cables	o Shorting or excessive leakage of embedded leads and cables	o Seismic loading of epoxy may accelerate loss of structural integrity
	Elastomer Seals (O-rings, gaskets)	o Thermal degradation causing embrittlement	o Seal looses structrual integrity and fails as a pressure boundary	o Failure of penetration to isolate containment atmosphere from environment	o No seismic-aging correlation
Switches (pressure, level, limit, etc.)	Elastomeric seals (O-rings, gaskets)	o Thermal degradation causing embrittlement	o Cracking of polymer causes failure of seal against the environment	o Corrosion of terminals causes failure in normal (open/closed) position	o No seismic-aging correlation
				o Corrosion of contacts causes failure in normal (open/closed) position	o No seismic-aging correlation
	Polymeric Covers	o Thermal degradation causing embrittlement	o Cracking of polymer causes failure of seal against environment and loss of electrical protection.	o Corrosion of terminals and/or contacts causes failure in normal (open/closed) position	o No seismic-aging correlation

Table 2-1 (Continued)

FAILURE MODES AND EFFECTS ANALYSIS FOR ELECTRICAL EQUIPMENT

EQUIPMENT	AGE DEGRADABLE COMPONENT	AGING MECHANISM	FAILURE MECHANISM	FAILURE MODE	SEISMIC-AGING CORRELATION
Switches (pressure, level, limit, etc.) (cont'd)	Contacts	o Oxidation/pitting of surface	o Corrosion layer and pitting cause loss of electrical continuity or welding of contacts	o Failure of contacts in open or closed (welded) position	o No seismic-aging correlation
	Lead Wire	o Thermal degradation of insulation causing embrittlement	o Cracking of insulation	o Shorting of lead wire causes failure of switch to respond to demand	o Seismic loading may create bending and tensile stresses that can accelerate cracking and insulation material loss
	Circuit Boards	o See "Circuit Board Assemblies" for Battery Chargers		o Failure of switch to respond to power or signal in normal (open/closed) position	o Seismic loading may create stresses that accelerate the opening of the terminal and/or circuit
	Coils	o See "Solenoid Operator"	o See "Solenoid Operator"	o See "Solenoid Operator"	o See "Solenoid Operator"
	Polymer Bearings	o Thermal degradation causing embrittlement	o Bearing clearances lost and seizure of bearing or shaft occurs	o Switch fails in normal (open/closed) position	o No seismic-aging correlation
Meter	Coil	o Thermal degradation of insulation causing embrittlement	o Cracking of insulation causing grounding of coil or shorting	o Failure of meter to measure signal	o No seismic-aging correlation
	Pivots	o Deposition of dirt in bearings	o Jamming of needle bearing	o Failure of instrument to respond to changes in signal	o No seismic-aging correlation
	Case Seals/ Window	o Thermal degradation of polymer causing embrittlement	o Cracking of seals/ window exposing metal parts to the environment with subsequent corrosion	o Loss of electrical continuity causing failure to operate or function correctly	o Seismic vibration and shock may accelerate failure of window
	Spring	o Little age related degradation occurs			
Motors (squirrel cage, induction)	Stator winding consisting of slot liner for ground insulation, wire insulation, phase insulation separation, slot cap)	o Thermal degradation causing embrittlement and reduction in strength	o Loss of intergity of insulation by cracking.	o Coil shorting to ground or between phases and stops running.	o Possible seismic aging correlation. Torque and vibration forces during normal cycling and operation will contribute to weakening of insulation.

Table 2-1 (Continued)

FAILURE MODES AND EFFECTS ANALYSIS FOR ELECTRICAL EQUIPMENT

EQUIPMENT	AGE DEGRADABLE COMPONENT	AGING MECHANISM	FAILURE MECHANISM	FAILURE MODE	SEISMIC-AGING CORRELATION
	Stator core lamination insulation	o Shrinkage of lamination from thermal degradation and torsional stress during cycling and motor operation.	o Loosened stator laminations leads to motor failure.	o Loosened lamination becomes jammed and stops motor.	o No seismic aging correlation because of significant torque and vibration during normal and cycling operations.
	Terminal leads	o Thermal degradation of lead insulation.	o Loss of lead protection from cracking or erosion.	o Lead shorting or grounding causes motor not to run.	o Seismic loading may cause cracking or erosion of degraded lead insulation with loss of electrical protection.
	O-rings	o See "Elastomeric Seals" for Switches		o Corrosion of terminals may cause failure to transmit signal	o Seismic vibration and shock may accelerate the failure of degraded parts
	Solder Joints	o See "Bonds & Solder Joints" for Electronic Equipment		o Corrosion of circuit lines may cause failure to operate or function correctly or o Possible failure of equipment to function	o Seismic vibration and shock may accelerate the failure of degraded parts
	Motor (for electronic force-balance system)	o See "Motors"	o See "Motors	o Failure of motor to call for current (which is proportional to measurement pressure) and deliver measurement signal	o Seismic vibration and shock may acclerate the failure of degraded parts
Radiation Monitor	High Voltage Cables	o See "Cables"	o See "Cables"	o Shorting or high electrical leakage in cables may cause failure of monitor to operate or function properly	o Seismic response of cable trays may cause bending and/or tensile stresses to occur in insulation causing cracks in insulation
	Lead Wires	o See "Terminal Leads" for Transformers		o Shorting or high electrical leakage may cause failure of monitor to to operate or function correctly	o Seismic loading may create bending and tensile stresses that can accelerate cracking & insulation material loss

Table 2-1 (Continued)

FAILURE MODES AND EFFECTS ANALYSIS FOR ELECTRICAL EQUIPMENT

EQUIPMENT	AGE DEGRADABLE COMPONENT	AGING MECHANISM	FAILURE MECHANISM	FAILURE MODE	SEISMIC-AGING CORRELATION
	Voltage Transformer	o See "Transformers"	o See "Transformers"	o Electrical failure of insulation may cause failure of transformer to operate or function correctly	o No seismic-aging correlation. Normal vibration from electromagnetic forces during operation may make significant contribution to mechanical fatigue beyond the effects from seismic testing
	Electronic Signal Amplification and Processing Equipment	o See "Electronics Equipment"	o See "Electronics Equipment"	o Failure of transmitter to transmit signal or to function correctly	o Seismic vibration and shock may accelerate failure by dimensional changes in some parts, failure of ceramic-metal and metal-metal bonds and of circuit lines by shorting or open circuits
	Photomultiplier Tube (PMT)	o Thermal and vibration stresses cause position of dynodes to shift	o Misalignment of dynodes changes calibration of tube	o Drift in amplification factor causes counter to operate improperly	o Seismic shock and vibration may accelerate misalignment of foil dynodes
	Gas Filled Tube	o Migration of gas through walls of tube	o Loss of halogen quenching agent or gas pressure	o Drift in amplification factor causes counter to operate improperly	o No seismic-aging correlation
		o Hardening of wire anode from thermal cycling and corrosion	o Failure of wire result-in open circuit	o Failure of detector to operate	o Seismic shock and vibration can accelerate failure of wire anode
	Sodium Iodide or Plastic Detector	o Thermal degradation leading to cracking	o Light pulses fail to be transmitted across cracks	o Failure of radiation to be detected	o Seismic shock and vibration can accelerate cracking of detector
Terminal Blocks	Terminal Block	o Thermal degradation causing embrittlement	o Cracks create areas where dirt & moisture can collect & create high electrical leakage paths	o Electrical leakage between terminals and from terminals to ground may occur	o No seismic-aging correlation
Recorder	Transformer	o See "Transformer"		o Recorder will fail to operate or function correctly	o Seismic vibration and shock may accelerate failure of degraded parts
	Battery	o Replaceable Item			

Table 2-1 (Continued)

FAILURE MODES AND EFFECTS ANALYSIS FOR ELECTRICAL EQUIPMENT

EQUIPMENT	AGE DEGRADABLE COMPONENT	AGING MECHANISM	FAILURE MECHANISM	FAILURE MODE	SEISMIC-AGING CORRELATION
	Electronic Components	o See "Electronic Equipment"		o Recorder will fail to operate or function correctly	o Seismic vibration and shock may accelerate failure of degraded parts
	Motors (for pen and chart)	o See "Motors"		o Recorder will fail to operate	o Seismic vibration and shock may accelerate failure of degraded parts
	Wire Insulation	o See "Terminal Leads" for Transformers		o Recorder will fail to operate or function correctly	o No seismic-aging correlation
	Variable Resistor Pots	o Thermal degradation of interturn insulation causing embrittlement	o Cracking of insulation causes shorting between turns	o Recorder will fail to operate or function correctly	o No seismic-aging correlation
		o Build-up of dirt & moisture on sliding contact & turns	o Sliding contact is electrically isolated from turns	o Recorder will fail to operate or function correctly	o No seismic-aging correlation
	Circuit Boards	See "Circuit Board Assemblies" for Battery Chargers		o Recorder will fail to operate or function correctly	o No seismic-aging correlation
	Standard Cell (in old equipment)	o	o	o Shift in cell output causes recorder to go out of calibration	o No seismic aging-correlation
	Potentiometer (slide wire)	o Thermal degradation of insulation leading to embrittlement	o Cracking in insulation leading to shorting in high circuit leakage paths	o Change in resistance causes instrument to go out of calibration	o Seismic shock and vibration may accelerate cracking in slide wire resistor
Temperature Sensors	Elastomer O-rings, Seals, Gaskets	o See "Elastomeric Seals" for Switches		o Corrosion of terminals causes failure of sensor to operate or function properly	o No seismic-aging correlation
	Polymeric Thermoset Connectors	o Thermal degradation causing embrittlement	o Cracks form in connector where dirt & moisture build-up & from electrical leakage paths	o Electrical leakage can cause failure of sensor to operate or function correctly	o No seismic-aging correlation

Table 2-1 (Continued)

FAILURE MODES AND EFFECTS ANALYSIS FOR ELECTRICAL EQUIPMENT

EQUIPMENT	AGE DEGRADABLE COMPONENT	AGING MECHANISM	FAILURE MECHANISM	FAILURE MODE	SEISMIC-AGING CORRELATION
	Lead Wire Insulation	o See "Terminal Leads" for Transformers		o Shorting or leakage in lead wire may cause failure of sensor to operate or function correctly	o Seismic vibration and shock may create stresses at the terminal connections which create an open circuit and cause failure of sensor to read out the temperature
Protective Relays	Protective Relay Contacts	o See "Contactor Contacts"	o See "Contactor Contacts"	o Failure of relay in open or closed (welded contacts) position	o No seismic-aging correlation
	Protective Relay Coil	o See "Solenoid Operators"	See "Contactor Contacts"	o Failure of relay in normal (open/closed) position	o Chattering during a seismic test may be correlated with aging
	Protective Relay Bearings	o Thermal degradation of polymer causing embrittlement	o Build-up of dirt, moisture or worn material on bearing surfaces which cause failure of latches or contacts to operate	o Failure of relay in normal (open/closed) position	o No seismic-aging correlation
	Protective Relay Transformers	o See "Transformers"	o See "Transformers"	o Failure of relay in normal (open/closed) position	o No seismic-aging correlation
	Coil Impregnation Material and Varnish	o Mass transport of organic vapors to other areas of relay	o Build up of varnish and impregnating material on sliding surface leading to "freezing" of movement	o Failure of relay in normal (open/closed) position	o No seismic-aging correlation
Motor Starters	Contactor Contacts	o Oxidation/Pitting of surface	o Oxidation or pitting causes loss of electrical continuity across closed contacts	o Contactor will fail opened or closed causing motor starter to fail to control motor	o No seismic-aging correlation
		o Mechanical wear of bearings and pivots	o Failure of contactor to clear	o Contactor will fail opened or closed causing motor starter to fail to control motor	o No seismic-aging correlation
	Contactor Operating coil	o See Solenoid Operators	o See Solenoid Operators	o Failure of contactor in open position will prevent power to motor	o Seismic load on operating coil may create bending and other applied stresses on polymeric components which may accelerate cracking and material losses

Table 2-1 (Continued)

FAILURE MODES AND EFFECTS ANALYSIS FOR ELECTRICAL EQUIPMENT

EQUIPMENT	AGE DEGRADABLE COMPONENT	AGING MECHANISM	FAILURE MECHANISM	FAILURE MODE	SEISMIC-AGING CORRELATION
	Contactor Holding Coil (for under-voltage protection)	o See Solenoid Operators	o See Solenoid Operators	o Failure of contactor in closed position when under-voltage surge occurs. Failure to stop motor will occur	o Seismic load on holding coil may create bending and other applied stresses on polymeric components which may accelerate cracking and material losses
	Circuit Breakers (when used)	o See Circuit Breaker	o See Circuit Breaker	o Failure of circuit breaker in normal (closed position)	o No seismic-aging correlation
	Protective Relay	o See Protective Relay	o See Protective Relay	o Failure of circuit breaker transient occurs in line	o Aging may reduce seismic capacity of relays
	Fuses (e.g., silver-sand type) for use with contactor	o Recrystallization and/or corrosion of fuse element	o Failure of fuse element	o Failure of motor stator to provide power to motor	o Seismic load may accelerate failure of fuse element
Solenoid Operators	Coil Insulation	o Thermal degradation of coil insulation causing embrittlement	o Cracking of insulation	o Electrical Discharging of coil or	o Seismic loading can create bending stresses and applied stresses in polymeric components which accelerate cracking and material losses
	Lead Wire	o Thermal degradation of wire insulation causing embrittlement	o Cracking of insulation	o Shorting of lead wire causes failure of coil	
	O-rings, seals, gaskets	o Thermal degradation of polymer causing embrittlement	o Cracking of polymer causes failure of seal against the environment	o Corrosion of electric terminals causes failure of coil	o No seismic-aging correlation expected
	Contacts on torque/limit switches	o Oxidation and material loss from contacts surface	o Corrosion layer and pitting cause loss of electrical continuity or welding of contacts	o Failure of contacts in open or closed (welded) position	o No seismic-aging correlation expected
Electronic Equipment (amplifiers, signal converters, inverters, rectifiers)	Resistors	Little age-related degradation occurs			o No seismic-aging correlation
	Capacitors Ceramic	o Temperature cycling producing dimensional changes	o Electrical failure of dielectric	o Possible failure of equipment	o Seismic vibration and shock may accelerate dimensional changes occuring from degradation

Table 2-1 (Continued)

FAILURE MODES AND EFFECTS ANALYSIS FOR ELECTRICAL EQUIPMENT

EQUIPMENT	AGE DEGRADABLE COMPONENT	AGING MECHANISM	FAILURE MECHANISM	FAILURE MODE	SEISMIC-AGING CORRELATION
		o Corona degradation of dielectric	o Electrical failure of dielectric	o Possible failure of equipment	o Seismic vibration and shock may accelerate dimensional changes occuring from degradation
	Electrolytic	o See "Electrolytic Capacitors" for Battery Chargers			
	Organic	o Thermal degradation of organic dielectric with formation of gases and dimensional changes	o Electric failures of dielectric	o Possible failure of equipment	o Seismic vibration and shock may accelerate dimensionl changes occuring from degradation
	Semiconductor Devices	o Temperature accelerated contact degradation, electromigration and bond fatigue	o Short circuit, open circuit or malfunction	o Possible failure of equipment	o Seismic vibration and shock may accelerate bond failure in degraded bonds
	Encapsulants	o Temperature accelerated diffusion of moisture contaminant through encapsulant	o Reaction of contaminants with metallic parts	o Possible failure of equipment	o Seismic vibration and shock may accelerate the creation of diffusion paths in degraded encaplant
	Printed Circuit Boards	o See "Circuit Board Assemblies" for Battery Chargers		o Possible failure of equipment	o Seismic vibration and shock can accelerate the failure of terminals and/or circuit lines weakened by age related degradation
	Bonds & Solder Joints	o Temperature cycling induced thermal fatigue and temp accelerated diffusion corrosion	o Short circuit or open circuit	o Possible failure of equipment to function	o Seismic vibration and shock can accelerate the failure of terminals and/or circuit lines weakened by age related degradation
Circuit Breakers	Trip Coil	o Embrittlement & cracking of insulation	o Loss of electrical protection of winding	o Coil force becomes less than spring force and circuit breaker fails open	o Loss of electrical protection may be promoted by seismic testing
	Heater Element (coil, bimetallic, etc.)	o Embrittlement & cracking of insulation	o Loss of electrical protection to leads	o Circuit breaker fails to open	o Loss of electrical protection promoted by shaking
	Molded case and/or insulation bushing	o Embrittlement & cracking of case	o Electrical discharge through case to ground	o Circuit breaker can fail open or closed depending on where fault is	o Crack growth in molded case/insulation bushing promoted by seismic testing

Table 2-1 (Continued)

FAILURE MODES AND EFFECTS ANALYSIS FOR ELECTRICAL EQUIPMENT

EQUIPMENT	AGE DEGRADABLE COMPONENT	AGING MECHANISM	FAILURE MECHANISM	FAILURE MODE	SEISMIC-AGING CORRELATION
	Contacts	o Oxidation/pitting of surface	o Pitting & oxidation causes loss of electrical continuity across closed contacts	o Circuit breaker will fail open	o No seismic-aging correlation
			o Contacts weld closed	o Circuit breaker fails closed	o No seismic-aging correlation
	Bearings	o Wear in bearings causing scoring or dirt build-up	o Bearings or sliding shaft seizes	o Failure of contacts to open	o Buildup in clearances by dirt or yielding promoted by shaking
	Undervoltage Coil	o Dirt accumulates on sliding surfaces and builds up in clearances	o Plunger in coil seizes	o Failure of circuit breaker in closed position because under voltage mechanism fails to actuate	o Buildup in clearances by dirt or yielding promoted by shaking
		o Embrittlement & cracking of insulation	o Loss of electrical protection to windings	o Coil force inadequate to activate circuit breaker. Circuit breaker fails closed	o Loss of insulation promoted by seismic testing
	Mechanical Linkages	o Build up of dirt and degradation (solidification) of lubricant	o Increase in friction of sliding surfaces	o Failure of contacts to open or close	o Seismic shock and vibration may cause fretting and increased friction or
					o Seismic shock and vibration may cause release of latched, spring operated mechanisms
	Shunt Coil	o Embrittlement & cracking of coil insulation	o Loss of electrical protection for windings	o Coil force becomes insufficient to activate circuit breaker. Circuit breaker fails closed	o Loss of insulation promoted by seismic testing
	Current Limiter	o Corrosion of terminals	o High resistance causes fuse element to prematurely "blow"	o Premature blow-out of fuse	o No seismic-aging correlation
Transmitters	Circuit Boards	o See "Circuit Board Assemblies" for Battery Chargers		o Failure of transmitter to transmit signal or to function correctly	o Seismic vibration and shock may accelerate the failure of degraded parts
	Metal Film	o See "Resistors" for electrical equipment		o Failure of transmitter to transmit signal or to function correctly	o Seismic vibration and shock may accelerate the failure of degraded parts

Table 2-1 (Concluded)

FAILURE MODES AND EFFECTS ANALYSIS FOR ELECTRICAL EQUIPMENT

EQUIPMENT	AGE DEGRADABLE COMPONENT	AGING MECHANISM	FAILURE MECHANISM	FAILURE MODE	SEISMIC-AGING CORRELATION
	Transformer	o See "Transformers"	o See "Transformers	o Failure may cause equipment not to function properly or operate or	o Seismic vibration and shock may accelerate the failure of degraded parts
	Insulation on Wire Leads	o See "Terminal Leads" for Transformers		o Failure may cause equipment not fo function properly or operate	

The most common degradation mechanism leading to seismic failure in these materials is thermal degradation of the electrical insulation and sealing materials. Other aging mechanisms are buildup of dirt (in vent caps of batteries, relays, variable resistors, meters), fatigue (in connectors and terminal leads from vibration), wear (in contactors, circuit breakers), and vapor transport of volatile and corrosive materials to susceptible areas in the equipment. A discussion of the aging and failure mode mechanisms in the major equipment items that are summarized in Table 2-1 is given below.

Batteries

A typical lead-acid battery cell is composed of approximately 15 lead alloy grids (the alloy being antimony or calcium to increase the strength of the lead) which are separated by porous rubber separators and suspended in a dilute sulfuric acid solution. The grids are further separated into two groups, negative and positive, with each group connected to a pair of terminals that are supported by the cell cover. The negative grid may have porous lead material on its surface. This active material is designed to have a high specific surface (surface area per weight) so that maximum contact with the electrolyte can be achieved.

The positive plate may be similarly constructed; however, there are several variations in the design which exist. The considerations driving the design of the positive grid are to achieve a high specific surface and to capture the reaction products from the electrochemical reactions that are responsible for the battery storing charge and discharging. These electrochemical reactions are discussed below.

When the battery is being charged, the active lead material on the positive plate reacts with the sulfuric acid (H_2SO_4) in the electrolyte to form lead dioxide (PbO_2). The porous lead on the negative plate does not react with the H_2SO_4 and remains as lead metal. During discharge, both the PbO_2 on the positive plate and the lead on the negative plate react with the H_2SO_4 to form PbO_2 (positive plate) and Pb (negative plate). The electrochemical reactions are:

$$\underline{\text{+ Plate}} \quad H_2SO_4 + PbO_2 + 2e^- \xleftrightarrow[\text{Charging}]{\text{Discharging}} PbSO_4 + H_2O + O^{--}$$

$$\underline{\text{- Plate}} \quad H_2SO_4 + Pb + O^{--} \xleftrightarrow[\text{Charging}]{\text{Discharging}} PbSO_4 + H_2O + 2e^-$$

$$\underline{\text{Cell}} \quad 2H_2SO_4 + PbO_2 + Pb \xleftrightarrow[\text{Charging}]{\text{Discharging}} 2PbSO_4 + 2H_2O$$

A primary cause of battery aging is the corrosion of the positive lead grid by the transformation in the electrolyte of the dense Pb to lower density PbO_2 leading to growth in the plates. The Pb has a specific volume of .088 cc/g and the PbO_2, .10 to .11 cc/g (depending on the stoichiometry) which is a 20% increase in volume over that of the lead. For swelling greater than approximately 10% (2-7) battery performance has been found to be erratic and, for this reason, 10% swelling is considered to be the end of battery useful life. If swelling is allowed to continue, the pressure created by the plates expanding against the cell case walls can cause the case to crack, plates to break, and the delicate plate separators to tear. These failure modes can be promoted by seismic testing.

One reason a battery loses capacity as it ages is because of degradation of the positive plates. The transformation of PbO_2 (0.11 cc/g) to $PbSO_4$ (0.16 cc/g) and vice versa during cycling and the poor adhesion of the reaction products to the grid, leads to the loss of the active material (PbO_2) and its deposition as sediment in the cell. This action can be aided by seismic testing and as it continues can lead to the buildup of a sediment composed of PbO_2, $PbSO_4$ and Pb on the floor of the battery until it creates a short circuit between the positive and negative plates.

The deposition of $PbSO_4$ on the floor of the cell leads to a reduction in the concentration of sulphuric acid because the solid material ties up the sulfate and does not take part in the electrochemical reactions which occur during cycling. Seismic loads on the battery plates may enhance the rate of deposition of the $PbSO_4$.

Oxygen and hydrogen gases are generated during charging at the positive and negative plates, respectively, by electrolysis of the water on areas of the plates where the specific gravity of the electrolyte is low. This occurs in a battery because of the lag time for the heavier H_2SO_4 to rise to the top of the cell and become completely mixed in the electrolyte during charging. Vent caps are ordinarily designed to permit the escape of the gas. If they become clogged, pressure may build up in the cell and promote cracking of the plastic case and cover. Seismic loading could contribute to this failure mode.

Battery Charger

The battery charger (or inverter) converts ac to dc power to maintain the batteries in a fully charged condition. The primary failure mode attributed to the battery charger under seismic stress is failure of the relay (2-10, 2-11). In the relay, as in other electromechanical devices (circuit breakers and switches), the predominant age-related failure modes are fatigue and coil insulation failure (2-12). The fatigued linkage or embrittled coil insulation could be weakened to a level at which the seismic loading would induce failure. This is the basis for suggesting an aging-seismic correlation in the FMEA.

In transformers and cables in which potential failure of the electrical insulation may occur, it is similarly felt that an aging-seismic correlation may exist. For cables having sections which may be seismically loaded by stresses transmitted through cable trays, this load may accelerate the cracking of embrittled insulation and jacket.

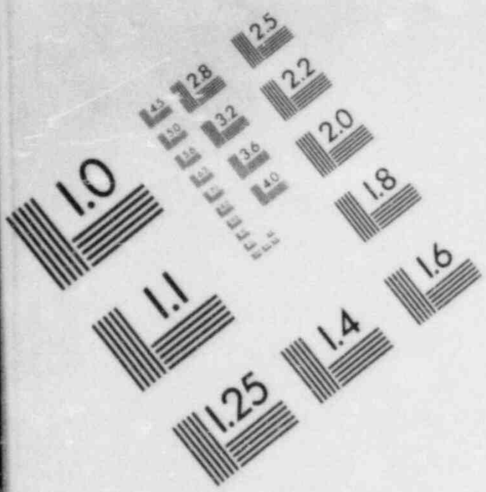
For the capacitor subject to vibration stresses and thermal stresses which fatigue the capacitor elements or connecting leads, an aging-seismic correlation may also exist.

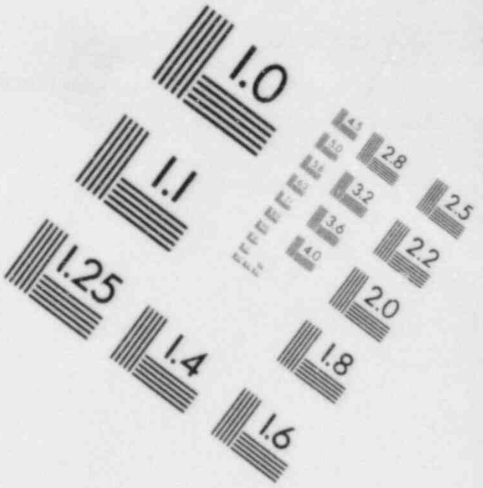
Circuit board assemblies which consist of deposited metal circuit lines soldered to terminals on an allyl based prepeg board are subject to failure particularly at the terminal connections. When these terminals are at an elevated temperature, corrosion and embrittlement may occur so that seismic vibration can lead to cracking and an open circuit.

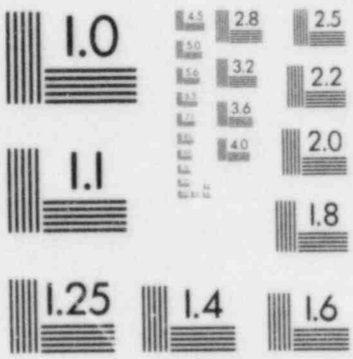
The voltage-clamping category of surge suppressors is commonly used in battery chargers and exists in three types: reverse selenium rectifiers, avalanche (zener) diodes, and varistors made of different materials such as silicon carbide and zinc oxide (2-13).

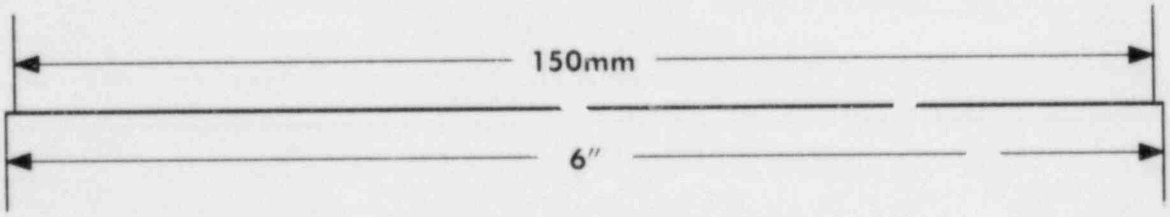
These components are fabricated from metallic or ceramic materials which have very low rates of degradation. For example, a representative metal oxide varistor made from zinc oxide operating at 130 V ac in a 55°C (131°F) environment has a mean life (< 10% shift in voltage) of 1045 years. This operating temperature is greater than that where the battery charger is located. It is,

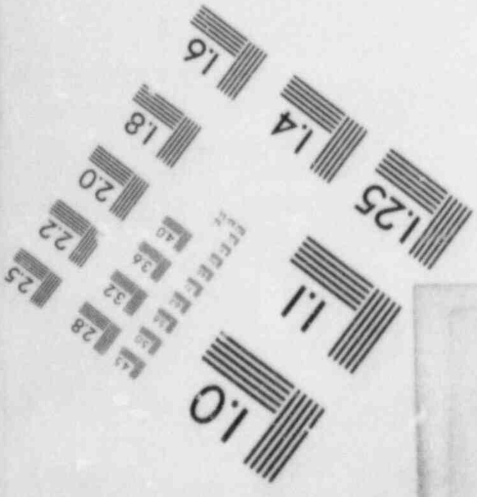
IMAGE EVALUATION TEST TARGET (MT-3)

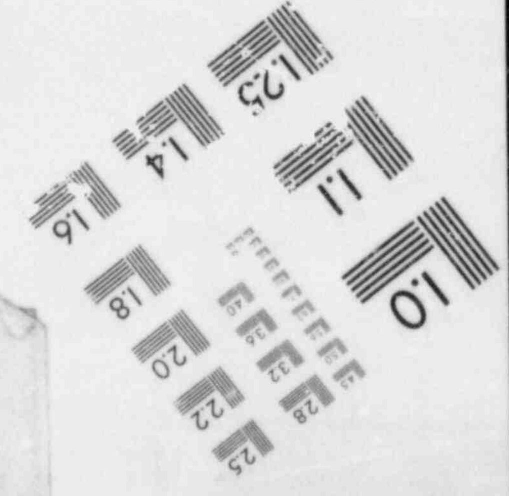












therefore, reasonable that no significant degradation would be expected to occur during the 40 year design life of a nuclear generating station.

Failure of a suppressor may occur when it is subjected to surges beyond its peak current/energy rating. Such a surge may initially cause melting to occur at the terminals leading subsequently to an open circuit.

Cables

Degradation in cable insulation may occur in several ways. Oxidation of the insulation leads to embrittlement which may cause cracks to develop and result in dielectric breakdown in the cracked area or excessive electrical leakage in the cable.

Faults may develop in the cable insulation from imperfections (e.g., voids and inclusions) which may grow in size under electrical stress by internal electrical discharges across the imperfection. The growth ordinarily occurs radially inward, leaving a path of material which has a low dielectric strength. Eventually, dielectric breakdown across this area will occur.

For cables with insulation that has become embrittled, the seismic loading may be transmitted through the cable trays causing bending of the cables which can lead to cracking. Such cracking would be expected to occur only if severely degraded areas in the cable insulation existed in which almost no elongation could be tolerated. The larger diameter cables (e.g., shielded cables, power cables) would be expected to be more sensitive to cracking because the strains on the cable surface are greater for the same bend radius.

Penetrations

Penetration assemblies are sealed structures mounted in the primary containment wall through which instrument leads and electrical service cables pass. A function of the penetration assembly is to maintain the containment integrity which is designed to retain fission products that might result from reactor operation or from an accident (2-14).

The cables passing through the penetration must remain electrically isolated throughout the life of the penetration.

In the penetration assembly, there are several critical components made from age degradable materials depending on the style of the assembly. In general, there are vacuum cast epoxy and elastomer O-ring seals on each end of such an assembly. In the middle of the assembly is a partial vacuum which may be monitored with a pressure gauge. The function of the epoxy seal is to form a tight and reliable bond to the cables and inside walls which will remain impermeable to gases and vapors. The O-rings generally form the outer seal. Thermal degradation, embrittlement, and cracking in either of these two materials could lead to an increase in permeability beyond a standard criteria, resulting in failure. Seismic testing of the penetration assembly with embrittled seals could accelerate the increase in permeability.

Switches (Pressure, Level, Limit, Temperature)

Switches encompass a broad category of items that include automatic switches (e.g., pressure and temperature switches) which are activated when a parameter goes beyond a set point and manual switches which have no sensor and set point. The weak link parts in which degradation may be associated with the aging-seismic effect are the insulation on the lead wires, circuit boards and coils. These parts are made from polymeric materials which can degrade, become embrittled, or crack, and result in sudden failure of the equipment.

Other critical parts such as elastomer seals, polymer covers, and polymer bearings (e.g., sliding bearings) may degrade and fail, but are less likely to cause the sudden failure of the equipment during a seismic test. Metal contacts are critical elements, but they will not degrade significantly under the normal environmental conditions inside or outside of containment.

Motors

The motors addressed in this report are relatively small (≈2 HP), and are used in applications related to motor operated valves, fans and small compressors. These are induction motors of the squirrel cage type design.

The fragility of motors in motor-operated valves has been discussed by Cover (2-10) and Campbell (2-15). Motors in both the horizontal and vertical positions were considered. Cover summarized fragility data from expert opinion sources, analyses and test data sources for 50 generic components. For large motor-operated valves (> 4 inches), the median acceleration for which electrical failure in the actuator is reported to occur is 11.19 g's.

In a preliminary study of failure modes in equipment in a "Seismic Safety Margins Research Program" reference plant, Campbell reported that electrical failures (which include lead wires and cables) in large motor-operated valves from seismic vibration can occur but are less likely than other failure modes.

Campbell et al. also reported that motor insulation failure may occur from a combination of service degradation and seismic induced vibration. Although it was not discussed in this reference, it has been found that the torsional and vibrational loads on the stator core may contribute to additional weakening of the stator insulation in the motor.

In this document, the insulation systems considered most susceptible to deterioration and which are critical to the operation of the random wound motor are considered to be the stator winding insulation (slot liner, wire insulation, phase insulation separators and slot caps), stator core lamination insulation and terminal leads.

Motor Starters

The failure modes for motor control centers which were identified by Cover (2-10) are

- Structural anchoring of cabinet base
- Structural mounting of component in cabinet
- Relay chatter
- Breaker trip

Failure of any of the electrical components (e.g., relay chatter and breaker trip) could lead to rapid failure of the motor starter. The coil insulation in these components is subject to age-related degradation and embrittlement leading to shorting of the turns and weakening of the pulling force on the core. Seismic vibration could promote this failure mode by creating or enlargening cracks in the insulation.

Premature breaker trip during a seismic event could occur if weakening has occurred in the latch spring and the circuit breaker is able to function.

A possible, though unlikely mode of failure for a fuse during a seismic event is by fatigue failure of the fuse element which has become embrittled from recrystallization.

Solenoid Operators

The solenoid valve contains many polymeric parts that may thermally degrade over time. These include gaskets, discs, insulating washers, etc (2-15). The solenoid coil materials, however, which are subjected to electrical and thermal stresses and failure of which may cause sudden failure of the valve to operate are considered to be particularly critical to the valve operability. Potential aging-seismic correlation may exist in the solenoid coil body insulation or in the lead wire insulation. The failure mode would be similar to that occurring in motors or the coils in circuit breakers in which degradation of the polymeric insulation embrittles the material and creates a condition favorable for cracks to initiate and grow, defeating the ability of the insulation to electrically isolate the conductor (coil turn, lead wire, etc.).

Electronic Equipment

Electronic equipment and instrumentation are fabricated from a large number of discrete components which can age at different rates and may have different aging-seismic sensitivities. For the purposes of this study, the effects of aging and seismic loading on resistors, capacitors, semiconductors, encapsulants, printed circuit boards, circuit bonds and solder joints were evaluated. The results of this preliminary evaluation are given below.

Resistors - A review of aging in electronics equipment by Johnson et al. (2-17) reported that little age-related degradation has been found to occur in resistors. The resistor types considered were oxide-film resistors, thin-film resistors, carbon resistors, thick-film resistors, and wire wound resistors.

For example, resistance changes of approximately 500 parts per million (0.5%) were found after the aging of anodized tantalum nitride resistors for 103 hours at 105°C (2-18). Wire-wound resistors are considered to be the most stable of all electronics components and will not experience any degradation well within their power ratings (2-4).

Capacitors - A typical ceramic capacitor may consist of alternate layers of barium titanate dielectric and silvered glass electrodes which were bonded together at temperatures of 700 to 800°C. This package may be only a fraction of an inch square and thin and may be encapsulated in a thermosetting plastic after leads are bonded to it. While degradation may occur at the electrode-dielectric interface in the ceramic package (2-19), the area where aging-seismic correlation is most likely to occur is at the lead connections. Embrittlement of the bonded areas from recrystallization and/or fatigue damage from normal vibration or thermal cycling may contribute to the separation of the lead from the component during seismic stress.

The glass capacitor is fabricated by stacking alternate layers of a glass frit dielectric and silver-glass frit plates and vitrifying the assembly at approximately 700°C. Copper leads are soldered to the ends of the capacitor and the part is coated with a polymer. Aging-seismic correlation for this component would also be expected to occur where the leads are bonded to the glass as discussed previously for the ceramic capacitor.

Electrolytic capacitors are made from a metal foil (aluminum or tantalum) with a surface that is anodized with an oxide film of the parent metal. The oxide film is the dielectric between the metal and electrolytic solution. One of the failure mechanisms of the electrolytic capacitor is the loss of electrolyte as a result of high operating temperatures in the core. However, no aging-seismic correlation is predicted for this failure mode. Aging-seismic correlation may exist for failure of the lead wire bond to the component or the circuit board.

Organic capacitors (with paper, impregnated paper or plastic dielectric between two electrode metal foil strips or deposited metal layers) would similarly have aging-seismic correlated failures at the lead wire bonded areas.

Semiconductor Devices (transistors, diodes) - A list of possible failure mechanisms for semiconductor devices is given in Table 2-2 (2-17). The failure mechanisms identified in the table which could be correlated with seismic failure are: corrosion leading to mechanical weakening of the metallized areas, intermetallic growth leading to embrittlement of circuit bonds, thermal and mechanical fatigue of circuit bonds, crack initiation and propagation in the encapsulant. Seismic vibration could accelerate the failure of the metallized areas in the semiconductor or cause cracks to grow in the encapsulant, permitting moisture and oxygen to enter and promote corrosion of the metallized circuitry.

Table 2-2

FAILURE MECHANISMS IN SILICON SEMICONDUCTOR DEVICES (2-17)

Material	Mechanism	Degradation Factors
Oxide and Oxide/Semiconductor Interface	Surface charge buildup	Ionic conductivity, voltage, radiation
	Dielectric breakdown	Electric field, temperature
	Charge Injection	Electric field, temperature
Metallization	Electromigration	Current density, grain size, geometry, temperature
	Corrosion	Humidity, contamination, temperature, voltage
	Contact degradation	Metals, impurities, temperature,
Bonds	Intermetallic growth	Impurities, bond strength, temperature
	Fatigue	Temperature cycling, bond strength
Encapsulation	Diffusion and Seal leaks	Atmosphere, pressure, humidity

Printed Circuit Boards - The printed circuit boards contain fine deposited metal circuit lines on their surfaces which end at terminals that are soldered to various electronic components (resistors, capacitors, semiconductors) and other circuits. Accelerated life tests on fine line, flexible printed circuits coated with UV-cured resins have created many different failure modes (2-14). These failures included:

- shorting between circuit lines on the same side of the circuit board.
- shorting through the substrate.
- failure by dendritic growth, blistering or delamination in the overcoat/substrate layer. This is initiated by contamination entrapped at the overcoat/substrate interface during the manufacturing process.

These failure modes and failures of the soldered connections on the printed circuit wiring board can be promoted by the vibration and shock which may occur during seismic stress.

Radiation Monitor

Gas filled detectors and scintillation detectors are the types of radiation monitors commonly used in a nuclear generating station for detecting radiation. Gas filled detectors may have applied voltages from 800 to 1500 volts between the anode wire and the walls of the ionization chamber. Thermal degradation in the insulation of the cables carrying the voltage may cause embrittlement and cracking leading to discharging to ground in the faulted areas if the cables are shaken during seismic testing. The thin anode wire which passes through the middle of the ionization chamber may be subject to breakage from seismic stresses after it hardens from thermal cycling and corrosion.

Scintillation detectors are commonly fabricated from plastic filled with an active element that emits light pulses when excited by radiation, ceramic materials (e.g., sodium iodide, cesium iodide, lithium iodide, calcium fluoride) which behave in the same way in the presence of radiation are also used. These plastic materials may degrade from oxidation causing them to become brittle and more susceptible to cracking when subjected to vibration and shock from a seismic test. Ceramic detectors are less susceptible to aging unless they are used in locations where thermal cycling may be severe. The light pulses from the plastic or ceramic detectors must be converted to electrical signals and amplified. This is done with a photomultiplier tube (PMT) which consists of numerous dynodes that are precisely aligned to induce a "multiplication" of the initial signal. The vibration and shock from a seismic test may cause misalignment of the dynodes so that excessive drift occurs in the signal.

The electronic signal amplification and processing equipment has several elements which may be subject to degradation and failure during a seismic test. The failure mechanisms in these components have been discussed previously.

2.4 Probabilistic Failure Analysis

The basic elements of the Probabilistic Failure Analysis (PFA) are:

- Calculation of the probability of the failure of the weak link components in the equipment
- Calculation of the probability of failure of the equipment from the failure probabilities of the weak link components
- Determination of the sensitivity of the failure probability with time related degradation.

These elements will be discussed more fully below.

Deciding if a material, component or equipment has failed is often not a straightforward task. A failure criteria for the material or equipment must be established so that a test can be developed and a judgment on whether a material or component passes or fails the test can be made. The test which is specified will depend on the purpose. For example, changes in the tensile strength or elongation at failure of cable insulation is commonly used to measure the age degradation of the material and the criteria of greater than 50% retention of the initial strength is often used as a threshold for acceptable performance. However, in practice, current leakage tests and hi-pot tests are conducted to monitor the performance of medium to high voltage cable and insulation resistance (IR) for low voltage cable (<1000 volts) even though mechanical tests are more accurate indicators of the age of the insulation than electrical tests (<u>2-9</u>, <u>2-20</u>).

Functional tests conducted to insure the equipment will perform according to specifications may give no indication of aging that may have occurred in one or more of the components. Often these tests are the "go-no-go" type and when failure occurs it is sudden and catastrophic. Electronic equipment often fails in this way.

In Table 2-3 a list of generic weak link components common to safety related electrical equipment is provided along with the criteria which is used to determine performance or the extent of aging. Battery criteria were included in the table because aging in a battery is most commonly determined by measuring a performance parameter such as discharge capacity and/or rate rather than monitoring a single component such as electrolyte specific gravity, tensile strengths of battery case and cover, impurities in electrolyte, etc. It has been suggested that battery age can be monitored by measuring the spacing between plates (which decreases as swelling from corrosion occurs) through the transparent case (2-9); however, there is no requirement for this.

The probability of failure of material or equipment can be determined by comparing the level at which it is stressed in the equipment (S) with the ultimate level of stress before it is expected to fail (S_u). The ultimate stress (e.g., tensile strength, yield strength, impact strength) of a material is determined by testing a number of representative samples to obtain a distribution of the number of failures for different stress levels. The mean (or sometimes a lower value, to account for margin of error) of that distribution is

Table 2-3

CRITERIA FOR WEAK LINK COMPONENTS IN ELECTRICAL EQUIPMENT

Component	Criteria
Electrical Insulation	Tensile Strength
	Tensile Impact Energy
	Elongation at Failure
	AC/DC Electrical Resistance
	AC/DC Electrical Leakage
	Dielectric Constant
	AC/DC Dielectric Breakdown Strength
	Dissipation Factor
	Partial Discharge
	Torsion Test for Stiffness
Seals & Gaskets	Compressive Set
	Tensile Strength
	Elongation at Failure
	Bursting Strength
	Durometer Hardness
	Tear Resistance
	Adhesion to Flexible and Rigid Substrates
Protective Envelopes (Encapsulants, Covers)	Tensile Strength
	Elongation at Failure
	Bending Strength
	Impact Resistance
	Hermeticity of Encapsulant
	Bearing Strength
	Permeability to Liquids and Gases
Lubricant	Viscosity
	Lubricity
	Dielectric Breakdown Voltage
	Foaming Characteristics
	Flow Properties of Grease
	Wear Preventive Properties of Grease
	Dropping Point of Grease
	Load Carrying Capacity
Battery	Rate of Discharge
	Charging Capacity
	Sediment Height

Table 2-3

CRITERIA FOR WEAK LINK COMPONENTS IN ELECTRICAL EQUIPMENT
(Concluded)

Terminals (e.g., battery, circuit board, etc.	Pull Strength of Wire Bonds Adhesive Strength of Metal Films (e.g., circuit lines)
Circuit Board	Tensile Strength Flexural Strength
Contacts	Resistance of Closed Contacts Hardness Voltage Drop Arc Erosion Resistance
Springs	Fatigue Life Coilability Spring Constant
Bearings	Abrasion Resistance
Radiation Detector Materials (e.g., plastics, sodium iodide, semiconductors, etc.	Light Output Efficiency Time Constant Energy Discrimination
Thermocouples	Calibration Insulation Resistance Sheath Integrity (pressure tightness) Metallurgical Structure of Sheath Resistance Between Thermoelements and Between Thermoelements and Sheath.

taken as the ultimate or "breaking" stress (to borrow a term from mechanical testing). A normal distribution and cumulative normal distribution are illustrated in Figures 2-2(a) and 2-2(b), respectively. The cumulative distribution which is the integral of the curve in Figure 2-2(a) is used to obtain the total number of failures at stresses less than or equal to the applied stress.

Some samples will fail below the mean and some will fail at stresses greater than the mean. For a normal distribution which is the one assumed to describe the data, 50% of the samples will fail above and 50% of the samples will fail below the mean. The spread in the distribution about the mean value is given by the standard deviation (σ) or estimate of the standard deviation (σ). For the strength of metals, $\sigma \approx 20\%$ is a good estimate for the breaking strength (2-21).

The assumption of the breaking strengths being normally distributed is examined further here. Some workers (2-22) have indicated that the repeatability in experimentally obtained breaking stresses is so poor that the differences in distributions assumed are not significant. Kennedy (2-23) assumed a lognormal distribution for the shear strength of concrete beams because the property he was studying was a product of normally distributed parameters and the product is not normally distributed. This reason does not apply to the work in this report in which the breaking stresses are experimentally and analytically obtained. In any case, the probability distribution assumed for the breaking stresses has no bearing on the validity of the methodology. The assumption of some other probability distribution (e.g., lognormal, chi square,) may

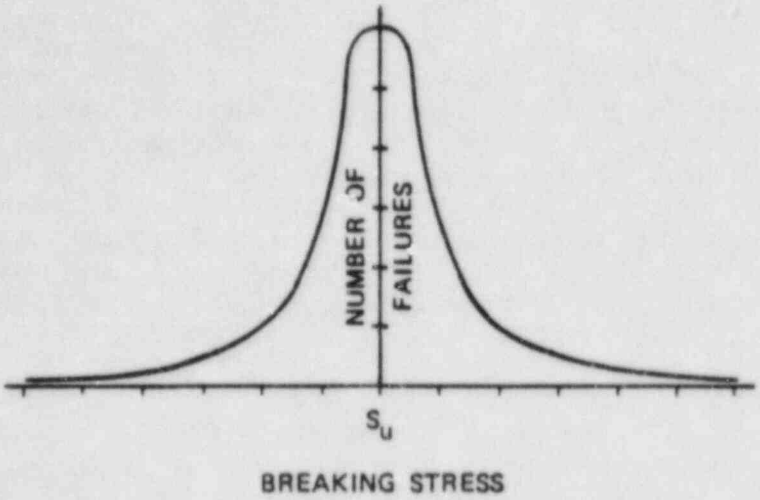


Figure 2-2(a). Normal distribution for breaking stresses of samples of weak link materials. S_u is the mean breaking strength.

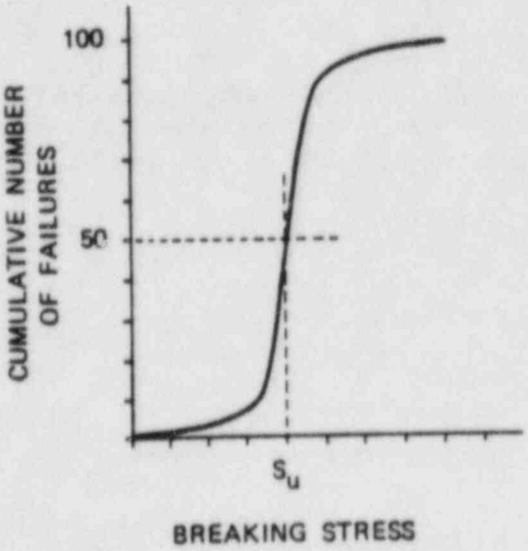


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Figure 2-2(b). Cumulative normal distribution for breaking stresses of samples of weak link materials.

only affect the calculated probability values depending on the range of independent stress values (mechanical loads on the components). The density function of the normal distribution illustrated in Figure 2-2(a) can be found in any statistics textbook and can be expressed as

$$p(x) = \frac{1}{\sqrt{2\pi}\quad\sigma} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \quad -\infty<x<\infty \qquad 2\text{-}1$$

where x can be any normally distributed variable such as the applied stress (S) and μ is the mean value of the breaking strength (S_u)* (2-2).

If a new variable, Z, is defined

$$Z \equiv \frac{S - S_u}{\sigma}$$

than the normal distribution function of S can be standardized and expressed as

$$P(S) = \frac{1}{\sqrt{2\pi}} \exp\left[\frac{-Z^2}{2}\right] \qquad 2\text{-}2$$

Tables in which the values for the error function of Z (erf Z) are given in most text books on statistics such as Reference 2-24 or in handbooks (2-25, 2-26).

The cumulative normal probability distribution of S, F(S) can be expressed as the integral of the normal probability distribution which is

$$F(S) = \int_{-\infty}^{S} F(S)\,dS = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{S} \exp\left[\frac{-(S - S_u)^2}{2\sigma^2}\right] dS \qquad (2\text{-}3)$$

This function can be evaluated from the values in the cumulative probability tables for erf x. Using F(S), the probability of failure of a component can be calculated, knowing the mean breaking strength of the component material and the total applied stress on it. For a piece of equipment having many components, for which the failure of any one will cause the equipment to fail, the cumulative probability of the equipment (or system) failing $F(S)_{SYS}$ is:

$$F(S)_{SYS} = 1 - \pi_{i}^{n} [1 - F_i(S)] \qquad 2\text{-}4$$

where $F_i(S)$ is the cumulative failure probability of the i^{th} weak link component which was discussed previously.

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* When the breaking strength is a function of time because of age related degradation the term S_t is used. This is discussed later.

As a material ages and degrades, S_u will decrease and the probability of failure will increase. The rate of degradation for a material in which the degradation processes are thermally activated can be expressed by a form of the Arrhenius equation as* (2-5)

$$\ln (S_t/S_u) = At\exp\,({}^{-E_A/kT})$$

or taking the exponent of both sides to solve for S_t/S_u,

$$S_t/S_u = \exp\,[At\exp\,({}^{-E_A/kT})] \qquad 2\text{-}5$$

where:

A = constant for the material (sometimes referred to as frequency factor or pre-exponential factor)
t = time at the temperature
E_A = activation energy (eV/atom)
k = Boltzmann's constant (0.8617×10^{-4} eV/°K-atm)
T = absolute temperature of the material (°K)
S_t/S_u = fractional breaking strength at time t which varies between 1 at t=0 and 0 at $t = \infty$.

The material constant, A, can be eliminated from equation 2-5 by setting $t = t_{T1}$ where t_{T1} is the time for S_u to be reduced by a fixed fraction of its initial value at temperature T_1 and setting $t = t_{T2}$ where t_{T2} is the time for S_u to be reduced by the same fraction as for t_{T1}. When t_{T1}, t_{T2}, T_1, T_2 are substituted for t and T, respectively, Eq. 2-5 can be rewritten as:

$$\frac{t_{T1}}{t_{T2}} = \exp \frac{E_A}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \qquad (2\text{-}6)$$

This is the familiar form of the Arrhenius equation which is used to extrapolate the lifetime of a material from the accelerated test temperature to the operating temperature. For example, T_2 and t_{T2} could be the accelerated test temperature and time, respectively, for a fixed fraction of degradation to occur and, likewise, T_1 and t_{T1} would be the temperature of the equipment part in the plant and the time expected for that part to

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* This expression assumes the relation between the measured property and the chemical reaction occurring in the material is linear.

degrade the same fixed fraction. To determine the change or degradation in S at different times for the same temperature, the expression

$$\frac{\ln (S_{t1}/S_u)}{\ln (S_{t2}/S_u)} = \frac{t_{s1}}{t_{S2}} \qquad (2\text{-}7)$$

can be used. This is derived from Equation 2-5 by setting $S_t = S_{t1}$, $t = t_{S1}$ to obtain one equation and $S_t = S_{t2}$ to obtain a second equation, and dividing the two equations by each other to eliminate A and T. Using Equation 2-5 and Equation 2-6, the time and temperature for any amount of degradation in a weak link material can be calculated.

This is shown in Figure 2-3 where the Arrhenius curve for the time (t_{S2}) for a 50% reduction in the initial strength of a material is drawn with a solid line. If the fraction of initial strength lost, $(S_u - S_{t1})/S_u$, after time, t_{S1} is wanted, then knowing S_u, the initial strength, and S_{t2}/S_u (=0.5 in the example in Figure 2-4), S_{t1}/S_u can be calculated using Equation 2-7 which is the fraction of the initial strength retained. The cumulative probabilities of the material failing after it has aged for t_{S1} and t_{S2} is shown in Figure 2-4. It can be seen in this figure that as the age of the component increases and its strength degrades, the probability of it failing, F(S) increases toward 1.0. At time $t = 0$, no degradation in the material has occurred and $S = S_u$, however, there is still a probability of failure from the applied load during the seismic test.

The age sensitivity of the failure probability at t_{S1}, $\frac{\Delta F(s)}{\Delta t}$ can be roughly approximated for an equipment part from the failure probability values at $t = 0$ and $t = t_{S1}$. To estimate the age sensitivity of the failure probability of the equipment, the failure probabilities for two different times using Equation 2-4 can be determined and the slope of these values, $\frac{\Delta F(S)SYS}{\Delta t}$ calculated.

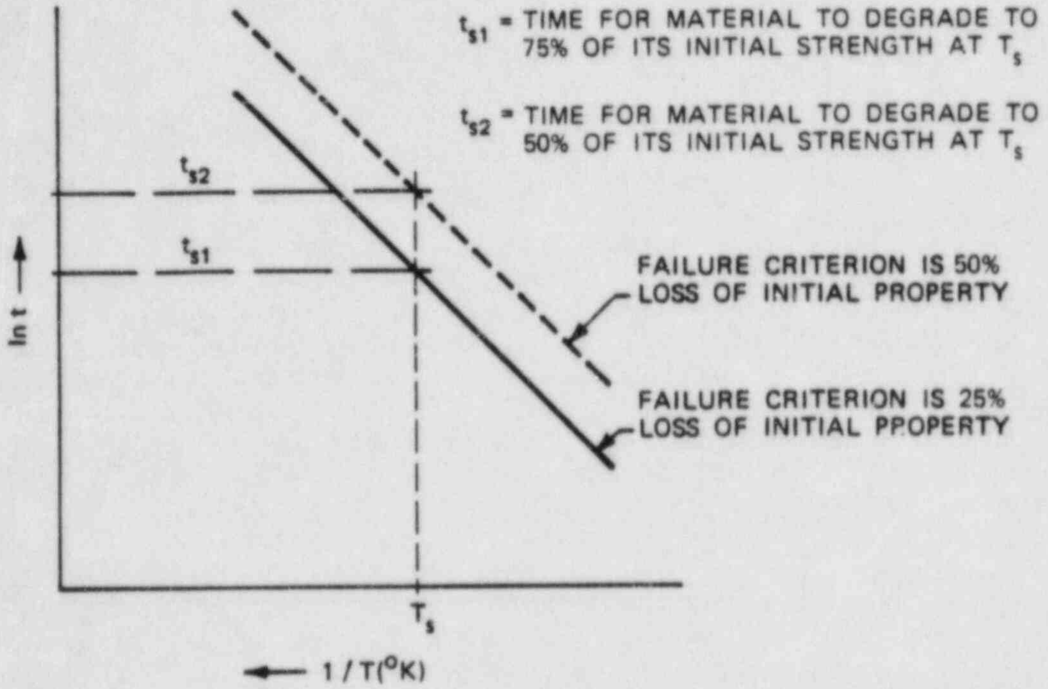

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Figure 2-3. Arrhenius curves for two different failure critera. t_{s1} and t_{s2} can be determined from Equation 2-7.

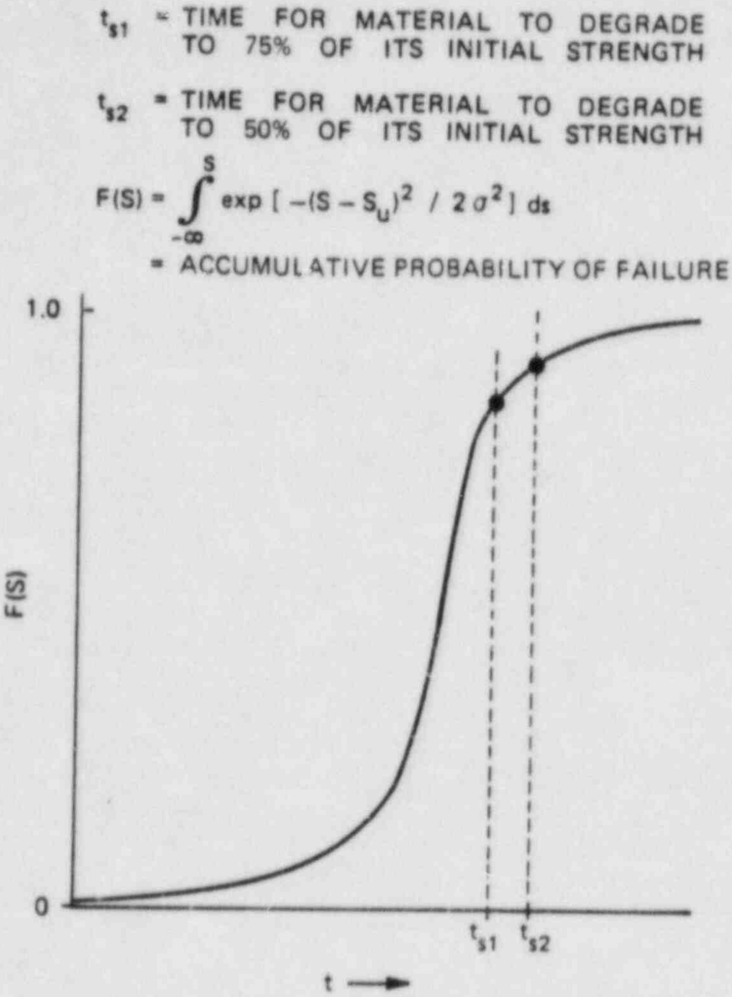

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Figure 2-4. Cumulative probability of the failure of a part fabricated from an age-degradable material.

3.0 EQUIPMENT SPECIFIC APPLICATIONS

3.1 Introduction

In this section, the methodology discussed previously for estimating the aging-seismic correlation will be applied to motors and to batteries. The purpose of this section is only to demonstrate the methodology and not to evaluate the subject equipment. For each of the equipment items, the seismic loads on the age-degradable parts and the strength of the unaged and aged materials was estimated. A standard deviation of 20% of the breaking strength (unaged and aged) of the material from which the part was fabricated was assumed. The failure probabilities for the unaged equipment and aged equipment were calculated using the above estimates and assumptions.

Because of the complexity of the insulation materials system in the motor operator and of the loads on the insulation generated from electromagnetic forces in the stator winding, centrifugal forces in the rotor and vibration, gross estimates were used in determining the parameters discussed above. These assumptions are discussed more fully below.

For the battery, a materials analysis and simple seismic loading analysis could be performed. The data from these preliminary analyses is used in obtaining the failure probabilities for the equipment.

3.2 Motor

The weak link components for the motor are:

- o Stator winding (consisting of the slot liner, wire insulation, phase insulation separator, and slot cap)
- o Stator core lamination insulation
- o Terminal leads

Relays, circuit breakers and contactors were not included because they are considered part of the motor control center.

A failure criterion for the electrical insulation that has been used in environmental qualification testing is the loss of 50 percent of the property such as elongation and tensile strength (3-1, 3-2) and flashover strength (3-3) of the unaged material. For the purpose of this analysis, the particular failure criterion selected is not important, so a failure criterion of the loss of 50 percent of its initial (or unaged) tensile strength will be used. It is further assumed that at the end of 40 years at a temperature of 25°C the failure criterion for the motor insulation will be met. In other words it is assumed that the motor insulation will have a 40 year life at room temperature. If the motor operates inside the containment structure of a nuclear generating station, the ambient temperature may be 40°C or greater. The equivalent motor life at the higher temperature can be calculated from the Arrhenius expression for thermally activated phenomena if enough data is known about the insulation material.

When this data is not available, the "10°C Rule" may be used. This is an empirical relationship based on observations that for every 10°C rise in temperature, the rate of reaction will increase by a factor of two. This relationship corresponds to an energy of activation considerably less than one electron volt and is therefore conservative. The 10°C Rule can be expressed as:

$$\frac{t_1}{t_2} = 2^{\left(\frac{T_2 - T_1}{10}\right)} \qquad (3-1)$$

where:

t_1 = time to failure at T_1
t_2 = time to failure at T_2
T_2 = 40°C
T_1 = 25°C

From Equation 3-1 the time for failure (the strength to degrade to $\frac{S_2}{S_u}$ = 0.5 of its initial value) at T_2 = 40°C is calculated to be t_2 = 14 years. The time for the insulation to lose only 10% of its original strength (S_1/S_u = 0.9) at 40°C can be calculated from the expression

$$\frac{\ln\left(\frac{S_1}{S_u}\right)}{\ln\left(\frac{S_2}{S_u}\right)} = \frac{t_1}{t_2} \qquad (2-7)$$

where:

$\frac{S_2}{S_u}$ and $\frac{S_1}{S_u}$ are the failure criterions.

t_1 and t_2 are the corresponding times for the failure criterions.

Substituting the values for S_1/S_u, S_2/S_u and t_2 into

Equation 2-7 and solving for t_1 gives $t_1 = 2$ years for 10% loss in the initial strength. The results of this calculation and assumptions for the seismic loading stresses are summarized in Table 3-1 for the weak link components in the motor.

The estimates for the maximum seismic plus operational stresses in Table 3-1 are made using engineering judgement. An analysis of these stresses would have been beyond the scope of this effort. The probabilities of failure for the unaged and aged weak link components and for the motor are summarized in Table 3-2.

Table 3-1

EXAMPLE OF SUMMARY OF STRESS ON WEAK LINK COMPONENTS IN MOTOR

Component	Maximum Seismic Plus Operational Stress	Ultimate Breaking 40°C/0 years	Stress (S_u')(a) 40°C/2 years
Stator Winding Insulation System	$0.7S_u$	S_u	$0.9S_u$
Stator Core Insulation	$0.5S_u$	S_u	$0.9S_u$
Terminal Leads	$0.2S_u$	S_u	$0.9S_u$

(a) Assuming 10°C Rule and 50% loss of initial strength after 40 years @ 25°C.

Table 3-2

PROBABILITIES OF MOTOR FAILURE FROM DATA IN TABLE 3-1

$$F(S) = \int_{-\infty}^{S} p(S)\, dS = \frac{1}{2\pi} \int_{-\infty}^{Z} \exp\left(\frac{-Z^2}{2}\right) dZ$$

$$\sigma = 0.25'_u$$

Component	Unaged Motor $Z \left(= \frac{S-S_u}{\sigma}\right)$	Unaged Motor Fi(S)	Aged Motor $Z \left(= \frac{S-S_u}{\sigma}\right)$	Aged Motor Fi(S)
Stator Winding Insulation System	-1.5	.0668	-1.11	0.133
Stator Core Insulation	-2.5	.0062	-2.22	.0132
Terminal Leads	-4.0	3.2×10^{-5}	-3.89	5.06×10^{-5}

$$F(S)_{sys} = 1 - \prod_{i}^{n} [1 - F_i(S)]$$

$$F(S)_{sys}\ [\text{Unaged}] = .073$$

$$F(S)_{sys}\ [\text{Aged}] = 0.144$$

$$\frac{\Delta F(S)}{\Delta t} = \frac{0.144 - .073}{2} = 3.6\%/\text{year}$$

3.3 Batteries

In this section, the methodology for estimating the aging-seismic correlation will be applied to batteries. The purpose of this section is only to illustrate the use of the methodology discussed in previous sections and not to evaluate the equipment. A reliable seismic loading analysis and materials analysis for the battery are beyond the scope of this report, and are not necessary for the purpose of this section. However, the simplistic assumptions made in this analysis are considered to make the results more conservative.

The seismic loading used for the battery is calculated from the Required Response Spectra (RRS) from IEEE P-744 (2-27) which was developed for 80 per cent of the locations for nuclear plants in the USA and is therefore a representative loading. From the testing done on batteries at Ontario Hydro (2-28), it was felt that the battery could be assumed to be rigid (no resonant frequencies at or below a frequency of 33 Hz and, therefore, it could be assumed that no amplification of the excitation occurs.

The details of the seismic loading analysis are presented in Appendix A.

A summary of the seismic loads on the weak link components and the component strengths are given in Table 3-3. The load estimated on the microporous rubber separators caused by swelling of the lead plates and their oscillation and the stresses bearing on the potentially clogged vent caps from the build-up of hydrogen gas pressure are estimated using engineering judgement. The ultimate stresses (S_u) at room temperature, are obtained from published values referenced in the table. The aging conditions of 77.8°C and 40 years were selected because at these conditions, the polycarbonate container case lost 5 per cent of its initial strength as calculated form the aging data obtained from General Electric Company (2-29). This data is summarized in Table 3-4.

While the temperature is higher than that expected for either the ambient conditions in the battery room or inside the battery, the loss of five percent of the initial strengths in the polycarbonate over 40 years does not seem as unreasonable.

The failure probabilities for the unaged and aged battery components and the battery are summarized in

Table 3-5. In this table, the positive and negative lead plates are treated independently because each is supported independently in the cell. The results in Table 3-5 and for the motor cannot be compared with the results here because of the different calculational bases for each of these equipment items.

Table 3-3

SUMMARY OF STRESSES ON WEAK LINK COMPONENTS IN LEAD ACID BATTERIES

Component	Static (psi)[b]	Seismic (psi)[c]	Total Applied Stress, S Static + Seismic (psi)	Ultimate Stress, S_u(psi) 77.8°C/0y	Ultimate Stress, S_u(psi) 77.8°C/40y
Lead Plate (+)	3.5	1,483	1,487	5,400 (σ_T)[d] (3-1)	3,500[a]
Lead Plate (-)	3.5	2,193	2,197	5,400 (σ_T)	3,500[a]
Polycarbonate Cell Wall	150.	5,974	6,124	12,000 (3-2)	11,400
Polycarbonate Cell Cover	328.	4,250	4,588	12,000 (3-2)	1,400
Polycarbonate V Caps	0	3,000 (estimated)	3,000	12,000 (3-2)	11,400
M porous Buffer Separators	0	1,000 (estimated)	1,000	2,000 (σ_T)* (d)	1,900

(a) Estimated from data for loss of strength with increasing temperature for Arsnical Lead "G" Babbitt (83.5Pb 12.75Sb, 3As 0.75Sn) (3-4)

(b) 10 percent of the weight of the lead plates supportd by the cell cover is assumed.

(c) Seismic level of 1.3 g's is assumed.

(d) This value is for tensile stress.

Table 3-4

DEGRADATION OF THE TENSILE IMPACT STRENGTH OF 1/8" THICK POLYCARBONATE SPECIMENS (2-29)

T°(C)	L (hours)[a]
110	85,000
120	28,000
130	9,500
140	3,500

$$\ln L = 1.6798 \times 10^4 \left(\frac{1}{T^{\circ}K}\right) - 32.5119$$

E_{ACT} = 1.45 eV/°K-atom

---

[a] L = time for tensile impact strength to degrade to 50 percent of its initial value (hours).

Table 3-5

PROBABILITY OF BATTERY FAILURE FROM DATA IN TABLE 3-3

$$F(S) = \int_{-\infty}^{S} p(S)\, dS = \frac{1}{2\pi} \int_{-\infty}^{Z} \exp\left(\frac{-Z^2}{2}\right) dZ$$

$\sigma = 0.2\ Su$

Component	Unaged Battery $Z\ (= \frac{S-Su}{\sigma})$	Fi(S)	Aged Battery $Z\ (= \frac{S-Su}{\sigma})$	(70°C/12.6y Fi(s)
Lead Plate (+)	-3.62315	$1.466\text{x}10^{-4}$	-2.87571	$2.0242\text{x}10^{-3}$
Lead Plate (-)	-2.96628	$1.514\text{x}10^{-3}$	-1.86143	.03135
Polycarbonate Cell Wall	-2.44833	$7.193\text{x}10^{-3}$	-2.31404	.01035
Polycarbonate Cell Cover	-3.08833	$1.012\text{x}10^{-3}$	-2.98772	$1.362\text{x}10^{-3}$
Polycarbonate Vent Cap	-3.75000	$8.913\text{x}1^{-5}$	-3.68421	$1.156\text{x}10^{-4}$
Microporous Rubber Separator	-2.5000	.006226	-2.36842	$8.951\text{x}10^{-3}$

$$F(S)sys\ [Unaged] = 1 - \overset{n}{\underset{i}{\pi}}[1-F_i(S)] = .017$$

$$F(S)sys\ [Aged] = .053$$

$$\frac{\Delta F(S)sys}{\Delta t} = 0.29\%/year$$

4.0 SUMMARY

A probabilistic methodology for evaluating the potential for aging-seismic correlation in electrical equipment is proposed. A basic assumption is that the predominant failure mechanism for the equipment during a seismic test will be the mechanical failure (either by breaking or yielding) of a weak link component that will cause the equipment to fail. If the component is carrying a load, there will always be a probability it will fail. A normal probability distribution of failure frequency with stress is assumed in which the known breaking strength is the mean and the standard deviation is assumed to be 20 percent of the breaking strength. This methodology can be used in screening Class 1E equipment for potential aging-seismic correlation. The methodology can be developed further to evaluate the age sensitivity of the seismic capacity of the equipment. To perform an aging-seismic analysis a materials analysis must be done to determine if the rate of degradation is significant in the parts of the equipment which are critical to the safety-related function. A seismic loading analysis is performed on the weak link parts and the results used to assess the probabilities of their failure.

To show how this methodology can be used, it was applied to motors and batteries using engineering approximations when data was not available. These examples showed how the aging-seismic correlation is related to:

- Number of age-degradable weak link components
- Rate of degradation in weak link components
- Seismic stresses on weak link components
- Failure strengths of weak link component

There are several areas where further work might be performed before the proposed Probabilistic Failure Analysis method is applied:

(a) Failure criteria for weak link components should be established. Without this, it is not possible to state when a weak link component has failed. For evaluating mechanical failure, only one failure criteria (i.e., the one associated with failure during a seismic event) should be considered.

(b) Failure probability criteria should be proposed for equipment components, and equipment which are consistent with the system reliabilities established by the reactor vendors.

(c) Simple weak link models for which degradation and applied loads may be easily analyzed should be physically tested. The easiest models to use may be tensile strength test specimens which have been aged from zero to the equivalent of 40 years (as an example). By using specimens of typical electrical insulation materials, the failure distributions for different levels of aging and applied loads could be better defined. The analysis and testing of simple commercially available parts such as terminal blocks might be a next step in examining the reliability of the Probabilistic Failure Analysis methodology.

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APPENDIX A

SEISMIC LOADING ANALYSIS ON BATTERIES

The objective of this analysis is to evaluate the seismic response of lead acid batteries during a seismic event. The response is obtained by developing an analytical model of the battery and evaluating its response to various static and seismic loading conditions. Described in this section are the assumptions and the procedure used to determine the stresses in the components of a battery.

The Exide lead acid battery, Model FOP-31, is selected for the purpose of this analysis. This typical battery consists of a plastic cover, case, positive and negative lead alloy plates, posts and a bridge insert. The plates are immersed in the electrolytic fluid in the cell.

It has been shown that the battery does not have any resonant frequencies below 33 Hz (2-28). Therefore, the battery can be considered to be "rigid." The analytical model considers the battery components as beam elements. The negative and positive plates are supported by the posts at the top and the bridge insert at the bottom. It is assumed that ten percent of the dead weight is taken by the posts. For seismic loading, however, all the load is transferred to the cell cover through the posts. These loads are then transferred to the cell walls which are fixed at the base. It is assumed that the electrolytic fluid in the cell does not have any resonant frequencies < 33 Hz. Therefore, a uniform hydrostatic pressure is imposed on the cell wall to represent the fluid acceleration. Using this model the element forces and moments are calculated. The stresses are obtained from those forces and moments.

Since the battery is rigid, the Zero Point Acceleration (ZPA) from the Required Response Spectra (RRS) can be used as the seismic input. For this analysis, the RRS was taken from IEEE P-744 (2-27), which was developed for 80% of the locations in the USA. Since the ZPA is used, damping is of no concern.

The approach to evaluating the battery response discribed in this section is conservative. A more refined analysis can be performed by developing a finite element model of the battery.

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This paper presents a new method of analysis for evaluating the effect of aging in electrical equipment on the seismic capacity. The method is based on the probability of mechanical failure of weak link materials which may be subjected to a load during an earthquake. It is shown that aging-seismic correlation is related to: number of age-degradable weak link components, rate of degradation in weak link components, the seismic stresses on the components and component material failure. Before conducting the Probabilistic Failure Analysis, preliminary screening for equipment with potential aging-seismic correlation is performed.

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