DE94 012584

CONTRACTOR REPORT

SAND93–7068 • UC–523
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Aging Management Guideline for Commercial Nuclear Power Plants – Power and Distribution Transformers

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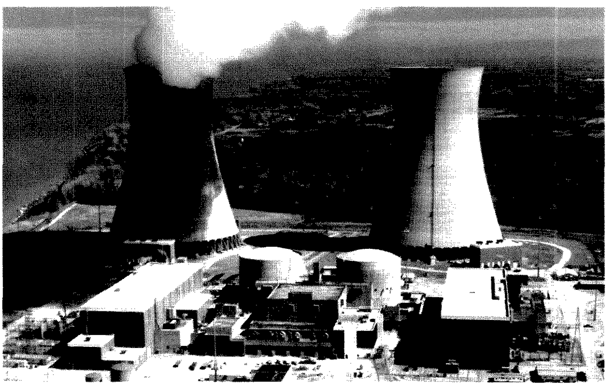

Prepared by Ogden Environmental and Energy Services, 1777 Sentry Parkway West, Abington Hall, Suite 300, Blue Bell PA, 19422, under contract to Sandia National Laboratories for the U.S. Department of Energy, in cooperation with the Electric Power Research Institute.

Funded by the U.S. Department of Energy under Contracts DE-AC04-76DP00789 and DE-AC04-94AL85000.

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SAND93-7068
Unlimited Release
Printed May 1994

Distribution
Category UC-523

AGING MANAGEMENT GUIDELINE FOR COMMERCIAL NUCLEAR POWER PLANTS-POWER AND DISTRIBUTION TRANSFORMERS

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Abstract

This Aging Management Guideline (AMG) provides recommended methods for effective detection and mitigation of age-related degradation mechanisms in power and distribution transformers important to license renewal in commercial nuclear power plants. The intent of this AMG to assist plant maintenance and operations personnel in maximizing the safe, useful life of these components. It also supports the documentation of effective aging management programs required under the License Renewal Rule 10 CFR Part 54. This AMG is presented in a manner which allows personnel responsible for performance analysis and maintenance to compare their plant-specific aging mechanisms (expected or already experienced) and aging management program activities to the more generic results and recommendations presented herein.

Acknowledgments

Preparation of this Aging Management Guideline was performed by Ogden Environmental and Energy Services, under the direction of the Department of Energy's Light Water Reactor Technology Center at Sandia National Laboratories, Advanced Nuclear Power Technology Department 6471. Funding for this guideline was provided by the Department of Energy Light Water Reactor Safety and Technology Branch, NE-451. Toledo Edison Company's Davis-Besse plant acted as the "host" utility and provided plant-specific data that helped to benchmark this report. Review and comments were provided by members of the Electric Power Research Institute (EPRI) Life Cycle Management (LCM) Subcommittee. Participation by personnel from the Davis-Besse plant is gratefully acknowledged, as is participation of the EPRI LCM Subcommittee reviewers. Cover photograph of the Perry Nuclear Power Plant provided courtesy of Cleveland Electric Illuminating Company. We also acknowledge the many survey respondents who provided data that helped to benchmark this guideline.

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4. APPLICABLE STRESSORS AND AGING MECHANISMS

4.1 Determination of Stressors Acting on Components

During operation, power and distribution transformers are exposed to a number of stressors that can lead to deterioration. These stressors may act individually or in combination with one another to produce an aging mechanism. The following discussion of stressors is provided to facilitate development of the discussion of aging mechanisms and age-related degradation that may occur in transformers. The potential stressors are:

- Temperature (ambient and internally generated)
- Voltage
- Mechanical and electrical cycling of auxiliary components
- Non-seismic vibration
- Radiation.

Although not directly producing stress, humidity, dirt, dust, and contamination may magnify the effects of the stresses acting on the transformer and can lead to deterioration of transformer components.

Temperature

Temperature exposure causes thermal deterioration of organic materials used in transformer subcomponents (such as insulators, structural members, and lubricants). Temperatures affecting transformers are associated with the ambient environment and temperature rise resulting from winding, core, and other losses. Elevated temperature existing in various portions of the transformer will cause gradual insulation deterioration; higher temperatures will result in more rapid degradation. Areas with elevated localized temperatures (hot spots) may develop in the windings as a result of blocked spaces or channels between windings, sharp bends in the winding, variations in magnetic flux density, and other factors. These hot spot temperatures can vary significantly from the average temperature of the winding, thereby causing accelerated degradation of any nearby winding insulation or other organic components. In addition, development of a high resistance connection in a primary current-carrying path can cause rapid deterioration of the surrounding insulating material due to ohmic heat generated. Heat generation by control circuits and other low-current components is considered negligible, except with respect to individual components whose temperature may be substantially elevated by internal heat production (such as coils of continuously energized relays).

Temperature effects may be mitigated in varying degrees by the cooling systems serving the transformer; this is based on such factors as the effectiveness of the cooling system, the existence/location of any hot spots, and ambient conditions. Generally, the ambient temperature surrounding indoor transformers is controlled between 21°C [70°F] and 29°C [85°F] and does not reach the 40°C [104°F] normal temperature limit assumed in transformer design and manufacturing standards. Transformers located outside may be subjected to more extreme temperature conditions (such as sustained periods of high temperature resulting from ambient/solar radiation, or sub-zero temperatures). Large power transformers used at nuclear power plants (such as start-up transformers) are frequently located in outdoor areas having

potentially severe environmental factors. (See Section 3.5.2 for a discussion of these environments). Smaller power transformers and distribution transformers are generally placed indoors, and hence are not subject to such severe conditions.

Voltage and Current

Stressors associated with the electrical functions of transformer components may also lead to age-related degradation. Electrical stressors are caused either by extreme voltage gradients from over-voltage transients, spikes, and fault interruption, or continuous energization at normal voltage levels.

Fault currents and inductive surges/electrical transients can cause stressors which contribute to insulation breakdown and winding/core dislocation. When an electrical pulse is applied to a transformer, the voltage does not distribute uniformly throughout the windings. Based on the type and duration of pulse applied, portions of the winding insulation will be stressed more severely than others. These stressors can ultimately result in localized breakdown of the insulation causing turn-to-turn shorts, flashover to ground, or flashover between phases. Lightning strikes are especially degrading to transformers; lightning may generate voltages in excess of 500,000 volts and 200,000 amperes; hence outdoor transformers and other susceptible equipment must be provided with appropriate protective devices such as lightning arresters. Excessive voltages and currents can also lead to deterioration of the bushings and other insulating components, and provide a source of heat for thermal degradation.

Energization at normal design voltage levels can significantly stress transformer insulation over the long term; the amount and severity of this stress is determined primarily by the dielectric strength of the insulating material used. Dielectric strength is defined as the maximum potential gradient a given material can withstand without breakdown; this value is usually given in terms of the breakdown voltage divided by the material thickness. The dielectric constant (or permittivity) is a measure of a material's ability to insulate against a potential gradient across it; it is a function of the sub-atomic composition of that material which varies with temperature, frequency, and several other factors. For a given potential gradient, the voltage drop across each of the materials interposed between that gradient will vary inversely with the material's dielectric constant; the highest fraction of voltage drop will occur across the material of lowest dielectric constant. Hence materials with lower dielectric constants will usually be limiting in terms of the overall effective dielectric strength of the insulation system. Gas (or air) entrained in the insulating fluid of a transformer is of particular concern in that the dielectric constant of the gas is low in relation to the surrounding fluid; hence, the gas pocket will be stressed more highly than the fluid and other insulation while, at the same time, having a lower dielectric strength. This can cause localized ionization and breakdown at the gas pockets which degrades the insulating material. Similarly, impurities and contaminants, particularly in the presence of moisture, can greatly reduce the dielectric strength of an insulating system. Extreme care must be used both during manufacture and maintenance to minimize the introduction of contaminants into the insulating system.

In some dry-type transformers, voltage and humidity can affect solid insulation that is dirty or deteriorated; this can result in surface tracking paths between phase and ground, and adjacent phases. Moisture in the tracking path will allow larger leakage currents to flow. The

leakage current flow will cause the moisture in the tracking path to evaporate; the leakage current will tend to remain constant such that the current density in the tracking path increases as moisture evaporates. This can result in localized burning of the insulation and ultimately insulation failure. Thermally deteriorated insulation, when exposed to humidity and dirt, may not only lose its surface insulating properties (in the form of surface current tracking), but may also lose its volumetric insulating properties. Thermally deteriorated insulation is most frequently brittle and prone to cracking. Leakage current, in addition to propagation across the surface of the insulation, may travel through the thickness of the insulation eventually resulting in flashover. Reasonable inspection and care of primary insulation systems in dry transformers should allow detection of surface and volumetric deterioration before it becomes severe.

Another phenomenon potentially affecting power and distribution transformers is internal electrostatic corona. This effect results from large potential gradients between conductors separated by air. A high electrostatic flux density results in ionization of the surrounding air; if the gradient is sufficiently large and the separation sufficiently small, complete dielectric breakdown (resulting in continuous discharge) may occur. Corona can occur between conducting surfaces internal to the transformer, such as between winding turns. Corona discharges are usually extinguished when the large voltage difference inducing its formation is reduced; however, the dielectric quality of organic materials may be reduced during each subsequent corona discharge. As a result, subsequent corona discharges will occur at progressively lower voltage levels. This process can continue until the corona extinction voltage level is less than the normal operating level, in which case the discharge will not extinguish and faulting will ultimately occur.

Currents may also be induced in transformer windings and components via geomagnetic interaction. Based on the intensity of the geomagnetic field present at a transformer's installed location, circulating currents of varying magnitude may be produced which can result in both increased losses and additional heat generation within the conductive elements of the transformer. This phenomenon has been identified as the cause of at least one main transformer failure at a commercial nuclear power plant; however, it is not expected to affect any significant portion of the total population of transformers covered by this guideline based on the specific environmental, design, and operational factors required for its occurrence. Accordingly, geomagnetically induced currents are not considered to result in age-related degradation and are therefore not considered further in this document.

Mechanical and Electrical Cycling

Cycling of transformer mechanical and electrical components such as oil pumps, fans, and load tap changers places stress on these components and may cause them to degrade or deteriorate with time. Cycling can vary significantly between individual transformer components, based primarily on their frequency of use. For instance, cooling system components may operate continuously or intermittently based on transformer load and ambient conditions; tap changers or pressure relief valves, on the other hand, may operate very infrequently (for example, only during shutdown conditions or periodic testing). Those components cycled or operated more frequently will experience significantly more wear and cyclic fatigue of mechanical internals, due to both mechanical stresses encountered during operation and any self-induced vibrational stresses such as those from rotating assemblies. Wear of moving parts can result in the loss of tolerances

or loss of adjustment. Components requiring lubrication (pump motor or fan bearings) may also experience accelerated wear due to deteriorated or displaced lubricants.

Mechanical stress may also be placed on transformer components via continuous heating/cooling. Heating occurs as a result of core, winding, and other losses, as well as changes in ambient temperature and incident solar energy; heat generated in the unit is generally related to the operating load. Cooling results from heat removal by the cooling system, conduction convection/radiation by the transformer enclosure, variations in the ambient/solar conditions, and variations in load. As a result of these competing heating and cooling effects, the temperature of many transformer components (i.e., the insulation, windings, cooling system components, etc.) will fluctuate with time. This fluctuation creates thermal stress on these components in varying degrees, as determined by their material (thermal expansion coefficient) and design, and may eventually result in fatigue of these components. Cyclic fatigue may be manifested as stressing or cracking of both organic and inorganic (i.e., metallic) subcomponents.

Non-Seismic Vibration

Non-seismic vibration may also induce mechanical wear, fatigue cracking, loss of tolerances/adjustment, and loosening of subcomponents. Vibration will produce varying amounts of wear and stress over time depending on a number of factors such as the mass of the subcomponent, its material composition, the frequency of oscillation, the rigidity of its mounting, tolerances between it and other subcomponents, etc. Notches, fatigue cracks, loss of tolerances or calibration, or other manifestations of wear may eventually result from long-term exposure to this type of vibration. For components such as pumps and fans, the vibrations may be self-induced due to the operation of the motor or hydraulic effects. It should be noted that heavy external non-seismic vibration is not normally imposed on power and distribution transformers in that they are not usually located adjacent to large vibrational sources, and are usually mounted on vibration-resistant foundations. Additionally, many transformers use vibration-resistant mountings for their internal components (such as the core and coils assembly) to effectively isolate these components. However, self-induced vibration (AC "hum") of the core and windings may produce loosening or losses of critical tolerances in other components, potentially resulting in their failure.

Radiation

Radiation should not be a significant environmental factor for most transformers because the units are located either in plant areas that are accessible under most design basis conditions or outdoors. Ionizing radiation may reduce a material's dielectric strength and integrity by causing breakdown of insulation polymer chains, cracking of some plastics, and the formation of gas bubbles in oil. Yet for most power and distribution transformers, the maximum integrated normal and accident radiation doses would be expected well below 10^3 gray [10^5 rad] (up to sixty years), which would not cause significant deterioration of transformer materials. Any units used in areas with higher radiation doses (possibly small distribution transformers) are qualified by analyses or tests. Generally, the largest portion of the radiation dose is associated with an accident environment, and little or no radiation-induced damage is expected under normal conditions.

Contaminants/Moisture

Several types of degradation may result from exposure of the transformer to moisture and other contaminants. For example, intrusion of moisture or foreign substances through leaks in transformer components (such as degraded sample valves or relief valve seals) can contaminate the insulating fluid thereby resulting in a variety of deleterious effects ranging from accelerated sludge formation to dielectric breakdown and eventual transformer insulation failure. Dust, salt, and other airborne contaminants can accumulate on bushing exterior surfaces and, in conjunction with moisture or humidity, create the conditions that may lead to bushing flashover. Contaminants and moisture, in combination or acting independently, can result in deterioration of the transformer structural components; the housing may corrode and/or rust if exposed to contaminants and/or moisture such that the structural members and fasteners will weaken. In some instances, foreign matter may also affect the contact surfaces of relays, magnetic contactors, and other electrical components used within the transformer housing, potentially interfering with the performance of a component's required functions. Exposure to contaminants may degrade mechanical components via increased friction (leading to wear), stiffening or freezing of moving components, hardening and deterioration of lubricants, and embrittlement of non-metallic materials. [4.1]

Table 4-1 summarizes the stressors acting upon power and distribution transformers and indicates the aging mechanisms, types of degradation, and failure modes that may result from exposure to these stresses. [4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9, 4.10, 4.11]

Table 4-1. Stressors, Aging Mechanisms, Potential Failure Modes

(Note: Aging mechanisms, age-related degradations, and failure modes apply to both liquid and dry-type transformers unless otherwise noted.)

Stressor	Intensifiers	Aging Mechanism	Age-Related Degradation	Potential Failure Mode	Comments
Temperature	Acidity of insulating fluid	Thermal deterioration	Loss of mechanical and electrical properties of solid insulation	Dielectric breakdown; flashover	Generally a slow process
	Ohmic heating; winding and core losses	Thermal deterioration; cracking	Loss of dielectric strength of organic winding and electrical connection insulation	Dielectric breakdown; flashover	
	Contaminants	Thermal deterioration of lubricants	Binding and high friction; wear	Seized motor bearings, load tap changer components, valves, and enclosure door hinges	

Table 4-1. Stressors, Aging Mechanisms, Potential Failure Modes (Continued)

Stressor	Intensifiers	Aging Mechanism	Age-Related Degradation	Potential Failure Mode	Comments
Temperature (continued)	Moisture and contaminants; dielectric stress	Thermal decomposition of insulating fluid (liquid only)	Loss of dielectric strength; sludge and/or gas formation	Localized breakdown and gas formation	Detected by periodic sampling and analysis
Voltage	Contaminants; moisture	Accumulation of contaminants on bushing weather shield	Loss of surface insulating properties; surface tracking	External flashover of bushing between phase and ground	Accelerated in high dust, salt, and moisture environments
	Gas pockets or other low dielectric contaminants	Degradation of insulating fluid (liquid only)	Fluid decomposition and deterioration; gas formation	Localized breakdown of insulating fluid; eventual flashover and possible explosion	Detected by periodic sampling and analysis
	Low dielectric strength contaminants (such as gas or particulates)	Ionization and corona breakdown	Degradation of insulating materials	Dielectric breakdown; flashover	
Current	External fault or surge conditions	Electromagnetic forces on conductors/core	Movement or dislocation of windings and/or core	Loss of spacing of windings; turn-to-turn shorts	Not significant at normal current levels
Mechanical and Electrical Cycling	Deteriorated lubricants in auxiliary components	High friction between moving parts	Wear	Binding of tap changer, pump, or fan motor bearings, and valves	Increases with increasing duty cycle
	Voltage; contaminants	Pitting or erosion of auxiliary device contact surfaces	Degradation of electrical components	Misoperation of load tap changer; loss of cooling components	Increases with number of make/break operations
Non-Seismic Vibration	Loose internal components	Cyclic wear/ fatigue	Wear and possible cracking of components; loss of tolerances, misalignment	Binding; component deformation or breakage	

4.2 Determination of Applicable Aging Mechanisms

Aging mechanisms were identified by considering the effects of stressors on each transformer component (Section 4.1) and the operating experience of each component (Section 3.6). Those aging mechanisms considered to be significant are discussed in Section 4.2.1. Those aging mechanisms considered to be non-significant are discussed in Section 4.2.2. Those aging mechanisms that have not yet been experienced because equipment has not aged sufficiently (assuming current preventive maintenance will not prevent failure) are discussed in Section 5.4.2.

4.2.1 Significant Aging Mechanisms

An aging mechanism is significant when, if allowed to continue without detection or mitigation measures, it will cause the component or structure to lose its ability to perform its required function. The following text discusses each significant aging mechanism for both liquid-immersed and dry-type power and distribution transformers. For definitions of aging terminology, see Appendix A.

4.2.1.1 Metal Enclosure (Tank) and Cover

Significant aging mechanisms for the transformer enclosure are:

- material degradation
- deterioration of organic sealing components
- metal fatigue
- loss/over-torquing of fastening components

all leading to a potential loss of structural or leak-tight integrity.

The first aging mechanism, material degradation, can take various forms, including rust or corrosion of metal surfaces and physical damage to enclosure components. Many transformers (especially the larger units) are located outdoors and are therefore exposed to the extremes of temperature, humidity, wind, and solar exposure. Chipping, cracking, or peeling of the enclosure's protective coating exposes the metal allowing the formation of rust and corrosion (most enclosures are fabricated from low-alloy steel which is highly susceptible to this type of effect). Moisture (i.e., condensation) may collect in areas of lower relative temperature such as the interior of the tank, cover, and any external electrical enclosures, thereby facilitating the degradation of these materials.

The second aging mechanism, deterioration of organic components, can occur as gaskets or other organic seals used in the construction of the enclosure degrade due to exposure to heat, ultraviolet radiation, moisture, or chemicals, while under mechanical stress or compression. Polymeric seal materials embrittle and harden with age and exposure, and generally must be replaced periodically, depending on the specific conditions present in their service environment.

The third aging mechanism, metal fatigue, can result from cyclic vibrational or thermal stresses placed on the enclosure (such as repeated heatup and cooldown cycles, operation of cooling system pumps and fans, or ac-induced hum). This can affect areas of high local stress

such as welds, tank edges, etc., resulting in tank leaks (oil or gas-filled units) and potentially a loss of structural integrity.

Loss of fastening components, although not a specific aging mechanism, can also degrade the structural integrity of the enclosure by weakening joints, flanges, and other sealing surfaces or allowing components mounted to the enclosure to vibrate excessively (such as fans or other motors). The loss of fastening components can be caused by equipment vibration during operation or result from improper maintenance techniques.

Because each of the aging mechanisms described above can result in a loss of the structural and/or leak-tight integrity of the transformer tank, they are considered significant for systems which rely on these types of integrity for their operation (i.e., liquid-immersed or sealed dry-type transformers). The most probable result of loss of structural integrity is tank leakage. Insulating fluids or gases may escape or contaminants may enter with the ultimate result of breakdown of the insulation.

4.2.1.2 Primary and Secondary Windings

The significant aging mechanisms for the primary and secondary windings and their electrical connections (in both liquid-immersed and dry-type transformers) are:

- degradation of organic insulating materials
- formation of localized hot spots
- loosening of the winding mounting system
- winding connection (conductor) failure

These mechanisms are discussed for each type of transformer in the following paragraphs. Insulation system aging mechanisms are discussed in Section 4.2.1.4 below.

Liquid-Immersed Transformer Windings

Degradation of organic insulating materials in liquid-immersed transformers occurs as a result of several influences, including exposure to heat, chemicals in the insulating fluid, as well as dielectric stress. Insulation systems in these transformers consist of both solid and liquid materials, each being susceptible to somewhat different aging mechanisms (see Section 4.2.1.3 below). Protective coatings on the windings themselves are subject to thermal degradation due to heating of the windings; these coatings, however, generally have no insulating function and are therefore not necessary for maintenance of the necessary dielectric strength between individual turns of the windings.

Localized high temperatures may occur in transformer windings as a result of poor insulating fluid flow (which acts to cool the windings) and high resistance areas of the winding due to sharp bends, variations in conductor diameter, or improperly made connections. These "hot spots" may have temperatures significantly above the average of the overall winding, and may induce accelerated degradation of surrounding organic materials. Poor insulating (cooling) fluid flow is generally the result of loss of separation between windings, either due to clogging by impurities (such as sludge formed by exposure of the fluid to oxygen), or physical movement

of the winding or supports. High resistance portions of the winding related to variations in conductor diameter are rare in that design of the winding is such as to minimize these effects. However, high resistance connections between windings and leads have been documented.

Loosening of winding mounting system can result from shipping of the transformer, normal operation (vibration), fault-related movement, or maintenance. Materials used to support the windings and core may degrade with time (many are fabricated from solid insulating materials) or loosen thereby allowing movement of the windings in relation to one another or the core under inrush or fault conditions. Core-to-winding and winding-to-winding tolerances are critical to maintaining satisfactory dielectric strength, therefore movement of these components with respect to each other can result in dielectric breakdown and localized discharge.

Although not a specific aging mechanism per se, conductor damage will potentially result in the loss of transformer function. Failure of the winding conductor is generally the result of either a pre-existing manufacturing flaw in the winding, a poorly made electrical connection (such as a braze or crimp), or a severe electrical transient which results from either an internal or external stimulus (such as loss of conductor tolerances described above, or exposure to short-duration transients or surges). Short-duration voltage transients will not affect the windings uniformly. Initially, current will flow preferentially through the shunt capacitance near the line-end of the winding; this produces a substantial voltage drop in these portions of the winding. Additionally, oscillations occur in the windings which affect various portions of the winding and insulation system based on their frequency and characteristics. In general, liquid transformers are more able to withstand severe electrical transients (such as lightning strikes and surge impulse voltages) than their dry-type counterparts (discussed below); this is primarily due to the physical properties of the immersion fluid (as opposed to the insulating medium used in dry transformers).

Dry-Type Transformer Windings

Failure mechanisms for dry-type transformer windings are similar to those for the liquid-immersed units described above, with the exception that the windings are not cooled by insulating fluid; rather, these transformers use air/gas (either forced or natural circulation) or a solid insulating material (such as resin) to dissipate heat generated in the windings. Similar to liquid-immersed units, these transformers may suffer degradation of the winding insulation (and coating, if used) due to thermal degradation induced by the windings and the lack of cooling. Air passages may become plugged with dirt or other contaminants, thereby creating hot spots and their resulting high temperatures. Resin-encapsulated or other sealed windings generally are not subject to this type of degradation, as there are no air passages to become obstructed by foreign materials.

In addition to obstruction of air passages, reductions in the spacing between windings (such as those resulting from movement of the winding due to fault currents, vibration, etc.) can occur and elevate the dielectric stress placed on the insulation present in the gap; this elevated stress in turn increases the potential for dielectric breakdown/corona discharge. A similar phenomenon may occur in resin-encapsulated transformers, where voids (bubbles) present in the resin during formation create areas of low dielectric strength, thereby allowing corona discharge and possible failure with time.

Airborne chemical vapors (such as paint fumes, solvents, etc.) may also come in contact with the winding surfaces (coatings) and solid insulation, thereby resulting in contamination or deterioration of these substances. Contamination could result in a loss of surface insulating capabilities.

Degradation of winding conductor connections has been documented; IE Information Notice 83-37, "Transformer Failure Resulting From Degraded Internal Connection Cables," [4.12] describes a failure due to an in-rush current on a dry-type ITE 4160-/480-Vac transformer initiating major arcing in the transformer winding tap lug causing the transformer failure. The failure was attributed to improper assembly of transformer winding tap cables and long-term undiagnosed, heat-induced degradation. It was believed that the set screw, which attaches the cable to the barrel of the lug, was over-tightened during installation, which caused some of the aluminum stranded wire to break, thereby creating a high resistance joint. Arcing is thought to have started in the barrel of the lug as a result of the resistance joint. Long-term localized heating of the terminal lug over a period of time weakened and degraded the connection.

Winding loosening and misalignment has been documented; examination of several transformers experiencing sustained overload, fault, and surge conditions has indicated dislocation of the winding turns, solid insulation and spacers, and core. [4.6, 4.7]

Because the primary and secondary windings and their connections are essential to the continued operation of both liquid-immersed and dry-type transformers, the degradation mechanisms described above are considered significant.

4.2.1.3 Magnetic Core

The significant degradation mechanisms for the magnetic core are:

- loosening of the core mounting system
- core material embrittlement

Each of these may result in the inability of the transformer to perform its required function.

Loosening of the core can result from loosening of its mountings due to vibration, shock, or severe electrical transients. Impacts or shocks received during shipping or installation can cause movement of the core on its mountings. Forces induced on the core after installation during electrical transients (by virtue of the magnetic interaction of the core, the windings, any surrounding materials) can be substantial and can loosen or permanently dislocate the core from its initial position. Fault currents (on the order of 10 to 20 times the rated output current) can induce severe forces on the conductors and core, as can surges resulting from proximate lightning strikes. Wear or deterioration of the insulation once dislocation occurs may lead to sufficient insulation damage to allow electrical failure.

Core embrittlement occurs primarily in older cores as a result of the relatively high thermal exposure resulting from core and winding losses. This embrittlement can result in weakening or failure of the laminations by which individual core segments are held together,

thereby potentially creating increased eddy currents and core losses. Although spontaneous core failure due to embrittlement was not noted in any of the documentation reviewed during preparation of this AMG, instances of core embrittlement encountered during repair/refurbishment have been noted. Newer cores appear less susceptible to this phenomenon due primarily to advances in manufacturing techniques, materials science, and reduced core losses (and therefore heat generated) in the newer cores. Because the core and its integrity are essential to the operation of the transformer, core loosening and embrittlement are considered significant.

4.2.1.4 Insulation System

Liquid-Immersed Transformer Insulation

Degradation of organic insulating materials in liquid-immersed transformers occurs as a result of several influences, including exposure to heat, chemicals in the insulating fluid, as well as dielectric stress. Insulation systems in these transformers consist of both solid and liquid materials, each being susceptible to somewhat different aging mechanisms. The most significant degradation mechanisms for the insulating fluid are:

- gaseous formation/dielectric breakdown
- particulate and/or moisture contamination
- high acidity
- oxidation (sludge formation)

The primary degradation mechanisms for solid insulation used in liquid transformers are:

- thermal decomposition of organic materials
- decomposition due to dielectric stress

Due to the importance of the insulating system to the operation of the transformers, these aging mechanisms are deemed significant.

Dielectric stress is produced in the insulating fluid as a result of the potential gradient across various portions of the windings and other components. Generally, the dielectric stress placed upon a material during operation of the transformer is related to its dielectric constant; materials with lower or reduced dielectric constants will experience an elevated stress as compared to other materials with higher constants. For example, gas pockets formed in the insulating fluid are exposed to substantially more dielectric stress than the surrounding insulating fluid; this may result in partial or localized breakdown of the dielectric capacity of the material (partial discharges) which may in turn produce other deleterious effects such as the formation of additional gaseous byproducts, decomposition of the surrounding insulating fluid, and ultimate failure of the insulation system.

Gaseous by-products formed from the breakdown of insulating fluids may include both combustible and non-combustible gases such as carbon monoxide, hydrogen, ethylene, and acetylene. During normal operation, liquid-filled transformers have small concentrations of these and other gases (especially if an inert gas pressurization system is used) dissolved in the insulating fluid. The transformer may experience no adverse effects under these conditions;

however, cooling of the transformer may result in a substantially lower pressure in the tank which may in turn allow additional gas in the insulating fluid to come out of solution, potentially forming pockets of low dielectric strength bubbles in the fluid. It should be noted that for liquid transformers equipped with inert gas systems, the formation of gas bubbles or pockets during cooldown is mitigated through the pressurization of the void space above the insulating fluid with inert gas.

Particulates, contaminants, and moisture introduced into the insulating fluid can result in a number of different effects. Particulates or contaminants entrained in the fluid will eventually be circulated through the winding interstitial regions; this may result in blockage of these passages leading to reduced localized heat dissipation or hot spots. Chemical contaminants in the insulating fluid may have adverse effects on the material properties (such as pH, viscosity, etc.) of the fluid which can in turn result in other adverse effects on transformer components over the long term. Water is especially damaging to the dielectric capability of the insulating fluid; any appreciable concentration may result in failure of the transformer during operation due to dielectric breakdown as described above. Transformer fluids (such as mineral oil) normally can maintain a small amount of water in solution (usually less than 10 ppm at 70°C [158°F]); at these levels there is little if any appreciable effect on the dielectric strength of the insulating fluid. However, increases in the amount of water in the fluid, whether in solution (by virtue of other substances in the fluid such as acids which increase the solubility of water in the fluid) or coalesced in pockets, may dramatically reduce the dielectric strength of the insulating system and result in partial discharge or complete dielectric breakdown.

High acidity in the insulating fluid can have a number of damaging consequences. As indicated above, the acidity of the fluid can affect its ability to maintain water in solution; higher acidity generally equates to more water capable of being held in solution and therefore reduced dielectric strength. High acidity also can affect the deterioration and decomposition of solid insulating materials used as supports and braces in liquid-immersed systems; higher acidity has been demonstrated to accelerate the rate of decomposition of various solid insulations thereby reducing their dielectric capability.

Exposure of the insulating fluid to oxygen (air) can lead to the formation of sludge (a highly viscous, tar-like substance) in the oil as a result of the chemical reaction of the oil with oxygen. This sludge can be damaging to the transformer in that it may block oil channels in the windings (creating hot spots) and reduce the efficiency of the cooling system in general. Dielectric properties associated with the sludge may also differ from those of the host insulating fluid. Various additives such as ditertiary butyl paracresol (DBPC) have been used to inhibit the formation of sludge in oil due to oxygen. Exposure to oxygen will also increase the acidity of the insulating fluid (see preceding paragraph).

Degradation of the insulating fluid in liquid-immersed transformers as described above has been extensively documented. For example, INPO SER 24-84 [4.13] describes the failure of several nuclear plant transformers resulting in fires. See Section 3.6.1 for additional details.

Dry-Type Transformer Insulation

The primary aging mechanisms for the insulation used in dry-type transformers are:

- thermal deterioration/dielectric breakdown

Depending on the configuration of the individual unit, air, inert gas, fluorogas, or resin may be used as the primary insulating substance. In addition, solid insulation used in the support or construction of the core and windings (usually fabricated from resins, mica, asbestos, etc.) and any coatings on the windings themselves (high temperature resins or enamels) will be subject to thermal degradation.

For air-insulated, air-cooled dry-type transformers, degradation of the insulation is less of a concern; free interchange of air provides the transformer with a limitless supply of new insulation. These units are, however, subject to contamination of the windings and interior surfaces with airborne dust and other contaminants entrained in the air (see Section 4.2.1.2. above). This can result in the fouling of airflow paths or closing of gaps causing localized hot spots or corona discharge sites that can result in degradation of the insulation. For sealed systems (including air, inert gas, fluorogas, and resin), the volume of insulating material is finite, and certain of these substances may be subject to thermal degradation. This is particularly true of solid resin-encapsulated transformers; the resin is in direct physical contact with the windings and core (heat source), thereby subjecting it to accelerated thermal aging. Sealed, gas-filled transformers may also develop leaks which allow escape of the insulating gas and possible intrusion of external contaminants.

Thermal deterioration of solid insulation in dry-type transformers has been documented; for example, NRC Information Notice 92-63, "Cracked Insulators in ASL Dry Type Transformers Manufactured by Westinghouse Electric Corporation," [4.14] addresses the cracking of high-voltage winding ceramic insulators on ASL Dry Type Power Center 4160/480 V 3-phase transformers manufactured by Westinghouse. IN 92-63 indicated that an insulator cracking could have a catastrophic effect on the structural integrity of the transformer. [4.1, 4.3, 4.4, 4.6, 4.7, 4.15, 4.16, 4.17, 4.18, 4.19, 4.20]

4.2.1.5 Bushings

Significant degradation mechanisms for bushings include:

- degradation of organic materials
- contamination of insulating surfaces
- deterioration/leakage of inert gas
- electrical connection loosening

Organic components used in bushings may include kraft paper condenser insulating layers (usually soaked in oil or other insulating fluid), various polymeric resins used as insulation, and rubber, asbestos, or composite gaskets used to seal the bushing against leakage or to seal the bushing against the tank. These materials may be subject to a variety of degradation mechanisms such as thermal aging, exposure to ultraviolet radiation (exposed components), exposure to

insulating fluids and other chemicals, and exposure to moisture. Kraft paper insulation is normally designed to operate while impregnated with insulating oil; improper storage or handling of the bushings prior to installation may result in drying out of the paper which can dramatically reduce its dielectric capabilities. Gaskets and seals used in the construction of the bushing may degrade over time with exposure to the elements (humidity, ultraviolet radiation, etc.) as well as heat generated by the bushing conductor, transformer, and incident solar radiation. All organic materials used in the fabrication of the bushing are subject to thermal degradation from these heat sources.

Contamination of insulating surfaces appears to be a significant degradation mechanism for transformer bushings, especially for outdoor units. External protective components such as the porcelain rain shield can accumulate significant quantities of dirt, dust, salt, and other contaminants from the environment; these contaminants, alone or in conjunction with rain, spray, or condensing humidity conditions, can result in the formation of a conductive path (tracking) along the surface of the rain shield which eventually leads to flashover of the bushing.

Depending on the construction of the bushing, it may contain insulating fluid (typically oil), inert gas, or both. Oil in the bushing is not exposed to atmosphere (air in the free space above the oil in the bushing is usually displaced with a charge of inert gas), and is generally not subject to many of the same types of degradation that transformer insulating fluid is. Therefore, unless the bushing seals are damaged, the only applicable degradation mechanisms for bushing fluid are exposure to heat and dielectric stresses. Heat is produced by the conductor (located at the bushing center), as well as from external sources (solar radiation, conduction with the transformer tank, etc.). Dielectric stress results from the potential gradient created between the central conductor and other surfaces. No degradation of the inert gas charge (other than leakage as described in the following paragraph) has been identified.

Leakage of the insulating oil and/or inert gas charge may occur as the seals of the bushing degrade, or as the result of damage or other conditions. Leakage of the insulating fluid from the bushing will eventually result in dielectric breakdown between the bushing conductor and other surfaces on the interior of the bushing. Because the bushing oil reservoir is not connected to the main tank insulating fluid, there is a finite volume of oil in each oil filled bushing. Most of these bushings, however, have some provision for periodic measurement of the oil level (either by gauge, sight glass, or direct measurement) which assists in the detection of this problem. Signs of leakage may also be detected during routine visual inspections or testing.

Additionally, leakage of the inert gas charge and subsequent depressurization of the bushing interior may expose the bushing insulating fluid to various ambient conditions (such as oxygen, moisture, and other contaminants) which may accelerate the deterioration of the fluid; this effect is expected to be small unless there is a significant interchange between the bushing internal and external environments.

Loosening or weakening of the bushing electrical connections may result from improper strain or mechanical stress. Excessive strain on the connectors can deform connecting hardware or other portions of the bushing. Under extreme circumstances, this can result in failure of the connections or damage to other bushing components.

Bushing failure has been documented in several instances; accordingly, the aging mechanisms described above are considered significant. IE Information Notice 82-53, "Main Transformer Failures at the North Anna Nuclear Power Station," [4.21] describes four bushing to ground failures and suggests that the improper storage of the bushings was a significant contributing factor. Additionally, INPO SER 13-85 [4.22] describes several transformer insulator (bushing) phase-to-ground flashovers resulting from combinations of condensation, salt accumulation, dust, and chalk powder. [4.1, 4.3, 4.4, 4.19, 4.23, 4.24]

4.2.1.6 Cooling System

Liquid-Immersed Transformer Cooling Systems

Significant aging mechanisms associated with the cooling system are:

- wear and mechanical fatigue of the pump and fan bearings (motor and pump unit)
- wear and fatigue of the pump impeller/shaft assembly
- degradation of motor winding insulation
- electrical component degradation
- fouling of heat transfer surfaces

Wear and fatigue of the bearings associated with the insulating fluid pump(s) and cooling fan(s) occur as a result of the routine operation of these components. Bearings (such as thrust and journal bearings) are commonly used on both the driven unit (i.e., pump) and the driving motor (for fans these bearings are typically part of the motor); these bearings wear over time due to friction and other stresses placed on them. Bearing longevity is determined by several factors such as the type of bearing, type and frequency of lubrication, and service conditions; wear on bearings may be accelerated by such stresses as frequent motor starting and stopping, undue vibration or transverse/longitudinal load placed on the driven unit (such as an out-of-balance fan), and inadequate or degraded lubrication. In many cases, liquid-immersed transformer oil pumps are partially or totally immersed in the insulating fluid; this assists in the reduction of friction and wear of the bearings. Fan motor bearings may require periodic lubrication, although these are often sealed units.

Wear and fatigue of the pump impeller/shaft assembly may occur after extended periods in service; this generally takes the form of loss of shaft tolerances, vane wear, or pitting, and results in reduced pump efficiency and increased noise and vibration during operation.

Organic winding insulation used in motors of this type is subject to thermal aging similar to that of the transformer insulation system described in Section 4.2.1.4 above.

A variety of different electrical devices are used in the cooling systems of transformers, including fan and pump motor contactors, thermal overload relays, thermostatic sensors and switches, general purpose relays, fuses, and control wiring. In general, the aging mechanisms applicable to each component will depend on the type of component and its operating environment. Aging mechanisms for the these components are discussed in Section 4.2.1.10 below.

Another potential aging mechanism for liquid transformer cooling systems is fouling of heat transfer surfaces. Most of the larger liquid-filled units utilize some sort of radiator to dissipate heat generated in the insulating fluid; heat transfer surfaces (i.e., fins or tubes) on these components may become fouled with dirt, debris, or other materials such that either the surface is insulated or airflow around the surface is obstructed. This can be easily prevented by periodic inspection and cleaning of these components (see Section 5). [4.2, 4.4, 4.5, 4.19]

Dry-Type Transformer Cooling Systems

Aging mechanisms for dry-type transformers are:

- wear of the fan motor bearings
- degradation of fan motor winding insulation materials
- electrical component degradation

These aging mechanisms are analogous to those discussed for liquid-immersed transformers in the preceding paragraphs.

4.2.1.7 Oil Preservation and Sampling System

The aging mechanisms for the oil preservation and sampling system are:

- deterioration of organic and inorganic materials
- wear
- loss of component adjustment

The primary organic materials used in the oil and preservation systems include gaskets and seals used to maintain the leak-tight integrity of any preservation and sampling system components (such as piping, flanged connections, inert gas bottle connections, etc.), as well as the separation diaphragm or air cell (used in the modified conservator design). Exposure of these materials to elevated temperatures (such as those from the heated insulating fluid or from incident solar radiation) results in thermal degradation; this may also be exacerbated by exposure to moisture, chemical contaminants, and possibly ultraviolet radiation (exposed materials on outdoor transformers). The separation diaphragm used in conservator systems may also become permeable to gaseous diffusion with time such that it may allow appreciable exposure of the insulating fluid to oxygen and other airborne gases.

Material degradation of inorganic system components can occur due to exposure to the elements (sun, moisture, salts, etc.), normal operation, and damage from other external sources. For transformers located outdoors, exposed preservation and sampling system components such as the conservator tank, piping, and valves are susceptible to rust, corrosion, and exposure to ultraviolet radiation. Heat transferred to these components by the insulating liquid or solar radiation accelerates corrosion, as does exposure to moisture/high humidity. Additionally, paint or other protective coatings applied to these surfaces may eventually bubble, chip, or peel, exposing the underlying surface to corrosion.

Wear can occur in a number of preservation/sampling system components, including frequently operated sampling and isolation valves, fittings, and pressure regulating valves used to maintain gas pressure (inert gas design). Subcomponents susceptible to wear include valve stems, seats, and packing, as well as other mechanically operated devices or fittings. This can result in valve leakage or binding, and malfunction of the regulating valve(s).

Loss of adjustment can result in the improper operation of the inert gas pressure regulating system; generally, this system must be adjusted such that the lowest possible purge pressure (accounting for deadband and setpoint variance) does not overlap the highest possible charge pressure; this would result in rapidly emptying the inert gas supply used to pressurize the void space above the insulating fluid. Loss of the adjustment of regulating valves can result from wear of the valve internals, mechanical agitation or shock, and changes in the ambient environment. [4.1, 4.4, 4.19, 4.24]

4.2.1.8 Tap Changers

<u>Load Tap Changers</u>

Load tap changers are typically constructed of numerous different mechanical and electrical components such as motors, gears, contacts, contactors, relays, solid state devices, and braking assemblies. The primary aging mechanisms for tap changing devices are:

- wear of mechanical components
- deterioration/failure of electrical components
- degradation of organic insulating materials
- loss of adjustment of braking systems
- wear of main contact surfaces
- tap changer compartment leakage

Wear of tap changer mechanical components may occur as a result of normal operation as well as abnormal operation. The main power circuit components of a load tap changer components are mounted in a separate tank chamber and are immersed in insulating fluid, therefore requiring no lubrication. In some models, however, tap changer motors and other mechanical assemblies (such as the braking system) are located in a separate compartment and have greasable bearings which must be periodically lubricated in accordance with the manufacturer's requirements. Exposure of this lubricant to elevated temperatures generated by both the operation of the motor/assembly itself and external sources (such as the transformer windings) can result in the deterioration, hardening, and separation of the lubricant with time. This deterioration results in increased friction and therefore accelerated wear.

In addition to wear of the bearings and lubricated mechanisms, the braking assembly linings of the tap changer (where equipped) may also degrade with use due to friction. These linings utilize friction to accomplish braking of the mechanism, hence by design they will degrade with use. Wear due to friction is the only real degradation mechanism for these components. Brake lining materials may vary from transformer to transformer, and hence the wear characteristics may differ.

Based on the type of braking mechanism used, loss of adjustment may occur with time such that the effectiveness of the system is impaired. Generally, braking system effectiveness can be gauged by the torque required to turn the mechanism under braked and unbraked conditions. When properly adjusted, the brake will have minimum braking torque and still provide positive braking; an optimum setting uses less than half of the design torque of the system. This gives a considerable margin for adjustment as the linings wear. As the system is operated, frictional wear of the linings, along with vibration and other mechanical stresses placed on the components, can result in a loss of this adjustment.

Wear may also occur on the main contact surfaces due to the motion of the moving contacts in relation to the stationary contacts during normal tap changer operation. This wear is generally a function of the frequency of operation of the tap changer unit and load current levels, and may be significant for transformers with numerous or repeated use of the tap changer over the course of their installed lifetime.

Degradation may occur in any organic insulating materials used in the construction of the tap changer. These will include insulation used in the motor windings, insulators surrounding or mounted to the main contacts, and materials used in related electrical components such as relays, contactors, and wiring. Normally, the primary degrading influence on these materials is heat; thermal aging of organic insulating materials can reduce their dielectric as well as mechanical properties.

Electrical devices used in the load tap changing mechanism may include switches, relays, contactors, terminal blocks, breakers or interrupting devices, fuses, minor electrical components (such as resistors and capacitors), solid state components, and wiring. Degradation and aging mechanisms associated with these components are described in Section 4.2.1.10 below; a complete discussion is contained in Reference 4.2.

4.2.1.9 Protection and Monitoring Systems

As discussed in Section 3 of this guideline, numerous protection and monitoring devices are used in power and distribution transformers; the number and type of these devices installed on any given transformer depends on the rating of the equipment as well as its plant application. For the larger liquid-filled units, most if not all of the devices described are used in one form or another. In contrast, smaller dry units may have few or no built-in protective/monitoring components. Many of the devices are only applicable to the liquid type transformer; for example, a liquid level indicator would not be found on a dry system. Although the specific characteristics of individual protection and monitoring devices change from manufacturer to manufacturer, the general operating principles are often quite similar. Hence, the degradation discussed in the following paragraphs describe generic component aging mechanisms, and therefore must be considered in light of the individual application. [4.1, 4.4, 4.5, 4.19, 4.23]

Fault Pressure Relay

As described in Section 3.4, the fault (or sudden) pressure relay is used on liquid filled transformers to detect the pressure transients associated with internal faults. These faults generate rapid increases in pressure within the tank. The significant aging mechanism for these relays is

degradation of organic seals and gaskets. Wear or failure of internal relay mechanical components (such as springs, bellows, rocker arms, etc.) and failure of relay internal electrical components (switch contacts, wiring terminations, etc.) are considered non-significant, and are discussed in Section 4.2.2 below.

Degradation of organic materials used to seal the relay (both internally and to its transformer tank mounting flange) occurs as a result of exposure to heated insulating fluid or solar radiation over long periods of time; sustained exposure to heat and/or sun will eventually embrittle and harden the gaskets such that leakage may occur. In many designs, the sensing bellows and upper relay components are isolated from the hot insulating fluid (there is essentially no flow through the upper bellows portion of the relay), thereby exposing the gaskets in these regions to lower temperatures. Many of the gasket materials are also specifically designed for extended operation in contact with transformer insulating fluids. However, constant exposure of the gasket, which seals the upper and lower chambers from one another to hot insulating fluid, may result in its eventual failure.

Pressure Relief Devices

Aging mechanisms for pressure relief devices are:

- relaxation of the compression springs
- deterioration of organic sealing gaskets

Only the latter is considered to be significant. See Section 4.2.2.4.

Degradation of the organic seals of the pressure relief device may have an impact on the operation of the transformer over the long term. Due primarily to thermal degradation, these seals may harden, embrittle, and otherwise degrade to the point where they are incapable of performing their sealing function. Under conditions where the internal tank pressure is higher than that of the ambient (such as during a fault), the contents of the transformer tank will leak outward through the degraded seal causing a loss of inert gas and possibly even insulating fluid. Given a leak, the flow of gas may be inward or outward depending on variations in atmospheric and tank pressures (tank pressure may increase upon heating of fluid from operations or solar radiation). If the leak is small, the loss of inert gas and fluid (if any) will be slow and therefore present no threat to transformer operation. However, under vacuum conditions (such as those which might be encountered in the sealed tank type systems), leakage through the seal would be inward, thereby potentially introducing contaminants (such as air, moisture, and particulates) into the transformer tank and insulating fluid. These contaminants could cause accelerated aging of the fluid and eventual dielectric breakdown as described in Section 4.2.1.4 above. Although it is expected that periodic fluid sampling would identify such contamination, the frequency of sampling may not be sufficient in all cases to mitigate the effects of substantial water or oxygen intrusion in a short period of time. For this reason, degradation of the pressure relief seals is considered significant for the sealed tank design.

Bushing Current Transformers

Bushing current transformers (BCTs) are relatively simple devices; the only significant aging mechanism applicable to these units is degradation of organic insulating materials used in the windings. By virtue of their location (normally circumferentially located around the bushing center conductor), they may be subject to somewhat elevated temperatures resulting from heat generated in the BCT windings and any heat generated by the bushing conductor (which acts as the primary winding) during operation. Cracking, hardening, and low insulation resistance may result from long-term thermal exposure. Thermal decomposition of cellulose insulation may also result in increased moisture content in the transformer fluid (coincident with increased carbon dioxide levels).

The output signal from the bushing current transformer may be used in a variety of capacities, such as protective relaying, load indication, or load simulation for hot spot temperature detectors. Bushing current transformers used in differential relay applications may induce tripping of the unit if the load current is sufficient to pick up the relay. Similarly, since temperature indicators may by used to trip the unit in the event of a high temperature signal, failure of the bushing current transformer supplying one of these temperature instruments may potentially impact the required function of the transformer. In some cases, failure of the BCT will simply remove the input used to simulate the heat under load, and therefore will be unlikely to initiate a protective action upon failure. However, this mode of failure may also provide an erroneously low hot spot temperature indication, which may mask an actual high temperature condition. In other cases, shorting of the secondary windings may increase the current output of the transformer, giving an erroneously high temperature reading and thereby potentially tripping the transformer. Based on the these possible failure modes, degradation of the bushing current transformer winding insulation is considered significant.

Temperature Indicators

The significant failure mechanism postulated for the bourdon tube-type temperature indicator is failure of the hot spot heating coil element.

Failure of the hot spot heating coil element may occur as the element degrades due to exposure to temperatures generated during operation. As previously noted, output from the bushing current transformer is used to generate a temperature rise in the hot spot detector probe which is proportional to the load on the transformer. This is accomplished via current passed through the coil which surrounds the temperature sensor. The metal coil is continually exposed to elevated temperature. Repeated heating and cooling of the element due to load variation induces thermal stresses which may eventually result in open-circuit failure of the element. Accordingly, the peak temperatures to which the element is exposed as well as the magnitude and frequency of load (and therefore temperature) variation are factors which can affect the longevity of the element. It should be noted that failure of the element as described will not directly affect the required function of the transformer; no automatic protective function or trip will occur as a result of low temperature. However, because failure of the coil will produce erroneous temperature readings (low), potentially damaging temperature conditions in the transformer may be masked. Therefore, failure of the element is deemed to be significant. In the event of

suspected heater element failure, other temperature monitoring devices installed in the transformer can be used to verify the correct operation of the hot spot detector.

Fault Gas Monitor

The fault gas monitor's function is to detect concentrations of certain gases produced during fault conditions in the transformer. The monitor provides alarm, indication, and automatic protective action (in certain applications); hence, degradation or failure of the monitor may adversely impact the operation of the transformer from which it samples (see Section 3.6.2.1.1). Due to the complexity of the fault gas monitor system, numerous aging mechanisms can be postulated. Based on these considerations, no specific aging mechanism or failure mode analysis was performed for this system.

4.2.1.10 Electrical Auxiliary Devices

Electrical auxiliary devices such as molded case circuit breakers, magnetic contactors, thermal overload relays, switches, terminal blocks, fuses, and wiring may be used on power and distribution transformers for a variety of functions including control of cooling system pumps and/or fans, alarm and monitoring, and load tap changer operation. The use of these components in a given transformer depends on such factors as the size and rating of the unit and its function in the plant electrical distribution system. For example, large liquid-immersed transformers can be expected to have several electrical devices to support auxiliary systems (such as cooling, tap changing, and protection/monitoring); smaller dry-type transformers, which do not have elaborate auxiliary systems, may have only a few such devices. A complete discussion of these devices is contained in the Aging Management Guideline for Motor Control Centers. [4.2]

4.2.2 Non-significant Aging Mechanisms

4.2.2.1 Fault Pressure Relay

Wear or failure of fault pressure relay mechanical components may occur as a result of continual variations in transformer tank pressure with ambient temperature and load. Small pressure fluctuations are considered normal; as a result of these fluctuations the sensing apparatus (typically a bellows) of the relay will move in response, thereby wearing the internal components. Due to the fact that the bellows and internal are immersed in viscous fluid (such as insulating fluid or silicone oil), little wear of these components is expected. Components not immersed in these fluids (such as the rocker arm assembly) could be expected to experience a greater amount of wear; however, these components are typically only actuated upon a fault pressure condition, which is extremely infrequent. Accordingly, the aging mechanism of wear of internal fault pressure relay mechanical components is considered non-significant.

Failure of the fault pressure relay internal electrical devices such as the switch may result from repetitive relay actuations; due to the extremely low number of actuations expected over the course of the unit's installed life, these failures are not significant.

4.2.2.2 No-Load Tap Changers

There are two potential aging mechanisms for the no-load tap changer mechanism;

- commutator contact surface wear
- wear of mechanical components

None of these mechanisms is considered to be significant.

In contrast to the load tap changers described above, no-load tap changers are relatively simple in design and operation. Accordingly, many of the degradation mechanisms pertinent to load tap changers are not applicable. In addition, no-load tap changers are only operated infrequently (when the transformer is de-energized) and some of its constituent components may be immersed in the transformer insulating fluid; for these reasons, little wear or degradation of the no-load tap changer mechanism or contact surfaces is expected. Contact surface and mechanism wear are therefore considered non-significant. [4.4, 4.5, 4.19]

4.2.2.3 Resistance Temperature Detectors (RTD)

Depending on the environment in which the RTD is placed and the materials of its construction, the element may be subject to corrosion of the constituent metals (Fe, Cu, etc.). Additionally, vibration or shock may damage the more sensitive varieties of RTD (such as the glass-encased platinum resistor type). Most transformer RTDs are designed with increased immunity to these types of degradations and are not considered to be susceptible to these types of failure. RTDs may be used for actuation of protective measures such as tripping; failure could therefore preclude a required transformer function. However, due to the lack of identifiable aging mechanisms, these devices are considered highly reliable and not likely to significantly degrade with time or fail. [4.4]

4.2.2.4 Pressure Relief Devices

Pressure relief devices usually consist of diaphragm and spring arrangement which automatically resets upon reduction of the tank pressure below the actuation pressure; an external indicator and alarm switch may also be included. As the device ages, the compression springs (usually maintained in partial compression) tend to relax, thereby lowering the retarding force applied to the diaphragm. This may eventually result in a reduced set pressure and premature lifting of the relief device. This type of degradation is therefore conservative, in that overpressure conditions will be mitigated, albeit at a lower pressure. Severe relaxation of the spring may lead to operation of the relief during normal pressure transients; however, such severe deterioration would be expected to have no significant effect.

4.2.2.5 Thermocouples

Thermocouples may degrade over time based on their physical properties. For example, depending on the thermocouple's age, environmental exposure, and temperature exposure, the performance and accuracy of the unit will degrade over time. Greater age and higher exposed temperature both exacerbate the degradation of the device. Additionally, the potential generated

by the junction is susceptible to several other external effects (such as temperature distribution along the connecting wires, strain, etc.). Generally, thermocouples are not used for continuous monitoring or automatic protective function initiation, therefore their aging is not considered significant to the operation of the transformer. [4.4]

4.2.2.6 Flow Indicator

Standard mechanical flow indicators are susceptible to wear of the internal moving components (such as vanes and flappers). Most transformers, however, use flow indicators on the oil systems (water cooled units, which are rarely used, may use them for indication of water flow); accordingly, these components are continuously lubricated. Additionally, not all of the flow capacity of the transformer is used at all times; hence some flow indicators may experience lower rates of wear due to the fact that the cooling loop or pump that they are monitoring is not in use. The flow indicator generally has no automatic protective function; rather, it actuates alarms or other indications for use by operations personnel. For these reasons, wear of the flow indicator is considered non-significant.

4.2.2.7 Liquid Level Indicator

Due to the relative simplicity and complete leak-tight integrity of the magnetic liquid level indicator design, no substantive aging mechanisms are postulated. Additionally, failure of the indicator would have no direct effect on the required function of the transformer.

4.2.2.9 Gas Detector

Bubble-type gas detecting devices, due to their simple designs, generally are not subject to significant degradation or aging. They are primarily employed to detect quantities of gaseous byproducts (i.e., bubbles) in the insulating fluid of liquid-immersed transformers; upon reaching a specified level, an electrical contact will close thereby actuating an alarm or warning device. There are few moving parts other than the indicator assembly and electrical switch contact (which is expected to be actuated very infrequently). No automatic protective functions are usually associated with these devices and their failure is of no direct consequence with regard to the operation of the transformer; periodic fluid and gas sampling would indicate actual problems if the gas detector failed. More sophisticated gas monitors or detectors (such as those capable of differentiating quantities of various gases present) may be used in the transformer; these are discussed in Section 4.2.1 above.

4.3 References

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4.23 General Electric Co. Instruction Book GEK-48320, "Transformer Instructions," June 1982.

4.24 General Electric Co. Instruction Book GEK-36874, "Transformer Instructions," February 1974.