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Effectiveness of Storage Practices in Mitigating Aging Degradation During Reactor Layup

W. I. Enderlin

September 1995

**Prepared for
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
under Contract DE-AC06-76RLO 1830
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**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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Abstract

One of the issues identified in the U.S. Nuclear Regulatory Commission's Nuclear Plant Aging Research program plan is the need to understand the state of "mothballed" or other out-of-service equipment to ensure subsequent safe operation. Programs for proper storage and preservation of materials and components are required by NRC regulations (10 CFR 50, Appendix B). However, materials and components have been seriously degraded due to improper storage, protection, or layup, at facilities under construction as well as those with operating licenses. Pacific Northwest Laboratory has evaluated management of aging for unstarted or mothballed nuclear power plants. The investigations revealed that no uniform guidance in the industry addresses reactor layup. In each case investigated, layup was not initiated in a timely manner, primarily because of schedule uncertainty. Hence, it is reasonable to assume that this delay resulted in accelerated aging of some safety-significant structures, systems, and components (SSCs). The applicable layup process is site-specific. The reactor type, climatic setting, operational status, and materials of construction are factors that strongly dictate the layup method to be used. The adequacy of current layup practices, and hence their impact on safety-significant SSCs, is not fully understood.

Acronyms and Abbreviations

AC	alternating current
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BWR	boiling-water reactor
CE	Combustion Engineering
DC	direct current
HEPA	high-efficiency particulate air filter
HPCI	high-pressure coolant injection
IEEE	Institute of Electrical and Electronics Engineers
in./yr	inch(es) per year
m/yr	meter(s) per year
MIC	microbiologically influenced corrosion
MPa	mega-Pascal
NPAR	Nuclear Plant Aging Research
NRC	U.S. Nuclear Regulatory Commission
PNL	Pacific Northwest Laboratory
psig	pounds per square inch
PWR	pressurized-water reactor
RCIC	reactor core isolation cooling
RH	relative humidity
SSC	structures, systems, and components
TMI-1	Three Mile Island Unit 1
UV	ultraviolet

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1.0 Introduction

One of the issues identified in the U.S. Nuclear Regulatory Commission's (NRC) Nuclear Plant Aging Research (NPAR) program plan (NRC 1991) is the need to understand the state of "mothballed" or other out-of-service equipment to ensure subsequent safe operation. NRC regulations require programs for proper storage and preservation of materials and components (10 CFR 50, Appendix B). However, licensee event reports, NRC inspection reports, and reports submitted in accordance with the requirements of 10 CFR 50.55(e) contain many instances where materials and components have been seriously degraded as a result of improper storage, protection, or layup, at facilities under construction or with operating licenses; Information Notice No. 85-56 (NRC 1985) describes a number of representative examples.

Presented in this report is an analysis performed by Pacific Northwest Laboratory (PNL)^(a) to evaluate management of aging for unstarted or mothballed nuclear power plants. Section 2 describes the methodology followed and the results obtained. Section 3 presents summary conclusions and recommendations.

1.1 Objective

The objective of this study is to augment present NPAR work on operating plants by developing a technical database to assist in understanding and managing the aging of unstarted or mothballed plants.

1.2 Scope

This report presents a detailed review of corrosion control and other preservation technologies for unstarted nuclear power plants and for plants that have been mothballed. Case studies presented in this report include

- N Reactor, a production reactor at Hanford, Washington
- WNP-1, a partially constructed pressurized-water reactor (PWR) at Richland, Washington
- WNP-3, a partially constructed PWR at Satsop, Washington
- Three Mile Island - Unit 1 (TMI-1), a PWR at Middletown, Pennsylvania
- Brown's Ferry - Unit 1, a boiling-water reactor (BWR) at Decatur, Alabama.

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2.0 Discussion

The evaluation presented in this report is based on both information in the open literature and information gained from visits to two nuclear plant sites. Section 2.1 describes the methodology; Section 2.2, the aging mechanisms and stressors for systems, structures, and components (SSCs) in unstarted and mothballed plants; Section 2.3, equipment preservation techniques; and Section 2.4, prioritization of layup activities.

2.1 Methodology

A computerized search of the open literature pertaining to reactor layup (mothballing) was performed and the pertinent citations were reviewed. Relevant facts contained in the open literature are cited in the body of this report where appropriate. The equipment preservation techniques reflected in the layup plans and procedures for each of the reactor facilities considered were reviewed. In addition, investigators visited TMI-1 and Brown's Ferry-1. A review of the layup plans and the information obtained from the site visits provides the basis for the case studies included in this report. Appendix A outlines the protocol followed during the site visits.

2.2 Aging Mechanisms and Stressors

It is the consensus of the plant operators contacted in this study that most of the degradation of SSCs experienced during plant layup is due to corrosion, as discussed in Section 2.2.1. Other aging mechanisms and stressors addressed by the plant operators are covered in Section 2.2.2.

2.2.1 Corrosion

All SSCs composed of a metal that would lose ions to its environment and/or weaken during electrochemical reactions were subject to corrosion degradation when all of the following were present:

1. an *anode* (a metallic electrode that is oxidized and then releases electrons)
2. a *cathode* (a metallic electrode that utilizes electrons in reduction reactions)
3. an *electrolyte* (a conductive solution into which the reaction product can enter and from which the cathode reactants are supplied).

It should be understood that the anode and cathode are not necessarily different metals; a potential difference often exists between components fabricated from the same metal type and exposed to a common electrolyte. In most corrosion processes, the reduction of oxygen from the air provides the cathodic reaction. An exception would be in the case of de-aerated systems, where reduction of positive hydrogen ions to hydrogen can provide this reaction.

Materials of construction common to the sites under consideration include the following metals: carbon steel, low-alloy steel, stainless steel, copper alloy, nickel alloys, zinc alloys, and titanium

alloys. Although these metals inherently have various degrees of corrosion resistance, each of them is subject to corrosion degradation under specific environmental conditions, some of which were encountered during layup of the facilities under consideration. A detailed discussion of the factors affecting corrosion in these metals is included in Section 2 of the *Electric Power Research Institute (EPRI)* (EPRI 1987).

The types of corrosion most commonly experienced at the sites under consideration include galvanic corrosion, microbiologically influenced corrosion (MIC), intergranular corrosion, and pitting/crevice corrosion.

Galvanic corrosion: Galvanic corrosion often occurs when two different metals are in contact in the presence of a conductive solution. The greater the potential difference between the metals, the greater the tendency for corrosion. Also, the relative sizes of the anode and cathode affect the rate of the corrosion process (a small anode in the presence of a large cathode will corrode more quickly than the reverse). After an extended layup at TMI-1, visual inspection of river-water heat exchangers, which had been partially drained and left exposed to ambient air, revealed galvanic corrosion at the tubesheet ligament areas.

Pitting corrosion: In this case the pit is an anode with a large cathode surrounding it. The metals least susceptible to this type of corrosion are those that readily form a surface oxide film, such as brass and copper. Pitting may occur as a result of one of the following: 1) a change in acidity of the pit area, 2) differential aeration, 3) depletion of an inhibitor. Pitting is common when aluminum and stainless steels are in aqueous environments containing metallic chloride salts. After the extended layup at TMI-1, visual inspection of the river-water heat exchangers also revealed a breakdown of the protective coal-tar coating and pitting corrosion in the affected areas.

Crevice corrosion: Crevices are present in all equipment. They occur naturally around bolts, rivets and gaskets, and in cracks. Crevices are influenced by the same factors as pits and, in fact, are a specific form of pitting corrosion. After extended layup, valve stems have been found to be pitted in cases where the stem packing had not been removed, especially when the packing was wet.

Intergranular and localized corrosion: In this case, local anodes and cathodes are formed on a microscale. Consequently, corrosion may occur because surfaces are not completely homogeneous and a potential exists between the boundary between grains and the interior of the grains, or because impurities and solidification segregation introduce localized galvanic cells. Plastically deformed regions of metals are also anodic to less deformed regions. Also, contact between metal and nonmetallic surfaces can cause corrosion. The steam generator at TMI-1 was not 100% filled with water during extended layup. During reactor startup, it was discovered that several nickel-alloy tubes in the steam generator were cracked at the water line from what appeared to be stress corrosion. The investigators concluded that the cracking was due to the presence of sulfur at the water line. It is known that sulfur-bearing gases attack and embrittle nickel and its alloys at elevated temperatures. The source of the sulfur in this case is unknown.

Microbiologically influenced corrosion: Letting raw water stand in contact with metal under low-flow conditions invites MIC. The types of microorganisms normally associated with MIC are the deposit-forming iron and manganese bacteria, the slime-forming pseudomonas species, the deposit-forming and iron-reducing bacilli, and the sulfate-reducing bacteria. Nearly all metals and alloys used in nuclear power plants are susceptible to MIC. Those least susceptible are titanium and nickel-

chrome. Moreover, many, if not all, water-filled systems in most nuclear facilities seem to be susceptible to some form of MIC during construction and outage phases (EPRI 1987).

2.2.2 Other Aging Effects and Stressors

Other aging mechanisms and stressors addressed by the plant operators include marine growth, high relative humidity, dirt/debris, gravitational force, long-term effects, extreme ambient temperatures, and ultraviolet light.

Marine growth: Clams (fresh water and salt water) will grow where raw water drawn from rivers or ocean is in contact with metal under low-flow or stagnant conditions. Small clams easily find their way into condensers, lodging typically at bends, constrictions, and tube-sheet faces. They grow rapidly, blocking water passages and causing significant maintenance and operational problems at reactor restart.

High relative humidity: Electrical and electronic components continuously exposed to high relative humidity (RH) during layup will experience a resistance breakdown of electrical insulation, and electric and electronic circuits exhibit decreased dielectric performance. Also, under certain temperature conditions, high RH will cause condensation to form on metal surfaces, providing the electrolyte required to complete a galvanic cell and hence creating a corrosive environment.

Dirt/debris: The effects of dirt, dust, and airborne contaminants on equipment in layup status are erosion and excessive wear of contact/sealing surfaces when the equipment is restored to service or when equipment (e.g., stroking valves) in layup status is periodically operated. Dirt and debris can also alter conductor-to-conductor or conductor-to-ground resistance and reduce the efficiency of heat-conducting surfaces. Dirt and debris can plug vital small orifices and lines required for the passage of instrument air and hydraulic and lubricating oil. The presence of dirt and debris may also contribute to establishing an environment (differential aeration) that would support pitting corrosion.

Gravitational force: A primary concern during layup of large rotating machinery with a horizontal shaft is the potential for shaft deformation (creep/sag) and for brinelling damage on bearing surfaces, caused by gravitational force. This degradation could adversely effect dynamic balance and bearing wear when the equipment is restored to service.

Long-term effects: With the passage of time during extended layup, some elastomers become hard or brittle, and packing and seal material tends to shrink as it dries out; the common result is loss of blanket pressure during layup or numerous system leaks on reactivation. These problems were experienced at TMI-1. Greases tend to become hard and lubricants tend to settle, stratify, gum, or cake. Also, with the passage of time, batteries and capacitors having liquid, gel, or paste-type electrolytes undergo local chemical reactions that result in decreased voltage capacity (EPRI 1991). Furthermore, spring life may diminish if springs in valves, motor brushes, and other components are left in tension.

Temperature extremes: Exposing components to high temperature during layup can accelerate aging in certain materials, such as lubricant and protective coatings, resins, elastomers, and other non-metallic materials, and accelerated loss of capacity in batteries and aluminum electrolytic capacitors. The potential effect of exposing SSCs in layup to low temperatures is rupture of undrained or partially drained components and piping that have not been protected. Cooling of lubricants below the pour

point can adversely affect the solubilities of oil additives (EPRI 1991). Also, exposing SSCs to low temperatures invites formation of condensation and all of the negative consequences attributed to high relative humidity.

Ultraviolet light: Exposure to ultraviolet (UV) light will cause degradation of rubber, plastic, and synthetic items.

2.3 Equipment Preservation Techniques Employed

The operators contacted for this study use preservation techniques that emphasize controlling corrosion (Section 2.3.1), monitoring corrosion (Section 2.3.2), and techniques to address other concerns (Section 2.3.3).

2.3.1 Corrosion Control

The corrosion control techniques employed during layup at the facilities under consideration in this study include dry layup, nitrogen layup, wet layup with chemical treatment of water, cathodic protection, protective coatings, desiccants, and inhibitors. The technical requirements for and applicability of each technique, as specified by the operators contacted, are discussed below.

Dry layup: When feasible, dry layup is the preferred method for control of corrosion during reactor mothballing. However, there currently is no uniform guidance within the industry that specifies acceptable temperature and humidity conditions for dry layup of SSCs. Dry layup is defined by EPRI (EPRI 1987) as "internal surfaces dry to the touch, atmosphere well below saturation."

Brown's Ferry requires that carbon steel SSCs be maintained at 40% or less RH; brief and infrequent excursions to 60% RH are acceptable; stainless steel SSCs must be maintained free of condensate or standing water. To establish and maintain the required environment, Brown's Ferry drains the systems designated for dry-layup, aligns valves for proper air passage, and continuously supplies forced dehumidified air to the systems. Dehumidifier units (Cargocaire, models HC-600 and HC-600-EA) are connected to the systems through flexible ducts and flange fittings designed specifically for this purpose. Connect points are at the condensate pump pit, at the off-gas system, at the feedwater heaters, and at the reactor-core isolation cooling (RCIC) and high-pressure coolant injection (HPCI) systems. High-efficiency particulate air (HEPA) filters are installed where appropriate to preclude the migration of contaminants. Components (flanges, check valve internals, etc.) removed from the systems to facilitate air passage are stored on location in boxes containing desiccant and having air-tight transparent covers, which make it possible to observe the condition of the desiccant without disrupting the dry atmosphere inside the container.

The layup plan for TMI-1, on the other hand, requires that for dry layup the lowest temperature inside the SSCs, generally at the outlet point(s), be maintained at -12°C (10°F) or more above ambient. To establish and maintain this environment, TMI-1 relies on ambient air and/or desiccants or dry instrument air. The shell sides of heat exchangers containing stainless-steel tubes (Type 304) were laid up with ambient air. The main turbine was also laid up with ambient air (heated building air) in natural draft circulation through the hotwell manway and exhaust hood manway. However, the layup plan for TMI-1 specifies that hot dry air be circulated through the turbines if prolonged outage is anticipated

(beyond a four-month period). Because of economic considerations, readily available dry instrument air [-56°C (-69°F) dew point] is circulated through the generator to provide the required layup environment, in lieu of the dry nitrogen at 0.105 MPa (0.5 psig) recommended by General Electric.

The N Reactor Layup Plan requires that SSCs be subjected to a controlled atmosphere maintained at less than 50 percent RH and 10°C (50°F) or higher. Dehumidifier units are operated continuously to maintain this environment, or the SSCs have been drained, dried, and opened to a controlled (heated) atmosphere. The Layup Plan further specifies that when this environment cannot be maintained at the operational location of the SSCs, the SSC is to be moved to a dehumidified area and protected as specified by the manufacturer or laid up in accordance with engineering judgment considering adequacy of protection, cost effectiveness, and capability for reactivation within two years any time within five years after layup.

The Assets Preservation Programs for WNP-1 and WNP-3 do not specify temperature and RH limits for dry-layup of SSCs. These programs are based on the requirements set forth in ASME NQA-2-1989, Part 2.2 (ASME 1989): "items subject to deleterious corrosion shall be protected by using either contact preservatives, inert gas blankets, or vaporproof barriers with desiccants." Where required, space heaters or heat tapes are also used to maintain an environment that has been deemed acceptable. The layup plan does require, however, that the environmental control system installed on the turbines be maintained in operation.

Nitrogen layup: Nitrogen layup is an alternative technique for maintaining a dry layup environment. This procedure involves draining the system, connecting the nitrogen supply to each region, purging approximately four times the region volume, and filling each region. The region's isolation valves are then closed, and the nitrogen supply regulators are set to maintain a slightly positive pressure of about 0.108 MPa (1 psig). If complete isolation cannot be accomplished, a low purge must be maintained during the lay-up period (EPRI 1987).

At TMI-1, nitrogen blanketing was restricted to units in the main feedwater system (eight feedwater heaters) with carbon steel shell and carbon steel tubes. The nitrogen blanket was used only on the shell side of these units. Significant nitrogen leakage (about 25,000 ft³ per week) resulted in appreciable cost (about \$11,100/year - 1983 dollars). The safety and drain valves were subsequently reworked in an effort to mitigate this loss.

At WNP-1 and WNP-3, a nitrogen cover gas is maintained on the primary and secondary sides of some heat exchangers; all of the steam generators; the DHR, boric acid evaporation, and surface condensers; air compressors and vacuum pumps (WNP-1 only); and the water side of the heat exchangers of the chillers.

Nitrogen layup was not employed at Brown's Ferry or at N Reactor.

Wet layup: Normally, primary and secondary systems selected for wet layup are filled completely with water or with water and an overpressure of nitrogen. The water is almost always chemically treated to inhibit corrosion, or some method of water circulation may be used (EPRI 1987).

At TMI-1, the procedure for placing the primary side into extended wet layup is to maintain the system in a de-oxygenated state and to maintain the ratio of lithium to sulfur inherently in the system at 10:1. Either peroxide or hydrazine is added to de-oxygenate the primary system. TMI-1 relies on

hydrogen overpressure in the makeup tank to maintain the de-oxygenated state. If the primary system were opened after shutdown, it would be required to reheat the system and re-establish the hydrogen overpressure for extended layup.

The procedure for placing the steam generator at TMI-1 into extended wet layup is to leave the system partly filled with water containing 5 to 20 ppm ammonium hydroxide (NH_3OH), thus establishing a pH level of approximately 9.8, and 50 to 200 ppm hydrazine (N_2H_4), thus providing an oxygen scavenger. Although morpholine (a film-forming amine) was used as a corrosion inhibitor during normal operations at TMI-1, it is not used during extended wet layup, because it has been reported to decompose in steam generators during layup (EPRI 1988). In addition to altering the water chemistry for extended wet layup of the steam generator, a nitrogen blanket is also provided. The source of sulfur responsible for stress corrosion cracking of the steam generator tubes during the previous extended wet layup has since been identified and eliminated.

The procedure for placing other systems on the secondary side at TMI-1 into extended wet layup is to fill the system with water containing 2 to 5 ppm hydrazine and 1 to 2 ppm ammonium hydroxide, thus establishing a pH level of 9.5 to 9.8. Systems placed in wet-layup with chemical treatment but without circulation include the main feedwater pumps and the emergency feedwater pumps. The generator closed cooling water system was laid up with chemical treatment and water circulation. The condensate pump, condensate booster pump, and the twelfth stage drains cooler tube side were laid up wet without chemical treatment or circulation.

At Brown's Ferry, the auxiliary boilers were placed into extended wet layup with chemically (ammonia and hydrazine) treated water. The layup chemicals were added before boiler shutdown. Also, the control rod drives were aligned to provide control rod drive flush water during layup. In addition, during layup, rubber-lined tanks contained a volume of demineralized water no less than 25% of the tank volume. The method of corrosion control (use of corrosion inhibitors and control of water purity) used for the reactor building closed cooling water system was deemed adequate for both operation and extended layup.

Wet layup was not employed at N Reactor. At WNP-1 and WNP-3, because construction has not been completed, all SSCs are in dry layup. Despite a vendor recommendation that rubber-lined tanks be stored wet (alcohol-water) or with an inert cover gas, it was deemed adequate at WNP-1 and WNP-3 to store the rubber-lined tanks dry without a cover gas and all openings closed.

Cathodic protection: Cathodic protection by galvanic coupling to zinc is widely used in power plants (EPRI 1987). However, this type of corrosion system has a limited life; hence, the amount of remaining sacrificial anode must be monitored periodically during layup to ensure continued protection.

At TMI-1, during a post-layup inspection, it was discovered that the sacrificial zinc anodes intended to protect the river water system were ineffective because they had become passivated due to the Susquehanna River water chemistry. To correct this problem, the zinc anodes were replaced with magnesium anodes.

Contact preservatives and corrosion inhibitors: Contact preservatives are compounds applied to base metal surfaces to prevent surface corrosion during storage (layup) and normally require removal before installation. Preservatives are often considered as an alternative to long-term storage in a controlled environment; however, only preservatives suitable for long-term layup should be

considered. These compounds are generally heavy oils or greases, waxes dissolved in solvents, or sulfonate salts dissolved in petroleum. Only approved solvents should be used for removal of contact preservatives. Preservatives for inaccessible inside surfaces of pumps, valves, and piping for systems containing reactor coolant water must be of a water flushable type (ASME 1989).

In some instances the amount of inhibitor present is critical in that a deficiency may result in localized or pitting attack, and the overall destruction would be greater than where none of the inhibitor is present. Use of inhibitors should therefore only be considered after review of experience in similar systems or investigation of requirements and limitations in new systems (Perry and Chilton 1973). It is worthy of note that the use of vapor phase inhibitors is conspicuously absent from ASME NQA-2-1989, Part 2.2 (ASME 1989).

The layup plan for Brown's Ferry required that the steam path internals be removed from the reactor feed pump turbine and stored in a controlled environment or coated with preservative. The layup plan also required that any unpainted critical exposed surfaces on pumps that are not stainless steel be coated with an approved corrosion-preventive compound. The plan further required that an approved volatile corrosion inhibitor be added at the manufacturer's recommended ratio to oil for oil-lubricated bearings and for oil-lubricated gear drive units. Furthermore, the inhibitor in the lube oil was to be replaced annually. A list of corrosion inhibitors approved for use at Brown's Ferry, along with a statement regarding the appropriate application of each inhibitor, is included in Appendix B.

With few exceptions, the use of vapor phase inhibitors in Combustion Engineering (CE) supplied equipment at WNP-1 and WNP-3 is strictly prohibited. This restriction also applies to equipment or piping that interconnects with CE-supplied equipment. The concern of CE is that vapor phase inhibitors may contain compounds that are deleterious to materials in plant systems, especially stainless steel or nickel alloys in the primary system. In other areas, however, WNP-3 generally relies on vapor phase inhibitors to alter the surface characteristics and hence protect selected materials, especially carbon steels. The wet conditions at WNP-3 cause more rapid corrosion of any unprotected carbon steel surfaces, compared to what is experienced at WNP-1, under considerably dryer conditions. Therefore, requirements to maintain surface protection systems at WNP-3 are deemed to be more important than comparable requirements at WNP-1.

Desiccants: Desiccants are often used within a vapor-proof barrier when condensation could contribute to a corrosive atmosphere within the barrier, resulting in damage to vital SSCs. Section 3.6.3 of ASME NQA-2-1989, Part 2.2 (ASME 1989) describes the method for determining the minimum quantity of desiccant that should be used in each situation. Section 3.6.3 also specifies that desiccants shall consist of nondeliquescent, nondusting, chemically inert dehydrating agents. The layup plans for WNP-1 and WNP-3 further require that a desiccant, together with bag material, that is used with austenitic stainless steels not have a halogen content in excess of 0.25%. The layup plan also requires that the canisters containing desiccant be placed so as to produce no deleterious effects such as galvanic corrosion, even when the desiccant has reached its absorptive capacity for water vapor.

2.3.2 Corrosion Monitoring

Perry and Chilton (1973) list the principal types of corrosion tests in decreasing order of reliability:

1. Actual operating experience with full-scale plant equipment exposed to the corroding medium.

2. Small-scale plant-equipment experience, under either commercial or pilot-plant conditions.
3. Sample tests in the field. These include coupons, stressed samples, electrical resistance probes exposed to the plant corroding medium, or samples exposed to the atmosphere, to soils, or to fresh, brackish, or saline waters.
4. Laboratory tests on samples exposed to "actual" plant liquids or simulated environments.

Of these tests, plant or field corrosion tests are most useful for studying the effectiveness of methods to prevent corrosion. The following standards are applicable to plant and field corrosion tests:

- ASTM G1, Recommended Practice for Preparing, Cleaning and Evaluation of Corrosion Test Specimens.
- ASTM G4, Recommended Practice for Conducting Plant Corrosion Tests.
- ASTM G33, Recommended Practice for Recording Data from Atmospheric Corrosion Tests of Metallic/Coated Steel Specimens.
- ASTM G46, Recommended Practice for Examination and Evaluation of Pitting Corrosion.
- ASTM G50, Conducting Atmospheric Corrosion Tests on Materials.

Attachment 1 of the *General Engineering Specification - Plant and Equipment Layup for Brown's Ferry* defines the requirements for corrosion monitoring of systems and materials during layup using weight-loss coupons. In the case of dry layup, the specification requires that the coupons be installed at locations where moisture is most likely to be present (e.g., system low points) with the coupons installed at the 6 o'clock position of piping and as close to the pipe wall as possible without touching the wall. In the case of wet layup, the specification requires that coupons be installed so that continuous immersion in the system layup fluid is maintained. It is further required that the coupons be periodically removed and examined and that the data from the examinations be trended and corrective action be taken when an unacceptable corrosion rate is indicated. In addition, the specification states that electrical resistance or polarization resistance probes may also be used to determine corrosion rates.

The objective of the corrosion monitoring program at WNP-3 is to provide both qualitative and quantitative data on the structural material changes due to the environment throughout the period of construction delay. The program identifies evidence of corrosion mechanisms that might adversely affect the integrity of the SSC in which it is used and is not concerned with the insignificant appearance of rust stains on stainless steel or even light rusting of unprotected carbon steel.

Atmospheric corrosion test racks are located in the field and in buildings. Two field test racks, each containing 40 coupons, are positioned within the construction perimeter. Building test racks, each containing six coupons, are positioned in the turbine, reactor auxiliary, and reactor buildings. One additional field test rack is positioned in a diesel exhaust weather-tight spool located on the south side of the WNP-3 refueling water storage tank. Corrosion coupons made from material similar to that of the vessel were also placed in the primary side of both steam generators. Due to the heavy reliance of

vapor phase inhibitors at WNP-1, several weight-loss coupons were also prepared to determine the effectiveness of vapor phase inhibitors on both uncorroded and previously corroded surfaces.

Coupons are monitored for uniform galvanic and pitting types of corrosion. Corrosion coupon materials are representative of actual plant components (i.e., nuclear steam supply system vessel and piping, carbon steel piping, steam piping, anchor bolting, equipment bolts, reinforcement bar, tanks, pumps, and stiff clamps).

In addition to the uniform type of corrosion caused by rain and humidity, several special conditions of possible enhanced or accelerated corrosion have been identified:

- Dew point moisture corrosion on internal surfaces of closed or capped piping and tanks.
- Accelerated corrosion due to galvanic action at dissimilar metal welds.
- Corrosion of exposed formed reinforcement bar ("rebar").

Corrosion testing to determine the rate of dew point moisture attack is accomplished with weight-loss coupons. Coupons are attached to a rack which is then placed inside a capped spool piece. Carbon steel coupons of two alloy compositions, similar to steam and water piping, are used. One coupon of each alloy set is examined every 12 months.

Testing for galvanic corrosion rates is accomplished with weight-loss coupons made from carbon steel to stainless steel weld samples with machined surfaces. At the end of the test period, these coupons are examined for the type and depth of attack.

Reinforcement bar corrosion is difficult to model. Acceptance criteria are not based on a minimum wall thickness. ASTM acceptance standards for this product form are based on tensile and bend tests. To avoid problems with non-standard qualitative data, rebar corrosion uses both corrosion rate determination and actual acceptance testing of exposed rebar. Weight-loss coupons of a similar alloy composition are exposed and tested along with the other coupons to obtain corrosion rates. Specimens of small diameter reinforcement bar are exposed throughout the layup period. These specimens are tensile and bend tested before restart. Small-diameter rebar is used to produce worst-case data on the ratio of surface area to mass.

In the early stages of the layup period, the extent and depth of the corrosion monitoring program at WNP-3 was limited by the relatively short time period available to establish corrosion rates and the relatively small amount of total metal loss occurring over this time period. Hence, to determine an upper bound, worst-case corrosion rates were determined by using the most corrosion-sensitive materials positioned at the most environmentally severe locations. At the same time, a sufficiently limited number of actual plant and field corrosion conditions were monitored and correlated with the worst-case data.

Carbon steel atmospheric corrosion rates are expected to range between 1.52×10^{-5} to 3.30×10^{-5} m/year (0.6×10^{-3} to 1.3×10^{-3} in./year at WNP-3, where the relative average humidity is greater than 60%). High strength low alloy carbon steels are expected to corrode at a rate of 0.76×10^{-5} m/year (0.3×10^{-3} in./year). Atmospheric corrosion rates for stainless steel, aluminum,

copper and zinc coated materials are approximately 2.79×10^{-7} , 7.62×10^{-7} , 5.84×10^{-7} , and 20.03×10^{-7} m/year (0.011, 0.03, 0.023, 0.08 in./year), respectively.

In conjunction with actual coupon testing, several areas in the plant were selected for visual examination and photographic documentation. Items examined included embedded plates, stiff clamps, water storage tanks, floor drain tanks, diesel generator room, turbine materials, piping, reinforcement bar, and dry cooling heat exchangers.

Both N Reactor and TMI-1 depend solely on visual examination for corrosion monitoring.

2.3.3 Other Preservation Techniques

Other preservation techniques employed during layup at the sites under consideration include shaft rotation, battery maintenance, valve stroking, covering/draping, meggering, packing removal, and preservation of wood structures.

To prevent shaft deformation and brinelling damage on bearing surfaces on large horizontal rotating machinery (e.g., motors, pumps, and generators), shaft rotation is performed quarterly, while running the lube oil system. At the end of rotation, the shaft is left in a position that is 90 to 270 degrees from the starting position.

Batteries are maintained in a charged condition in a ventilated area that is kept within an acceptable temperature range. The cells are checked quarterly. IEEE 450 is recognized as an acceptable guide for battery preservation during layup.

To minimize the potential for pitting corrosion, the packing is removed from valves and pump seals. Temporary packing may or may not be installed during layup. New packing is installed upon restart.

Valves, operators, and/or actuators with established preventive maintenance activities are cycled periodically (manually, electrically, by air or nitrogen pressure), providing they are not required for boundary control. While cycling the valves, the stems are checked for pitting corrosion. If the packing has been removed from the valve, care is exercised to prevent binding of the stem. Where practical, motor operated valves are provided with stem covers.

Motors should be megger checked periodically, especially in areas with high average humidity. Generators should also be megger checked according to the manufacturer's recommendation. At WNP-3, where the average humidity is relatively high, alternating current (AC) motors greater than 100 hp and direct current (DC) motors equal to or greater than 1 hp are megger checked semiannually. Safety-related AC motors smaller than 1 hp, other AC motors larger than 10 hp and equal to or smaller than 100 hp, and DC motors smaller than 1 hp are megger checked annually. If meggering results indicate potential degradation, then space heating requirements are enhanced.

Experience has shown that wooden structures (deck and pipe) associated with cooling towers dry out and shrink, resulting in numerous leaks in the wood pipe upon restart and posing a significant fire hazard during layup. Consequently, these structures are currently kept wet throughout the layup period or are dismantled.

2.4 Prioritization of Layup Activities

Ideally, all layup activities are initiated as soon as possible following shutdown. However, this has not been the case for the reactors considered in this study. At WNP-1 and WNP-3, budgetary constraints dictate the rate of implementation based on priority needs. In the case of N Reactor, approximately 2 years elapsed between the time the reactor was shut down and the time dry layup was initiated. In the case of TMI-1, layup began approximately 18 months after reactor shutdown, because of uncertainty about the anticipated operation schedule. In the case of Brown's Ferry, Unit-1, dry layup was initiated 3 to 4 years after reactor shutdown, again because of schedule uncertainty.

To aid in implementing a layup program, a suggested prioritization of layup activities for BWRs is proposed in Section 4 of the *Plant Layup and Equipment* (EPRI 1987); however, layup prioritization for PWRs is not addressed.

3.0 Conclusions

The following conclusions are based on the results of this investigation to date.

- Operators interviewed for this study agree that there is currently no uniform guidance within the industry that addresses reactor layup. They further concur that implementing reactor layup has been a "learn-as-you-go" experience. In some cases, some costly lessons were learned when startup was initiated; however, the findings of this study suggest that these lessons have not been adequately shared throughout the industry. The operators interviewed expressed an interest in the potential for the development of uniform guidance for reactor layup.
- In each case investigated, it was evident that layup was not initiated in a timely manner, primarily because of schedule uncertainty. Hence, it is reasonable to assume that this delay resulted in accelerated aging of some safety-significant SSCs.
- The applicable layup process is site-specific. The reactor type, climatic setting, operational status, and materials of construction are factors that strongly dictate the layup method to be employed.
- The adequacy of current layup practices, and hence their impact on safety-significant SSCs, is not fully understood. This is evidenced by the difficulties encountered during the startup of TMI-1 and the extensive corrosion monitoring program currently being carried out at WNP-1. Because N Reactor is proceeding to decommissioning, the effectiveness of this layup program will never be verified. The effectiveness of the layup program at Brown's Ferry, Unit-1, will not be fully assessed until restart has been completed.

It is recommended that the scope of this study be expanded to encompass the following research tasks:

1. Assess the safety implications of currently employed reactor layup methods, focusing on the potential impact of these methods on the reliability of safety-significant SSCs.
2. Based on the findings of Task 1, identify specific safety issues that should be addressed when formulating a reactor layup plan.
3. Assess the potential impact of layup schedule and layup prioritization on the reliability of safety-significant SSCs.

It is further recommended that these three tasks address layup of both BWRs and PWRs for both completed and uncompleted plants.

4.0 References

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Appendix A

Site Visitation Protocol for Mothballing

Appendix A

Site Visitation Protocol for Mothballing

Date: _____

Site Name: _____

Contact: _____

Phone: _____

Documentation to be Obtained

General Operating Instruction (GOI)

Layup plan(s) and procedures (systems and components)

Photographs

database

layup system priorities (component/activities)

schedule and sequence table (days after shutdown/description)

Discussion

Type of Plant (BWR/PWR/OTHER)?

When did the plant go into layup?

How soon after shutdown did the plant initiate the layup process?

How long did the layup process take? Prioritization?

When did the plant come out of layup? How long did it take?

What were the circumstances leading to plant layup?

What was basis/guidance for layup plans and procedures development?

survey of other plant experience? Which plants?

EPRI studies/reports?

workshops (date/sponsor/documented results)?

other industries/facilities experience (Navy ships/fossil plant)?

plant specific technical database?

how developed?

how documented?

Type of layup procedure employed?

Dry?

forced air?

dehumidified air?

RH limit ____ %?

Wet?

chemical treatment? ____ pH ____ ppm hydrazine

water circulation? (continuous/periodic) how?

filled/partially filled?

nitrogen overpressure?

maintenance activity without interruption? how?

Nitrogen layup?

purge? (continuous or ____ x region volume)

blanket? ____ psi positive pressure

Drained?

"As Is"?

any combination of the above (which type/which systems - regions)?

What system modifications were required?

What special maintenance access requirements must be accommodated?

What problem areas were encountered for region isolation?

Did you regard your approach to plant layup "field proven" at the outset?

Method of corrosion control used?

Other types of preservation technologies employed?

Conclusions

Effectiveness of layup procedure?

how determined?

method of assessment/surveillance?

NDE techniques? which ones?

before and after layup?

initiated how soon after layup?

level of sophistication?

What did you regard as the greatest degradation issue?

lessons learned (what would you do different next time)?

cost effectiveness (cost benefit ratio)?

Recommendation for Further Study

What areas/topics do you feel need further study/investigation?

Appendix B

Corrosion Inhibitors Approved for Use at Brown's Ferry

Appendix B

Corrosion Inhibitors Approved for Use at Brown's Ferry

CRC-2-26 - Sprayed on electrical contacts, this compound provides protection against corrosion for up to 2 years. It can be reapplied and does not need to be removed before the component is placed in service.

CRC Lectra Shield - Sprayed on electrical contacts, this compound provides protection against corrosion for up to 5 years. It must be removed before the component is placed in service.

Cortec VCI-100 Series Device, Emitter, and Tape - These volatile corrosion inhibitors provide protection for up to 2 years before replacement. Cleaning is not required before the component is placed in service.

Zerust Vapor Capsules - These inhibitors have a life span of 1 to 2 years, after which they require replacement. They can be used in electrical enclosures. Surface cleaning is not required before the component is placed in service. *Zerust vapor capsules shall not be used to protect carbon steel.*

Cortec VCI-329 Oil Additive - Added to lubricating oil, this component provides protection against corrosion for up to 12 months.

Cortec VCI-307 Powder and Cortec VCI-309 Powder - These powders can be directly applied to the interior of mechanical components. Depending on the conditions, one application can provide protection for up to 2 years. These powders are water soluble and are readily removed by flushing to meet water quality requirements before placing the component in service.

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