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EFFECT OF COMPONENT AGING ON PWR CONTROL ROD DRIVE SYSTEMS*

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ABSTRACT

An aging assessment of PWR control rod drive (CRD) systems has been completed as part of the U.S. NRC Nuclear Plant Aging Research (NPAR) Program. The design, construction, maintenance, and operation of the Babcock & Wilcox (B&W), Combustion Engineering (CE), and Westinghouse (W) systems were evaluated to determine the potential for degradation as each system ages.

Operating experience data were evaluated to identify the predominant failure modes, causes, and effects. This, coupled with an assessment of the materials of construction and operating environment, demonstrate that each design is subject to degradation, which if left unchecked, could affect its safety function as the plant ages.

An industry survey, conducted with the assistance of EPRI and NUMARC, identified current CRD system maintenance and inspection practices. The results of this survey indicate that some plants have performed system modifications, replaced components, or augmented existing preventive maintenance practices in response to system aging. The survey results also supported the operating experience data, which concluded that the timely replacement of degraded components, prior to failure, was not always possible using existing condition monitoring techniques. The recommendations presented in this study also include a discussion of more advanced monitoring techniques, which provide trendable results capable of detecting aging.

INTRODUCTION

In Pressurized Water Reactors (PWRs), the CRDs are flange mounted on top of the reactor pressure vessel head, and serve to position the control rod assemblies in the core in response to automatic or manual reactivity control signals. The systems are also designed to provide a rapid insertion of the control rods upon loss of AC power. B&W plants utilize a roller nut mechanism, while W and the majority of CE plants use a magnetic jack mechanism. Two CE plants, Fort Calhoun and Palisades use a rack and pinion type of mechanism.

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With the exception of the rack and pinion CRDs, stator coils, which are mounted externally to the pressure housings, produce a magnetic field which actuates the latches or the roller nuts. When sequentially activated, control rod movement either into or out of the core, results. Similar rod motion is produced in the rack and pinion mechanism by an electric motor which drives the rack and pinion gear mechanisms.

Rod position indication is provided by two independent systems. Combustion Engineering and Babcock & Wilcox use magnetically actuated reed switches to provide an absolute position indication signal. Westinghouse utilizes a linear transformer type of detector, concentrically mounted around the upper portion of the CRD housing to provide an equivalent signal. Each power and control system monitors the individual control signals or pulses provided to the CRDs to provide a demanded rod position indication. Both systems are highly accurate, however in the event of a dropped or stuck rod, the demanded rod position will not correspond to the actual rod position in the core.

The rod control system consists of the electrical power, signal conditioning, and control circuitry which regulates individual or group (safety or regulating) movement. The control portion of this sub-system ensures proper sequential group movement which results in smooth, continuous rates of reactivity change. The power portion contains the equipment necessary to convert the three-phase AC power to the DC current required for CRD operation.

Forced air cooling is provided for the Westinghouse and Combustion Engineering magnetic latch mechanisms. The B&W roller nut and the CE rack and pinion mechanisms use cooling water. Redundant equipment is provided for all the designs to ensure continuous cooling.

OPERATIONAL AND ENVIRONMENTAL STRESSES

Operational and environmental stresses may lead to age degradation of the CRD over the design life. Common mechanical stresses include wear, fatigue, vibration, and corrosion. Electrical stresses result from arcing, power surges, electrical noise and drift. Temperature, radiation, and humidity are common environmental stresses. Other stresses, such as abnormal operating conditions, improper or excessive maintenance, testing, and human error may also contribute to component or system aging. Westinghouse and Combustion Engineering CRDs are designed with a 40-year life, while Babcock & Wilcox specifies a 20-year design life.

Design and location are primarily responsible for determining which stresses affect individual system components. The drive mechanisms, portions of the rod position indication systems, and the associated power and control cabling, which are located on top of the reactor vessel head, are subjected to severe operating and environmental stresses. In comparison, the power and control system components are situated in a more controlled environment outside of containment. However, failures due to overheating and contamination of these components have also been reported.

Aging failure mechanisms result from the long term exposure to operating, environmental, and external stresses. Such stresses may gradually degrade the components physical properties or operating characteristics. A failure to identify and correct degradation mechanisms in a timely manner causes failures of the components and may impair plant safety. The specific type, number, and intensity of operating and environmental stresses which affect a particular component are related to the function, physical configuration, and characteristics of the operating environment. The overall effect that a particular stressor may have upon a component primarily depends on the intensity, frequency, and duration of the applied stress, and the endurance limit of the material. A particular component may have more than one stress acting upon it at a particular time. These stresses, acting in combination tend to produce greater synergistic effects than if they were acting individually. Typical degradation mechanisms and potential failure modes for the major CRD sub-components are presented in Table 1. Potential CRD cooling system degradation mechanisms and failure modes are incorporated into the four CRD sub-systems contained in this table.

OPERATIONAL EXPERIENCE DATA ANALYSIS (1980-1990)

In order to determine the effect of aging upon the PWR control rod drive system, operating experience data were reviewed for the 1980 to 1990 time period. This information was obtained from three national sources of nuclear plant operating experience (NPRDS, LER, and NPE). The NPRDS database, maintained by INPO, contains performance information based upon failure event reports of key components submitted by nuclear utilities. The LER database contains abstracts for each LER generated as a result of component failure or degradation which affected plant operation. NPE is a commercial technical publication service which compiles descriptive summaries of significant events affecting components and systems.

Each of the three databases was reviewed to determine the effect of age upon the CRD system, and duplicate events were identified to avoid double counting. Failures which resulted in plant operating events were typically reported in the LER database, while events discovered during outages and maintenance were reported to the NPRDS database. The NPE database contained events which were reported by the other databases, but in some instances contained more detailed follow-up failure information. The root cause of the failure if known, was reported by the databases, but often, such detailed information was not available.

Based upon this review, CRD failures were categorized as being caused by failure or degradation within five primary subassemblies. These were:

1) Cables and Connectors,
2) Power and Logic Cabinets,
3) Control Rod Drive Mechanisms,
4) Rod Position Indication,
5) Miscellaneous Components (Control Rods, Guide Tubes, etc).

The contribution of each individual subassembly failure to the CRD system failures is shown on Figure 1.

Table 1. PWR Control Rod Drive System Potential Degradation Mechanisms and Failure Modes

Subsystem/Component	Material	Potential Degradation Mechanism	Potential Failure Mode
I. Control Rod Assembly			
a. Control Rods	Type 304 SS Clad (B&W, W), Inconel (CE) Ag-In-CD (B&W, W), B4C Poison (CE)	Stress Corrosion Cracking Mechanical Wear	Clad Cracking, Poison Wash Out
b. Spider	Stainless Steel (B&W, CE, W)	Stress Corrosion Cracking Mechanical Wear, Radiation Embrittlement, Fatigue	Surface Cracks, Dropped Rod, Stuck Rod
c. Fuel Assembly Guide Tube	Zircaloy-4 (B&W, CE, W)	Mechanical Wear	Cracking Wear, Stuck Rod
d. Split Pin	Inconel (W)	Stress Corrosion Cracking	Stuck Rod, Loose Parts
II. Control Rod Drive Mechanism			
a. Pressure Housing	Stainless Steel (B&W, CE,W) Inconel clad with low allow steel (B&W)	Thermal Embrittlement, Corrosion, Fatigue, Cracking	Housing Crack, Primary Coolant Leaks
b. Rotor Assemblies, Latch Assemblies	Stellite (W), Stainless Steel (B&W, CE, W)	Mechanical Wear, Fatigue, Debris/Crud Buildup	Dropped CRA, Immovable CRA

Table 1. Continued

Subsystem/Component	Material	Potential Degradation Mechanism	Potential Failure Mode
c. Leadscrew Drive Rod	Stainless Steel (B&W, CE, W)	Mechanical Wear, Fatigue, Stress Corrosion Cracking	Dropped Rod, Immovable CRA, Inoperable Locking Mech.
d. Coils	Copper Wire, Epoxy, Kapton (B&W, CE, W)	Corrosion, Mechanical Wear, Insulation Degradation, Fatigue, Thermal Embrittlement	Dropped Rod, Electrical Short, Voltage Variation Spurious Rod Control Alarms Incorrect Rod Position
e. Vent Valve	Stainless Steel, O-rings (B&W, CE, W)	Corrosion Buildup, Mechanical Wear, Fatigue, Thermal Embrittlement	Inoperable Valve, Primary Coolant Leak
III. Power & Control System	Elec. Power Supplies, Semiconductors, SCRs, Cables, Connectors (B&W, CE, W)	Corrosion, Fatigue, Mechanical Wear, Thermal Degradation, Output Drift, Power Surge	Dropped CRA, Spurious CRA Movement, Inoperable Rods, Electrical Signal Drift
IV. Rod Position Indication Systems	Reed Switches (B&W, CE), Stepping Motor (B&W), Wiring, Cables, Connectors (B&W, CE, W), Linear Transformer Detector (W)	Corrosion, Fatigue, Mechanical Wear, Thermal Degradation, Radiation Degradation, Vibration, Insulation Degradation, Electrical Drift	Loss of Position Indication, Spurious Position Indication

The primary objective of this study was to assess the impact of aging on the PWR control rod drive system performance. Before a failure was categorized as being age related, the following criteria had to be satisfied:

1) The failure had to be the result of cumulative changes with the passage of time, which, if not corrected, could result in loss of function and impairment of safety. Factors which could cause aging include operational stresses, and external stresses, such as storage and environmental.

2) The component must have been in service for a minimum of six months.

The percentage of failures attributable to aging is shown on Figure 2. As indicated by this figure, a significant number of failures have been categorized as potentially age related. This is indicative of the poor root cause failure information available from the data.

Each of the individual CRD system designs was found to be susceptible to aging degradation which resulted in significant plant operational effects, including reactor trips, power reductions, safety system actuation, and loss of rod position indication. System failures and component degradation were described in nine separate Information Notices for the time period, as shown on Table 2.

Examples of some of the major failures in each subcategory included:

1) <u>Cables and Connectors:</u> Connector failure due to mechanical wear of the contacts and corrosion were noted for all the CRD designs. Power and rod position indication cabling failures were also noted. Brittle and cracked cabling resulted in the replacement of all the power cabling at one plant. Degraded cables and connectors within the power and control cabinets and circuitry external to the primary containment were also reported.

2) <u>Power and Logic System:</u> The modularized components which comprise this system, are located in enclosed electrical cabinets. The majority of reported failures were due to printed circuit card failure, which is not surprising given their widespread use. Fuse failures and power supply failure and drift were also reported which often resulted in dropped or slipped rods. A significant portion of failures within the subsystem were due to environmental stresses, caused by overheating, dirt contamination, and improper or excessive maintenance. System modifications and improvements have been made to the systems. For example, CE has modified the power and control system to monitor and adjust the power supplied to the individual gripper coils. This change eliminated many of the slipped rods due to the sluggish gripper actuation due to improper voltage applied to the gripper coils which was commonly experienced in the early 1980s.

3) <u>Control Rod Drive Mechanism:</u> Primary coolant leakage, due to vent valve leakage, gasket failure, and housing cracks was reported. Though only two CE plants utilize the rack and pinion mechanisms, failures and degradation

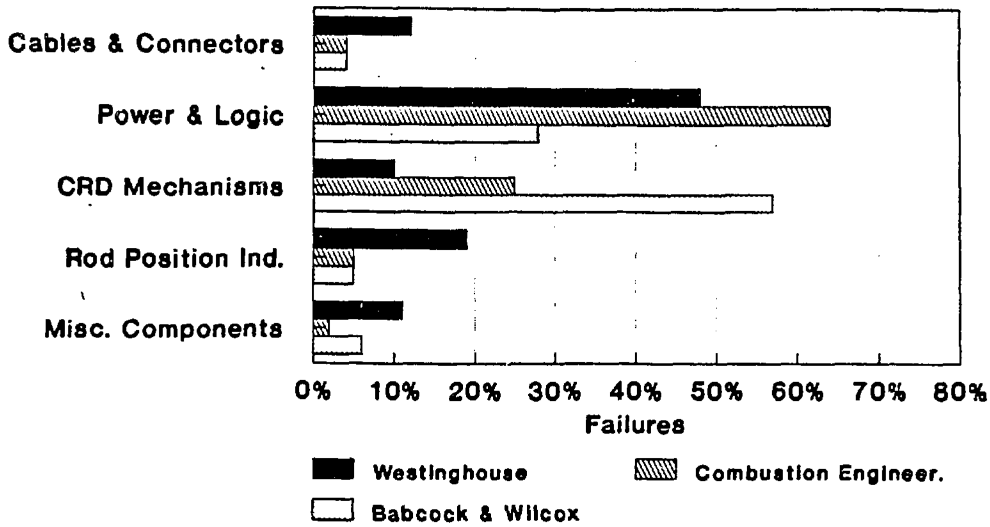

Figure 1. PWR CRD sub-system failures

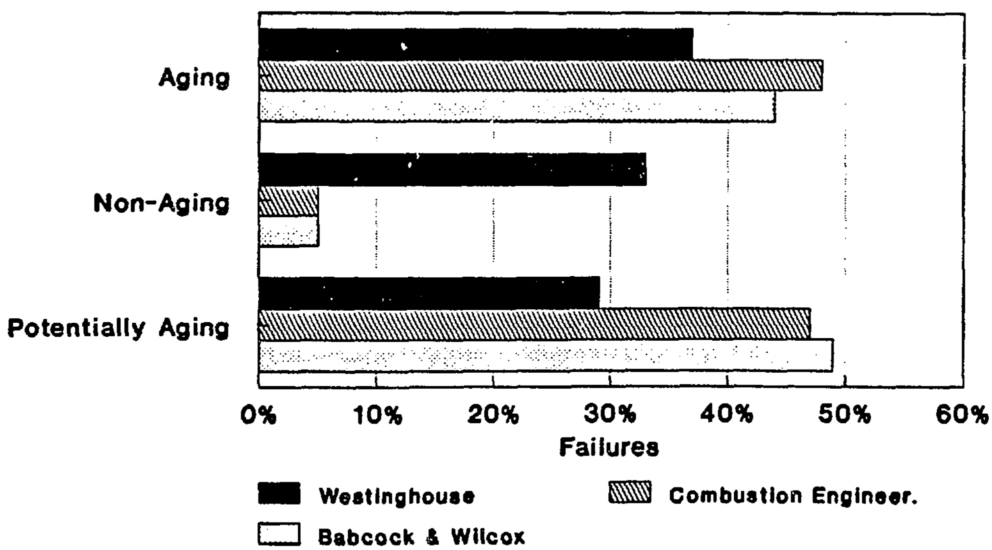

Figure 2. CRD system failures due to aging

Table 2. PWR CRD System Information Notices

Year	NRC Reference	CRD Component	Age Related Concern
1980	NUREG-0641	Control Rod Guide Tube	Wear, structural integrity
1982	IN 82-29	Guide Tube Support Pins	Stress corrosion cracking
1985	IN 85-14	Breech Guide Screw	Loose parts in latch assembly cause stuck rod
	IN 85-38	Stuck CRDM	Loose parts from handling tool result in jammed CRDM
	IN 85-86	Power & Logic Cabinets	Electrical transient effects on solid state components
1986	IN 86-108	CRD Pressure Housing	Degradation of RCS pressure boundary from boric acid corrosion
1987	IN 87-05	Rod Control System	Interface with protection systems
	IN 87-109	RCCA	Flow induced vibration caused perforation
1988	IN 88-47	Rod Drop Times	Change in Tech. Spec. test procedure resulted in slower rod drop times
1989	IN 89-31	Control Rods	Swelling and cracking of Hf rods

of the rotating seals in these CRDs have resulted in numerous instances of primary coolant leaks. The main concern with primary coolant leakage, other than it may lead to a small-break LOCA, is the deleterious corrosive properties of boric acid in the primary coolant which could degrade other components in the vicinity of the leak, including the reactor head. Additionally, boric acid buildup may deposit and obstruct CRD coil cooling passages, resulting in the overheating and failure of the stator coils. Flexatallic gasket failures in B&W reactors, due primarily to the aging embrittlement of the seals, has resulted in the gasket design being replaced with a new configuration and material.

Housing cracks have also been detected as a result of stress corrosion cracking. French reactors have recently reported instances of cracked CRD penetrations due to pure water stress corrosion cracking of Inconel 600. While no similar instances have been reported in US reactors to date, studies are underway to identify specific combinations of stresses, operating temperatures, and water chemistry which may be conducive to the development of such cracks.

4) <u>Rod Position Indication:</u> Both B&W and CE utilize magnetically actuated reed switches, while <u>W</u> employs detector coils, to provide indication of actual rod position. The B&W and CE designs have been improved to allow continued rod position signals with several reed switch failures. Calibration drift, possibly caused by temperature variations of the CRDM, was a prime failure cause of the <u>W</u> linear transformer detector. Power supply failures also accounted for a significant number of RPI failure events. Westinghouse has made design improvements in response to the RPI failures. A digital system has been designed and installed in some plants which allows position indication to be sensed and displayed upon the loss of a single coil.

5) <u>Miscellaneous Failures:</u> In addition to the above, other specific failures have occurred. Both CE and Westinghouse have experienced control rod failures due to poison swelling (B4C and Hafnium), and guide tube wear due to flow induced vibration with the control rods when inserted in the core. CE has incorporated a stainless steel sleeve inside the upper portion of the guide tube in response to the wear. Westinghouse has modified the guide tube heat treating and location of the rods in the core during the cycle in response to the same problem. Stress corrosion cracking failures have been reported with the Westinghouse control rod guide tube support (or split) pins, and fuel assembly hold down spring clamps with Westinghouse and B&W. Failures such as these may interfere with control rod motion, or result in loose parts which may become lodged in the guide tubes or CRD internals.

DETECTING AND MITIGATING DEGRADATION

An evaluation of current inspection, surveillance, monitoring and maintenance activities for the CRD system was also performed. The information was obtained from a survey of the plants conducted with the assistance of EPRI and NUMARC. Ten Westinghouse, four CE and two B&W plants responded, representing 24 plants responded to the surveys.

Table 3 summarizes the major preventive maintenance activities performed on the CRD system. The majority of the inspections performed are electrical in nature. Though some differences exist between the three vendors, the same functional inspections are performed. The mechanical PM consists of visual inspections of the drive rod when it is exposed during refuel operations, and of the seals, welds, and vent valve to ensure no leakage. Electrical inspections include DC and insulation resistance tests on the stator coils, thermocouple resistance, and for B&W, functional tests for all new coils consisting of minimum run and latching/unlatching current tests.

Most utilities commonly use meggering to check the electrical integrity of the system components. Meggering is a go/no-go test which does not produce results which may be trended to detect age degradation. Failure of meggering is not conclusive of component failure, since moisture intrusion commonly results in low megohm readings. CE and Westinghouse plants perform coil current traces, which provide an indication of the coil actuation at specific times and currents. These coils are visually compared to those obtained from the previous cycle to determine any changes in operability. Age degradation may not be clearly discernible from this type of test.

Visual inspections for primary coolant leakage are conducted following each cycle. Any leakage greater then 1 gpm must be repaired before operation can continue. This repair typically involves weld repair or gasket replacement. Vent valve leakage was another common cause of primary coolant leakage, resulting from wear, inappropriate maintenance, or component failure. CE recommends that the vent valve be rebuilt with new sealing components each time it is opened. Some utilities, in lieu of repairing leaking vent valves during operation, will weld them shut, and replace them during the following outage.

All plants which responded to the survey reported as being in compliance with the ten-year ISI inspections applicable to the CRDs. Currently, this requirement is that 10 percent of the peripheral housings be inspected every ten years. Given the continued instances of housing defects and failures, consideration should be given to modifying this requirement to include interior housings as well.

The majority of the respondents reported that they do not have a sophisticated reliability program for the CRDs. Such a program should be established, and include accessing one (or more) of the operating databases. This would result in a more efficient predictive maintenance program capable of alerting utility personnel to failures at other plants, and allow for corrective maintenance before component failure. Relying solely upon vendor supplied information, as is often the case, may not be timely enough.

The use of commercially available, advanced system monitoring and inspection techniques, should be evaluated for use with the CRD system. These methods are non-invasive and capable of detecting and trending age degradation. These methods include infrared thermography for electronic components, motor

Table 3. CRD System Preventive Maintenance

Subsystem/Component	Preventive Maintenance Practice
I. Control Rod Assembly	
a. Control Rods	Eddy Current, Ultrasonic, Profilometry
b. Guide Tubes	Eddy Current, Profilometry
c. Split Pin	Eddy Current
II. Control Rod Drive Mechanism	
a. Pressure Housing	Visual, Weld NDE
b. Rotor/Latch Assemblies	None
c. Lead Screw/Drive Rod	Visual (if possible)
d. Coils	Insulation Resistance Coil Resistance Thermocouple Resistance Coil Timing Signature Traces Polarity Checks
e. Vent Valves	Visual, Hydrostatic
III. Power and Control System	
a. Cables	Meggering Visual
b. Connectors	Tightness Inspection Watertight Seal Check
c. Power Supplies	Visual Inspection Calibrations Vendor Refurbishment
d. Control/Logic Cabinets	Functional Test Visual Inspection Vendor Refurbishment Replace Fuses Measure Cabinet Temperature Timing/Functional Tests Clean
IV. Rod Position Indication Systems	
a. Cables	Visual Resistance Measurement Insulation Resistance

current signature analysis to verify proper CRDM operation, and alternatives to meggering which produce quantitative results.

CONCLUSIONS AND RECOMMENDATIONS

The results of this study indicate that age degradation and failures have occurred with the B&W, CE, and W control rod drive systems. Though these failures have not prevented the system from performing its primary safety function, they do present unnecessary challenges to the operation of other plant safety systems when they result in unplanned reactor scrams.

Design changes and modifications have been made to reduce or eliminate the stresses which contribute to aging degradation, or improve the materials to better withstand the existing stressors. Examples of such design improvements include controlling the temperatures both in the reactor head area and in the power and control cabinets. These changes would result in decreased stresses on the power and control cables and modularized components, and the CRD coils. Consideration should also be given to extending the current ISI inspections to include interior CRD housings as well as those on the periphery of the reactor head. The occurrences of primary coolant leakage highlight the need for thorough inspection, and repair, of all leaks, especially from degraded gaskets.

Monitoring techniques are available to detect system aging. Specific emphasis needs to be applied to the mechanical condition of the drive shaft, guide tubes, and control rods. Any indication of wear or degradation should be evaluated and corrected prior to component failure. Many of the common inspection techniques, which are adequate to determine the operability of the system, are not suitable for detecting age degradation. Advanced system monitoring methods should be used in combination with some of the existing methods. Monitoring the CRD system for mechanical and electrical integrity is justified based upon the safety significance and operational performance. Techniques such as motor current signature analysis, ultrasonics, eddy current, and infrared thermography all produce valuable indications of age degradation.

Utilities should also be cognizant of the importance of a thorough root cause analysis. Instances of common failures, which occurred at similar plants, were reported before the actual failure cause was identified and corrected. A greater emphasis needs to be placed [illegible] operating experience gained at all nuclear plants. Tremendous benefits [illegible]ved through shared information. Degradation experienced at older plants shou[illegible]rongly influence the maintenance practices at newer plants.

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