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Auxiliary Feedwater System Risk-Based Inspection Guide for the Palo Verde Nuclear Power Plant

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Abstract

In a study sponsored by the U.S. Nuclear Regulatory Commission (NRC), Pacific Northwest Laboratory has developed and applied a methodology for deriving plant-specific risk-based inspection guidance for the auxiliary feedwater (AFW) system at pressurized water reactors that have not undergone probabilistic risk assessment (PRA). This methodology uses existing PRA results and plant operating experience information. Existing PRA-based inspection guidance information recently developed for the NRC for various plants was used to identify generic component failure modes. This information was then combined with plant-specific and industry-wide component information and failure data to identify failure modes and failure mechanisms for the AFW system at the selected plants. Palo Verde was selected as one of a series of plants for study. The product of this effort is a prioritized listing of AFW failures which have occurred at the plant and at other PWRs. This listing is intended for use by NRC inspectors in the preparation of inspection plans addressing AFW risk-important components at the Palo Verde plants.

Contents

Figure

Table

Summary

This document presents a compilation of AFW system failure information which has been screened for risk significance in terms of failure frequency and degradation of system performance. It is a risk-prioritized listing of failure events and their causes that are significant enough to warrant consideration in inspection planning at the Palo Verde plant. This information is presented to provide inspectors with increased resources for inspection planning at Palo Verde.

The risk importance of various component failure modes was identified by analysis of the results of PRAs for many pressurized water reactors (PWRs). However, the component failure categories identified in PRAs are rather broad, because the failure data used in the PRAs is an aggregate of many individual failures having a variety of root causes. In order to help inspectors focus on specific aspects of component operation, maintenance and design which might cause these failures, an extensive review of component failure information was performed to identify and rank the root causes of these component failures. Both Palo Verde and industry-wide failure information was analyzed. Failure causes were sorted on the basis of frequency of occurrence and seriousness of consequence, and categorized as common cause failures, human errors, design problems, or component failures.

This information is presented in the body of this document. Section 3.0 provides brief descriptions of these risk-important failure causes, and Section 5.0 presents more extensive discussions, with specific examples and references. The entries in the two sections are cross-referenced.

An abbreviated system walkdown table is presented in Section 3.2 which includes only components identified as risk important. This table lists the system lineup for normal, standby system operation.

This information permits an inspector to concentrate on components important to the prevention of core damage. However, it is important to note that inspections should not focus exclusively on these components. Other components which perform essential functions, but which are not included because of high reliability or redundancy, must also be addressed to ensure that degradation does not increase their failure probabilities, and hence their risk importance.

Acknowledgments

We wish to thank Dave Lorenzi, A. Fernandez, Dave Fan, and Roy Linthicum of the Arizona Public Service Company for reviewing and validating this document. Their input to Sections 2, 3, and 4 make this report a more useful inspection tool. Their cooperation is greatly appreciated.

1 Introduction

This document is one of a series providing plant-specific inspection guidance for auxiliary feedwater (AFW) systems at pressurized water reactors (PWRs). This guidance is based on information from probabilistic risk assessments (PRAs) for similar PWRs, industry-wide operating experience with AFW systems, plant-specific AFW system descriptions, and plant-specific operating experience. It is not a detailed inspection plan, but rather a compilation of AFW system failure information which has been screened for risk significance in terms of failure frequency and degradation of system performance. The result is a risk-prioritized listing of failure events and their causes that are significant enough to warrant consideration in inspection planning at the Palo Verde plant.

This inspection guidance is presented in Section 3.0, following a description of the Palo Verde AFW system in Section 2.0. Section 3.0 identifies the risk important system components by Palo Verde identification number, followed by brief descriptions of each of the various failure causes of that component. These include specific human errors, design deficiencies, and hardware failures. The discussions also identify where common cause failures have affected multiple, redundant components. These brief discussions identify specific aspects of system or component design, operation, maintenance, or testing for inspection by observation, records review, training observation, procedures review, or by observation of the implementation of procedures. An AFW system walkdown table identifying risk important components and their lineup for normal, standby system operation is also provided.

The remainder of the document describes and discusses the information used in compiling this inspection guidance. Section 4.0 describes the risk importance information which has been derived from PRAs and its sources. As review of that section will show, the failure categories identified in PRAs are rather broad (e.g., pump fails to start or run, valve fails closed). Section 5.0 addresses the specific failure causes which have been combined under these categories.

AFW system operating history was studied to identify the various specific failures which have been aggregated into the PRA failure mode categories. Section 5.1 presents a summary of Palo Verde failure information, and Section 5.2 presents a review of industry-wide failure information. The industry-wide information was compiled from a variety of NRC sources, including AEOD analyses and reports, information notices, inspection and enforcement bulletins, and generic letters, and from a variety of INPO reports as well. Some Licensee Event Reports and NPRDS event descriptions were also reviewed. Finally, information was included from reports of NRC-sponsored studies of the effects of plant aging, which include quantitative analyses of reported AFW system failures. This industry-wide information was then combined with the plant-specific failure information to identify the various root causes of the PRA failure categories, which are identified in Section 3.0.

2 Palo Verde AFW System

This section presents an overview description of the Palo Verde Combustion Engineering System 80 with a Bechtel designed AFW system, including a simplified schematic system diagram. In addition, the system success criterion, system dependencies, and administrative operational constraints are also presented.

2.1 System Description

The AFW system provides feedwater to the steam generators (SG) to allow secondary-side heat removal from the primary system when main feedwater is unavailable. The system is capable of functioning for extended periods, which allows time to restore main feedwater flow or to proceed with an orderly cooldown of the plant to where the shutdown decay heat cooling (SDC) system can remove decay heat. A simplified schematic diagram of the AFW system is shown in Figure 2.1.

The system consists of a Condensate Storage Tank (CST), one seismic category I motor-driven (MD) AFW pump, one seismic category I turbine-driven (TD) AFW pump, one seismic category II motor-driven pump, associated piping, valves, control, and instrumentation. The seismic category I and II pumps are designated as essential and non-essential, respectively. The essential portions of the system is designed to start up and establish flow automatically. Both seismic category I pumps start when a steam generator low level generates an Auxiliary Feedwater Actuation System (AFAS) signal to feed an intact steam generator. The turbine-driven pump will also start automatically on a loss of power (LOP) signal and the motor-driven pump will start when the standby diesel generator re-energizes bus E-PBB-SO4, on a blackout.

Separate lines from the CST supply each motor-driven pump and the turbine-driven pump. Isolation valves in the lines supplying the essential pumps are wired open manual valves. The non-essential pump takes suction from the CST, through redundant, motor-operated, isolation valves. Power, control, and instrumentation associated with each pump is independent from each other. Steam for the turbine-driven pump is supplied from either one or both steam generators upstream of the main steam isolation valves, through SGA-UV-134 and SGA-UV-138. Each AFW pump is equipped with a minimum recirculation flow system, which discharges back to the CST.

Auxiliary feedwater is normally supplied the essential turbine-driven and motor-driven pumps through two redundant headers, to steam generators "1" and "2", respectively. Each header contains two check valves, a wired open manual discharge isolation valve, two motor-operated regulating and isolation valves, a flow measuring device, and another check valve, before it joins the main feedwater line inside containment. Each essential AFW header also contains a crossover line with redundant valving that allows either essential pump to feed either steam generator. The non-essential AFW pump is used to supply feedwater to the steam generators through the main feedwater lines, upstream of the main feedwater control valves during startup and shutdown conditions and it is isolated from the essential portions of the AFW system during emergency conditions.

The CST is the normal source of water for the AFW System and is required to store sufficient demineralized water (300,000 gallons) to cooldown and maintain the reactor coolant system (RCS) at hot standby conditions for 8 hours with steam discharge to atmosphere. All tank connections except those required for instrumentation, emergency feedwater pump suction, chemical analysis, and tank drainage are located above this minimum level. A backup water supply for the essential AFW pumps can be manually aligned from the Reactor Makeup Water Tank (RMWT).

2.2 Success Criterion

System success requires the operation of at least one pump supplying rated flow to at least one steam generator.

2.3 System Dependencies

The AFW system depends on AC power for the motor-driven pump and AFW system instrumentation, DC power for control power to pumps and valves, and an automatic actuation signal. The RMWT provides a backup water supply to the essential AFW pumps. The Main Feedwater System provides the flow path for normal reactor startup and shutdown operation of the AFW system through the main feedwater regulating control valves. Also, the turbine-driven pump requires steam availability.

2.4 Operational Constraints

When the reactor is in Modes 1, 2, 3, or 4, the Palo Verde Technical Specifications require that three AFW pumps and their associated flowpaths are operable with each motor-driven pump powered from a separate emergency bus. If one AFW pump becomes inoperable, it must be restored to operable status within 72 hours or the plant must be shutdown to hot standby within the next 6 hours. If two AFW pumps are inoperable, the plant must be shutdown to hot standby within 6 hours and in hot shutdown within the following 6 hours. If all three pumps are inoperable, action must be taken to immediately restore one.

The Palo Verde Technical Specifications require a minimum inventory of 300,000 gallons (8 hour supply) of demineralized water be stored in the CST. With the CST inoperable, it must be restored to operable status within 4 hours or if the RMWT is demonstrated to be operable within the initial 4 hour period, it may serve as a backup supply to the essential AFW pumps for seven days.

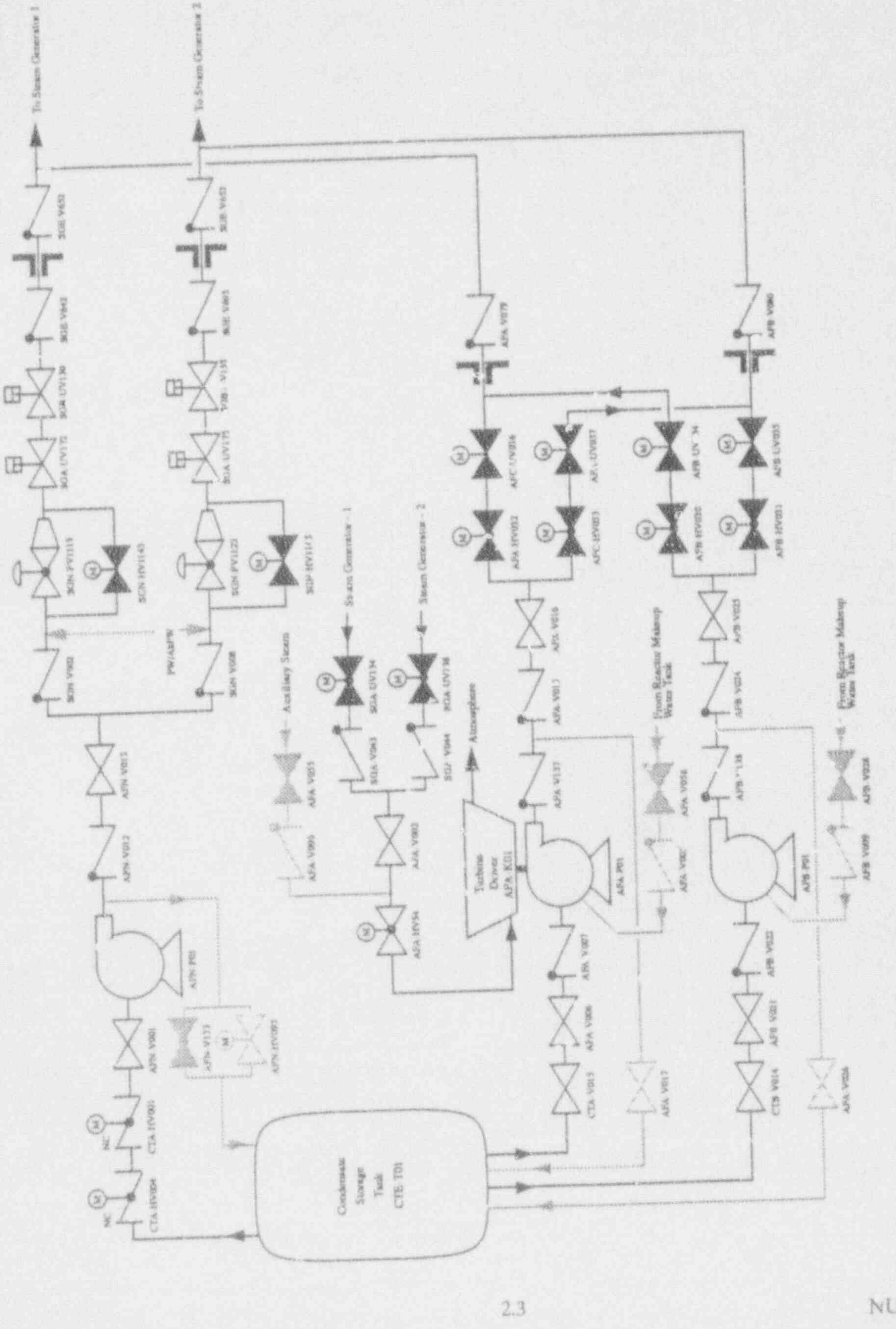

Figure 2.1 Palo Verde Auxiliary Feedwater System

3 Inspection Guidance for the Palo Verde AFW System

In this section the risk important components of the Palo Verde AFW system are identified, and the important modes by which they are likely to fail are briefly described. These failure modes include specific human errors, design problems, and types of hardware failures which have been observed to occur for these types of components both at San Onofre and at PWRs throughout the nuclear industry. The discussions also identify where common cause failures have affected multiple, redundant components. These brief discussions identify specific aspects of system or component design, operation, maintenance, or testing for observation, records review, training observation, procedures review or by observation of the implementation of procedures.

Table 3.1 is an abbreviated AFW system walkdown table which identifies risk important components. This table lists the system lineup for normal, standby system operation. Inspection of the components identified addresses essentially all of the risk associated with AFW system operation.

3.1 Risk Important AFW Components and Failure Modes

Common cause failures of multiple pumps are the most risk-important failure modes of AFW system components. These are followed in importance by single pump failures, level control valve failures, and individual check valve backleakage failures.

The following sections address each of these failure modes, in decreasing order of importance. They present the important root causes of these component failure modes which have been distilled from historical records, from Palo Verde and other plants. Each item is keyed to discussions in Section 5.2 which present additional information on historical events.

3.1.1 Multiple Pump Failures Due to Common Cause

The following listing summarizes the most important multiple-pump failure modes identified in Section 5.2.1, Common Cause Failures, and each item is keyed with a 3-digit code to entries in that section.

- Incorrect operator intervention into automatic system functioning, including improper manual starting and securing of pumps, has caused failure of all pumps, including overspeed trip on startup, and inability to restart prematurely secured pumps. CC1.

Inspection Suggestion. Observe Abnormal and Emergency Operating Procedure (AOP)/EOP) simulator training exercises to verify that the operators comply with procedures during observed evolutions. Observe surveillance testing on the AFW system to verify it is in strict compliance with the surveillance test procedure.

- Valve mispositioning has caused failure of all pumps. Pump suction, steam supply, and instrument isolation valves have been involved. CC2.

Inspection Suggestion. Verify that the system valve alignment, air operated valve control and valve actuating air pressures are correct using 3.1 Walkdown Table, the system operating procedures, and operator rounds logsheet. Review surveillance procedures that alter the standby alignment of the AFW system. Ensure that an adequate return to normal alignment section exists.

- Steam binding has caused failure of multiple pumps. This resulted from leakage of hot feedwater past check valves and a motor-operated valve into a common discharge header. CC10. Multiple-pump steam binding has also resulted from improper valve lineups, and from running a pump deadheaded. CC3. The multiple isolation valves in each essential AFW

flowpath which are normally closed minimize the hazard associated with steam binding at Palo Verde.

Inspection Suggestion. Verify that the pump discharge piping temperature monitoring tape is the appropriate color for the tape installed.

- Pump control circuit deficiencies or design modification errors have caused failures of multiple pumps to auto start, spurious pump trips during operation, and failures to restart after pump shutdown. CC4. Incorrect setpoints and control circuit calibrations have also prevented proper operation of multiple pumps. CC5.

Inspection Suggestion. Review design change implementation documents for the post maintenance testing required prior to returning the equipment to service. Assure the testing verifies that all potentially impacted functions operate correctly, and includes repeating any plant start-up or hot functional testing that may be affected by the design change.

- Loss of a vital power bus has failed both the turbine-driven and one motor-driven pump due to loss of control power to steam admission valves or to turbine controls, and to motor controls powered from the same bus. CC6.

Inspection Suggestion. The material condition of the electrical equipment is an indicator of probable reliability. Review the Preventative Maintenance (PM) records to assure the equipment is maintained on an appropriate frequency for the environment it is in and that the PMs are actually being performed as required by the program. Review the outstanding Corrective Maintenance records to assure the deficiencies found on the equipment are promptly corrected.

3.1.2 Turbine Driven Pump AFA-P01 Fails to Start or Run

- Improperly adjusted and inadequately maintained turbine governors have caused pump failures. HE2. Problems include worn or loosened nuts, set screws, linkages or cable connections, oil leaks and/or contamination, and electrical failures of resistors, transistors, diodes and circuit cards, and erroneous grounds and connections. CF5. Similar failures have been experienced at Palo Verde.

Inspection Suggestion. Review PM records to assure the governor oil is being replaced or sampled and analyzed within the designated frequency. During plant walkdowns carefully inspect the governor and linkages for loose fasteners, leaks, and unsecured or degraded conduit. Review vendor manuals to ensure PM procedures are performed according to manufacturer's recommendations and good maintenance practices.

- Terry turbines with Woodward Model EG governors have been found to overspeed trip if full steam flow is allowed on startup. Sensitivity can be reduced if a startup steam bypass valve is sequenced to open first. DE1.

Inspection Suggestion. Observe the operation of the turbine driven Aux Feed pump during pump testing, and assure that the one inch steam supply valves SG-UV-134A and 138A open first, and after a time delay the steam supply MOVs open.

- Condensate slugs in steam lines have caused turbine overspeed trip on startup. Tests repeated right after such a trip may fail to indicate the problem due to warming and clearing of the steam lines. Surveillances should exercise all steam supply connections. DE2. At Palo Verde, the steam supply lines are kept warm and free of condensate using controlled leakage, some of which passes through the turbine. Operators verify the line temperature is greater than 190°F on their rounds.

Inspection Suggestion. Verify that the steam traps are valved or bypassed on the steam supply line. If the steam trap discharge is visible, assure there is evidence of liquid discharge.

- Trip and throttle valve (AFA-HV-54) problems which have failed the turbine driven pump include physically bumping it, failure to reset it following testing, and failures to verify control

room indication of reset. HE2. Whether either the overspeed trip or trip and throttle valve (TTV) trip can be reset without resetting the other, and unambiguity of control room and local indication of TTV position and overspeed trip linkage reset status, all affect the likelihood of these errors. DE3. At Palo Verde, the TTV has failed to reset properly due to misalignment of the mechanical trip latch and control indication has been lost due to a blown fuse. A job performance measure (JPM) now exists to train the operators on reset of the linkage.

Inspection Suggestion. Carefully inspect the TTV overspeed trip linkage and assure it is reset and in good physical condition. Review training procedures to ensure operator training on resetting the TTV is current. Observe operators during the monthly surveillance, and randomly select operators and have them simulate a reset of the linkage.

3.1.3 Motor Driven Pump AFB-P01 or AFN-P01 Fails to Start or Run

- Control circuits used for automatic and manual pump starting are an important cause of motor driven pump failures, as are circuit breaker failures. CF7. A circuit breaker failure at Palo Verde has caused a motor driven pump to fail to start.

Inspection Suggestion. Review corrective maintenance records and non-conformance reports when control circuit problems occur to determine if a trend exists. Every time a breaker is racked in a post maintenance test (PMT) should be performed to start the pump, assuring no control circuit problems have occurred as a result of the manipulation of the breaker. (Control circuit stabs have to make up upon racking the breaker, as well as cell switch damage can occur upon removal and reinstallation of the breaker.)

- Mispositioning of handswitches and procedural deficiencies have prevented automatic pump start. HE3.

Inspection Suggestion. Confirm switch position using Table 3.1. Review administrative procedures concerning documentation of procedural deficiencies. Ensure operator training on procedural changes is current.

3.1.4 Pump Unavailable Due to Maintenance or Surveillance

- Both scheduled and unscheduled maintenance remove pumps from operability. Surveillance requires operation with an altered line-up, although a pump train may not be declared inoperable during testing. Prompt scheduling and performance of maintenance and surveillance minimize this unavailability.

Inspection Suggestion. Review the time the AFW system and components are inoperable. Assure maintenance is scheduled to have a minimum of equipment outages. The maintenance should be scheduled before the routine surveillance test, so credit can be taken for both post maintenance testing and surveillance testing, avoiding excessive testing. Review surveillance schedule for frequency and adequacy to verify system operability requirements per Technical Specifications. Review quarterly safety system performance indicator for the Auxiliary Feed system.

3.1.5 Motor Operated Valves

Train A: HV-32, HV-33, UV-36, UV-37
Train B: HV-30, HV-31, UV-34, UV-35
Non-Essential Pump Suction; Recirculation: HV-4, HV-1; HV-95

- Common cause failure of MOVs has resulted from failure to use electrical signature tracing equipment to determine proper settings of torque switch and torque switch bypass switches. Failure to calibrate switch settings for high torques necessary under design basis accident conditions has also been involved. CC11. Palo Verde has experienced MOV failure due to improper torque switch settings.

Inspection Suggestion. Review the MOV analytical test records to assure the testing and settings are based on dynamic system conditions. Overtorquing of the valve operator can result in valve damage such as cracking of

the seat or disc. Review the work documents to assure overtorquing is identified and corrective actions are taken to assure valve operability following an overtorque condition. Review the work documents to assure equipment qualification (EQ) seals are renewed as required during the restoration from testing to maintain the EQ rating of the MOV.

- Valve motors have been failed due to lack of, or improper sizing or use of thermal overload protective devices. Bypassing and oversizing should be based on proper engineering for design basis conditions. CF4.

Inspection Suggestion. Review work documents to assure setpoints match the design settings.

- Grease trapped in the torque switch spring pack of Limitorque SMB motor operators has caused motor burnout or thermal overload trip by preventing torque switch actuation. CF8. Palo Verde has experienced similar failures.

Inspection Suggestion. Review this only if the MOV testing program reveals deficiencies in this area.

- Manually reversing the direction of motion of operating or coasting down MOVs has overloaded the motor circuit. Operating procedures should provide cautions, and circuit designs may prevent reversal before each stroke is finished. DE7. A valve motor operator was shorted as a result of personnel error during performance testing.

Inspection Suggestion. Verify procedures and training address reversal of valve direction midstroke.

- Space heaters designed for preoperation storage have been found in DC MOVs wired in parallel with valve motors which had not been environmentally qualified with them present. DE8.

Inspection Suggestion. Spot check MOVs during MOV testing to assure the space heaters are physically removed or disconnected.

3.1.6 Manual Suction or Discaarge Valves Fail Closed

Train A: AF-006, AF-016
Train B: AF-021, AF-025
Non Essential Pump: AF-001, AF-013

These manual valves are all normally wired open. For each train, closure of the first valve listed would block pump suction and closure of the second valves would block pump discharge, except for recirculation to the CST.

- Valve mispositioning has resulted in failures of multiple trains of AFW. CC2. It has also been the dominant cause of problems identified during operational readiness inspections. HE1. Due to Palo Verde's design, multiple valve mispositioning would be required to defeat AFW function. Events have occurred most often during maintenance, calibration, or system modifications. Important causes of mispositioning include:
  - Failure to provide complete, clear, and specific procedures for tasks and system restoration
  - Failure to promptly revise and validate procedures, training, and diagrams following system modifications
  - Failure to complete follow a written procedure
  - Failure to adequately review uncompleted procedural steps after task completion
  - Failure to verify support functions after restoration
  - Failure to adhere scrupulously to administrative procedures regarding tagging, control and tracking of valve operations

- Failure to log the manipulation of sealed valves

- Failure to follow good practices of written task assignment and feedback of task completion information

- Failure to provide easily read system drawings, legible valve labels corresponding to drawings and procedures, and labeled indications of local valve position

Inspection Suggestion. Review the application of administrative controls that relate to valve positioning and sealing, system restoration following maintenance, valve labeling, system drawing updating, and procedure revision, for proper implementation.

3.1.7 Leakage of Hot Feedwater through Check Valves:

Train A: AF-139, AF-015, AF-079
Train B: AF-138, AF-024, AF-080
Non-Essential Pump: AF-012

- Leakage of hot feedwater through several check valves in series has caused steam binding of multiple pumps. CC10.

Inspection Suggestion. Covered by 3.1.1 bullet 3.

- Slow leakage past the final check valve of a series may not force the check valve closed. Other check valves in series may leak similarly. Piping orientation and valve design are important factors in achieving true series protection. CF1.

Inspection Suggestion. Covered by 3.1.1 bullet 3.

3.2 Risk Important AFW System Walkdown Table

Table 3.1 presents an AFW system walkdown table including only components identified as risk important. The lineup indicated is for normal power operation. This information allows inspectors to concentrate their efforts on components important to prevention of core damage. However, it is essential to note that inspections should not focus exclusively on these comments. Other components which perform essential functions, but which are absent from this table because of high reliability or redundancy, must also be addressed to ensure that their risk importances are not increased. Examples include the (open) steam lead isolation valves upstream of HV-4716, an adequate water level in the CST, and the (closed) valves cross connecting the discharges of the two motor-driven AFW pumps.

Table 3.1. Risk Important AFW System Walkdown Table for Palo Verde AFW System Components

Component Number	Component Name	Required Position	Actual Position
	B ESF Switchgear Room		
AFB-PO1	Motor-Driven Pump	Racked In Indicating Lights Lit Lockout-Black Flag	______
	A ESF Switchgear Room		
AFN-PO1	Motor-Driven Pump	Racked In/ Indicating Lights Lit Lockout-Black Flag	______
	A Auxiliary Feed Pump Room		
AFA-HV-54	Trip and Throttle Valve	Reset/Open	
AFC-HV-33	AFW Pump A Flow Control to SG/ #2	Closed	______
AFA-UV-37	AFW Pump A Supply to S/G #2 Isolation	Closed	______
AFA-V-137	Piping Upstream of Check Valve	Cool	______
AFA-V-160	Body Drain T&T Valve	Throttled	______
AFA-V-155	Turbine Exhaust Drain	Throttled	______
AFA-FV-157	Turbine Casing Drain	Throttled	______
AFA-HV-32	AFW Pump A Flow Control to S/G #1	Close	______
AFC-HV-36	AFW Pump A Supply to S/G #1 Isolation	Closed	______
AFA-V-002	Main Steam Supply to AFW Pump A Isolation	Locked Open	______
AFA-V-016	AFW Pump A Discharge Isolation	Wired Open	______
AFA-V-017	AFW Pump A Miniflow Isolation	Locked Open	______

Table 3.1 (Continued)

Component Number	Component Name	Required Position	Actual Position
AFA-V-058	AFW Pump A Suction from Reactor Makeup Water Tank	Clo:	____
AFA-V-006	AFW Pump A Suction from CST	Wired Open	____
AFA-V-015	Piping Upstream of Check Valve	Cool	____
	B Auxiliary Feed Pump Room		
AFB-HV-31	AFW Pump B Flow Control to S/G #2	Closed	____
AFB-UV-35	AFW Pump B Supply to S/G #2	Closed	____
AFB-V-138	Piping Upstream of Check Valve	Cool	____
AFB-HV-30	AFW Pump B Flow Control to S/G #1	Closed	____
AFB-UV-34	AFW Pump B Supply to S/G #1 Isolation	Closed	____
AFB-V-025	AFW Pump B Discharge Isolation	Locked Open	____
AFB-V-026	AFW Pump B Miniflow Isolation	Locked Open	____
AFB-V-028	AFW Pump B Suction from Reactor Makeup Water Tank	Closed	____
AFB-V-021	AFW Pump B Suction from CST	Locked Open	____
AFB-V-024	Piping Upstream of Check Valve	Cool	____
	Condensate Transfer Pump Room		
CT-V-014	CST Isolation to AFW Pump B	Locked Open	____
AFB-V-078	AFW Pump B Recirculation to CST	Locked Open	____
CT-V-015	CST Isolation to AFW Pump A	Locked Open	____
AFA-V-077	AFW Pump A Recirculation to CST	Locked Open	____

Table 3.1 (Continued)

Component Number	Component Name	Required Position	Actual Position
CT-HV-4	Non-Essential AFW Pump Suction from CST	Closed	_____
CT-HV-1	Non-Essential AFW Pump Suction from CST	Closed	_____
	Turbine Building 100 ft		
AFN-V-001	Non-Essential AFW Pump Suction Isolation	Locked Open	_____
AFN-V-012	Piping Upstream of Check Valve	Cool	_____
AFN-V-013	Non-Essential AFW Pump Discharge	Locked Open	_____
AFN-HV-95	Non-Essential AFW Pump Miniflow	Open	_____
AFN-V-133	Recirculation Bypass	Lock Closed	_____
AFA-V-055	AUX Steam Supply to AFW Pump A	Lock Closed	_____
	Main Steam Support Structure 120 ft		
SGA-UV-134	A S/G #1 Supply Isolation to AFW Pump A	Closed	_____
SGA-UV-138	B S/G #2 Supply Isolation to AFW Pump A	Closed	_____
	Control Room Panel 6		
SGA-UV-134A	S/G #1 Supply Isolation Solenoid Bypass Valve	Closed	_____
SGA-UV-138A	S/G #2 Supply Isolation Solenoid Bypass Valve	Closed	_____

4 Generic Risk Insights From PRAs

PRAs for 13 PWRs were analyzed to identify risk-important accident sequences involving loss of AFW, and to identify and risk-prioritize the component failure modes involved. The results of this analysis are described in this section. They are consistent with results reported by INEL and BNL (Gregg et al. 1988, and Travis et al. 1988).

4.1 Risk Important Accident Sequences Involving AFW System Failure

Loss of Power System

- A loss of offsite power is followed by failure of AFW, resulting in core damage.
- A station blackout fails all AC power except Vital AC from DC invertors, and all decay heat removal systems except the turbine-driven AFW pump. AFW subsequently fails due to battery depletion or hardware failures, resulting in core damage.
- A DC bus fails, causing a trip and failure of the power conversion system. One AFW motor-driven pump is failed by the bus loss. AFW is subsequently lost completely due to other failures.

Transient-Caused Reactor or Turbine Trip

- A transient-caused trip is followed by a loss of PCS and AFW.

Loss of Main Feedwater

- A loss of main feedwater trips the plant, and AFW fails due to operator error and hardware failures.

Steam Generator Tube Rupture

- An SGTR is followed by failure of AFW. Coolant is lost from the primary until the RWST is depleted. HPI fails since recirculation cannot be established from the empty sump, and core damage results.

4.2 Risk Important Component Failure Modes

The generic component failure modes identified from PRA analyses as important to AFW system failure are listed below in decreasing order of risk importance.

(1) Turbine-Driven Pump Failure to Start or Run.

(2) Motor-Driven Pump Failure to Start or Run.

(3) TDP or MDP Unavailable due to Test or Maintenance.

(4) AFW System Valve Failures

- steam admission valves
- trip and throttle valve
- flow control valves
- pump discharge valves
- pump suction valves
- valves in testing or maintenance.

(5) Supply/Suction Sources

- condensate storage tank stop valve
- suction valves.

In addition to individual hardware, circuit, or instrument failures, each of these failure modes may result from common causes and human errors. Common cause failures of AFW pumps are particularly risk important. Valve failures are somewhat less important due to the multiplicity of steam generators and connection paths. Human errors of greatest risk importance involve: failures to initiate or control system operation when required; failure to restore proper system lineup after maintenance or testing; and failure to switch to alternate sources when required.

5 Failure Modes Determined From Operating Experience

This section describes the primary root causes of component failures of the AFW system, as determined from a review of operating histories at Palo Verde and at other PWRs throughout the nuclear industry. Section 5.1 describes experience at Palo Verde. Section 5.2 summarizes information compiled from a variety of NRC sources, including AEOD analyses and reports, information notices, inspection and enforcement bulletins, and generic letters, and from a variety of INPO reports as well. Some Licensee Event Reports (LERs) and NPRDS event descriptions were also reviewed. Finally, information was included from reports of NRC-sponsored studies of the effects of plant aging, which include quantitative analyses of AFW system failure reports. This information was used to identify the various root causes expected for the broad PRA-based failure categories identified in Section 4.0, resulting in the inspection guidelines presented in Section 3.0.

5.1 Palo Verde Experience

The AFW system at Palo Verde has experienced approximately 50 significant equipment failures between 1986 and 1990. These include failures of the AFW pumps, the pump discharge flow control valves to steam generators, numerous valve operators, the turbine governor and several circuit breakers. Failure modes include electrical, instrumentation, and hardware failures.

5.1.1 AFW Pump Control Logic, Instrumentation and Electrical Failures

There have been twelve failures of the AFW pumps to start and/or run properly experienced from 1986 to 1990. These have resulted from failures of governor speed control linkages, circuit breakers, motor bearings, high vibration, and impeller failures. The failure causes are mechanical wear, corrosion, inadequate design and inadequate preventative maintenance procedures.

5.1.2 Failure of AFW Pump Discharge Flow Control and Isolation Valves to Steam Generators

There have been fifteen failures of the pump discharge flow control and isolation valves from 1986 to 1990. These have resulted from excessive hardened grease in torque switch spring packs, failed circuit breakers, out of adjustment torque and limit switches, and excessive packing leakage. The failure causes were attributed to normal wear, corrosion, inadequate valve design and inadequate preventative maintenance.

5.1.3 AFW Valve Failures

Between 1986 and 1990 there have been seven events involving AFW valve failures resulting in excessive leakage. The failure cause in all cases was normal wear of valve components.

5.1.4 Human Errors

There have been nine significant human errors affecting the AFW system from 1986 to 1990. Personnel have inadvertently actuated the AFW pumps during surveillance testing, failed to calibrate or realign equipment in the correct position following maintenance and testing, and improperly installed valve internals. Both personnel error and inadequate procedures have been involved.

5.2 Industry-Wide Experience

Human errors, design/engineering problems and errors, and component failures are the primary root causes of AFW System failures identified in a review of industry wide system operating history. Common cause failures, which disable more than one train of this operationally redundant system, are highly risk significant, and can result from all of these causes.

This section identifies important common cause failure modes, and then provides a broader discussion of the single failure effects of human errors, design/engineering problems and errors, and component failures. Paragraphs presenting details of these failure modes are coded (e.g., CC1) and cross-referenced by inspection items in Section 3.

5.2.1 Common Cause Failures

The dominant cause of AFW system multiple-train failures has been human error. Design/engineering errors and component failures have been less frequent, but nevertheless significant, causes of multiple train failures.

CC1. Human error in the form of incorrect operator intervention into automatic AFW system functioning during transients resulted in the temporary loss of all safety-grade AFW pumps during events at Davis Besse (NUREG-1154 1985) and Trojan (AEOD/T416 1983). In the Davis Besse event, improper manual initiation of the steam and feedwater rupture control system (SFRCS) led to overspeed tripping of both turbine-driven AFW pumps, probably due to the introduction of condensate into the AFW turbines from the long, unheated steam supply lines. (The system had never been tested with the abnormal, cross-connected steam supply lineup which resulted.) In the Trojan event the operator incorrectly stopped both AFW pumps due to misinterpretation of MFW pump speed indication. The diesel driven pump would not restart due to a protective feature requiring complete shutdown, and the turbine-driven pump tripped on overspeed, requiring local reset of the trip and throttle valve. In cases where manual intervention is required during the early stages of a transient, training should emphasize that actions should be performed methodically and deliberately to guard against such errors.

CC2. Valve mispositioning has accounted for a significant fraction of the human errors failing multiple trains of AFW. This includes closure of normally open suction valves or steam supply valves, and of isolation valves to sensors having control functions. Incorrect handswitch positioning and inadequate temporary wiring changes have also prevented automatic starts of multiple pumps. Factors identified in studies of mispositioning errors include failure to add newly installed valves to valve checklists, weak administrative control of tagging, restoration, independent verification, and locked valve logging, and inadequate adherence to procedures. Illegible or confusing local valve labeling, and insufficient training in the determination of valve position may cause or mask mispositioning, and surveillance which does not exercise complete system functioning may not reveal mispositionings.

CC3. At ANO-2, both AFW pumps lost suction due to steam binding when they were lined up to both the CST and the hot startup/blowdown demineralizer effluent (AEOD/C404 1984). At Zion-1 steam created by running the turbine-driven pump deadheaded for one minute caused trip of a motor-driven pump sharing the same inlet header, as well as damage to the turbine-driven pump (Region 3 Morning Report, 1/17/90). Both events were caused by procedural inadequacies.

CC4. Design/engineering errors have accounted for a smaller, but significant fraction of common cause failures. Problems with control circuit design modifications at Farley defeated AFW pump auto-start on loss of main feedwater. At Zion-2, restart of both motor driven pumps was blocked by circuit failure to deenergize when the pumps had been tripped with an automatic start signal present (IN 82-01 1982). In addition, AFW control circuit design reviews at Salem and Indian Point have identified designs where failures of a single component could have failed all or multiple pumps (IN 87-34 1987).

CC5. Incorrect setpoints and control circuit settings resulting from analysis errors and failures to update procedures have also prevented pump start and caused pumps to trip spuriously. Errors of this type may remain undetected despite surveillance testing, unless surveillance tests model all types of system initiation and operating conditions. A greater fraction of instrumentation and control circuit problems has been identified during actual system operation (as opposed to surveillance testing) than for other types of failures.

CC6. On two occasions at a foreign plant, failure of a balance-of-plant inverter caused failure of two AFW pumps. In addition to loss of the motor driven pump whose auxiliary start relay was powered by the invertor, the turbine driven pump tripped on overspeed because the governor valve opened, allowing full steam flow to

the turbine. This illustrates the importance of assessing the effects of failures of balance of plant equipment which supports the operation of critical components. The instrument air system is another example of such a system.

CC7. Multiple AFW pump trips have occurred at Milistone-3, Cook-1, Trojan and Zion-2 (IN 87-53 1987) caused by brief, low pressure oscillations of suction pressure during pump startup. These oscillations occurred despite the availability of adequate static NPSH. Corrective actions taken include: extending the time delay associated with the low pressure trip, removing the trip, and replacing the trip with an alarm and operator action.

CC8. Design errors discovered during AFW system re-analysis at the Robinson plant (IN 89-30 1989) and at Millstone-1 resulted in the supply header from the CST being too small to provide adequate NPSH to the pumps if more than one of the three pumps were operating at rated flow conditions. This could lead to multiple pump failure due to cavitation. Subsequent reviews at Robinson identified a loss of feedwater transient in which inadequate NPSH and flows less than design values had occurred, but which were not recognized at the time. Event analysis and equipment trending, as well as surveillance testing which duplicates service conditions as much as is practical, can help identify such design errors.

CC9. Asiatic clams caused failure of two AFW flow control valves at Catawba-2 when low suction pressure caused by starting of a motor-driven pump caused suction source realignment to the Nuclear Service Water system. Pipes had not been routinely treated to innibit clam growth, nor regularly monitored to detect their presence, and no strainers were installed. The need for surveillance which exercises alternative system operational modes, as well as complete system functioning, is emphasized by this event. Spurious suction switchover has also occurred at Callaway and at McGuire, although no failures resulted.

CC10. Common cause failures have also been caused by component failures (AEOD/C404 1984). At Surry-2, both the turbine driven pump and one motor driven pump were declared inoperable due to steam binding caused by backleakage of hot water through multiple check valves. At Robinson-2 both motor driven pumps were found to be hot, and both motor and steam driven pumps were found to be inoperable at different times. Backleakage at Robinson-2 passed through closed motor-operated isolation valves in addition to multiple check valves. At Farley, both motor and turbine driven pump casings were found hot, although the pumps were not declared inoperable. In addition to multi-train failures, numerous incidents of single train failures have occurred, resulting in the designation of "Steam Binding of Auxiliary Feedwater Pumps" as Generic Issue 93. This generic issue was resolved by Generic Letter 88-03 (Miraglia 1988), which required licensees to monitor AFW piping temperatures each shift, and to maintain procedures for recognizing steam binding and for restoring system operability.

CC11. Common cause failures have also failed motor operated valves. During the total loss of feedwater event at Davis Besse, the normally-open AFW isolation valves failed to open after they were inadvertently closed. The failure was due to improper setting of the torque switch bypass switch, which prevents motor trip on the high torque required to unseat a closed valve. Previous problems with these valves had been addressed by increasing the torque switch trip setpoint--a fix which failed during the event due to the higher torque required due to high differential pressure across the valve. Similar common mode failures of MOVs have also occurred in other systems, resulting in issuance of Generic Letter 89-10, "Safety Related Motor-Operated Valve Testing and Surveillance (Partlow 1989)." This generic letter requires licensees to develop and implement a program to provide for the testing, inspection and maintenance of all safety-related MOVs to provide assurance that they will function when subjected to design basis conditions.

CC12. Other component failures have also resulted in AFW multi-train failures. These include out-of-adjustment electrical flow controllers resulting in improper discharge valve operation, and a failure of oil cooler cooling water supply valves to open due to silt accumulation.

5.2.2 Human Errors

HE1. The overwhelmingly dominant cause of problems identified during a series of operational readiness evaluations of AFW systems was human performance. The majority of these human performance problems resulted from incomplete and incorrect procedures, particularly with respect to valve lineup information. A study of valve mispositioning events involving human error identified failures in administrative control of tagging and logging, procedural compliance and completion of steps, verification of support systems, and inadequate procedures as important. Another study found that valve mispositioning events occurred most often during maintenance, calibration, or modification activities. Insufficient training in determining valve position, and in administrative requirements for controlling valve positioning were important causes, as was oral task assignment without task completion feedback.

HE2. Turbine driven pump failures have been caused by human errors in calibrating or adjusting governor speed control, poor governor maintenance, incorrect adjustment of governor valve and overspeed trip linkages, and errors associated with the trip and throttle valve. TTV-associated errors include physically bumping it, failure to restore it to the correct position after testing, and failures to verify control room indication of TTV position following actuation.

HE3. Motor driven pumps have been failed by human errors in mispositioning handswitches, and by procedure deficiencies.

5.2.3 Design/Engineering Problems and Errors

DE1. As noted above, the majority of AFW subsystem failures, and the greatest relative system degradation, has been found to result from turbine-driven pump failures. Overspeed trips of Terry turbines controlled by Woodward governors have been a significant source of these failures (AEOD/C602 1986). In many cases these overspeed trips have been caused by slow response of a Woodward Model EG governor on startup, at plants where full steam flow is allowed immediately. This oversensitivity has been removed by installing a startup steam bypass valve which opens first, allowing a controlled turbine acceleration and buildup of oil pressure to control the governor valve when full steam flow is admitted.

DE2. Overspeed trips of Terry turbines have been caused by condensate in the steam supply lines. Condensate slows down the turbine, causing the governor valve to open farther, and overspeed results before the governor valve can respond, after the water slug clears. This was determined to be the cause of the loss-of-all-AFW event at Davis Besse (AEOD/602 1986), with condensation enhanced due to the long length of the cross-connected steam lines. Repeated tests following a cold-start trip may be successful due to system heat up.

DE3. Turbine trip and throttle valve (TTV) problems are a significant cause of turbine driven pump failures (IN 84-66). In some cases lack of TTV position indication in the control room prevented recognition of a tripped TTV. In other cases it was possible to reset either the overspeed trip or the TTV without resetting the other. This problem is compounded by the fact that the position of the overspeed trip linkage can be misleading, and the mechanism may lack labels indicating when it is in the tripped position (AEOD/C602 1986).

DE4. Startup of turbines with Woodward Model PG-PL governors within 30 minutes of shutdown has resulted in overspeed trips when the speed setting knob was not exercised locally to drain oil from the speed setting cylinder. Speed control is based on startup with an empty cylinder. Problems have involved turbine rotation due to both procedure violations and leaking steam. Terry has marketed two types of dump valves for automatically draining the oil after shutdown (AEOD/C602 1986).

At Calvert Cliffs, a 1987 loss-of-offsite-power event required a quick, cold startup that resulted in turbine trip due to PG-PL governor stability problems. The short-term corrective action was installation of stiffer buffer springs (IN 88-09 1988). Surveillance had always been preceded by turbine warmup, which illustrates the importance of testing which duplicates service conditions as much as is practical.

DE5. Reduced viscosity of gear box oil heated by prior operation caused failure of a motor driven pump to start

due to insufficient lube oil pressure. Lowering the pressure switch setpoint solved the problem, which had not been detected during testing.

DE6. Waterhammer at Palisades resulted in AFW line and hanger damage at both steam generators. The AFW spargers are located at the normal steam generator level, and are frequently covered and uncovered during level fluctuations. Waterhammers in top-feed-ring steam generators resulted in main feedline rupture at Palo Verde and feedwater pipe cracking at Indian Point-2 (IN 84-32 1984).

DE7. Manually reversing the direction of motion of an operating valve has resulted in MOV failures where such loading was not considered in the design (AEOD/C603 1986). Control circuit design may prevent this, requiring stroke completion before reversal.

DE8. At each of the units of the South Texas Project, space heaters provided by the vendor for use in pre-installation storage of MOVs were found to be wired in parallel to the Class 1E 125 V DC motors for several AFW valves (IR 50-489/89-11; 50-499/89-11 1989). The valves had been environmentally qualified, but not with the non-safety-related heaters energized.

5.2.4 Component Failures

Generic Issue II.E.6.1, "In Situ Testing Of Valves" was divided into four sub-issues (Beckjord 1989), three of which relate directly to prevention of AFW system component failure. At the request of the NRC, in situ testing of check valves was addressed by the nuclear industry, resulting in the EPRI report, "Application Guidelines for Check Valves in Nuclear Power Plants (Brooks 1988)." This extensive report provides information on check valve applications, limitations, and inspection techniques. In situ testing of MOVs was addressed by Generic Letter 89-10, "Safety Related Motor-Operated Valve Testing and Surveillance" (Partlow 1989) which requires licensees to develop and implement a program for testing, inspection and maintenance of all safety-related MOVs. "Thermal Overload Protection for Electric Motors on Safety-Related Motor-Operated Valves - Generic Issue II.E.6.1 (Rothberg 1988)" concludes that valve motors should be thermally protected, yet in a way which emphasizes system function over protection of the operator.

CF1. The common-cause steam binding effects of check valve leakage were identified in Section 5.2.1, entry CC10. Numerous single-train events provide additional insights into this problem. In some cases leakage of hot MFW past multiple check valves in series has occurred because adequate valve-seating pressure was limited to the valves closest to the steam generators (AEOD/C404 1984). At Robinson, the pump shutdown procedure was changed to delay closing the MOVs until after the check valves were seated. At Farley, check valves were changed from swing type to lift type. Check valve rework has been done at a number of plants. Different valve designs and manufacturers are involved in this problem, and recurring leakage has been experienced, even after repair and replacement.

CF2. At Robinson, heating of motor operated valves by check valve leakage has caused thermal binding and failure of AFW discharge valves to open on demand. At Davis Besse, high differential pressure across AFW injection valves resulting from check valve leakage has prevented MOV operation (AEOD/C603 1986).

CF3. Gross check valve leakage at McGuire and Robinson caused overpressurization of the AFW suction piping. At a foreign PWR it resulted in a severe waterhammer event. At Palo Verde-2 the MFW suction piping was overpressurized by check valve leakage from the AFW system (AEOD/C404 1984). Gross check valve leakage through idle pumps represents a potential diversion of AFW pump flow.

CF4. Roughly one third of AFW system failures have been due to valve operator failures, with about equal failures for MOVs and AOVs. Almost half of the MOV failures were due to motor or switch failures (Casada 1989). An extensive study of MOV events (AEOD/C603 1986) indicates continuing inoperability problems caused by: torque switch/limit switch settings, adjustments, or failures; motor burnout; improper sizing or use of thermal overload devices; premature degradation related to inadequate use of protective devices; damage due to misuse (valve throttling, valve operator hammering); mechanical problems (loosened parts, improper assembly); or the torque switch bypass circuit improp-

erly installed or adjusted. The study concluded that current methods and procedures at many plants are not adequate to assure that MOVs will operate when needed under credible accident conditions. Specifically, a surveillance test which the valve passed might result in undetected valve inoperability due to component failure (motor burnout, operator parts failure, stem disc separation) or improper positioning of protective devices (thermal overload, torque switch, limit switch). Generic Letter 89-10 (Partlow 1989) has subsequently required licensees to implement a program ensuring that MOV switch settings are maintained so that the valves will operate under design basis conditions for the life of the plant.

CF5. Component problems have caused a significant number of turbine driven pump trips (AEOD/C602 1986). One group of events involved worn tappet nut faces, loose cable connections, loosened set screws, improperly latched TTVs, and improper assembly. Another involved oil leaks due to component or seal failures, and oil contamination due to poor maintenance activities. Governor oil may not be shared with turbine lubrication oil, resulting in the need for separate oil changes. Electrical component failures included transistor or resistor failures due to moisture intrusion, erroneous grounds and connections, diode failures, and a faulty circuit card.

CF6. Electrohydraulic-operated discharge valves have performed very poorly, and three of the five units using them have removed them due to recurrent failures. Failures included oil leaks, contaminated oil, and hydraulic pump failures.

CF7. Control circuit failures were the dominant source of motor driven AFW pump failures (Casada 1989). This includes the controls used for automatic and manual starting of the pumps, as opposed to the instrumentation inputs. Most of the remaining problems were due to circuit breaker failures.

CF8. "Hydraulic lockup" of Limitorque SMB spring packs has prevented proper spring compression to actuate the MOV torque switch, due to grease trapped in the spring pack. During a surveillance at Trojan, failure of the torque switch to trip the TTV motor resulted in tripping of the thermal overload device, leaving the turbine driven pump inoperable for 40 days until the next surveillance (AEOD/E702 1987). Problems result from grease changes to EXXON NEBULA EP-0 grease, one of only two greases considered environmentally qualified by Limitorque. Due to lower viscosity, it slowly migrates from the gear case into the spring pack. Grease changeover at Vermont Yankee affected 40 of the older MOVs of which 32 were safety related. Grease relief kits are needed for MOV operators manufactured before 1975. At Limerick, additional grease relief was required for MOVs manufactured since 1975. MOV refurbishment programs may yield other changeovers to EP-0 grease.

CF9. For AFW systems using air operated valves, almost half of the system degradation has resulted from failures of the valve controller circuit and its instrument inputs (Casada 1989). Failures occurred predominantly at a few units using automatic electronic controllers for the flow control valves, with the majority of failures due to electrical hardware. At Turkey Point-3, controller malfunction resulted from water in the Instrument Air system due to maintenance inoperability of the air dryers.

CF10. For systems using diesel driven pumps, most of the failures were due to start control and governor speed control circuitry. Half of these occurred on demand, as opposed to during testing (Casada 1989).

CF11. For systems using AOVs, operability requires the availability of Instrument Air, backup air, or backup nitrogen. However, NRC Maintenance Team Inspections have identified inadequate testing of check valves isolating the safety-related portion of the IA system at several utilities (Letter, Roe to Richardson). Generic Letter 88-14 (Miraglia 1988), requires licensees to verify by test that air-operated safety-related components will perform as expected in accordance with all design-basis events, including a loss of normal IA.

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11. ABSTRACT (200 words or less)

In a study sponsored by the U.S. Nuclear Regulatory Commission (NRC), Pacific Northwest Laboratory has developed and applied a methodology for deriving plant-specific risk-based inspection guidance for the auxiliary feedwater (AFW) system at pressurized water reactors that have not undergone probabilistic risk assessment (PRA). This methodology uses existing PRA results and plant operating experience information. Existing PRA-based inspection guidance information recently developed for the NRC for various plants was used to identify generic component failure modes. This information was then combined with plant-specific and industry-wide component information and failure data to identify failure modes and failure mechanisms for the AFW system at the selected plants. Palo Verde was selected as one of a series of plants for study. The product of this effort is a prioritized listing of AFW failures which have occurred at the plant and at other PWRs. This listing is intended for use by NRC inspectors in the preparation of inspection plans addressing AFW risk-important components at the Palo Verde plants.

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