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Auxiliary Feedwater System Risk-Based Inspection Guide for the St. Lucie Unit 1 Nuclear Power Generation Station

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Pacific Northwest Laboratory
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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. St. Lucie Unit 1 was selected as one in 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 St. Lucie Unit 1 plant.

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Summary

This document presents a compilation of auxiliary feedwater (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 St. Lucie Unit 1 Nuclear Power Plant. This information is presented to provide inspectors increased resources for inspection planning at St. Lucie Unit 1.

The risk importance of various component failures modes was identified by analysis of the results of probabilistic risk assessments (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 the rank and root causes of these component failures. Both St. Lucie Unit 1 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 that 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.

Due to the similarity of backup emergency feedwater systems, industry wide data from both Westinghouse and Combustion Engineering design nuclear plants was used in the development of this document. Because of the difference in terminology between the two designs, auxiliary feedwater system (AFW) and emergency feedwater system (EFW) may both be found in this document and used to refer to a plants' emergency backup feedwater system.

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 St. Lucie Unit 1.

This inspection guidance is presented in Section 3, following a description of the St. Lucie Unit 1 AFW system in Section 2. Section 3 identifies the risk important system components by St. Lucie Unit 1 identification numbers, 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 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 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 St. Lucie 1 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.

2 St. Lucie Unit 1 AFW System

This section presents an overview description of the St. Lucie Unit 1 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 cooling system (SCS) can remove decay heat. A simplified schematic diagram of the AFW system is shown in Figure 2.1.

The AFW system is controlled automatically by an Auxiliary Feedwater Actuation Signal (AFAS). Initiation of an AFAS automatically actuates the AFW system to provide an AFW supply to the steam generators on low steam generator water level. When an AFAS signal is generated, the turbine-driven pump and the motor-driven pump supplying the steam generator in a low level condition, are automatically started. To deliver flow to the affected steam generator, auxiliary feedwater flow control valves receive an open signal. When steam generator level is regained and level is greater than the AFAS actuation setpoint, the flow control valves will receive a close signal. The actuation circuit will operate as described unless a steam generator is determined to be ruptured, as defined if a low water level trip is accompanied by either a steam generator delta pressure or a feed water header delta pressure trip of the associated steam generator, and no rupture has been detected in the other steam generator. The actuation circuit is designed to prevent the discharge of AFW to a ruptured steam generator.

The normal AFW pump suction is from the condensate storage tank. The system is designed with two (2) independent supply headers. One header supplies the motor driven AFW pumps (1B and 1A), while an independent supply header provides suction for the turbine driven pump (1C). Control, and instrumentation associated with each pump are independent from one another. Steam for the turbine driven pump is supplied by each of the two main steam lines from a point between the containment penetration and the main steam isolation valves. Each of the steam supply lines to the turbine has a motor-operated steam supply valve. The steam from either supply line is directed to the turbine via a trip and throttle valve and a governor valve. The motor operated steam supply valve, the trip and throttle valve, and the controls to the governor are supplied with power from an emergency DC power source. Each AFW pump discharge is designed with a recirculation flow path to prevent pump deadheading. Flowrate of the recirculation flowpath is restricted by a flow limiting orifice to ensure adequate AFW supply is provided for heat removal when needed. Each auxiliary feedwater pump discharge is provided with a check valve and a locally operated isolation valve. The Auxiliary Feedwater System discharge piping and valving arrangement is designed with the flexibility to allow any pump to supply feedwater to either or both steam generators. The supply lines to each steam generator are provided with control valves to ensure isolation of a faulted steam generator and the continued feeding of the non-faulted steam generator. The feedwater valves to the S/Gs associated with the steam driven AFW pump (MV-09-12 and MV-09-11) have DC motor operators which are powered from Emergency DC Buses. The feedwater valves to the S/Gs associated with the AC motor driven AFW pumps (MV-09-9 and MV-09-12) are AC motor operated valves which are powered from vital AC buses.

Unit 1 Condensate Storage Tank is the normal source of water for the AFW System and is required to store sufficient demineralized water to maintain the reactor coolant system (RCS) at hot standby conditions for one (1) hour followed by subsequent cooldown to 325°F. The CST and all interconnecting piping below the minimum required reserve level for emergency steam generator feed is a Seismic Class I system. A cross-tie from the

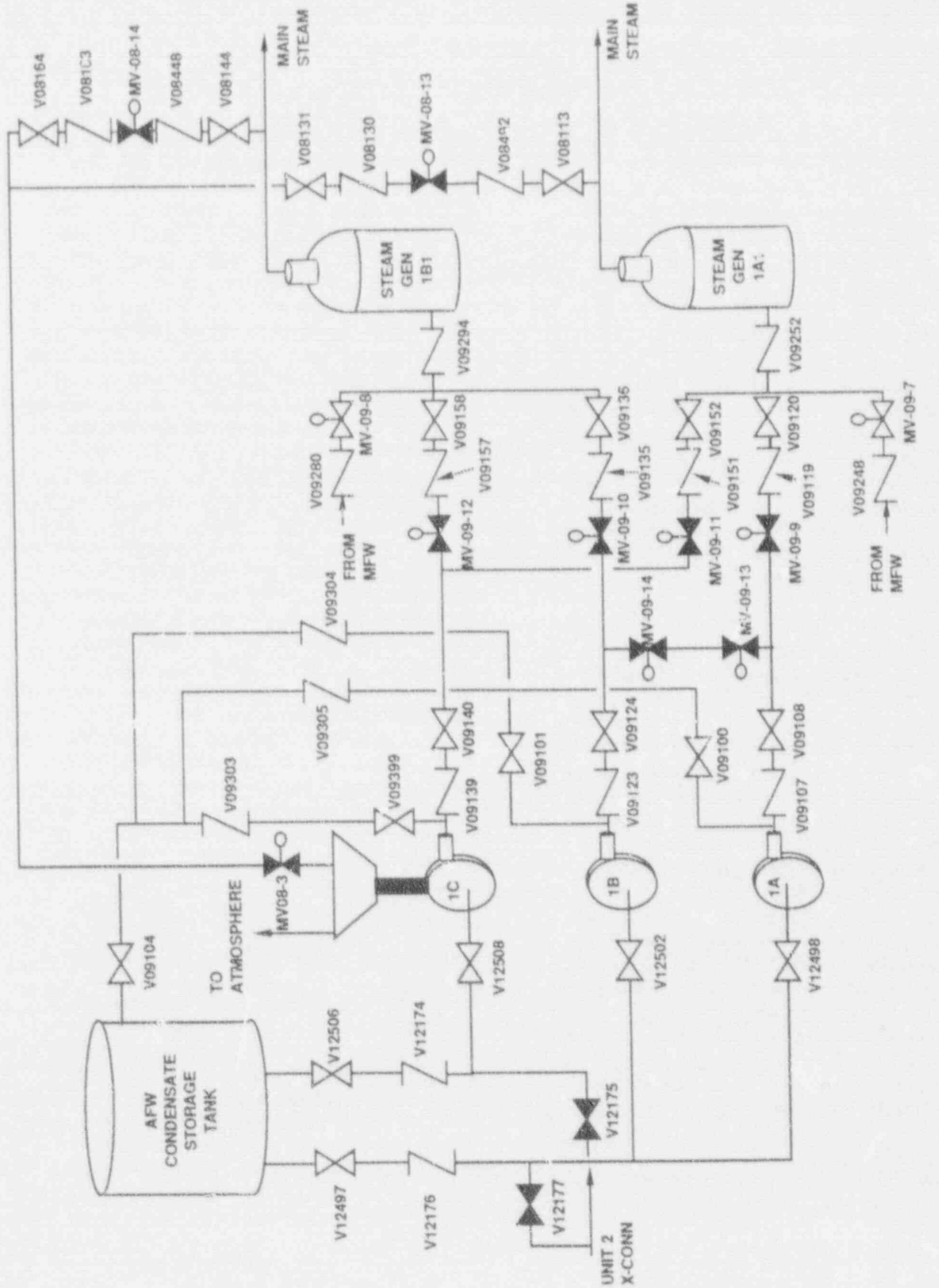

Figure 2.1 St. Lucie Auxiliary Feedwater

Unit 2 CST to the suction lines of Unit 1 AFW pumps, provides a backup supply of demineralized water in the event of loss of Unit 1 CST.

2.2 Success Criterion

System success requires the operation of at least one pump supplying rated flow to at least one of the two steam generators. In this condition, the system is capable of decay heat removal sufficient to allow placing the plant in a safe shutdown condition.

2.3 System Dependencies

The AFW system depends on train-related AC power for the motor-driven pump and associated flow control and cross-connect valves. DC power is required for motor operated valves associated with the turbine discharge flowpath, control power to pumps and DC powered valves, and an automatic actuation signal. In addition, the turbine-driven pump also requires steam availability.

2.4 Operational Constraints

When the reactor is critical the St. Lucie Unit 1, Technical Specifications require that all AFW pumps and associated flow paths are operable with the motor-driven pumps powered from a separate, operable vital bus and the turbine driven pump capable of being powered from an operable steam supply system. If one EFW pump becomes inoperable, it must be restored to operable status within 72 hours or the plant must be in HOT SHUTDOWN within the next twelve hours.

The St. Lucie Unit 1 Technical Specifications require the condensate storage tank (CST) to be operable with a minimum contained water volume of 116,000 gallons available for use.

3 Inspection Guidance for the St. Lucie AFW System

In this section the risk important components of the St. Lucie 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 St. Lucie 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. 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 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.
- Valve mispositioning has caused failure of all pumps. Pump suction, steam supply, and instrument isolation valves have been involved. CC2.
- Steam binding has caused failure of multiple pumps. This resulted from leakage of hot feedwater past check valves into a common discharge header, with several valves involved including a motor-operated discharge valve. CC7.
- 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. CC3. Incorrect setpoints and control circuit calibrations have also prevented proper operation of multiple pumps. CC4.
- 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. CC5.

3.1.2 Turbine Driven Pump "1C" Fails to Start or Run

- Improperly adjusted and inadequately maintained turbine governors have caused pump failures both at St. Lucie and elsewhere. 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.

- 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.

- Turbines with Woodward Model PG-PL governors have tripped on overspeed when restarted shortly after shutdown, unless an operator has locally exercised the speed setting knob to drain oil from the governor speed setting cylinder (per procedure). Automatic oil dump valves are now available through Terry. DE4.

- 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. Surveillance should exercise all steam supply connections. DE2.

- Turbine stop valve (MV-08-3) 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 TTV trip can be reset without resetting the other, indication in the control room of TTV position, and unambiguous local indication of an overspeed trip affect the likelihood of these errors. DE3.

3.1.3 Motor Driven Pumps "1A" or "1B" Fail 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. CF6. Control circuit and breaker failures have been experienced at St. Lucie.

- At St. Lucie, high pump bearing temperature has been found due in part to loose bearings resulting from inadequate vendor maintenance information.

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

- Low lubrication oil pressure resulting from heatup due to previous operation has prevented pump restart due to failure to satisfy the protective interlock. DE5.

3.1.4 Pumps "1A" or "1B" 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.

3.1.5 Failure of Motor Operated Valves MV-09-9, MV-09-10, MV-09-11,MV-09-12

These motor operated valves control or isolate flow from the AFW pumps to each of the steam generators. They fail as-is on loss of power.

- Common-cause failure of MOVs has occurred at St. Lucie 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. CC8.

- At St. Lucie, valve failure has resulted from corroded circuit components caused by environmental conditions.

- 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.

- Out-of-adjustment electrical flow controllers have caused improper discharge valve operation, affecting multiple trains of AFW. CC12.

- 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. CF7.

- Manually reversing the direction of motion of operating MOVs has overloaded the motor circuit. Operating procedures should provide cautions, and circuit designs may prevent reversal before each stroke is finished. DE7.

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

3.1.6 Manual Suction or Discharge Valves Fail Closed

TD Pump "1C": Valves V12508, V09140, V09158,V09152
MD Pump "1A": Valves V12498, V09108, V09120
MD Pump "1B": Valves V12502, V09124, V09136

These manual valves are normally locked open. For each train, closure of the first valve listed would isolate pump suction from all possible sources. Closure of the second valve would block all pump discharge to the steam generators. Closure of the third or fourth valve listed would result in the pumps inability to supply flow to at least one S/G.

- 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. 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 all steps in a 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.

3.1.7 Leakage of Hot Feedwater through Check Valves:

Between Pump "1A" and MFW: Valves V09107, V09119
Between Pump "1B" and MFW: Valves V09123, V09135
Between Pump "1C" and MFW: Valves V09139, V09157, V09151

- Leakage of hot feedwater through several check valves in series has caused steam binding of multiple pumps. Leakage through a closed level control valve in series with check valves has also occurred, as would be required for leakage to reach St. Lucie's AFW pumps. CC7.

- Slow leakage past the final check valve of a series may not force upstream 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.

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 an adequate water level in the CST, and the (closed) valves cross connecting the discharges of the AFW pumps.

Table 3.1 Risk Important AFW System Walkdown Table

Component #	Component Name	Required Position	Actual Position
Bkr 1-20212	1A AFW Pump Breaker	Racked In/Open Control Power Available	_____
Bkr 1-20412	1B AFW Pump Breaker	Racked In/Open Control Power Available	_____
	1A Flowpath		
V12498	1A AFW Pump Suction	Locked Open	_____
V09108	1A AFW Pump Discharge	Locked Open	_____
MV-09-9	1A AFW Hdr to 1A S/G	Closed	_____
VO9120	A AFW Hdr to 1A S/G Isol.	Locked Open	_____
	1B Flowpath		
V12502	1B AFW Pump Suction	Locked Open	_____
V09124	1B AFW Pump Discharge	Locked Open	_____
MV-09-10	1B AFW Hdr to 1B S/G	Closed	_____
V09136	B AFW Hdr to 1B S/G Isol.	Locked Open	_____
	1C Flowpath		
V12508	1C AFW Pump Suction	Locked Open	_____
V09140	1C AFW Pump Discharge	Locked Open	_____
MV-09-12	C AFW Hdr to 1B S/G	Closed	_____
MV-09-11	C AFW Hdr to 1A S/G	Closed	_____
V09158	C AFW Hdr to 1B S/G Isol.	Locked Open	_____
V09152	C AFW Hdr to 1A S/G Isol.	Locked Open	_____

Table 3.1 (contd)

Component #	Component Name	Required Position	Actual Position
	1C Steam Supply		
V08164	MV-08-14 Outlet Isol.	Locked Open	____
MV-08-14	1B S/G Supply to IC AFW Pump	Closed	____
V08144	MV-08-14 Outlet Isol.	Locked Open	____
V08113	MV-08-13 Outlet Isol.	Locked Open	____
MV-08-13	1A S/G Supply to 1C AFW Pump	Closed	____
V08131	MV-08-13 Outlet Isol.	Locked Open	____
MV-08-3	1C AFW Pump T and T Valve	Closed	____
	Cross-Tie Flowpath		
MV-09-14	B to A AFW Hdr Cross-Tie	Closed	____
MV-09-13	A to B AFW Hdr Cross-Tie	Closed	____
	CST Isolation		
V12497	CST to 1A/1B AFW Pumps	Locked Open	____
V12506	CST to 1C AFW Pump	Locked Open	____
V12177	Unit 2 CST to 1A/1B AFW Pumps	Locked Closed	____
V12175	Unit 2 CST to 1C AFW Pump	Locked Closed	____
	Check Valves		
V09107	Piping Upstream of Check Valve	Cool	____
V09123	Piping Upstream of Check Valve	Cool	____
V09139	Piping Upstream of Check Valve	Cool	____

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. Due to lack of actuating power, the PORVs cannot be opened, preventing adequate feed-and-bleed cooling, and 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, and the turbine-driven pump fails due to loss of turbine or valve control power. AFW is subsequently lost completely due to other failures. Feed-and-bleed cooling fails because PORV control is lost, resulting in core damage.

Transient-Caused Reactor or Turbine Trip

- A transient-caused trip is followed by a loss of PCS and AFW. Feed-and-bleed cooling fails either due to failure of the operator to initiate it, or due to hardware failures, resulting in core damage.

Loss of Main Feedwater

- A feedwater line break drains the common water source for MFW and AFW. The operators fail to provide feedwater from other sources, and fail to initiate feed-and-bleed cooling, resulting in core damage.

- A loss of main feedwater trips the plant, and AFW fails due to operator error and hardware failures. The operators fail to initiate feed-and-bleed cooling, resulting in core damage.

Steam Generator Tube Rupture

- A 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
   - hot well inventory
   - 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 St. Lucie Unit 1 and at other PWRs throughout the nuclear industry. Section 5.1 describes experience at St. Lucie Unit 1. 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, resulting in the inspection guidelines presented in Section 3.

5.1 St. Lucie Unit 1 Experience

Fifty-four (54) reports of AFW system equipment failures at St. Lucie between 1982 and 1990 were reviewed. These include failures of the AFW pumps, pump discharge flow control valves to steam generators, and pump suction and discharge valves. Failure modes include electrical, instrumentation, hardware failures, and human errors.

5.1.1 AFW Pump Control Logic, Instrumentation and Electrical Failures

Seven (7) failures of the AFW pumps to start, run, trip when required or achieve rated speed were found in the events examined. These occurrences resulted from failures of the turbine governor, breakers, relays and contacts, turbine overspeed device, faulty wiring and power supplies. The failure causes are mechanical wear, corrosion, or improper design and installation.

5.1.2 High AFW Pump Bearing Temperatures

High bearing temperatures were found on one AFW pump, and bearing damage was also found when the other AFW pumps were subsequently inspected. The problem was traced to loose bearings resulting from inadequate vendor information addressing pump reassembly after maintenance. Maintenance procedures have been modified, eliminating this potential common cause mode of pump failure.

5.1.3 Failure of AFW Pump Discharge Flow Control Valves to The Steam Generators

Eighteen (18) failures of the AFW pump discharge flow control valves were found in the events examined. These resulted from failures of valve control circuits, valve operators and valve breakers. Failures have resulted from DC control grounds, valve binding, dirty or worn contacts, improper torque switch operation, electrical component failure, frayed wiring, and valve operator mechanical failure. Failure causes are mechanical wear, contact oxidation, inadequate or improperly performed maintenance or testing activities and improper design and/or installation.

5.1.4 AFW Turbine Trip and Throttle Valve

Three (3) failures of the AFW Trip and Throttle valve were found in the events examined. These failures resulted from solenoid failure, misadjusted limit switches, and trip linkage failure. Failure causes are mechanical wear, component aging, and inadequate maintenance or testing activities.

5.1.5 AFAS and AFW Related Instrumentation

Fifteen (15) failures related to AFAS or system status type instrumentation were found in the events examined. These failures resulted from electrical component failure, bistable card failure and electrical grounds. Failure causes are normal aging, corroded terminals, water intrusion in cable runs and transmitters, and inadequate component cooling.

5.1.6 Check Valves

Seven (7) events of check valve failure were found in the events examined. In all but a few cases normal wear and aging was cited as the failure mode, resulting in leakage.

5.1.7 Human Errors

Several events relating directly to significant human errors affecting the AFW system were found in the events examined. Valve operators have been installed incorrectly or damaged after maintenance activities. Improper adjustment of valve components has resulted in valve binding and motor damage. Improperly adjusted torque switches, and equipment failure due to air in hydraulic lines has resulted in equipment failure or decreased operability. 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 EFW 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. 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).

CC4. 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.

CC5. 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.

CC6. 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 inhibit 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.

CC7. 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.

CC8. 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.

CC9. 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 Maine Yankee 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 improperly 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. 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.

CF7. "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.

CF8. 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.

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), [illegible]ic 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. St. Lucie Unit 1 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 St. Lucie Unit 1 plant.

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