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Emergency Feedwater System Risk-Based Inspection Guide for the Arkansas Nuclear One Unit 2 Power Plant

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Operated by
Battelle Memorial Institute

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U.S. Nuclear Regulatory Commission

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Summary

This document presents a compilation of emergency feedwater (EFW) 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 ANO-Unit 2 plant. This information is presented to provide inspectors with increased resources for inspection planning at ANO-Unit 2.

The risk importance of various component failure 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 and rank the root causes of these component failures. Both ANO-Unit 2 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.

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Tables

1 Introduction

This document is one of a series providing plant specific inspection guidance for emergency and auxiliary feedwater (EFW/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 EFW/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 ANO Unit 2.

This inspection guidance is presented in Section 3.0, following a description of the ANO Unit 2 EFW system in Section 2.0. Section 3.0 identifies the risk important system components by ANO Unit 2 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 EFW 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.

EFW/AFW system operating histories were studied to identify the various specific failures which have been aggregated into the PRA failure mode categories. Section 5.1 presents a summary of ANO Unit 2 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 EFW/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 ANO Unit 2 EFW System

This section presents an overview description of the ANO Unit 2 EFW 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 EFW 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 EFW system is shown in Figure 2.1.

The EFW system is controlled automatically by an Emergency Feedwater Actuation Signal (EFAS). Initiation of an EFAS automatically actuates the EFW system to provide an EFW supply to the steam generators on low steam generator water level. When an EFAS signal is generated, the turbine-driven pump (2P7A) and the motor-driven pump (2P7B) are automatically started. To deliver flow to the affected steam generator, emergency feedwater control valves and isolation valves receive an open signal. When steam generator level is regained and level is greater than the EFAS actuation setpoint, the control valves will receive a close signal. Initiation of a Main Steam Isolation Signal (MSIS) automatically shuts all remotely actuated emergency feedwater control valves and isolation valves unless an EFAS signal is present. Actuation of both a MSIS and an EFAS automatically isolates emergency feedwater flow to the ruptured steam generator and controls flow to the intact steam generator.

The normal EFW pump suction is from condensate storage tanks 2T41A and B. A single condensate header supplies a header which cross-connects pump suctions. 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 check valve and a motor-operated steam supply isolation valve. The steam from both supply lines combines and is then directed to the turbine via an isolation valve, trip and throttle valve, and governor valve. The motor operated isolation valve, the trip and throttle valve, and the controls to the governor are supplied with power from an emergency DC power source. Each EFW pump discharge is designed with a recirculation flow path to prevent pump deadheading. The recirculation flowpath is restricted to a 50 gpm flowrate by a flow limiting orifice. The recirculation flowpath is normally lined up to the Start-up and Blowdown Demineralizers.

Each emergency feedwater pump discharge is provided with a stop check valve. The motor operated pump (2P7B) is provided with a locally operated isolation valve. The Emergency Feedwater System discharge piping and valving arrangement is designed to allow either pump to supply feedwater to either or both steam generators. Each supply line to each steam generator is provided with redundant 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 EFWP (CV-1076 and CV-1026) have DC motor operators. The feedwater valves to the S/Gs associated with the AC motor driven EFWP (CV-1075 and CV-1025) are AC motor operated valves. The downstream feedwater isolation valves (CV-1036, CV-1038, CV-1037, and CV-1039) are electrically operated ball valves that are cross-power supplied from the other train and are normally positioned in the OPEN position. CV-1036 and CV-1038 are powered from "Green" AC power. CV-1037 and CV-1039 are powered from "Red" DC battery power. This arrangement of normal valve position and power supply is used to meet single failure criteria for emergency feed and main steam isolation actuations.

CST T41B and T41A are the normal source of water for the EFW System. [illegible] are required to store sufficient demineralized water to maintain the reactor coolant system (RCS) at hot standby conditions for 1 hour followed by subsequent cooldown to 350 °F. Since the CST is not seismically qualified, an assured source of water must be available to ensure EFW operability under all conditions. The safety grade service water system provides this source of water. Service Water Loop 1 supplies the motor-driven pump, while Service Water Loop 2 supplies the turbine-driven pump. The Service Water supply valves (CV-0711-2 and CV-0716-1) will automatically open if EFW pump suction pressure decreases to five psig and an engineered safety features signal is present. The valves are individually controlled by pressure switches installed on the separate pump suction lines.

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 removing 2.9% full power heat load or approximately 100 Mwt.

2.3 System Dependencies

The EFW system depends on AC power for the motor-driven pump and associated level control and isolation valves. DC power for motor operated valves associated with the turbine discharge flowpath, control power to pumps and 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 ANO Unit 2, Technical Specifications require that both EFW pumps and associated flow paths are operable with the motor-driven pump powered from an 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 ANO Unit 2 Technical Specifications require at least one condensate storage tank (CST) to be operable with a minimum contained water volume of 160,000 gallons available for use.

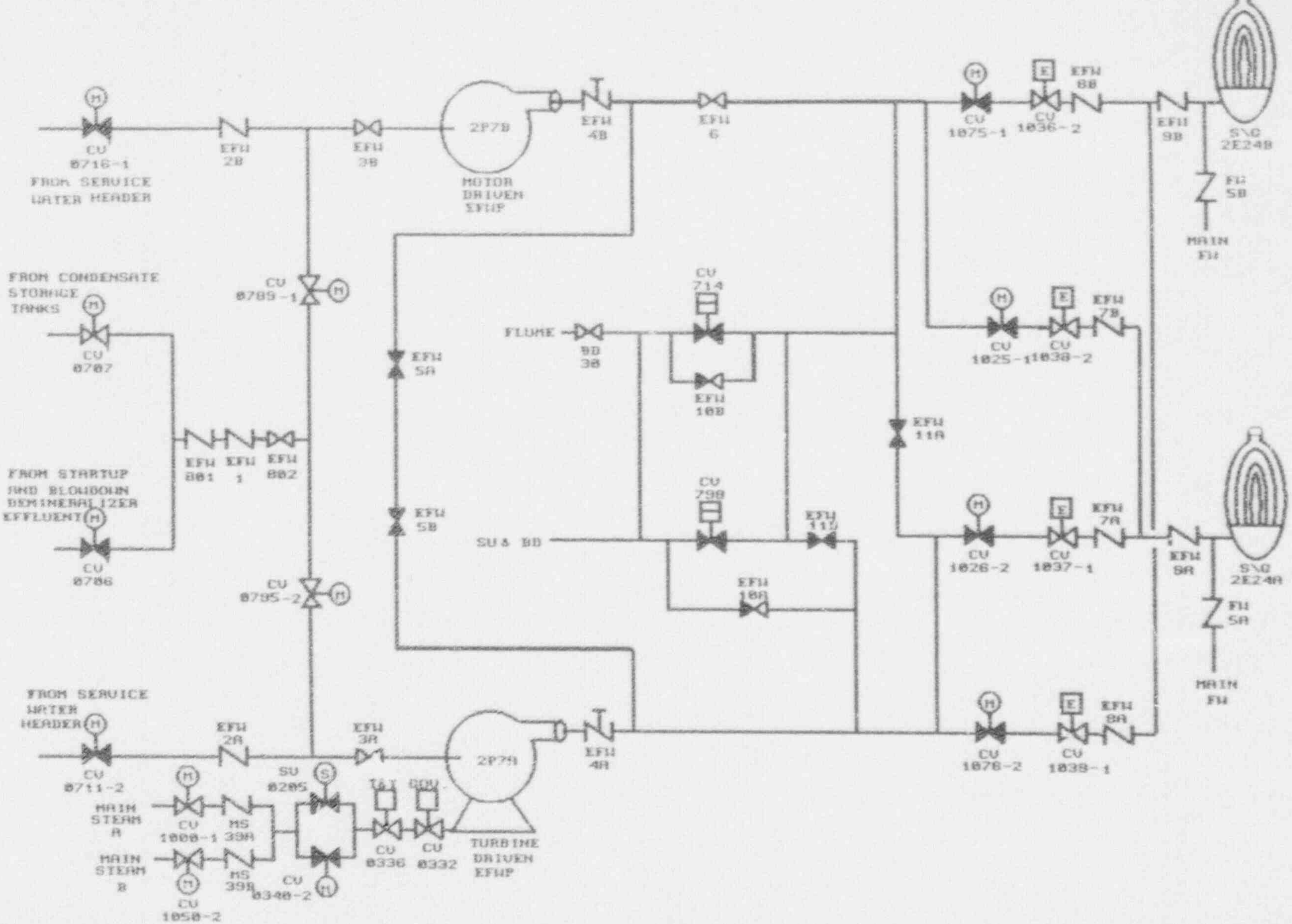

Figure 2.1 ANO unit 2 EFW system

3 Inspection Guidance for the ANO Unit 2 EFW System

In this section the risk important components of the ANO Unit 2 EFW 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 ANO 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 inspection activities. These activities include: observation, records review, training observation, procedures review or by observation of the implementation of procedures.

Table 3.1 is an abbreviated EFW 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 EFW system operation.

3.1 Risk Important EFW Components and Failure Modes

Common cause failures of multiple pumps are the most risk-important failure modes of EFW system components. These are followed in importance by single pump failures, level control valve failures, and individual check valve leakage 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 and a motor-operated valve into a common discharge header. CC10. Multiple-pump steam binding has occured at ANO-2 resulting from improper valve lineups and from running a pump deadheaded. CC3.

- 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 2P7A Fails to Start or Run

- Improperly adjusted and inadequately maintained turbine governors have caused pump failures both at ANO 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 [illegible] 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 (CV-0336) 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 Pump 2P7B 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. CF6. Control circuit failures have been experienced at ANO.

- 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 Pump 2P7A or 2P7B 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 CV-1025, 1026, 1036, 1037, 1038, 1039, 1075 and 1076

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

- Common cause failure of MOVs has occurred at ANO 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.

- 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. ANO has experienced similar type failures.

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

<u>TD Pump 2P7A: Valves EFW-3A, EFW-4A MD Pump 2P7B: Valves EFW-3B, EFW-4B, EFW-6</u>

These manual valves are normally locked open. For each train, closure of the first valve listed would block isolate pump suction from all possible sources. Closure of the second (or third) valve would block all pump discharge including recirculation to the start-up and blow down demineralizers.

- Valve mispositioning has resulted in failures of multiple trains of EFW. 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

<u>Between Pump 2P7A and MFW: Valve EFW-4A</u>
<u>Between Pump 2P7B and MFW: Valve EFW-4B</u>

- 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 the motor driven pump 2P7B. CC7.

- Slow leakage past the final check valve of a series may not force the 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 EFW System Walkdown Table

Table 3.1 presents an EFW 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 EFW pumps.

Table 3.1 Risk Important EFW System Walkdown Table

Component #	Component Name	Location	Required Position	Actual Position
	Electrical			
2P7B	Motor breaker 2A311	A3 SWGR RM	Racked in on Closing springs CHG Motor Energized	________
	EFW Flowpath			
2SW-39B	Loop 2 Supply to EFW System	2P7A PMP RM	Locked Open	________
2SW-39A	Loop 1 Supply to EFW System	2P7B PMP RM	Locked Open	________
2CV-0716-1	Service Water to 2P7B	2P7B PMP RM	Closed	________
2CV-0711-2	Service Water to 2P7A	2P7A PMP RM	Closed	________
2EFW-0706	EFW Pumps Suction from SU and BD	335' ELEV TB	Locked Closed*	________
2EFW-802	EFW Pump Suction from 2T41A or DI Effluent	2P7B PMP RM	Locked Open	________
2CV 707	EFW Pump Suction from CST 2T41A/B	335' ELEV TB	Open	________
	2P7B Flowpath			
2EFW-3B	2P7B Suction Isolation Valve	2P7B PMP RM	Locked Open	________
2EFW-4B	2P7B Discharge Stop-Check	2P7B PMP RM	Locked Open	________
2EFW-6	2P7B Discharge Valve	2P7B PMP RM	Locked Open	________
2CV-1075-1	2P7B Discharge Control Valve to S.G. 2E24B	NPPR	Closed	________
2CV-1036-2	2P7B Discharge to S.G. 2E24B Isolation	NPPR	Open	________
2CV-1025-1	2P7B Discharge Control Valve to S.G. 2E24A	SPPR	Closed	________

* Locked Closed Above 10 Percent Reactor Power
NPPR - North Piping Penetration Room
SPPR - South Piping Penetration Room

Table 3.1 (Continued)

Component #	Component Name	Location	Required Position	Actual Position
2CV-1038-2	2P7B Discharge to S.G. 2E24A Isolation	SPPR	Open	
	2P7A Flowpath			
2EFW-3A	2P7A Suction Isolation	2P7A PMP RM	Locked Open	
2EFW-4A	2P7A Discharge Stop-Check	2P7A PMP RM	Locked Open	
2CV-1076-2	2P7A Discharge Control Valve to S.G. 2E24B	NPPR	Closed	
2CV-1039-1	2P7A Discharge Isolation Valve to S.G. 2E24B	NPPR	Open	
2CV-1026-2	2P7A Discharge Control Valve to S.G. 2E24A	SPPR	Closed	
2CV-1037-1	2P7A Discharge Isolation Valve to S.G. 2E24A	SPPR	Open	
	Recirc and Fl[illegible]ine			
2EFW-11A	Recirc Line Isolation	SPPR	Locked Closed	
2EFW-11B	Recirc Line Isolation	NPPR	Locked Closed	
2EFW-10A	2P7A Minimum Recirc Flow Control	NPPR	Locked Open	
2EFW-10B	2P7B Minimum Recirc Flow Control	SPPR	Locked Open	
	Cross-Connect Valves			
2CV-0789-1	Pump Suction X-TIE	2P7B PMP RM	Open	
2CV-0795-2	Pump Suction X-TIE	2P7A PMP RM	Open	
2EFW-5A	Pump Discharge X-TIE	2P7B PMP RM	Closed	
2EFW-5B	Pump Discharge X-TIE	2P7A PMP RM	Closed	
	Steam Supply Valves			
2SV-0205	Steam Supply Bypass	2P60A PMP RM	Closed	
2CV-0340	Steam Supply Valve	2P60A PMP RM	Closed	
2CV-0336	Trip and Throttle Valve	2P7A PMP RM	Open	
2CV-1000-1	"A" Main Steam Supply Isolation	Main Steam Penthouse	Open	

Table 3.1 (Continued)

Component #	Component Name	Location	Required Position	Actual Position
2CV-1050-2	"B" Main Steam Supply Isolation	Main Steam Penthouse	Open	________
	EFW SG Check Valves			
2TW [illegible]0	2P7B Discharge Temperature	2P7B PMP RM	150 Deg Maximum	________
2TW0713	2P7A Discharge Temperature	2P7A PMP RM	150 Deg Maximum	________

4 Generic Risk Insights From PRAs

PRAs for 13 PWRs were analyzed to identify risk-important accident sequences involving loss of EFW/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; Travis et al. 1988).

4.1 Risk Important Accident Sequences Involving AFW System Failure

4.1.1 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.

4.1.2 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.

4.1.3 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.

4.1.4 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 EFW system, as determined from a review of operating histories at ANO Unit 2 and at other PWRs throughout the nuclear industry. Section 5.1 describes experience at ANO Unit 2. Section 5.2 summarizes industry-wide 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 incl e quantitative analyses of EFW 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 ANO Unit 2 Experience

Sixty-eight (68) reports of EFW system equipment failures at ANO Unit 2 between January of 1980 and October 30 1989 were reviewed. These include failures of the EFW 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 EFW Pump Control Logic, Instrumentation and Electrical Failures

Ten failures of the EFW 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 Failure of EFW Pump Discharge Flow Control to Steam Generators

Twenty-eight failures of the EFW pump discharge flow control and bypass 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, valve operator mechanical failure and low hydraulic fluid pressure. Failure causes are mechanical wear, contact oxidation, inadequate maintenance or testing activities and improper design and/or installation. These valves have also experienced various packing leaks, as have pump discharge check valves.

5.1.3 EFW Steam Generator Isolation Valve Failures

Ten failures of the EFW steam generator isolation valves were found in the events examined. These failures resulted from valve binding, solenoid coil failure, fouled torque switch contacts, control power short circuits, fouled closing coil motor controlling contactors, and breaker failure. Failure causes are mechanical wear, contact oxidation, component aging, and inadequate maintenance or testing activities and original circuit design problems.

5.1.4 EFW Turbine Steam Inlet

Five failures of the EFW steam inlet valve were found in the events examined. These failures resulted from valve binding, actuator motor failure, improper installation of valve operator and installation of improperly sized thermal overloads. Failure causes are mechanical wear, component aging, contact oxidation or fouling and inadequate maintenance or testing activities.

5.1.5 Human Errors

Nine events relating directly to significant human errors affecting the EFW system were found in the events examined. Valve operators were wired incorrectly or damaged after maintenance activities. Improper installation of valve components has resulted in valve binding and motor damage. Miswiring turbine control circuits has rusulted in inability of the turbine to reach desired speed. Improper installation of special test equipment has resulted in loss of turbine control power and automatic turbine start capability.

5.2 Industry Wide Experience

Human errors, design/engineering problems and errors, and component failures are the primary root causes of EFW/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/1416, 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 preinstallation 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.

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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. Arkansas Nuclear One Unit 2 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 Arkansas Nuclear One Unit 2 plant.

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