NUREG/CR-5404
ORNL-6566/V1
Vol. 2

Auxiliary Feedwater System Aging Study

Phase I Follow-On Study

Prepared by J. D. Kueck

Oak Ridge National Laboratory

Prepared for
U.S. Nuclear Regulatory Commission

AVAILABILITY NOTICE

Availability of Reference Materials Cited in NRC Publications

Most documents cited in NRC publications will be available from one of the following sources:

1. The NRC Public Document Room, 2120 L Street, NW., Lower Level, Washington, DC 20555

2. The Superintendent of Documents, U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20013-7082

3. The National Technical Information Service, Springfield, VA 22161

Although the listing that follows represents the majority of documents cited in NRC publications, it is not intended to be exhaustive.

Referenced documents available for inspection and copying for a fee from the NRC Public Document Room include NRC correspondence and internal NRC memoranda; NRC bulletins, circulars, information notices, inspection and investigation notices; licensee event reports; vendor reports and correspondence; Commission papers; and applicant and licensee documents and correspondence.

The following documents in the NUREG series are available for purchase from the GPO Sales Program: formal NRC staff and contractor reports, NRC-sponsored conference proceedings, international agreement reports, grant publications, and NRC booklets and brochures. Also available are regulatory guides, NRC regulations in the *Code of Federal Regulations*, and *Nuclear Regulatory Commission Issuances*.

Documents available from the National Technical Information Service include NUREG-series reports and technical reports prepared by other Federal agencies and reports prepared by the Atomic Energy Commission, forerunner agency to the Nuclear Regulatory Commission.

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, and transactions. *Federal Register* notices, Federal and State legislation, and congressional reports can usually be obtained from these libraries.

Documents such as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings are available for purchase from the organization sponsoring the publication cited.

Single copies of NRC draft reports are available free, to the extent of supply, upon written request to the Office of Administration, Distribution and Mail Services Section, U.S. Nuclear Regulatory Commission, Washington, DC 20555.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at the NRC Library, 7920 Norfolk Avenue, Bethesda, Maryland, for use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from the American National Standards Institute, 1430 Broadway, New York, NY 10018.

NUREG/CR-5404
ORNL-6566/V1
Vol. 2
RV, RG, RM

Auxiliary Feedwater System Aging Study

Phase I Follow-On Study

Manuscript Completed: June 1993
Date Published: July 1993

Prepared by J. D. Kueck

Oak Ridge National Laboratory
Operated by Martin Marietta Energy Systems, Inc.

Oak Ridge National Laboratory
Oak Ridge, TN 37831-6285

Prepared for
Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
NRC FIN B0828
Under DOE Contract No. DE-AC05-84OR21400

Abstract

The Phase I study found a number of significant Auxiliary Feedwater System functions that were not tested and verified operable by periodic surveillance testing. In addition, the Phase I study identified components actually degraded by the periodic surveillance tests. Thus, it was decided that this follow-on study would not deal with aging assessments or in situ examination but would instead focus on the testing omissions and equipment degradation found in Phase I.

In this follow-on study, the deficiencies in current monitoring and operating practice are categorized and evaluated. Areas of component degradation caused by current practices are discussed. Recommendations are made for improved diagnostic methods and test procedures that will verify operability without degrading equipment.

Contents

List of Figures

List of Acronyms

ACP	Auxiliary control panel
AFW	Auxiliary feedwater system
AMSAC	Anticipated transient without scram mitigating system actuation circuit
AOV	Air-operated valve
ASME	American Society of Mechanical Engineers
ASE	Average system effect
B&W	Babcock and Wilcox
BDIV	Blowdown isolation valve
BEP	Best efficiency point
BMDLCV	Bypass motor-driven pump level control valve
BWR	Boiling water reactor
CMCV	Common miniflow check valve
CST	Condensate storage tank
DBE	Design basis event
DCV	Discharge check valve
DDP	Diesel-driven pump
EHOV	Electrohydraulic-operated valve
ESF	Engineered safety feature
ESW	Emergency service water
FC	Failure count
FSAR	Final safety analysis report
FWIV	Main feedwater isolation valve
GV	Turbine governor valve
I&C	Instrumentation and control
INEL	Idaho National Engineering Laboratory
INPO	Institute for Nuclear Power Operations
ISCM	Inspection, surveillance and condition monitoring
IST	In-service test
LCO	Limiting condition for operation
LCV	Level control valve
LCVCV	Level control valve check valve
LER	Licensee event report
LOFW	Loss of main feedwater
MCB	Main control board
MCC	Motor control center
MCV	Miniflow check valve
MDLCV	Motor-driven pump level control valve
MDP	Motor-driven pump
MFCV	Main feedwater check valve
MFLB	Main feed line break
MFSA	Magnetic Flux Signature Analysis
MFW	Main feedwater
MI	Maintenance test-inspection
MOV	Motor-operated valve
MOVATS	Motor Operated Valve Analysis and Test System™
MSIS	Main steam isolation signal
MSLB	Main steam line break
MSSV	Main steam safety valve
NPAR	Nuclear Plant Aging Research
NPE	Nuclear Power Experience, Stoller Power, Inc.
NPRDS	INPO's Nuclear Plant Reliability Data System
NPSH	Net positive suction head
NRC	Nuclear Regulatory Commission
NSSS	Nuclear steam supply system
OP	Operating procedure

ORNL	Oak Ridge National Laboratory
PMTR	Periodic maintenance test requirement
PORV	Power-operated relief valve
PS	Pressure switch
PT	Periodic test
PWR	Pressurized-water reactor
PZR	Pressurizer
RCP	Reactor coolant pump
RCS	Reactor coolant system
RGSC	Ramp generator/signal converter
RHR	Residual heat removal
RSD	Relative system degradation
SBO	Station blackout
SCV	Pump suction check valve
SG	Steam generator
SI	Safety injection
SOV	Solenoid-operated valve
SSC	Structure, system or component
SSIV	Steam supply isolation valve
SSV	Steam supply valve
ST	Surveillance test
SWS	Service Water System
TDLCV	Turbine-driven pump level control valve
TDP	Turbine-driven pump
TOL	Thermal overload
T&T	Trip and throttle valve (for AFW turbine)

1 Introduction and Summary

The Phase 1 aging study for the Auxiliary Feedwater (AFW) System dealt less with organic and chemical aging mechanisms and more with historical failure modes that could be traced to current maintenance and surveillance practices. A thorough review of system controls and functions was performed, and several significant deficiencies in maintenance and surveillance practices were identified, such as failure to verify many of the safety-related control functions by periodic testing and degradation of the AFW pumps by testing at low flow.

This follow-on study categorizes the deficiencies in current monitoring/operating practice identified in Phase I and evaluates failure modes and component degradation caused by these practices. Although the deficiencies identified in Phase I are for a specific plant, the findings have applicability to all plants in that they point out typical testing omissions or sources of degradation. This follow-on study also provides recommendations for alternate methods of performing testing that will greatly reduce equipment degradation caused by testing and will greatly improve verification of system operability. The primary areas where alternate test methods are discussed are AFW pump testing, instrumentation and controls (I&C) functional verification, and check valve testing. Section 2 of the follow-on study categorizes the deficiencies in current monitoring/ operating practices. Section 3 discusses areas of significant degradation caused by current practices. Section 4 provides a discussion of problematic monitoring and maintenance practices. Section 5 provides recommendations for six new monitoring and maintenance practices, and Sect. 6 provides a recommended change to the technical specifications to eliminate AFW pump degradation caused by miniflow testing.

1.1 Background

The Phase I AFW system aging study[1] focused on how and to what extent the various AFW system component types fail, how the failures have been and can be detected, and on the value of current testing requirements and practices. For each of the component types and for the various sources of component failure, the methods of failure detection were designated and tabulated and the following findings became evident:

- I&C-related failures dominated the group of failures that were detected during demand conditions.
- Many of the potential failure sources not detectable by current monitoring practices were related to the I&C portion of the system.
- Some components appear to be tested in excess of what failure history indicates to be appropriate.
- Enhanced testing requirements appear to be needed to reduce excessive testing while ensuring that thorough performance verification is conducted periodically.

The goal of this follow-on study was to categorize and evaluate the deficiencies in testing identified by Phase I and to make specific recommendations for corrective action. In addition, this study presents discussions of new, state-of-the-art test methods and provides a proposed AFW pump test at normal operating pressure that should do much to verify system operability while eliminating degradation.

1.2 Summary of Results

Several significant conclusions of this follow-on study follow:

1. The present method of testing the AFW pumps at the minimum flow condition leads to degradation of the pump and does not provide an adequate indication of pump condition. An alternate method is proposed that consists of testing at normal operating pressure to eliminate degradation and to verify flow at design conditions. This alternate test would also allow verification of other component's design basis operation, such as the steam generator blowdown isolation valve (BDIV) and level control valves (LCVs). These valves are currently tested only at the low-flow, low differential pressure condition.

2. There are a large number of safety-related control functions that are presently not verified to be operable by the periodic surveillance testing. This is a significant concern. It is recommended that the entire set of control wiring diagrams for the system be evaluated against the periodic test requirements by an experienced engineer to locate all omissions in testing.

3. Check valve condition is not adequately assessed by the present test methods. Recommendations are made in the report for new check valve diagnostic methods, and a comparison of diagnostic methods is provided.

4. Evaluations of current surveillance and testing are also made for other AFW components such as the turbine-driven feedwater pump, valve actuator motors, flow verification of emergency service water (ESW), and so forth.

5. Recommendations are provided in Sect. 5 for improved methods of diagnosing degradation in check valves, AFW pump testing at full flow, functional testing of control circuits, improved testing of the turbine-driven pump (TDP), and assessment of service water system fouling.

2 Deficiencies in Current Monitoring/Operating Practices

These areas of deficiency in current monitoring practice were developed from a Review of Sect. 3.3, "Failure Modes and Features that Are Not Detectable by Current Monitoring Practices" of the *Auxiliary Feedwater System Aging Study*, Vol. 1, NUREG/CR-5404.[1] The noted deficiencies were categorized into three areas, "Mechanical Failure Modes Not Detected by Current Monitoring/Operating Practices," "Component or Group of Components Unable to Perform as Required Because I&C Failures Were Not Observed During Routine Testing," and "Component or Group of Components Unable to Perform as Required Because No Function Verification Test Is Performed." Although many of the deficiencies noted were specific to the plant being studied in the Phase I study, the findings are considered to be generically applicable because they point out testing deficiencies that can easily exist at any plant.

2.1 Mechanical Failure Modes Not Detected by Current Monitoring/ Operating Practices

2.1.1 Check Valve Undetected Failures

Check valve failure to open sufficiently—Degradation could occur without detection when the valves are not included in a periodic inspection program, and neither pump flow nor differential pressure is monitored during testing. Failure to open to the required position could also occur if the valve is required to operate under different pressure conditions than the test conditions. Usually, the AFW pump flow test, performed at miniflow conditions, does not verify that design basis flow is available. Correct obturator movement is difficult to verify using flow and pressure. (Section 4.6 discusses alternate methods for check valve testing.)

Examples from Ref. 1 of Check Valve Failure to Open Sufficiently:

- Table 3.1, Item 2, AFW Pump Suction
- Table 3.8, Item 1, AFW Pump Discharge
- Table 3.11, Item 1, Steam Generator Level Control Valve
- Table 3.12, Item 1, Steam Generator (SG) AFW to Main Feedwater

Check valve failure to close—Gradual degradation may not be detected because not all valves are included in the periodic disassembly and inspection program. Also, leak rate testing may allow leakage substantially in excess of the level required to meet AFW system design requirements. The acceptance criteria for main feedwater check valves must reflect the AFW system functional requirements.

Examples from Ref. 1 of Check Valve Failure to Close:

- Table 3.1, Item 3, AFW Pump Suction Check Valves Failure to Close When ESW Suction Valves Open
- Table 3.13, Item 1, MFW Check Valves Fail to Close to Ensure that Adequate AFW Flow is Delivered to the SG

Miniflow check valve (MCV) fails in the closed position or fails to open sufficiently to allow required recirculation flow. The quarterly testing flow rate is so low that the valves would not be fully stroked.

Examples from Ref. 1:

- Table 3.6, Item 1, AFW Pump Miniflow Check Valve Fails Closed or Fails to Open Sufficiently
- Table 3.7, Item 1, Common Miniflow Check Valve Fails Closed or Fails to Open Sufficiently

2.1.2 AFW Pump Undetected Failures

The motor-driven pump (MDP) fails to deliver required flow to its steam generators at the required pressure conditions. The pump testing is performed at low pressure. At high (operational) pressure, the pump head-capacity curve will intersect the system curve at a different point with lower flow. In addition, actual flow, steam generator pressure, and developed pump head are not measured. Also, no testing is done with all pumps operating simultaneously.

Example from Ref. 1:

- Table 3.4, Item 4, MD AFW Pump Fails to Deliver Required Flow

The TDP failure to develop required flow—Pump condition is not fully monitored; no testing is performed to verify ability of the TDP to deliver required feedwater flow at a steam supply pressure less than 842 psig. It is important to recognize that the TDP must be capable of operating at steam pressures as low as 120 psig. These low pressures will be present before the reactor coolant temperature is low enough to start the residual heat removal system.

Example from Ref. 1:

- Table 3.5, Item 4, TD AFW Pump Fails to Develop Required Flow

2.1.3 Valve Undetected Failures

The LCV fails to open sufficiently to allow adequate flow. Only flow (not pressure) is monitored during testing.

Deficiencies

Under different pressure conditions, valves may not open sufficiently.

Example from Ref. 1:

- Table 3.9, Item 3, MD AFW Pump Level Control Valve Fails to Open Sufficiently
- Table 3.10, Item 5, TD AFW Pump LCV Fails to Open Sufficiently

The BDIV fails to close under blowdown conditions; it is tested under low-flow, low-pressure conditions.

Example from Ref. 1:

- Table 3.15, Items 1 & 2, SG BDIVs Fail to Isolate Blowdown Flow

2.2 Component or Group of Components Unable to Perform as Required Because of I&C Failures Not Detected During Routine Testing

2.2.1 Valve Operator Undetected Failures

Valve operator fails to open or close in response to sensed condition. Failure in control logic is not detected because logic is not tested in the periodic tests. Pump auxiliary contacts, station blackout contacts, or limit switches fail to provide required control inputs to automatically actuated equipment. Proper function is not verified.

Examples from Ref. 1:

- Table 3.2, Item 1, ESW to MDPs Supply Valves
- Table 3.9, Item 2, MD AFW Pump LCVs
- Table 3.15, Item 1, SG BDIVs
- Table 3.16, Item 3, AFW TDP Steam Supply Valve
- Table 3.16, Item 4, AFW TDP Steam Supply Valve
- Table 3.16, Item 4, AFW TDP Steam Supply Valve
- Table 3.3, Item 3, ESW to TDP Suction Isolation Valve
- Table 3.10, Item 2, TDP LCVs
- Table 3.17, Item 2, TDP Steam Supply Isolation Valves
- Table 3.4, Item 5, MD AFW Pump Auxiliary Contact
- Table 3.5, Item 5, TD AFW Pump Valve Stem Switches
- Table 3.9, Item 1, MDP LCV
- Table 3.9, Item 2, MDP LCV
- Table 3.9, Item 5, MDP LCV
- Table 3.10, Item 2, TD AFW Pump LCVs
- Table 3.10, Item 3, TD AFW Pump LCVs
- Table 3.10, Item 6, TD AFW Pump LCVs
- Table 3.15, Item 1, SG BDIVs
- Table 3.16, Item 1, AFW TDP Steam Supply Valves
- Table 3.16, Item 2, AFW TDP Steam Supply Valves

Valve operator failure to open because of improper thermal overload actuation—Thermal overload (TOL) bypass had not been verified. TOL setting had not been verified. Proper TOL selection will provide motor protection, while improper TOL selection will result in spurious trips or motor degradation.

Example from Ref. 1:

- Table 3.5, Item 1, TD AFW Pump T&T Valve Fails to Open

During extended TDP operation, the ambient temperature may rise to the point that a steam supply line pipe break signal is generated. This signal is generated by high ambient temperature. The steam supply isolation valve would then close. This test is typically performed only over a short time and may not simulate extended TDP operation.

Example from Ref. 1:

- Table 3.17, Item 1, AFW Turbine Steam Supply Isolation Valves Spurious Closure

2.2.2 TD AFW Pump Undetected Failures

Turbine electronic overspeed trip function fails to trip before mechanical overspeed trip occurs. Trip is tested under simulated rather than operating conditions. No verification is made of auto resetting; the mechanical overspeed set point is not verified at all.

Example from Ref. 1:

- Table 3.5, Item 3, TD AFW Pump T&T Valve

2.3 Component or Group of Components Unable to Perform as Required Because No Design Basis Function Verification Test Is Performed

2.3.1 ESW Function Verification

Flow verification of ESW—This test cannot be performed because it would introduce lake water into the condensate/feedwater system. This verification is important, however, because of the various types of biological contamination, such as Zebra Mussels, which can foul ESW piping and reduce flow. There are a number of measures that can be taken to ensure that adequate flow is available. These measures are discussed in Sect. 5.6.

Example from Ref. 1:

- Table 3.2 Item 2, ESW to MDP Supply Valves Open but Insufficient Flow Is Delivered

Verification of switchover time for ESW—If the transfer takes place too slowly it could result in air binding of the AFW pumps because of vortexing on the low condensate storage tank (CST) level and possible pump damage. This test also cannot be performed because it would introduce lake water; however, an alternate test is described in Sect. 4.3.2. The alternate test compares the sum of the switchover times of the various components with the analyzed maximum time.

Example from Ref. 1:

- Table 3.2, Item 3, ESW to MDP Supply Valves Switchover Results in Pump Damage

Verification of ability of motor-driven pumps to continue to operate satisfactorily during and following transfer of suction source to the ESW—Excessive friction caused by corrosion or biological contamination of the ESW lines may result in inadequate AFW pump suction head. This test would also introduce lake water and thus cannot be performed.

Example from Ref. 1:

- Table 3.4, Item 2, ESW to MDP Supply Valves

2.3.2 TDP Function Verification

Verification of TDP LCV opening—The valve operator may not open or stay open because the ability of the accumulator air supply to stroke the valve and the proper seating of the control air check valve are not demonstrated.

Example from Ref. 1:

- Table 3.10, Item 2, TDP Level Control Valves Do Not Open or Stay Open

3 Areas of Significant Component Degradation Caused by Unnecessary or Excessive Test-Related Wear

The following three areas of component degradation have already resulted in some industry attention and are discussed here as the major areas of component degradation resulting from current test practices.

3.1 Degradation of AFW Pumps Caused by Low Flow Operation

Degradation of AFW pumps caused by extended operation at minimum flow condition occurs because of hydraulic instability within the pump during operation at low flow conditions. These pumps are usually tested with minimum flow lines that allow the pump discharge flow to be recirculated to the CST. The flow rates using the minimum flow lines are sized to pass ~10 to 15% of pump best efficiency point flow. (See Sect. 4.4.1 for an evaluation of current test practice.)

As explained in Ref. 2, p. 30, "Operation of these pumps 'far' from the BEP flow induces very strong unsteady flow conditions within the pump hydraulic passages." In summary, Ref. 2 states that strong unsteady flow conditions result in very large dynamic forces on pump internals, both the stationary and rotating parts. The result of these forces is a high-amplitude vibration that causes rapid wear at critical clearances in the pump because of severe vibration-induced rubbing. This leads to a rapid increase in stage-to-stage leakage and a measurable reduction in delivered pump capacity. In addition, these large dynamic fluid forces can break loose pieces of diffuser vanes, impeller side plates, and impeller vanes. This deterioration of pump internals will result in considerable reduction in the delivered capacity of the pump as well as eventual structural failure.

Deterioration of the impeller and diffuser caused by cavitation erosion also degrades performance. The net effect of the deterioration is a slow reduction in the delivered capacity of the pump.

Hydraulic instability is the term most commonly used to describe the unsteady flow phenomena that become progressively more severe the farther from best-efficiency flow that a pump is operated. These unsteady flows are the most significant contributor to deterioration of pump components because of the dynamic forces they produce.

Figure 3.1 (Ref. 2, Fig. D.1) shows the stable and unstable flow regions for various classes (i.e., different specific speeds) of power plant pumps. This figure is based on a composite of field experience, shop tests, and laboratory tests.

Hydraulic instability has also been described by the label, internal "flow recirculation," which occurs both at the inlet and discharge regions of a pump stage at off-design operating flows. These flow recirculation cells, as illustrated in Figs. 3.2 and 3.3 (Ref. 2, Figs. D.2 and 3), are highly unsteady, producing large vibration excitation forces and hard-to-control flow pulsations in the entire pump loop. Figure 3.4 (Ref. 2, Fig. D.4) illustrates hydraulic instability in the unstable flow regime.

Reference 3, "Notification of 10CFR21 Reportability," filed with the Nuclear Regulatory Commission (NRC) by a pump manufacturer, discusses AFW pump damage experienced by several utilities and is summarized as follows:

After the AFW pump was disassembled, it was found that some of the cast iron diffuser vanes within the pumps had broken and had traveled through the pump discharge piping to eventually lodge in the venturi. Considerable corrosion pitting of the cast iron internals was also observed, and cracklike crevices were noted in a number of areas along the vane to shroud junctions. The other AFW pumps of the same design at this plant were inspected and found to have similar damage.

The 10CFR21 Notification (Ref. 3) concludes, after examination and analysis, that "the primary cause of diffuser vane inlet edge breakage was the undermining of the vane inlet ends due to the accumulated hours of operation of the pump at minimum flow, on the low flow recirculation line used in inservice testing. The plant had been in commercial service for 15 years at the time of the subject failure. Based upon the facts presented above, Ingersoll-Rand concludes that the damage observed is primarily due to accumulated operating time on the pump at the minimum flow condition."

An evaluation of current flow testing is provided in Sect. 4.1.2, alternative testing is discussed in Sect. 4.4, and an alternate full flow test recommendation is provided in Sect. 5.2.

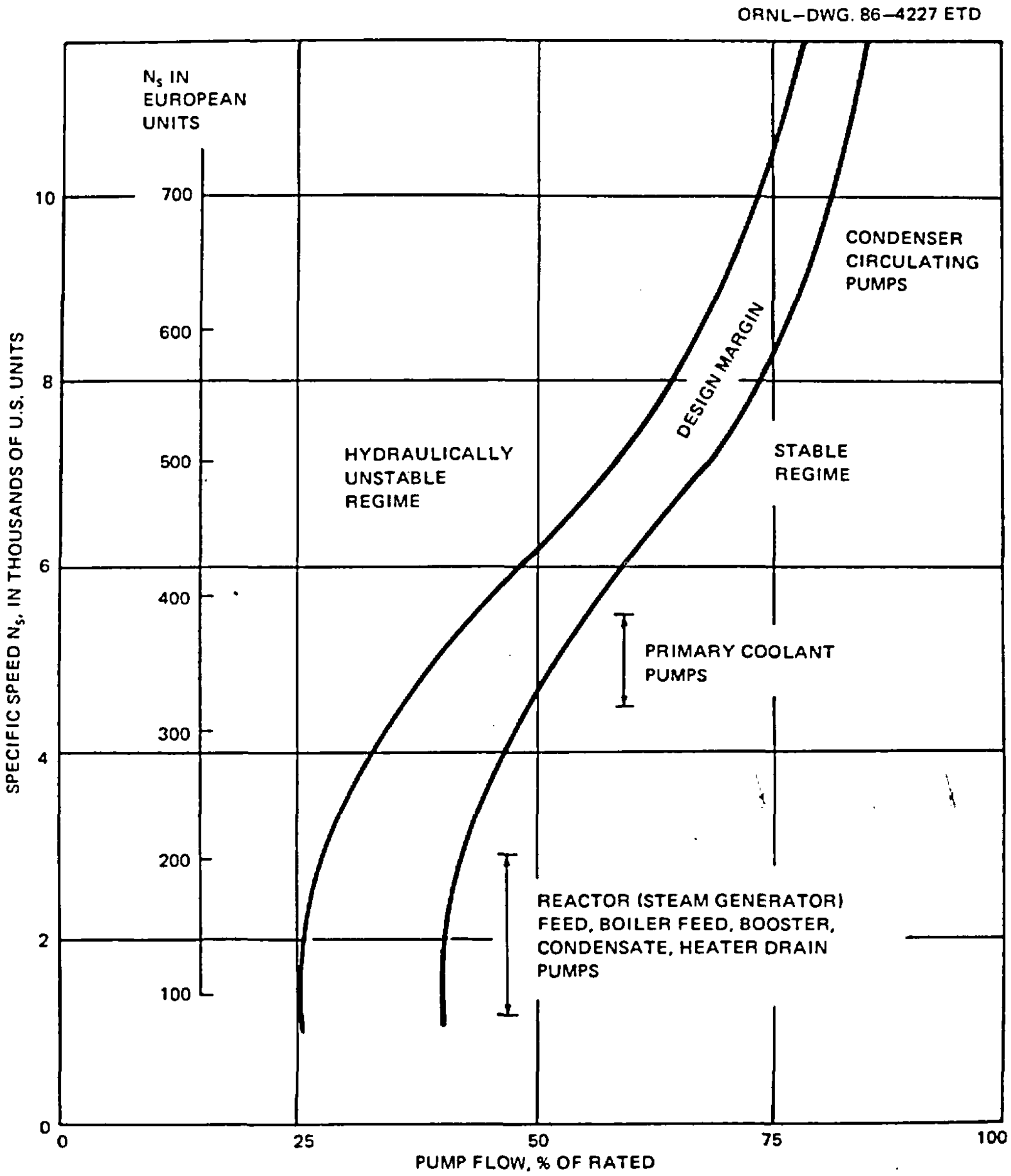

Figure 3.1 Anticipated useful operating ranges for pumps used in large nuclear and fossil power generating units. (Inner line of design margin area is preferred; if hydraulic instability occurs at higher flows, various pump and system problems can be expected.) ***Source:*** **E. Makay and O. Szamody,** ***Survey of Feed Pump Outages*****, EPRI FP-754, Electric Power Research Institute, April 1978**

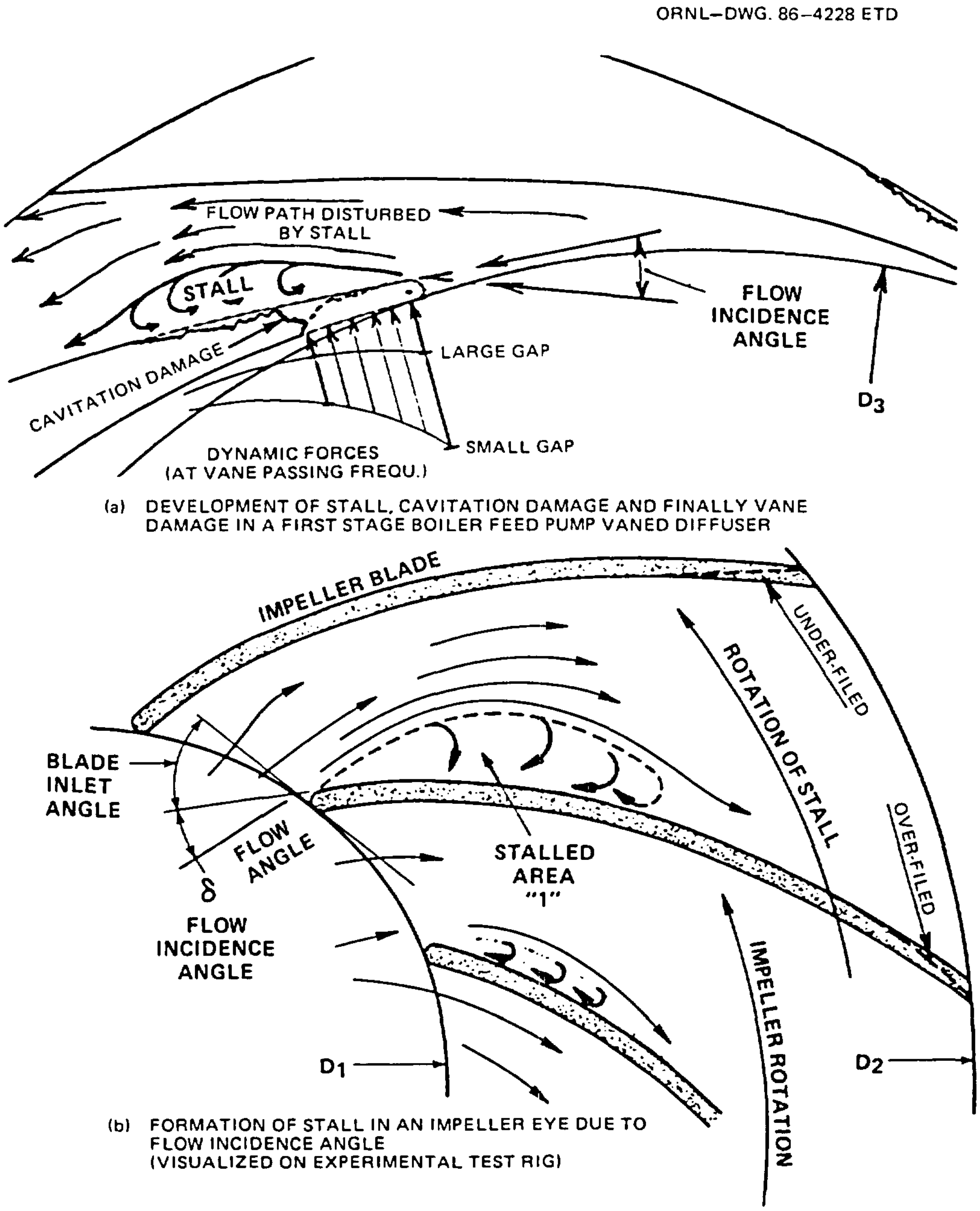

Figure 3.2 Formation of stall (*a*) in diffuser and (*b*) in eye of impeller. ***Source:*** **E. Makay and O. Szamody, *Recommended Design Guidelines for Feedwater Pumps in Large Power Generating Units*, EPRI CS-1512, Electric Power Research Institute, September 1980**

ORNL-DWG 86-4229 ETD

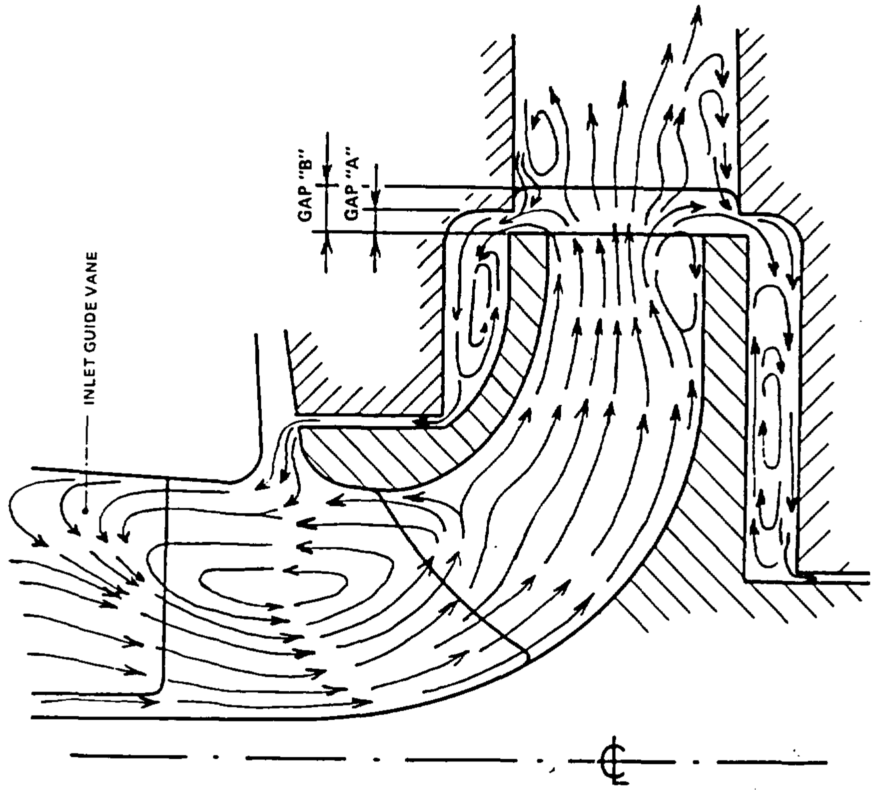

Figure 3.3 Secondary flow pattern in and around pump impeller stage at off-design flow operation. ***Source:*** ***E.*** **Makay and O. Szamody,** ***Survey of Feed Pump Outages,*** **EPRI FP-754, Electric Power Research Institute, April 1978**

ORNL-DWG. 86-4230 ETD

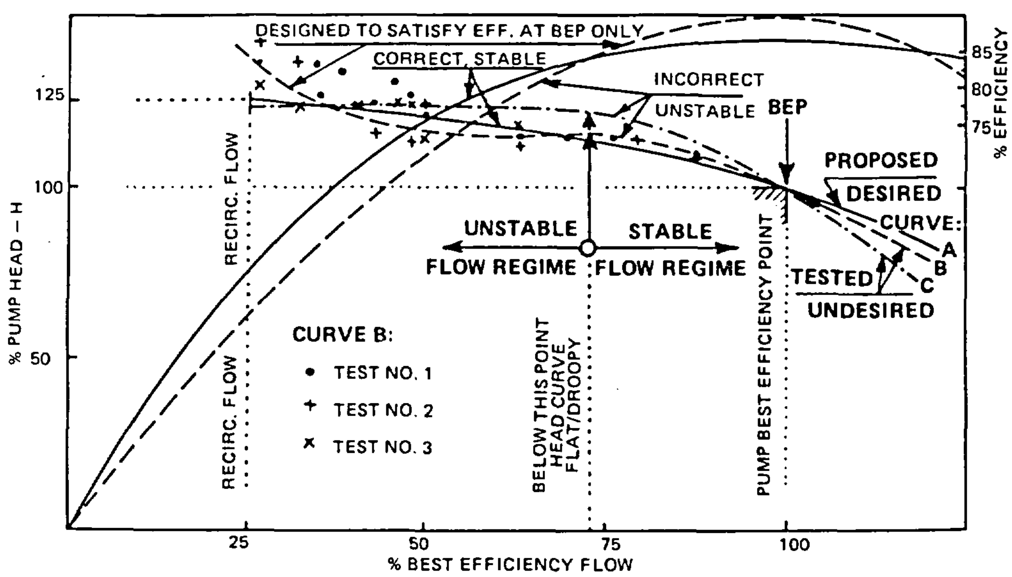

Figure 3.4 Head-capacity characteristics of multistage boiler feed pumps. Curve "A" is correct and desired for stable system operation. Curve "B" represents hydraulically unstable impeller–diffuser design. Parallel, as well as single-pump operation, is difficult in the unstable flow regime. Curve "C" shows design with flat head curve at part load resulting in control system malfunctioning. Single-pump operation is possible in unstable regime. Designs "B" and "C" are not acceptable for utility applications. ***Source*****: E. Makay and O. Szamody,** ***Survey of Feed Pump Outages*****, EPRI FP-754, Electric Power Research Institute, April 1978**

3.2 Degradation of Valve Actuator Motors

Degradation of valve actuator motors occurs quite often during testing because of the large number of duty cycles that may be experienced when performing a series of periodic tests. Valve actuator motors are typically provided with very short time ratings, on the order of 5 to 15 min, and it is not uncommon for periodic testing to be scheduled during an outage so that a motor is called upon to stroke its valve several times within a relatively short period (perhaps 1 h) so that time to cool down is not provided between strokes. If the valve has a 30-s stroke time, it only takes five open/close operations in close succession before the rating of a 5-min motor is exceeded. In many cases, TOL protection for the motor may not be provided because the TOL has been either bypassed or purposely set higher than the motor's thermal damage point.[4,5] With no thermal protection, the motor will be thermally degraded by operation in excess of the duty cycle. In some cases, valve actuator motors are "rotor limited." This means that the thermal degradation will occur first in the rotor.[6] Degradation in the rotor is difficult to detect with conventional diagnosis equipment but will result in a significant decrease in motor torque output. Alternate methods for testing valve actuator motors to assess degradation are discussed in Sect. 4.5.

4 Evaluation of Monitoring and Maintenance Practices

4.1 Evaluation of Monitoring/ Operating Practices Where Mechanical Failures Are Currently Undetected

Typically, there are several motor-operated valves (MOVs) in the AFW system. The issue of MOV actuator operability is dealt with thoroughly by Ref. 7, "Generic Letter 89-10." This *Generic Letter* provides recommended actions for the testing, inspection, and maintenance of MOVs to provide assurance they will function when subjected to the Design Basis Condition. As all nuclear utilities are now in the process of developing MOV maintenance and testing programs to comply with Generic Letter 89-10, there is no need to expand on the issue of MOV maintenance and testing here except to direct the reader to Refs. 4 and 8 through 14, which provide a general overview of the issues associated with ensuring MOV reliability. Other maintenance practices that were found to contribute to component failure or that were found to be profoundly inadequate in detecting component failure in the Phase I study are discussed in the following paragraphs.

4.1.1 Undetected—Check Valve Failure to Open or Close

Currently, most AFW system check valves are verified operable by exercising the valve and verifying obturator movement. A small number of valves at each plant cannot be tested in this way because flow cannot normally be put through the valve. The American Society of Mechanical Engineers (ASME) Operation and Maintenance (OM) Code, Subsection ISTC,[15] states that as an alternative to testing by exercising, disassembly may be used to verify operability of check valves. When disassembly is used, it may provide indications of premature wear or degradation; however, disassembly should only be used as a last resort when no other option is available.

If significant degradation is detected in the disassembled valve, a failure analysis should be conducted to determine the cause of failure and the appropriate corrective action. Other check valves that may also be affected because of similar design, manufacturer, service, size, materials of construction, orientation, flow instabilities, etc., should also be inspected or tested.

Nonintrusive testing techniques should be used to verify operation of check valves. Simply exercising the valve by putting flow through it does not verify complete obturator movement. A partially open valve can significantly reduce flow, as discussed in Sect. 4.1.2. There are three basic diagnostic methods for assessing check valve degradation without disassembly—acoustic emission, ultrasonic inspection, and magnetic flux signature analysis (MFSA). These methods are discussed in Sect. 4.6, and recommendations are made in Sect. 5.1. A typical check valve is shown in Fig. 4.1.

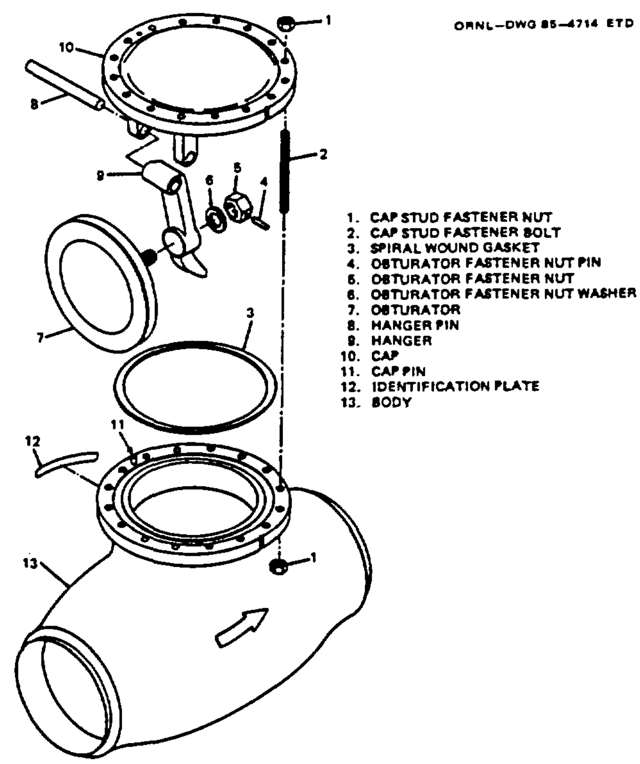

Figure 4.1 Swing check valve, exploded view

4.1.2 Undetected—AFW Pump Failure to Deliver Required Flow at Design Conditions

A key concern regarding AFW pump functionality is that sufficient operating parameters to establish functionality are not measured during testing. In addition, the pumps are often not tested at the required pressure condition, and no testing is done with all pumps operating simultaneously. To quote Ref. 16, p. 46, "The primary purpose of an AUXFP is to deliver flow to the feedwater system to provide secondary system emergency heat removal." It is essential that pump flow capability be accurately assessed during periodic testing.

The flow delivered by a centrifugal pump will decrease as a pump ages and wears and the internal clearances between the impeller and stationary surfaces become larger. When the internal clearances become too large, the stage-to-stage recirculation flow becomes a significant portion of the normal through-flow, and the pump provides less head. Figure 4.2 shows the effect of this internal leakage increase on the pump head-capacity curve.[16] Undetected degradation of pump internals, such as cracking of diffuser vanes or impeller blades, will also lead to reduced flow as discussed in Sect. 3.1.

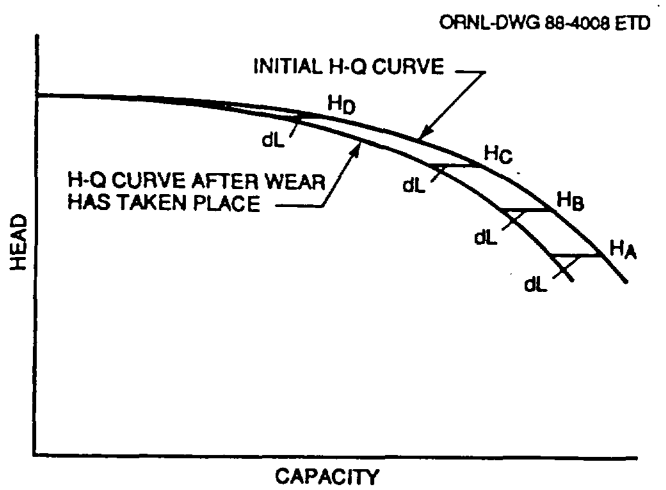

Figure 4.2 Effect of wear on head-capacity curve. *Source:* Adapted with permission from Igor J. Karassick, *Centrifugal Pump Clinic*, Marcel Dekker, Inc., 1981

Currently, AFW pump flow testing is done at the minimum flow rate where the effect of wear and increased clearances is much less obvious. Testing at minimum flow may demonstrate that the pump does actuate, but it does not provide assurance that the pump will perform at conditions of higher flow. In the low-flow portion of the curve, the change in head caused by wear in the pump is small compared to the change at the typical design basis event (DBE) condition; therefore, significant degradation may go undetected.

A centrifugal pump will produce flow at a rate that corresponds to the intersection of its own head-capacity curve and the system curve for the particular system of piping and valves in which the pump is installed. As the head on the system curve is increased, the intersection of the system curve with the head-capacity curve will result in lower capacities. See Fig. 4.3 for an example of a typical AFW system curve. Here, it can be seen that the intersection of the head-capacity curve with the system curve at a static head curve of 50 psig provides a flow of ~950 gal/min. At a static head of 1000 psig, the same pump will produce a flow of 600 gal/min. (At typical minimum flow conditions of 1500 psig, the pump will produce a flow of 100 gal/min.)

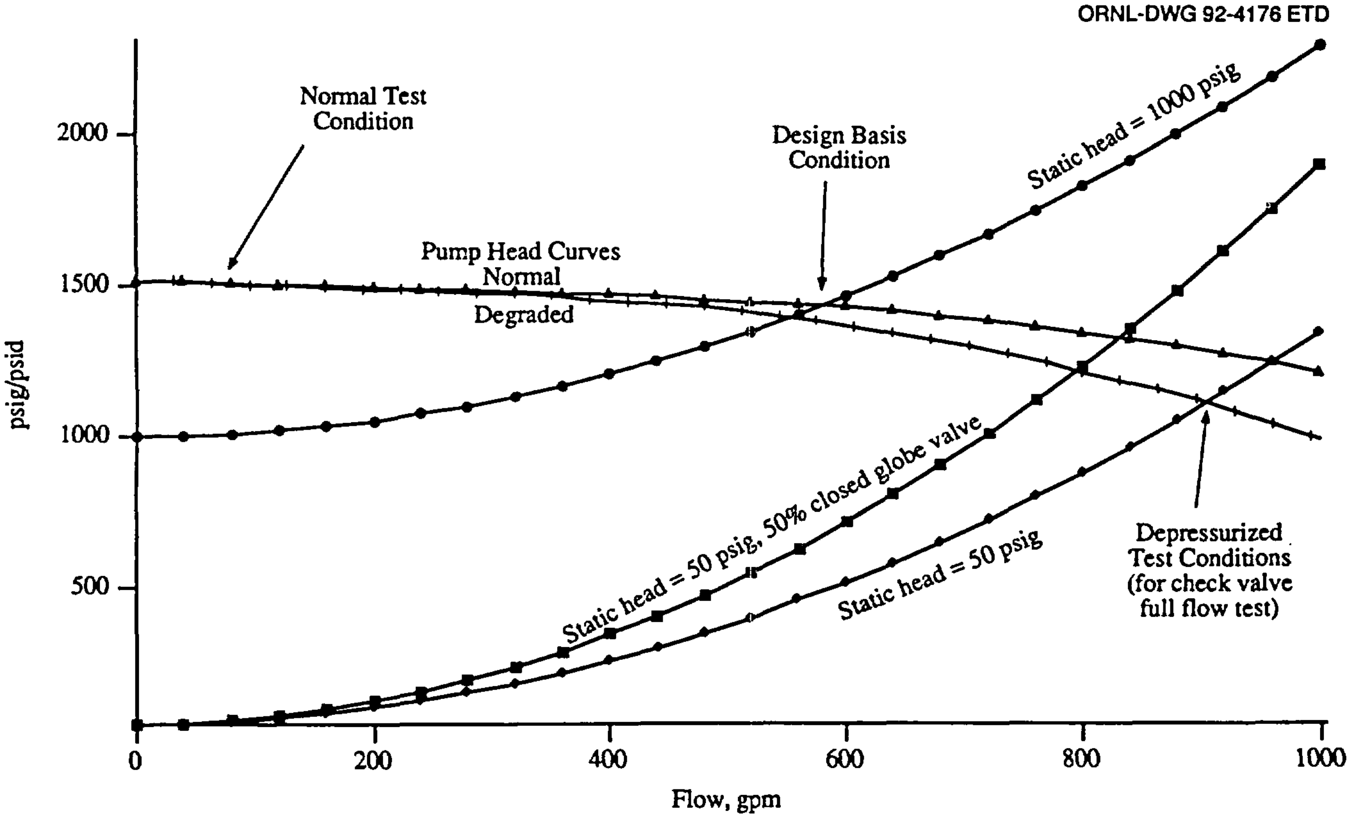

Figure 4.3 Example pump and system head-capacity curves

The 1000-psig value corresponds to the typical DBE system condition. The static head curve for a 50%-closed globe valve includes the additional friction that would result from a partially closed valve, a check valve, for example. One 50%-closed valve is seen to reduce the flow from 950 to 830 gal/min at 50-psig static head.

It is essential that this effect be considered when evaluating minimum flow test results. To do this, the system curve for the AFW system and the pump head curve must be evaluated and the DBE flow calculated based on the measured flow at the actual tested discharge pressure condition.

Section 5.2 provides a table of AFW pump monitoring methods and a test guideline for full-flow periodic testing that would eliminate uncertainties associated with minimum flow testing.

4.1.3 Undetected—LCV Failure to Open Sufficiently to Allow Adequate Flow

These valves are normally closed, and they open on the loss of air or control power. Per Ref. 1, p. 70, none of the surveillance tests for the particular plant studied in Phase I that officially demonstrate the operability of the MDP LCVs actually put any flow though the valves. The periodic test that is used to demonstrate full stroking of various check valves does demonstrate that the valves can be opened (using manual controls) to allow ≥220 gal/min to each steam generator. This flow is provided, however, at relatively low differential pressure, on the order of 100 psid, when the motor-driven (MD) AFW pump is tested at cold shutdown conditions. It would be highly preferable, from the viewpoint of verifying operability, to perform this test during the transition from hot standby to hot shutdown. The AFW is normally used in hot shutdown to provide core cooling after the main feedwater (MFW) is isolated. A short test performed at hot standby, when the steam generator is at normal operational pressure, would provide the opportunity to verify the operability of a number of AFW components. This test is discussed in Sect. 5.2. Although this is a plant-specific example of a testing weakness, this opportunity to verify AFW component operability at hot standby does exist at all plants.

4.1.4 Undetected—BDIVs Failure to Close Sufficiently to Isolate Flow

The blowdown valves are 0.2-in. air-operated valves that close automatically in response to the start of the AFW pumps. For the specific plant studied in the Phase I study,[1] the blowdown valves are tested at low-flow conditions, and an upstream valve is simultaneously closing to isolate flow. This does not provide a meaningful test of the BDIVs. Testing of the AFW pumps at operational pressure would also provide the opportunity to test the auto close function of the BDIVs and their capability of closing against operational pressure. This test of the AFW pumps is described in Sect. 5.2. Again, this is a plant-specific example of a testing weakness; however, the opportunity to test these valves at operating conditions does exist at all plants.

4.2 Evaluation of Routine Testing in Areas Where I&C Failures Are Currently Undetected

4.2.1 Examples of Undetected I&C Control Logic Failures

In Sect. 2.2.1 are a significant number of examples at the studied plant of a valve actuator failing to open or close the valve in response to the sensed condition. In each case, a failure in control logic had not been detected because logic had not been tested, in either a periodic test or periodic maintenance test requirement. These major issues of a nondetectability discussed in Ref. 1 are as follows:

1. Only one of three possible logic coincidences was verified by testing to result in an open signal to the ESW to MD AFW pump supply valve.
2. ESW to MD AFW pump isolation valves are not restroked after reconnecting the control circuit leads following testing of other valves, thereby creating the potential for improper reconnection.
3. The automatic de-energization of the MD LCV solenoids following an automatic pump start is not tested.
4. There is no testing that the BDIVs close in response to any AFW pump start.
5. There is no testing to verify that the interlock for the normally open motor-operated steam supply valve to the TDP will cause the alternate motor-operated supply valve to close.
6. There is no testing to verify that contacts from the alternate steam supply valve to the turbine-driven AFW pump cause the automatic steam supply transfer sequence.
7. There is no testing to verify automatic closure of the ESW to the turbine-driven AFW pump suction isolation valves upon receipt of auto close signal.
8. The de-energization of the TDP LCV solenoids is not demonstrated with the control switches in AUTO.
9. There is no testing to verify that automatic closure of the TDP steam supply isolation valves will occur on high temperature.
10. Auxiliary contacts used to provide control signals to the MD LCVs are not tested.

Evaluation

11. There is no verification of the switch that results in auto closure of the steam generator BDIVs.
12. The ability to transfer the control of the MD LCVs from automatic to manual in the presence of an AFW actuation signal is not demonstrated.
13. The turbine-driven (TD) LCV is not verified to close in response to a faulted steam generator condition.
14. The ability to transfer the control of the TD LCVs from automatic to manual in the presence of an AFW actuation signal is not demonstrated.

Many of these examples of failure to test could be broken down into more examples, but the point has been clearly made that there are many significant control functions that are not demonstrated to be operable by test. This is partially because of the fact that, traditionally, solely checking the operation of the actuation relays was considered to be a satisfactory operability test of an engineered safety feature, but another more unsettling observation is that an experienced engineer with the ability to discern all the required system functions and the authority to include them in the test procedures had apparently never been tasked with the responsibility of performing the type of review that was performed for Ref. 1. These examples are specific to the plant studied in Ref. 1 but are indicative of a generic need for a careful review of system logic.

Failure to incorporate all safety-related logic into functional testing can only be prevented by performing a comprehensive review of safety system logic and ensuring that all logic circuits are completely tested, including all contacts, wiring, actuation devices, and terminal points. Obviously, this review is a significant and time-consuming effort, but the large number of examples above are indicative of the fact that serious omissions in safety feature actuation do remain undetected by current testing programs. This is a serious safety concern.

The manpower resources required to correct this concern are significant. One experienced engineer could reasonably be needed 1 year for a comprehensive review of all functional logic and wiring diagrams for one safety system where each system function is checked to ensure that it is completely tested by the current plant periodic maintenance procedures. After this, the maintenance procedures would require a significant work-hour effort for revision, and maintenance staff would require familiarization and possibly training based on the extent of the revisions.

4.2.2 Undetected I&C Failures—Thermal Overload (TOL) Setting Not Verified

Proper valve actuator motor TOL setting has received much attention from both the NRC and industry groups. The key to proper TOL selection is an understanding of duty cycle and selection of the motor and TOL to meet this duty cycle. Generic Letter 89-10 requires that sizing calculations for TOLs be verified,[7] and industry guidance (IEEE 741)[4] provides detailed instructions for accomplishing this. Performing adequate research to determine the valve's intended duty cycle and then selecting both the valve actuator motor and its protection to meet this duty cycle will eliminate spurious TOL actuation. Again, this review will require an experienced engineer who is familiar with all facets of system operation.

4.2.3 Undetected I&C Failures—Turbine Electronic Overspeed Function Fails to Trip Before Mechanical Overspeed Trip Occurs

The electronic trip is tested under simulated, rather than operating conditions. There is no verification of automatic resetting, thereby requiring local resetting and preventing auto restart. Testing the electronic overspeed trip by simulation provides no assurance that there is proper coordination between the electronic and manual trip devices. A controlled, manual turbine overspeed test should be performed; this is discussed in Sect. 5.3.

4.3 Evaluation of Additional Functional Verification Testing in Areas Where No Functional Verification Test Is Presently Performed

4.3.1 Flow Verification of ESW

It is not practical to verify ESW flow by test because lake water should not be introduced into the condensate/feedwater system; however, the ESW lines should be inspected periodically to ensure that design flow will be available and that the lines are not corroded or blocked by an accumulation of organic material. Section 5.7 provides a recommendation for a full-flow ESW test line.

Per Ref. 17, NUREG/CR-5379, *Nuclear Plant Service Water System Aging Degradation Assessment, Phase I*, the following considerations are obvious for the maintenance of service water systems:

- timely painting of exposed structures,
- replacement of sacrificial anodes in cathodic protection systems,
- proper attention to material selection in components prone to failure,
- coating application and repair,
- chemical and/or mechanical cleaning, and
- water treatment.

Thus, as an alternative to actual performance of the ESW flow test, maintenance attention to cathodic protection, coating application, and inspection of the service water lines is essential. A discussion of service water system fouling is provided in Sect. 5.6. In addition, an analysis of the untestable flow switchover function should be performed as discussed in Sect. 4.8.

4.3.2 Verification of Switchover Time for ESW

A single complete functional test of the automatic switchover to ESW also should not be performed because it would introduce lake water into the condensate/feedwater system. However, this is a critical safety function that must be demonstrated as operable. The principal concern is that a slow transfer could result in a temporary loss of water flow to an AFW pump with resultant air binding damage to the pump and loss of the pump at the time when it is most needed. There are a number of factors that could result in slow transfer times. These include degradation of valve actuator motor, degradation of relay logic, and degradation of sensing circuit.

The maximum allowable ESW switchover time should be determined by analysis so that an acceptable time for the switchover is established.

Even though the complete functional test cannot be performed, overlapping portions of the sensing and actuation logic and actual valve stroking should be performed and the total switchover time determined from the test results. This switchover time can then be compared to the allowable switchover time, and the operability of the switchover can be verified.

There is another option worthy of consideration and that is the addition of an ESW full-flow test line. See Sect. 5.7 for a discussion of this option.

4.3.3 Verification of TDP LCV

There is one significant failure mode of the TD LCV that is presently not detected by conventional testing (Ref. 1, p. 93) as follows: "The ability of the accumulator to stroke the valve and the proper seating of the control air check valve for the accumulator are not demonstrated." A test should be performed that tests the function of the accumulator to stroke the valve for the minimum required cycles and the seating of the control air check valve for the accumulator. In this test, control air to the accumulator would be isolated, then a discharge path to atmosphere from the accumulator would be opened to test the accumulator check valve. If accumulator pressure stayed constant, then the TD LCV would be stroked for the minimum required cycles under operating system pressure to test the ability of the accumulator to provide an alternate source of power.

4.4 Evaluation of Alternate Methods for AFW Pump Testing

Several considerations for AFW pump surveillance and monitoring practices are provided in Ref. 2. These are summarized in Sects. 4.4.1 through 4.4.3.

4.4.1 Current AFW Pump Surveillance Practice and Limitations

Unlike equipment used in continuous service, AFW pumps typically are not provided with vibration monitors or internal temperature sensors. Thus, trending of parameters such as temperature and vibration during operation is not easily done. Some newer plants use a nonnuclear safety AFW pump for startup and shutdown, thus "saving" the nuclear safety pumps for DBEs. The safety-related pump is still tested, however, nominally every 3 months, by operation with the miniflow line. As discussed in Sect. 3.1, this low-flow operation will degrade the pump and has been shown to lead to pump failure. A 10CFR21 report has been issued on this concern. In addition, this low-flow test at low head does not provide the proper operating range of flow or sufficient running time to comprehensively trend AFW pump performance and operating characteristics, even if complete monitoring were installed. The current status of AFW pump surveillance practice is concluded then to be not only harmful to the pump but inconclusive in verifying pump design basis operability.

4.4.2 Interim Recommendations for Surveillance and Monitoring Practices

In light of this obvious problem of the inadequate and damaging current flow test practices, Ref. 2 provides recommendations for interim surveillance and operating practices. These are summarized as follows:

1. AFW systems should be studied for the possibility of installing permanent full-flow test lines. Full-flow test lines have been installed by Virginia Power at the Surry Plant, which was the plant that identified the AFW pump low-flow failures.
2. Complete monitoring should be periodically conducted on every AFW pump. Parameters for monitoring should include rotor orbital motion; oil-film bearing temperature; head, flow, and speed values; rotor axial position; metal fragment or sound emission detection; and vibration monitoring.
3. A trending data base should be prepared for each pump for all the monitored parameters. The trending would help to indicate the need for maintenance, overhaul, and replacement.

4.4.3 Interim Recommendations for Detailed Inspection Program

In addition to monitoring and trending, a disassembly and inspection of the AFW pumps should be carried out at appropriate intervals, perhaps one pump every third outage. Each pump would then be disassembled every 10 years. If significant wear were detected in one pump, then all pumps would be disassembled.

Reference 2 provides a number of procedures and reliability enhancing actions that could be taken during disassembly. These are summarized as follows:

1. replace bearings;
2. replace shaft seals;
3. replace wear rings;
4. replace worn impellers and diffuser vanes;
5. replace any worn journals, bearing surfaces, or thrust balancing components;
6. inspect sealing joint surfaces;
7. check shaft for run out; and
8. replace any degraded fastener.

The most conclusive option for AFW testing is a full-flow test during normal operation. This could alleviate the need for the extensive monitoring devices just described and perhaps provide the basis for less frequent disassembly and inspection. Section 5.2 provides a recommendation for a full-flow method of performing AFW testing.

4.5 Alternate Methods for Valve Actuator Motor Testing

Several methods for detecting degradation in valve actuator motors have been developed recently. Surveillance of safety-related valve actuator motors, especially the large frame sizes, is essential because of the many failure modes associated with these motors.[11] The magnesium alloy used for the cast end rings and conductor bars in the larger motors is susceptible to failure from overheating or corrosion.[18]

The typical motor tests that have been common surveillance practice over the last 40 years, such as high-potential testing, winding resistance, megger testing, and polarization index are valuable for testing the condition of the stator but provide little or no information on the condition of the rotor. The rotor can be examined using a flexible fiber optic borescope, but this requires a technician to actually insert the borescope in the motor, which at times can be quite difficult because of motor location.

A new method of assessing rotor degradation is called motor current signature analysis. This method has been tested on a valve actuator motor and was successful in detecting broken rotor bars before the motor's torque output had been appreciably reduced.[19] This method is based on the principal that an electric motor acts as a transducer. When broken rotor bars are present, harmonic fluxes are produced in the air gap that induce harmonic components in the motor current waveform. The motor current waveform can be readily converted from a time domain to a frequency domain using fast Fourier analysis, and the amplitude of each of the component frequencies can be evaluated to determine problems both in the motor and in the driven equipment.

4.6 Evaluation of Alternate Methods for Check Valve Testing

Check valve testing has become the subject of considerable attention. Reference 20, NRC Generic Letter on Developing Acceptable Inservice Testing Programs, discusses check valve reliability and states that, in some cases, an electrical signal initiated by a position-indicating device may be used for position verification. Because check valve testing has developed into a major issue with many methods being offered in the industry, only a brief summary of some of the techniques can be discussed in this study.

No single diagnostic technique will satisfy all requirements, but a combination of acoustic emission with either ultrasonic inspection or Magnetic Flux Signature Analysis (MFSA) will detect most major check valve operating conditions. The acoustic signature will not indicate disk position when the disk is stationary in the fully open and fully closed positions, nor will it detect a slowly moving disk or disk flutter in midstroke. In all three tapping modes (seat tapping, backstop tapping, and hinge arm rocking), however, the acoustic signature will detect the tapping but not the position.

The magnetic signature is a technique of applying external magnetic fields to the valve and then monitoring disk movement as it either completes or partially opens the magnetic circuit. This method does not unambiguously detect the tapping, but, in conjunction with the acoustic signature, does identify its location. A discussion of the diagnostic techniques and a recommendation for detecting check valve failures are provided in Sect. 5.1.

Aging and service wear of check valves are also discussed in Ref. 21, which describes several check valve monitoring methods and identifies their strengths and weaknesses, as summarized in Table 2.1 of that report.

4.7 Evaluation of Alternate Methods for TD AFW Pump Testing

The present TD AFW pump test is performed at normal operating steam generator pressure. The steam supply to the AFW turbine is taken from the steam generators through the main steam system. The steam supply pressure can range from a high that corresponds to the main steam safety valve relief pressure (~1215 psia) to a low of ~120 psia. This low pressure corresponds to a temperature of ~340°F. The AFW system is required to operate until the reactor coolant temperature is reduced to the point at which the residual heat-removal system can be started (350°F). Because the steam generators are a heat sink for the reactor, steam generator temperature typically must be below 350°F. Therefore, it is possible that the AFW turbine could be operating with steam supply pressures as low as 120 psia. Therefore, the turbine should be tested with steam supply pressures as low as 120 psia to ensure that adequate flow is developed. This could be accomplished by performing the pump flow test at startup when the steam supply pressure is low. This is discussed in Sect. 5.3.

4.8 Evaluation of Untestable Functions

In the design of the AFW system, there are some functions that cannot be tested. The analysis of these functions should be independently verified by an alternate analysis to ensure that an appropriate degree of conservatism exists. Two examples of these are the flow switchover from the CST to ESW and the system flow curve for flow from ESW. As is discussed in Sect. 4.3.1, additional functional verification testing can be performed to verify portions of the ESW switchover, but then the individual times must be summed and compared with the total allowable switchover time, which is determined by analysis. Because an error in this analyzed total allowable switchover time could result in air binding and possible destruction of an AFW pump and because this function typically can never be tested, it is crucial that the analysis used to determine an acceptable switchover time be independently verified by an alternate, independent analysis to verify that the result is correct.

This is also true for the analysis of the system head flow curve for the ESW lines. These lines typically can never actually be tested, but their correct operation is absolutely essential. Additionally, they are also notoriously susceptible to increased friction from fouling (see Sect. 5.6). Because of this, the ESW system head flow curve could easily change with time as the lines became fouled. The ESW lines must be periodically inspected for fouling, and the curve should be established as accurate and acceptable by an independent calculation.

Other potential function failures may be hidden in the untested portions of the AFW system. An example is the routing of the ESW line feeding the AFW suction. When the ESW line is filled, the presence of a high point in the line may allow a bubble to form if the designer does not provide a high-point vent. This bubble could remain undetected and cause failure of the AFW pump if it were called upon to operate with suction from ESW. To the author's knowledge, this potential failure caused by a design oversight has occurred at a minimum of three plants and was the subject of NRC Information Notice 93-12 (Ref. 22). Potential failures such as these could not be discovered by testing because the ability to test was not provided in the system design; they are "caught" only by carefully analyzing operation of the system function.

5 Recommendations for Alternative Monitoring/Operating Practices to Detect Failure Modes Currently Undetected

The discussion of failure modes provided in Sect. 2 provided the following areas where failure modes were not detected by current monitoring/operating practices:

1. check valve failures,
2. AFW pump failures at operating pressure conditions,
3. turbine-driven AFW pump failure to provide required flow at reduced steam pressure,
4. various air-operated valve failures to open or close,
5. I&C failures not observed during routine testing,
6. turbine electronic overspeed trip function,
7. turbine steam supply isolation valve failure to close correctly,
8. ESW failure to switchover in time, and
9. ESW failure to provide adequate flow.

Recommendations for alternative monitoring/operating practices to address each of these failure modes are provided in Sects. 5.1 through 5.7 and are summarized in Table 5.1.

5.1 Recommendations for Improvements in Current Monitoring/ Operating Practices to Detect Check Valve Failures

Check valves failing to open were a significant AFW system failure mode found in the AFW aging study.[1] In the aging and service wear of check valves study,[21] the discussion of monitoring practices may be summarized as follows:

There are five primary methods for check valve monitoring: acoustic emission monitoring, ultrasonic inspections, magnetic flux monitoring, radiography, and pressure noise monitoring. Radiography and pressure noise monitoring are limited to special test applications. Acoustic emission monitoring, ultrasonic inspection, and magnetic flux monitoring provide the best general diagnostic capability, especially when they are used in combination with each other.

Radiography, as a check valve diagnostic, is limited to inspections for flaws, cracking, or erosion over a specific valve area.

Pressure noise monitoring requires penetrating the pressure boundary and installing a transducer. In addition, Ref. 21 (p. 30) states that pressure noise monitoring is influenced by many system phenomena and sometimes provides nonreproducible results. Acoustic emission monitoring is excellent for detecting a tapping valve but has the major drawback that when the obturator is fluttering in midstroke, lodged in one position, or completely broken from the hinge pin, there will be no tapping to indicate these conditions. Thus the absence of tapping does not show that the valve is open and stable.

MFSA is nonintrusive because the magnets or magnetic coils are typically installed outside the valve. The analysis of the magnetic field provides a continuous, real-time indication of the obturator position.

A combination of two of the monitoring methods provides the best overall diagnostic capabilities. Acoustic emission provides unique information on obturator contact (tapping) and use of acoustic emission with MFSA will provide information on leakage (acoustics), impacts within valve (acoustics), and detecting disk position to assess whether the disk is open, closed, or partial (MFSA).

One method for detecting check valve leakage is infrared thermography. This is useful in an operating condition where one side of the valve is pressurized with hot water.

5.2 Recommendations for Full-Flow Testing of AFW Pumps

Reference 16 provides a discussion on the problem of development of minimum flow rate criteria. This discussion concludes that no proven formulas are available to determine how long a specific pump design can operate at reduced flow rates and that the continued use of miniflow testing will, over time, continue to produce possibly damaging effects in the tested pumps.

The alternative, which will both conclusively verify operability and eliminate damage caused by miniflow operation, is full-flow testing. A proposed test guideline is provided in Ref. 16 as Appendix G and is summarized here as it is a logical alternative to the minimum flow test.

Allowing the AFW pumps to deliver flow to the steam generator during system operation would require no

Table 5.1 Recommended alternative testing practices

Component	Test	Value	Drawback	Suggested frequency
Check valve	Radiography	Verifying integrity	No information on positioning	As needed
	Pressure noise monitoring		Overly sensitive	Not ordinarily recommended
	Acoustic emission	Verifies tapping	Will not detect stuck or broken obturator	As needed, in combination with MFSA
	Ultrasonic inspection	Nonintrusive	May not operate over full range of travel	Ordinarily, not recommended
	Magnetic flux signature analysis	Verifies position	Relatively new technology	As needed, in combination with acoustic emission
	Disassembly	Allows for assessment of wear and obturator motion	Valve must be removed from service for extended period, possibility of error in reassembly	10 years
AFW pump	Visual inspection	Will sometimes detect external signs of degradation	External evidence must be present	At each flow test (quarterly)
	Motor power monitoring and rotational speed	Indicates hydraulic degradation	Must be corrected and trended	At each flow test (quarterly)
	Dimensional inspection	Indicator of mechanical wear	Can only be done at disassembly	At 10-year interval
	Developed head monitoring	Essential for assessing hydraulic degradation	Must be corrected for system friction, pump speed, etc.	At each flow test (quarterly) and trended
	Developed flow monitoring	Indicates hydraulic degradation	Must be corrected for system condition, static head, pump speed, etc.	At each flow test (quarterly) and trended
	Vibration monitoring	Indicates mechanical degradation	High implementation cost	At each flow test (quarterly) plus trend
	Balance return line flow	Indicates hydraulic degradation	High implementation cost	At each flow test (quarterly)
	Audible noise monitoring	May indicate developing problem	Requires experienced individual	At each flow test (quarterly)
	Bearing temperature monitor	Indicates mechanical degradation	High implementation cost	Trend
	Bolt torque inspection	Indicates worn fasteners	None	At 10-year interval
	Leakage inspection	Indicates shaft seal condition	None	At each flow test (quarterly)
	Lube oil analysis	Indicates bearing wear corrosion or contamination	None	At each refueling outage plus trend

Table 5.1 (continued)

Component	Test	Value	Drawback	Suggested frequency
	Liquid penetrant inspection	Indicates cracking caused by stress or corrosion	None	At each disassembly (10 years)
	Hot standby full-flow test	Indicates ability to provide flow at operating pressure	Possible cyclic fatigue of FL system	At each refueling outage plus trend
Valve actuator motor (ac & dc)	Winding megger	Indicates insulation resistance	Test is sensitive to environmental conditions (humidity)	At each refueling outage plus trend
	Winding bridge	Indicates windings are not shorted or open circuited	None	At each refueling outage plus trend
Valve actuator motor (ac)	MCSA	Detects rotor degradation	None	At each refueling outage plus trend
LCVs and BDIVs	Stroke at cold shutdown	Indicates logic is operable	None	At each refueling outage
	Stroke at transition from hot standby to hot shutdown	Indicates valve is operable at design basis conditions	Requires special test procedure	At each refueling outage
Turbine drive AFWP	Flow test at low steam pressure	Confirm flow is adequate at point where RHR is started	None	At each refueling outage plus trend
	Chemical analysis of turbine and governor oil	Detect wear corrosion or contamination	None	At each refueling outage plus trend
	Verify electrical and mechanical overspeed trips by actually taking turbine to overspeed condition	Confirm coordination between two trip actuations	Turbine must be controlled manually	At each refueling outage
Safety-related logic	Entire control function, in overlapping segments, from sensor to end component action, for all functions	Confirm safety features are operable	Complete review of control logic requires a significant commitment of resources. Plus, procedures must be revised and training required	At each refueling outage
ESW, service water	Monitor corrosion with inspection or ultrasonic wall thickness testing	Ensure system integrity	None	At each refueling outage plus trend
	Monitor flow to detect fouling, both organic and inorganic	Ensure design basis flow is available	Flow instrumentation may not be installed	Trend

hardware changes, unlike increasing the flow through the miniflow lines. This test would result in additional temperature transients on the steam generators and a small transient effect on the steam generator system. A significant precaution would be that the source of AFW during testing (typically the condensate storage tank or refueling water storage tank) be condensate quality, noncontaminated, and that all noncondensate quality sources of feedwater be isolated during testing. The test would typically be performed during refueling outage intervals during entry into hot shutdown.

Only one AFW pump should be tested at a time. (If one pump is isolated, the others should be operable and remain aligned and ready to deliver flow in the event of an automatic start signal.)

The flow rate delivered into any one steam generator typically should not exceed 500 gal/min. A plant-specific flow rate would have to be determined. Each pump should be permitted to deliver flow into all steam generators to which it is normally aligned. At least one point well out on the head-flow curve, for example, at 80% or greater of the BEP flow rate, should be verified.

The remote manual flow control valve(s) leading from the pump to the steam generator(s) may be closed immediately preceding the test and then opened slowly during the test until the flow rate reaches the limit (typically 500 gal/min). This should minimize the transient experienced by the steam generator and level control systems.

With the pump delivering flow, operators should record pump discharge pressure, suction pressure, discharge flow, recirculation flow, flow to each steam generator, turbine inlet pressure, and pump speed, in addition to other pertinent data. Analysis should be performed to verify that the pump is operating on its design head-flow curve and that the system friction, pump motor efficiency, flow from CST, etc., are within design requirements.

Following testing, operators should verify that each valve in the AFW system is in its correct position.

In addition to the determination of the plant-specific flow rate, a review of the following two potential concerns should be performed before the full-flow test is adopted.

1. There will be a temperature transient on the steam generator system because of the injection of the cooler auxiliary feedwater. A review of the steam generator pressure and level control system should be performed to ensure that no deleterious effects will result from the test.
2. There will be a thermal cycling effect on the feedwater piping and nozzle to the steam generator. A review should be performed to ensure that the effect of this cycling, once per refueling interval, is acceptable.

5.3 Recommendations for Improvements in Detection of TD AFW Pump Failures

There are four areas of particular importance in ensuring turbine reliability and are not typically included in periodic maintenance, as follows:

1. Periodically perform a pump flow test at low steam supply pressure conditions (e.g., at startup from refueling). This would verify that TDP flow is adequate at the point at which the residual heat removal system can be started.
2. Periodically perform chemical analysis of turbine and governor oil to reveal the presence of contaminants and/or oil degradation. The experience of each utility should be used to determine a time period that will increase reliability (e.g., annual or semiannual analysis).
3. Calibrate governors on a regular basis.
4. Periodically verify overspeed trip operation by manually taking the turbine to overspeed to verify the function of the electrical and mechanical overspeed trip mechanisms, including the electrical automatic reset.

Recommendations 2 through 4 are vendor recommendations and will provide assurance that the entire overspeed trip system is operable.

5.4 Valve Failure to Open or Close

Both of the undetected valve failures noted in the study were for air-operated valves. The first failure, Sect. 2.1.6, was for level control valves failing to open sufficiently to allow adequate flow; the second was for the BDIV failing to close under blowdown conditions. As discussed in Sect. 4.1.6, the AFW pump level control valves are tested at a relatively low differential pressure, whereas it would be possible to perform the test at normal operating pressure by doing the test during the transition from hot standby to hot shutdown. Testing during this transition would provide assurance that the valves are operable during design conditions.

5.5 Recommendations for Alternative Routine I&C Testing in Areas Where I&C Failures Are Not Detectable

As discussed in Sect. 4.2.1, most instances of the failure to test safety-related logic were because the functional tests simply had not been incorporated into the periodic logic verification testing. A thorough and comprehensive review of the safety system logic requires an engineer who is not only well versed in the detailed function of the system but also understands the plant's control wiring diagrams and the translation of the control logic into functional tests as provided in the written periodic test instructions. Confirming operation of a single relay or output contact does not provide assurance that the safety function will operate as required. The entire function must be tested, in overlapping segments, from initiating sensor to actuated equipment.

As discussed in Sect. 4.2.1, performance of a system review to ensure that each logic function is properly written into the periodic test instructions is a significant and labor-intensive effort. However, based on the number of instances of failure to test found in the study of a sample AFW system in Ref. 2, where there existed 14 significant engineered safety feature design functions that were not periodically verified to be operable, the author recommends that the performance of a review of the safety system logic be made a regulatory requirement. All engineered safety feature logic functions would be identified and documented and reviewed as being properly designed into the plant's control wiring and be confirmed to be written into the periodic logic verification testing with the possible exception of older plants.

For the older plants, the work-hours required to perform this comprehensive testing may be excessive. A large number of jumpers or circuit modifications may be needed to perform the test. Use of excessive jumpers could result in the failure to properly restore the safety circuits after testing. Extensive circuit modifications could potentially reduce the reliability of the safety systems. In these cases, the improvement in reliability provided by the comprehensive testing would be outweighed by the decrease in reliability caused by the jumpers and circuit modifications. In these cases, this recommendation would not be applicable.

For new plants, and older plants that have upgraded their I&C systems because of obsolescence, the upgraded microprocessor-based control systems have diagnostic capabilities that will allow on-line testing of all input signals, signal conversion functions, logic functions, and output commands. Overlapping testing can be used to test complete actuations with relative ease. Plants with the capability to perform comprehensive safety system logic functional testing should be required to do so.

5.6 Recommendations for Detection of Service Water System Piping Fouling with Subsequent Flow Reduction

NUREG/CR-5379, *Nuclear Plant Service Water System Aging Degradation Assessment Phase I*, provides an excellent study of fouling of service water systems (SWSs) surfaces.[17] The concern of flow reduction caused by fouling is summarized as follows:

- Fouling refers to all deposits on system surfaces that increase resistance to fluid flow or heat transfer. There are basically two sources of fouling—organic (microorganisms e.g., bacteria, and macroorganisms e.g., Zebra Mussels) and inorganic (scales, silt, corrosion product).
- Fouling deposits result in reduced flow of cooling water. In addition, corrosion can occur underneath sediment deposits and drastically reduce piping system lifetime. Typically, because ESW piping rarely (if ever) experiences design flow operation, fouling deposits may go undetected, and their effect on system friction and flow rate is unknown. For this reason, it is essential that the potential for fouling be kept to an absolute minimum.
- Chlorination is the predominant method to control biofoulants, but federal discharge regulations limit the effectiveness of this method. Other methods include bromination, backflushing, organic coating, or thermal shock. Sometimes chemical and mechanical cleaning methods are used periodically to remove fouling. The size and extent of SWS piping dictates the requirement to focus antifouling procedures on areas that have the most safety significance. These areas must include the lines that supply ESW to the AFW pumps.
- Corrosion in service water lines is often discovered by leaks or inspections. Although pipe wall thickness is periodically measured ultrasonically, reduced flow area from material buildup and pinhole leaks are not detected by ultrasonic wall thickness measurements. Trending of corrosion parameters in key locations would be of great value in ensuring system integrity.

Some of the antifouling procedures that should be practiced for the key SWS lines are as follows:

- coating application and repair;
- chemical and/or mechanical cleaning;
- water treatment and

- most importantly, periodic inspection, evaluation, and trending.

5.7 Recommendation for Full-Flow ESW Test Line

It is not practical to verify ESW flow because lake water should not be introduced into the condensate/feedwater system. However, is it possible to add an ESW full-flow test line to the AFW system (see Fig. 5.1). It is essential to provide a test line that can be thoroughly flushed at the completion of the test to eliminate the possibility of introducing contaminants to the steam generators. As shown in the figure, the AFW pump discharge could be isolated to prevent lake or river water from entering the steam generators and contaminating the AFW system piping during the test. The AFW pump suction would then be isolated from the CST and realigned to the ESW. The pumps would then be started and the discharge flow returned to the service water header via the ESW full-flow test line. A butterfly valve or flow venturi could be installed to simulate steam generator backpressure. Following the test, the AFW pump suction would then be realigned to the CST to flush out the AFW pump(s) and associated piping. (In some cases, at plants where the CST has been contaminated by a previous evolution, an analysis would have to be performed to ensure that flushing the AFW pump to the service water header would not introduce an unacceptable level of contamination into the service water header.) After the AFW pumps and the small section of piping have been thoroughly flushed, the AFW system would then be returned to service.

ORNL-DWG 92-4177 ETD

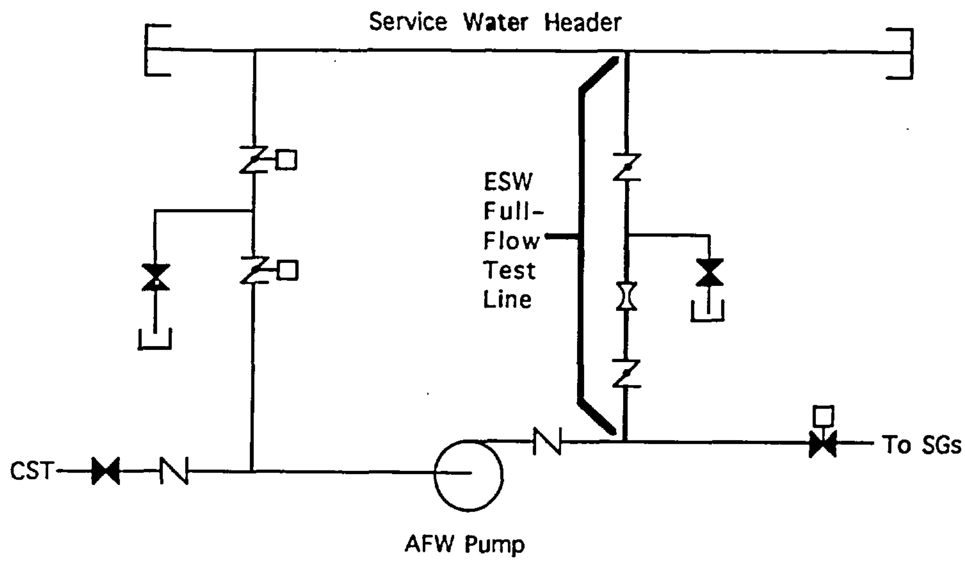

Figure 5.1 ESW full-flow test line added to AFW system

6 Recommended Changes to Technical Specifications to Allow Auxiliary Feedwater Pump Testing on a Quarterly Frequency

As discussed in Sect. 3.2, the present method of performing periodic testing of the AFW pumps at miniflow conditions is producing significant degradation in the pumps because of the hydraulic instability associated with the high-head, low-flow operation. This degradation is leading to premature pump failure.

6.1 Recommendation for Quarterly Testing

Presently, the typical standard pressurized water reactor technical specifications[23] require operability testing of the AFW pump on a monthly basis. Because this mode of operation degrades the pump, it is strongly recommended that this test interval be increased to quarterly rather than monthly. There are no age-related failure mechanisms identified as a result of the Phase I Study that would not be detected by a quarterly test cycle, and the quarterly cycle will significantly reduce the present rate of test-related pump degradation.

6.2 Recommendation for Full-Flow Testing

In addition, some plant technical specifications specify a test flow rate and discharge head that correspond only to miniflow operation. It is strongly recommended that a flow rate and discharge head that correspond to a full-flow test be permitted by the technical specifications.

A full-flow test to the steam generator on an 18-month interval would verify complete system operability including the ability of the check valves and flow control valves to open at design flow and pressure conditions, as discussed in Sect. 5.2. This test would also eliminate AFW pump degradation as a result of low-flow hydraulic instability. This test would result in a temperature transient on the steam generator and level control system because of the injection of the relatively cool CST water, but by opening the flow control valve slowly and only performing the test on an 18-month frequency, the effect of the transient and the number of thermal cycles imposed on the steam generator would be minimized.

6.3 Preferred and Optional Test Method

The optimum resolution to the problem of low-flow testing is the addition of full-flow test lines. With full-flow test lines, a quarterly full-flow test could be performed to verify pump performance with an 18-month test of flow to the steam generator to verify complete system operability. This is the preferred test method.

In cases where installation of full-flow test lines is impracticable, an optional test method is to perform the miniflow test on a quarterly basis and only for a period of 30 s or less to verify that the pump operates and that a predetermined discharge pressure is developed. The 18-month full-flow test to the steam generator would be performed to verify complete system operability.

References

1. D. A. Casada, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., "Auxiliary Feedwater System Aging Study," USNRC Report NUREG/CR-5404, Vol. 1 (ORNL-6566/V1), March 1990.*

2. M. L. Adams et al., Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., "Aging and Service Wear of Auxiliary Feedwater Pumps for PWR Nuclear Power Plants," USNRC Report NUREG/CR-4597, Vol. 1 (ORNL-6282/V1), July 1986.*

3. Letter from Ingersoll-Rand to the NRC, Subject: Notification of 10CFR21 Reportability of a Potential Safety Hazard from Broken Cast Iron Diffuser Pieces in Auxiliary Feed Water Pumps, October 1991.†

4. IEEE/STD 741-1990, "IEEE Standard Criteria for the Protection of Class 1E Power Systems and Equipment in Nuclear Power Generating Stations."‡

5. O. Rothberg, USNRC, "Thermal Overload Protection for Electric Motors on Safety-Related Motor-Operated Valves – Generic Issue 11.E.6.1," USNRC Report NUREG-1296, June 1988.*

6. A. Richards et al., "Motor Overload Protection for Motor Actuated Valves," *IEEE Transactions on Power Apparatus and Systems*, PAS-100 (1), 43–50 (January 1981).**

7. NRC Generic Letter 89-10 to all licensees of operating nuclear power plants and holders of construction permits for nuclear power plants from the U.S. Nuclear Regulatory Commission, Subject: Safety-Related Motor-Operated Valve Testing and Surveillance, June 28, 1989.

8. A. J. Weiss, "Application of Signature Analysis for Determining the Operational Readiness of Motor-Operated Valves Under Blowdown Test Conditions," in *Proceedings of the Sixteenth Water Reactor Safety Meeting*, USNRC Conference Proceeding NUREG/CP-0097, March 1988.*

9. W. J. Foley et al., Parameter Inc., "Failure of Gate-Type Valves to Close Against Differential Pressure," USNRC Report NUREG/CR-3050, September 1983.*

10. M. Subudhi et al., Brookhaven National Laboratory, "Operating Experience & Aging–Seismic Assessment of Electric Motors," USNRC Report NUREG/CR-4156, June 1985.*

11. H. D. Haynes, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., "Aging and Service Wear of Electric Motor-Operated Valves Used in Engineered Safety-Feature Systems of Nuclear Power Plants," USNRC Report NUREG/CR-4234 (ORNL-6170/V2), August 1989.*

12. G. A Murphy et al., Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., "Operating Experience Review of Failures of Power-Operated Relief Valves and Block Valves in Nuclear Power Plants," USNRC Report NUREG/CR-4692 (ORNL/NOAC-233), October 1987.*

13. J. C. Higgins, "Value-Impact Analysis for Extension of NRC Bulletin 85-03 to Cover all Safety-Related MOVs," USNRC Report NUREG/CR-5140, July 1988.*

14. W. Grant et al., MPR Associates, "Application Guide for Motor-Operated Valves in Nuclear Power Plants," EPRI Nuclear Maintenance and Analysis Center, NP-6660-D, March 1990.

15. ASME OM Code-1990, *Code for Operation and Maintenance of Nuclear Power Plants*.‡

16. D. M. Kitch et al., Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., "Aging and Service Wear of Auxiliary Feedwater Pumps for PWR Nuclear Plants," USNRC Report NUREG/CR-4597, Vol. 2 (ORNL-6282/V2), June 1988.*

17. D. B. Jarrell et al., Pacific Northwest Laboratories, "Nuclear Plant Service Water System Aging Degradation Assessment Phase I," USNRC Report NUREG/CR-5379, Vol. 1, pp. 117–121, June 1989.

18. J. D. Kueck, "An Investigation of Magnesium Rotors in Motor Operated Valve Actuators," *IEEE Transactions on Energy Conversion*, 3(1), March 1988.**

19. J. D. Kueck et al., "Assessment of Valve Actuator Motor Rotor Degradation by Fourier Analysis of Current Waveform," IEEE/PES 1992 Winter Meeting, 92 MM 079-4EC.**

References

20. NRC Generic Letter No. 89-04, to all holders of LWR operating licenses and construction permits, Subject: Guidance on Developing Acceptable Inservice Testing Programs, April 3, 1989.

21. H. D. Haynes, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., "Aging and Service Wear of Check Valves Used in Engineered Safety-Feature Systems of Nuclear Power Plants," USNRC Report NUREG/CR-4302, Vol. 2 (ORNL-6193/V2), April 1991.*

22. NRC Information Notice 93-12 to all holders of LWR operating licenses and construction permits, Subject: Off-Gassing in Auxiliary Feedwater System Raw Water Sources, February 11, 1993.

23. M. J. Virgilio, USNRC, "Standard Technical Specifications for Westinghouse Pressurized Water Reactors," USNRC Report NUREG-0452, Rev. 4, November 1981.*

*Available for purchase from National Technical Information Service, Springfield, VA 22161.
†Available in NRC PDR for inspection and copying for a fee.
‡Available from American National Standards Institute, 1430 Broadway, New York, NY 10018, Copyrighted.
**Available in public technical libraries.

NUREG/CR-5404
Volume 2
ORNL-6566/V2
Dist. Category RV

INTERNAL DISTRIBUTION

1. D. A. Casada
2. D. F. Cox
3. E. C. Fox
4. R. H. Greene
5. H. D. Haynes
6. J. E. Jones Jr.
7–16. J. D. Kueck
17. J. C. Moyers
18. G. A. Murphy
19. C. E. Pugh
20. C. C. Southmayd
21. ORNL Patent Section
22. Central Research Library
23. Document Reference Section
24–25. Laboratory Records Department
26. Laboratory Records (RC)

EXTERNAL DISTRIBUTION

27. B. P. Brooks, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303
28. J. W. Tills, Institute for Nuclear Power Operations, 1100 Circle 75 Parkway, Atlanta, GA 30339-3064
29. R. J. Lafaro, Brookhaven National Laboratory, Bldg. 130, Upton, NY 11973
30. R. P. Allen, Battelle-PNL, MS P8-10, P.O. Box 999, Richland, WA 99352
31. J. P. Vora, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Electrical and Mechanical Engineering Branch, 5650 Nicholson Lane, Rockville, MD 20852
32. M. Vagins, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Chief, Electrical and Mechanical Engineering Branch, Division of Engineering, 5650 Nicholson Lane, Rockville, MD 20852
33. J. J. Burns Jr., U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Electrical and Mechanical Engineering Branch, 5650 Nicholson Lane, Rockville, MD 20852
34. M. J. Jacobus, Sandia National Laboratories, P.O. Box 5800, Division 6447, Albuquerque, NM 87815
35. H. L. Magleby, Idaho National Engineering Laboratory, MS 2406, P.O. Box 1625, Idaho Falls, ID 83415
36. Office of Assistant Manager for Energy Research and Development, Department of Energy, Oak Ridge Operations Office, Oak Ridge, TN 37831
37–38. Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831

NRC FORM 335
(2-89)
NRCM 1102,
3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC. Add Vol., Supp., Rev., and Addendum Numbers, If any.)

NUREG/CR-5404
ORNL-6566/V1
Vol. 2

2. TITLE AND SUBTITLE

Auxiliary Feedwater System Aging Study

Phase I Follow-On Study

3. DATE REPORT PUBLISHED

MONTH	YEAR
July	1993

4. FIN OR GRANT NUMBER

B0828

5. AUTHOR(S)

J. D. Kueck

6. TYPE OF REPORT

7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION – NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

Oak Ridge National Laboratory
Oak Ridge, TN 37831-6285

9. SPONSORING ORGANIZATION – NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

This report documents the results of a Phase I follow-on study of the Auxiliary Feedwater (AFW) System that has been conducted for the U.S. Regulatory Commission's Nuclear Plant Aging Research Program. The Phase I study found a number of significant AFW System functions that are not being adequately tested by conventional test methods and some that are actually being degraded by conventional testing. Thus, it was decided that this follow-on study would focus on these testing omissions and equipment degradation. The deficiencies in current monitoring and operating practice are categorized and evaluated. Areas of component degradation caused by current practice are discussed. Recommendations are made for improved diagnostic methods and test procedures.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

auxiliary feedwater, surveillance, monitoring, pump, flow, aging, NPAR, inspection, operating experience, instrumentation and control

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page)

Unclassified

(This Report)

Unclassified

15. NUMBER OF PAGES

16. PRICE

NRC FORM 335 (2-89)