CONF-8710111--3

AGING ASSESSMENT OF AUXILIARY FEEDWATER PUMPS*

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DE88 001739

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For Publication in the Proceedings of the 15th Water Reactor Safety Information Meeting at the National Bureau of Standards, Gaithersburg, Maryland, October 26-29, 1987.

*Research sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission under Interagency Agreement DOE 0551-0551-A1 with the U.S. Department of Energy under Contract DE-AC05-84OR21400 with the Martin Marietta Energy Systems, Inc.

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ABSTRACT

ORNL is conducting aging assessments of auxiliary feedwater pumps to provide recommendations for monitoring and assessing the severity of time-dependent degradation as well as to recommend maintenance and replacement practices. Cornerstones of these activities are the identification of failure modes and causes and ranking of causes. Failure modes and causes of interest are those due to aging and service wear.

Design details, functional requirements, and operating experience data were used to identify failure modes and causes and to rank the latter. Based on this input, potentially useful inspection, surveillance, and condition monitoring methods that are currently available for use or in the developmental stage were examined and recommendations made. The methods selected are listed and discussed in terms of use and information to be obtained.

Relationships between inspection, surveillance, and monitoring and maintenance practices entered prominently into maintenance recommendations. These recommendations, therefore, embrace predictive as well as corrective and preventative maintenance practices. The recommendations are described, inspection details are discussed, and periodic inspection and maintenance interval guidelines are given.

Surveillance testing at low-flow conditions is also discussed. It is shown that this type of testing can lead to accelerated aging.

INTRODUCTION

This paper describes investigations done under the Detection of Defects and Degradation Monitoring element of the Nuclear Plant Aging Research (NPAR) Program. Objectives of the auxiliary feedwater pump studies are to identify and evaluate practical, cost-effective methods for detecting, monitoring, and assessing the severity of time-dependent degradation (aging and service wear); recommend inspection and maintenance practices; and to establish acceptance criteria. Emphasis is given to identifying and assessing methods for detecting failure in the incipient stage and to developing degradation trends to allow for timely maintenance, repair, or replacement actions.

Studies under the NPAR Program are divided into phases. In the case of auxiliary feedwater pumps, the studies are to be conducted in three phases. Phase 1 studies provide baseline information for use in subsequent phases of the study. Failure modes and causes attributable to aging and service wear are identified, as are measurable parameters (or functional indicators) for potential use in assessing operational readiness, detecting incipient failure, and establishing degradation trends.

Phase 2 studies are to complete the failure cause identification and verification and to rank the causes in terms of importance. Recommendations are developed for inspection, surveillance, and condition monitoring methods and for inspection and maintenance practices.

Phase 3 studies are to provide guidance on application of the recommendations developed in Phase 2. In addition, criteria are to be developed for operational readiness determination and for establishing maintenance or replacement needs.

The results of the Phase 1 and 2 studies are discussed in this paper; detailed descriptions of these investigations are given in Refs. 1 and 2. Also included here is a brief discussion of surveillance, or in-service testing of pumps, and the adverse consequences that can result when low flows are used.

Auxiliary feedwater pumps are generally classified as low specific speed, low energy, high head-per-stage machines. They are multistage devices, with the number of stages ranging from 6 to 12. Both opposed- and in-line impeller configurations are used. The inlet stage can be single- or double-suction, and discharge collection chambers can be either diffuser or volute type. The casing is horizontally split. The cross-sectional view of a single-suction, opposed-impeller auxiliary feedwater pump is shown in Fig. 1

The pressure rise ranges from 1000 to 1450 psi, and the brake horsepower ranges from 350 to 800. Table 1 lists examples of typical best efficiency point (BEP) parameters.

Functional requirements vary from plant to plant. General requirements are as follows:

1. Supply feedwater to the steam generators under plant startup, normal shutdown, hot standby, and emergency conditions;
2. meet automatic starting requirements;
3. operate under normal and accident conditions of temperature, pressure, humidity, radiation, and available net positive suction head (NPSH); and
4. withstand seismic loadings without loss of function.

Auxiliary feedwater pumps have both safety and non-safety roles. The safety role is to supply feedwater to the steam generators when a unit trip occurs coincident with a loss of off-site power and when dissipation of reactor decay heat is required. More generally, auxiliary pumps are to operate when the main feedwater system is unavailable and heat removal is required. The non-safety role is operation during plant start-ups and shut-downs, or when only a small amount of feedwater is required.

Technical Specifications require in-service inspection and testing of auxiliary feedwater pumps in accordance with Section XI of the ASME Boiler and Pressure Vessel Code. Technical Specification testing is oriented toward operational readiness determinations.

Section XI requires measurements of inlet pressure, pressure differential across the pump, flow rate, and bearing temperature. These parameters are to be measured while the pump is operating at specific conditions, and the test quantities are to be compared with reference values.

The ASME Code Sect. XI covers surveillance intervals as well as test requirements. It specifies that pumps be tested nominally every three months. However, monthly tests are conducted to ensure on-demand performance.

FAILURE MODE AND CAUSE ANALYSIS

Failure mode and cause analysis is based on design details, operating requirements, experience as revealed by data bases, such as the Licensee Event Report (LER) file, Nuclear Plant Reliability Data System (NPRDS), In-Plant Reliability Data System (IPRDS), and Nuclear Power Experience (NPE), post-service examinations, and in-situ assessments. A failure mode is defined as the way a component does not perform a function for which it was designed (e.g., fails to actuate or leaks through the boundary). Three failure modes are defined for auxiliary feedwater pumps. These are failure to operate, failure to operate as required, and external leakage.

Failure to operate applies in two situations. The first is one where required driver torque is applied, but the rotor does not rotate. The second is power interruption by automatic tripping, such as by an overspeed trip in turbine-driven units. This includes the possibility of a true trip or one resulting from malfunction of the tripping device.

Failure to operate as required denotes failure to provide the required head-capacity pumping characteristic. It also denotes that critical parameter measurements (e.g., vibration, bearing temperature, delivered flow) are outside acceptable ranges. Although the pump can perform the design function and is, therefore, not failed, it is either repaired or replaced because it might fail in the immediate future.

Because the pump has to be taken out of service to repair the potential problem, these events are considered failures.

External leakage refers to escape of the contained medium from the component boundary. This failure mode pertains to leakage rates that indicate either impending loss of function or significantly reduce the flow delivered by the pump.

Failure causes of interest are proximate causes, that is, the final cause contributing to failure in each case. In addition, only causes associated with aging and service wear are addressed. Therefore, for the purposes of NPAR program studies, failure cause is defined simply as degradation (the presence of a defect) in a component that is the proximate cause of its failure (e.g., loss of lubricant, or loosening of a fastener).

Discussion of failure causes are enhanced by dividing pump assemblies into segments and component parts. The pump is divided into five segments as shown in Table 2, and major parts are listed under each.

Failure causes are listed by pump segment in Table 3, which also gives correlations to failure modes. Twenty failure causes are identified. These causes were ranked in importance according to three measures; these are frequency of occurrence, influence on operational readiness, and interaction consequences. The latter refers to one cause activating other causes. The overall ranking derived is given in Table 4; importance decreases with increase in assigned number. This overall ranking was used in guiding inspection, surveillance, and condition monitoring method selection. Note that the lowest ranking in Table 4 is 15 since ranking beyond this number is not meaningful.

The four highest ranked causes are: shaft seal deterioration, breakage; bearing wear, corrosion, breakage; binding between rotor and stationary parts; and impeller wear, breakage. Brief discussions of these are given here to provide examples of aspects considered in each case.

Shaft seals are typically packing which is contained within a stuffing box located near each shaft end. There is a disproportionately large number of shaft seal failures compared to other failure causes, and these failures are frequently accompanied by interaction consequences, such as water contamination of the lubrication systems. Shaft seal failures alone normally do not have a significant effect on pump operational readiness; they are associated with the external leakage failure mode.

Bearing failures have significant impact on operational readiness. Rolling contact bearings are subjected to normal fatigue wear and ultimate failure. However, premature bearing failure can result from non-aging and service wear influences, such as incorrect installation and maintenance, inadequate or excessive lubrication, moisture in the lubricant, ineffective seals, vibration during idle times, and flow of electric current through the bearing. False brinelling can also lead to failure.

Binding between the rotor and stationary parts can lead to total inoperability of a pump. Such binding results from the loss of clearance between impellers and nonrotating internal wear surfaces, balance drum to nonrotating bushing wear surface clearance, or thrust runner to bearing surface clearance. Factors which affect these internal clearances are pump starts and stops, overheating due to pump operation with a closed discharge and bypass flow valve or a closed suction valve, worn bearings, shaft misalignment, dirt or debris, or improper material hardness selection.

Impeller wear, breakage is ranked fourth in importance. Centrifugal pump impellers normally have wear surfaces on both the front and rear hubs. These surfaces together with the wear surfaces (or rings) of the non-rotating internals form internal seals that restrict leakage from stage to stage. This leakage increases as clearances between the surfaces increase. Vibration and the associated degradation also increase because of loss of bearing effect from water in the clearance spaces with increased clearance.

An additional cause of worn or broken impellers is loose impeller-to-shaft fit that results in fretting wear of the impeller bore or key and slipping of the impeller on the shaft. In addition, catastrophic impeller structural failures can be caused by hydraulically-induced resonance.

Low-flow testing can be a source of impeller damage and breakage. The disorganized flow that occurs at low-flow rates results in damage causing phenomena including cavitation, unstable head curve, pressure surges, and pulsations. Low-flow testing will be discussed in more detail later.

ISCM PARAMETERS AND METHODS

A review of currently used and developmental inspection, surveillance, and condition monitoring (ISCM) methods was conducted to identify methods and practices potentially useful for detecting aging and service wear degradation and developing trends. Potentially useful measurable parameters are listed in Table 5; these are paired with ISCM methods in Table 6.

An examination of Table 5 shows that there is not unique correspondence between failure causes and measurable parameters. Therefore, results obtained from the use of ISCM methods must be carefully analyzed and interpreted to differentiate between causes and to track degradation; this is illustrated by considering the informational content of vibration signals and the detailed interpretations required to use the information obtained. Measurable parameters are paired with ISCM methods in Table 6.

Since the role of ISCM methods is to provide bases for operational readiness determinations and assessing and tracking aging and service wear degradation, these factors strongly influenced the selection process. In addition, guidance was taken from the importance ranking in Table 4 and from Westinghouse experiences with a number of components. The latter include field experience with pumps similar to auxiliary feedwater pumps, reactor coolant pumps, heat exchangers, steam turbines, steam generators, reactor internals, and piping systems as well as laboratory tests on pumps and valves.

Methods recommended are those denoted by an asterisk in Table 6. To enlarge on the applicability of these methods, parameter versus degradation correspondence is shown in Table 7. The methods denoted plus thorough visual inspection, which includes pump disassembly, will provide needed bases for decision making regarding acceptability as well as maintenance, repair or replacement needs.

MAINTENANCE PRACTICES

Utility organizations currently use a combination of corrective and preventative maintenance. Corrective maintenance deals with the repair of a disabled machine, while preventative maintenance embraces routine servicing, inspection, and repair, or replacement, of equipment. The preventative maintenance actions are based on factors such as elapsed time, experience, vendor recommendations, codes and standards, and regulatory requirements.

Utility companies establish maintenance requirements for equipment that are based on vendor recommendations, NRC inspection and enforcement bulletins, circulars, notices, Institute of Nuclear Power Operations (INPO) recommendations, and other information provided by industrial organizations. Complete disassembly, followed by inspection and maintenance, is not normally done on pumps unless a problem develops which requires this action.

Surveillance and condition monitoring actions are defined by the plant technical specifications. These involve ASME Code Section XI testing, as described earlier. Acceptance criteria for pump head values are given by the Technical Specifications.

Predictive maintenance involves the use of methods for predicting degradation in combination with preventative maintenance practices. Since establishment of predictive capabilities through use of ISCM methods and practices is to be an outcome of the NPAR program, implementation of the recommendations provided will allow predictive maintenance plans to be developed and adopted. This can yield significant benefits in terms of reduced component downtime, forced outage avoidance, improved plant efficiency, and reduced maintenance costs.

Recommendations in this area are as follows. Inspection and surveillance practices recommended for use are listed in Table 8. These are separated into three categories: non-disassembly, condition monitoring, and disassembly. The first includes actions to be carried out on a regular basis; the second follows from ISCM recommendations described earlier; the third entails disassembly and detailed inspection. The last is a part of so-called periodic inspection, surveillance, and maintenance which is described below.

Maintenance practices to be used include regular inspection, surveillance and maintenance to assure machinery operational readiness. Pump disassembly is not required. The second combination is to be based on surveillance and condition monitoring information derived from use of the ISCM methods as defined above, coupled with appropriate maintenance actions. The third, termed periodic inspection, surveillance and maintenance, involves disassembly followed by inspection, repair, replacement, and cleaning of assemblies after a designated operating time. Interval guidelines are given in Table 9. Note that periodic inspection intervals are predominantly keyed to a period equal to three refueling outages. The overall inspection, surveillance and maintenance program embracing the three categories will require experience for optimization.

LOW FLOW TESTING

Although it is not directly a part of aging and service wear investigations, in-service testing is discussed briefly because it can be a major contributor to accelerated aging. Current practice with auxiliary feedwater pumps is to perform operational readiness testing using bypass recirculation lines. Such lines must be carefully sized to ensure that each pump operates at hydraulically stable conditions so that damage is avoided or minimized. The larger the percentage of best efficiency point (BEP) flow routed through the bypass line, the better it is for the pump. In well engineered pumps, 25 to 35% bypass flow is sufficient to avoid the dangerous range of off-design operating flows. However, for some pumps, any flow below 50% of BEP capacity may cause severe vibration.

It is generally required that each auxiliary feedwater pump be tested at monthly intervals to demonstrate acceptable on-demand response and continued operational readiness. In most plants, the auxiliary feedwater pump bypass line is a single line sized to bypass 5 to 15% of BEP flow. These lines were sized on the basis of limiting the temperature rise of the pump when operating in the testing mode.

Hydraulic instability is a term used to describe unsteady flow phenomena which became progressively more pronounced as a pump is operated farther away from the BEP. Hydraulic instability is manifested by flow recirculation in both the suction and discharge regions of an impeller stage when operating below the design flow.[1,3-7] This recirculation, or hydraulic stall, is the result of disorganization of the internal flow field which occurs in the impeller eye and exit as well as outside the impeller shroud and hub. (See Fig. 2 for nomenclature).[3] These disorganized flows can be significant contributors to deterioration (i.e., aging and service wear) of pump components because of resultant pressure pulsations and cavitation. The intensities of any pressure fluctuations accompanying such flows increase with pressure rise or energy level of the pump.

Since auxiliary feedwater pumps are relatively low-specific speed, low energy, high head-per-stage machines, degradation due to low-flow operation requires a greater length of time to cause catastrophic failure, on a relative basis, than in the case of other machines with higher power intensity and suction specific speed. In addition, degradation will be more difficult to detect on the basis of measurements taken during in-service testing. This follows from the fact that, in most plants, the bypass flow test provides neither the proper operating range of flow nor sufficient running time to comprehensively trend and assess vital signs.

Although failures attributed to low-flow testing have not been documented for auxiliary feedwater pumps, evidence that low-flow induced failures occur is provided by the results of a survey of feedpump outages.[8] This survey was based on input from 96 utilities covering 240 generating stations. It covered centrifugal pumps used in utility applications for both fossil-fueled and nuclear plants. Pump types included were boiler feed, nuclear feed, and feedwater booster pumps. A total of 1327 pumps was covered, with 1204 being feed pumps. Boiler feed pumps that are the same as those used as auxiliary feedwater pumps were included.

The results show that hydraulic instability, such as that associated with operation at less than BEP flow rates is a leading cause of failure. Hence evidence is available to indicate that low-flow induced failures of auxiliary feedwater pumps in nuclear power plants are to be expected.

It is recommended that bypass flow rates for auxiliary feedwater pumps be reconsidered based on the above considerations, and acceptable values be established by plant owners and operators in consort with pump manufacturers. In addition, the same considerations should be given to other pumps in engineered safety feature systems of nuclear power plants.

CLOSURE

Failure modes and causes associated with aging and service wear of auxiliary feedwater pumps were identified. A ranking of failure causes in terms of importance, based on frequency of occurrence, influence on operational readiness, and interaction consequences, showed that shaft seal and bearing related failures have the highest importance followed by binding between rotor and stationary parts and impeller and thrust balancer failure. Least important are casing and support related failures.

Twenty ISCM methods are considered; of these, 16 were recommended for detecting and tracking degradation. All are based on the current state of the art, and a number are in current use. Broadening of current vibration monitoring practices is required to meet the specifications given because use of proximity probes is recommended to measure shaft orbital displacement; it is also recommended that proximity probes be used to measure shaft axial displacement. Acoustic, or stress wave, emission monitoring is recommended to detect and monitor bearing, coupling, and gear wear on shaft seal deterioration. Overlap in monitoring method coverage will aid in cause differentiation.

Both regular inspection and periodic disassembly and inspection at specified intervals are to be important parts of the maintenance program. The recommendations include corrective and preventative maintenance practices, which are currently in use, and predictive maintenance. Capability for introducing predictive maintenance will be reached when the ISCM recommendations are adopted and monitoring is carried out.

Low-flow testing can cause accelerated aging. Therefore, plant owners and operators together with pump manufacturers should review current practice and make necessary changes to increase flow to reduce or eliminate hydraulic instability effects.

The third phase of the auxiliary feedwater pump investigation will provide needed criteria for decision making. Criteria both for accepting operating performance and for making maintenance, repair, or replacement decisions will be developed.

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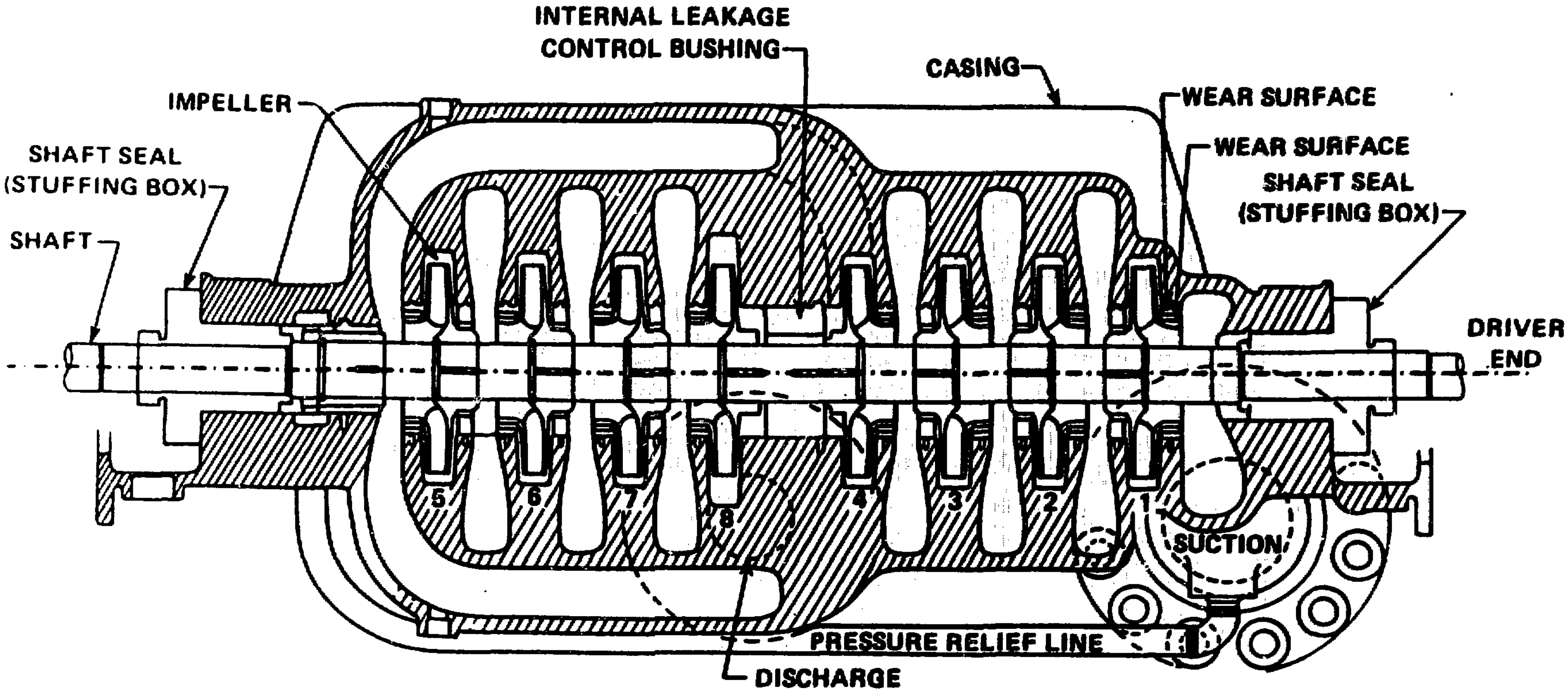

Fig. 1. Single-suction, opposed-impeller auxiliary feedwater pump.

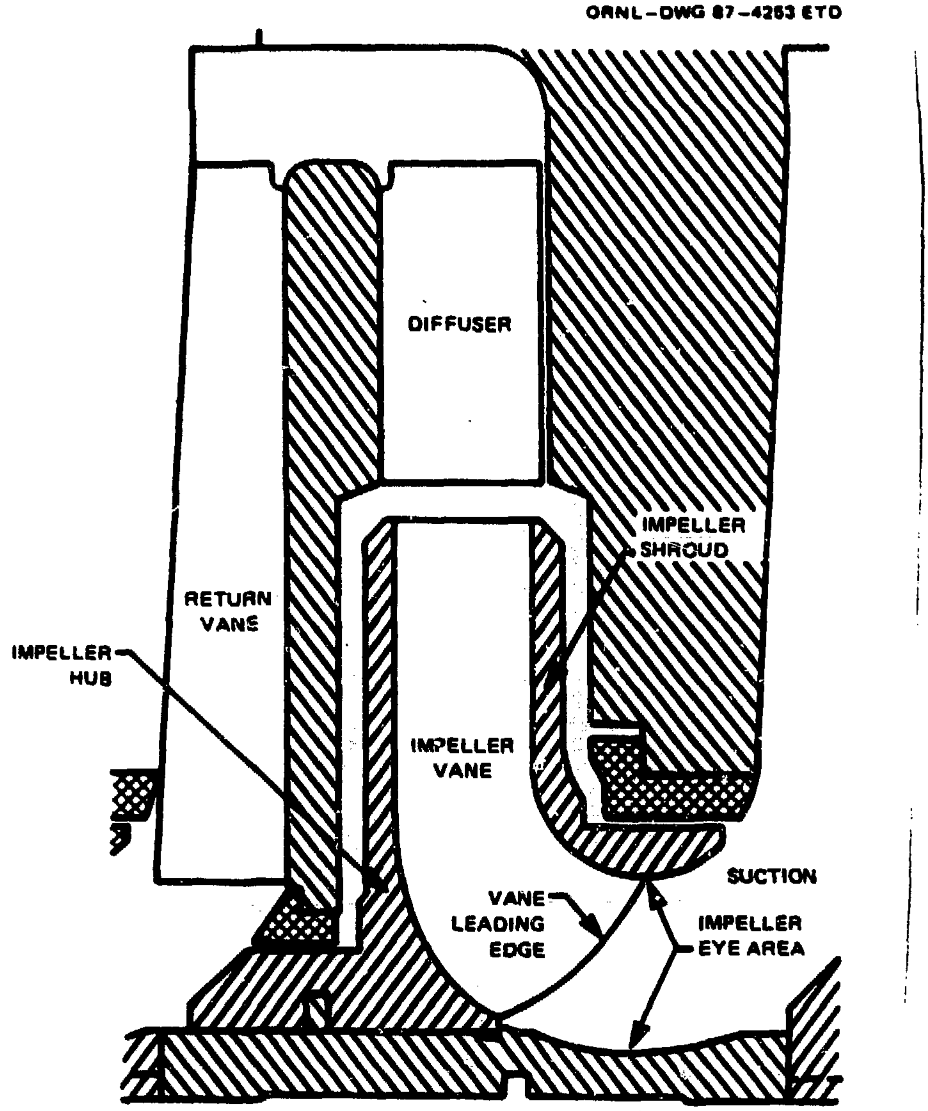

Fig. 2. Pump stage terminology
(Diffuser-type discharge chamber)

Table 1. Examples of typical auxiliary feedwater pump BEP operating parameters

Power plant	Number of stages	Speed (rpm)	Flow (gal/min)	Suction (psig)	Discharge (psig)
TVA Sequoyah	5	3950	920	25	1120
TVA Sequoyah	9	3570	440	25	1252
North Anna 1 and 2	6	4200	735	−2.6	1216
North Anna 1 and 2	8	3560	370	−2.6	1216
TVA Watts Bar 1 and 2	6	3850	1000	10	1277
TVA Watts Bar 1 and 2	9	3577	500	10	1277
Seabrook 1 and 2	9	3577	500	10	1277
Shearon	9	4400	850	0	1270
Shearon	9	3550	425	0	1270
Ginna 1	10	3560	200	23	1475
Maine Yankee	5	4400	530	0	1095
Maine Yankee	8	3575	500	0	1095
Donald C. Cook Station	6	4350	900	25	1195
Donald C. Cook Station	8	3560	450	25	1195
Beaver Valley Station	8	3560	370	0	1165
Arkansas Power and Light Co.	9	3560	780	60	1172
Three Mile Island	8	3560	470	23	1128
Three Mile Island	6	4250	940	23	1128

Table 2. Pump segments and component parts

Pump segment	Parts
Rotating elements	Shaft Impellers Miscellaneous spacers Fasteners Thrust runners
Non-rotating internals	Diffusers or volutes Return channels Wear surfaces Fasteners
Pressure-containment	Upper casing Lower casing Fasteners Suction and discharge nozzles
Mechanical subsystems	Bearings Seals Thrust balancer Coupling Fasteners
Support	Base frame Fasteners

Table 3. Pump failure causes related to aging and service wear

Pump segment	Parts	Failure cause	Failure modes[a] 1	2	3
Rotating elements		Binding between rotor and stationary parts	X		
	Shaft	Shaft breakage	X		
	Impeller	Impeller wear, breakage		X	
	Thrust runner	Thrust runner wear, breakage	X	X	
	Fasteners	Fastener loosening, breakage	X	X	
Non-rotating internals	Diffusers or volutes	Structural damage to stationary vanes (diffuser or volute)		X	
	Wear surfaces	Wear-surface wear, erosion, corrosion, seizing	X	X	
	Fasteners	Fastener loosening, breakage		X	
Pressure containment casing	Casing	Leak at casing split			X
		Leak at casing rupture disk			X
	Suction nozzle	Suction nozzle leak, breakage			X
	Discharge nozzle	Discharge nozzle leak, breakage			X
	Fasteners	Fastener loosening, breakage			X
Mechanical subsystems	Bearings	Bearing wear, corrosion, breakage	X	X	
	Shaft seals	Shaft seal deterioration, breakage		X	X
	Thrust balancer	Thrust balancer wear, galling, seizing	X	X	
	Coupling	Coupling wear, breakage	X	X	
	Fasteners	Fastener loosening, breakage		X	
Support	Base frame	Base frame breakage		X	
	Fasteners	Fastener loosening, breakage		X	

[a]Failure mode designation

1 — Failure to operate
2 — Failure to operate as required
3 — External leakage

Table 4. Pump failure causes attributed to aging and service wear ranked in overall terms of importance[a]

Pump segment	Parts	Failure cause	Ranking
Rotating elements		Binding between rotor and stationary parts	3
	Shaft	Shaft breakage	7
	Impeller	Impeller wear, breakage	4
	Thrust runner	Thrust runner wear, breakage	12
	Fasteners	Fastener loosening, breakage	8
Non-rotating internals	Diffusers or volutes	Structural damage to stationary vanes (diffuser or volute)	15
	Wear surfaces	Wear-surface wear, erosion, corrosion, seizing	6
	Fasteners	Fastener loosening, breakage	11
Pressure containment casing	Casing	Leak at casing split	13
		Leak at casing rupture disk	
	Suction nozzle	Suction nozzle leak, breakage	
	Discharge nozzle	Discharge nozzle leak, breakage	
	Fasteners	Fastener loosening, breakage	
Mechanical subsystems	Bearings	Bearing wear, corrosion, breakage	2
	Shaft seals	Shaft seal deterioration, breakage	1
	Thrust balancer	Thrust balancer wear, galling, seizing	5
	Coupling	Coupling wear, breakage	10
	Fasteners	Fastener loosening, breakage	9
Support	Base frame	Base frame breakage	
	Fasteners	Fastener loosening, breakage	14

[a]Failure cause ranking is based on (1) frequency of occurrence, (2) interaction consequences, and (3) influence on operational readiness.

Table 5. Failure causes and measurable parameters to be considered in an auxiliary feedwater pump ISCM program

Pump segment	Parts	Failure cause	Measurable parameters
Rotating elements		Binding between rotor and stationary parts	Rotational torque, appearance, motor current, steam flow, speed, wear surface and critical fit clearance
	Shaft	Shaft breakage	Rotational torque, appearance, developed head, delivered flow, motor current, steam flow, speed, vibration, surface indications, dynamic pressure
	Impeller	Impeller wear, breakage	Rotational torque, appearance, developed head, delivered flow, motor current, steam flow, speed, vibration, balance return line flow, noise, wear surface and critical fit clearance, surface indications, dynamic pressure
	Thrust runner	Thrust runner wear, breakage	Rotational torque, appearance, motor current, steam flow, speed, vibration, temperature, axial position, surface indications, noise
	Fasteners	Fastener loosening breakage	Rotational torque, bolt torque, motor current, steam flow, vibration, speed, axial position, dynamic pressure
Non-rotating	Diffusers or volutes	Structural damage to stationary vanes (diffuser or volute)	Appearance, developed head, delivered flow, vibration, noise, dynamic pressure
	Wear surfaces	Wear-surface wear, erosion, corrosion seizing	Rotational torque, appearance, developed head, delivered flow, vibration, axial position, balance return line flow, wear surface and critical fit clearance, noise, dynamic pressure
	Fasteners	Fastener loosening, breakage	Bolt torque measurement, appearance, vibration, noise

Table 5 (continued)

Pump segment	Parts	Failure cause	Measurable parameters
Pressure containment casing	Casing	Leak at casing split	Appearance, leakage rate
Mechanical subsystems	Bearings	Bearing wear, corrosion, breakage	Rotational torque, appearance, motor current, steam flow, speed, vibration, temperature, lube oil purity, axial position, wear surface and critical fit clearance, noise, dynamic pressure
	Shaft seals	Shaft seal deterioration, breakage	Rotational torque, appearance, temperature, vibration, leakage rate, wear surface and critical fit clearance, noise, dynamic pressure
	Thrust balancer	Thrust balancer wear, galling, seizing	Rotational torque, appearance, wear surface and critical fit clearance, motor current, steam flow, developed head, delivered flow, vibration, axial position, balance return line flow, noise
	Coupling	Coupling wear, breakage	Rotational torque, appearance, motor current, steam flow, speed, vibration, noise
	Fasteners	Fastener loosening, breakage	Bolt torque, appearance, vibration, noise
Support	Fasteners	Fastener loosening, breakage	Bolt torque, appearance, vibration, noise
	Base frame	Base frame breakage	Bearing temperature, transmitted torque, noise, vibration, appearance, bolt torque

Table 6. Measurable parameters and their relative ISCM methods

Measurable parameters	ISCM methods[a]
Rotational torque	*Rotor binding inspection
Appearance	*Visual inspection
Motor current	Motor current monitoring
Steam flow	Steam flow monitoring
Speed	*Rotational speed monitoring
Wear surface and critical fit clearance	*Dimensional inspection
Developed head	*Pump pressure or developed head monitoring
Delivered flow	*Pump delivered flow monitoring
Vibration	*Rotor vibration monitoring
Surface indications	Liquid penetrant inspection
Balance return line flow	*Balance return line flow monitoring
Noise	*Audible noise inspection
	*Acoustic emission monitoring
Temperature	*Bearing temperature monitoring
	*Stuffing box temperature monitoring
Axial position	*Rotor axial position monitoring
Bolt torque	*Bolt torque inspection
Leakage rate	*Leakage rate inspection
Lube oil purity	*Lube oil analysis inspection
Dynamic pressure	Discharge dynamic pressure monitoring

[a]Selected methods denoted by asterisk.

Table 7. Parameter versus degradation correlation

Parameter	Degradation
Rotational torque	Rotor-stationary part binding
Audible noise	Rotor-stationary part rubbing or binding, rotating part wear
Motor current Steam flow	Rotor rubbing or binding, loss of efficiency due to wear
Rotational speed	Rotor-stationary part rubbing, binding
Wear surface and critical fit clearance	Rotating and stationary part wear, galling
Pump pressure or developed head	Overall machine health
Pump delivered flow	Overall machine health
Vibration	Wear of wear surfaces, impeller, bearings, coupling; loose fasteners
Balance return line flow	Internal clearance increase
Acoustic emission	Wear of rolling element bearings, coupling, and gears; shaft seal deterioration; and rotor rubbing
Bearing temperature	Bearing wear
Stuffing box temperature	Packing seal deterioration
Rotor axial position	Thrust balancer, thrust runner, or bearing wear
Bolt torque	Fastener loosening
Leakage rate	Shaft seal and casing split seal deterioration
Lube oil purity	Bearing wear
Discharge dynamic pressure	Passage clearance changes due to wear

Table 8. Recommended inspection and surveillance practices

Segment	Part	Non-disassembly	Condition monitoring	Disassembly
Rotating elements	Shaft	Rotor binding inspection	Speed, rotor vibration, developed head, delivered flow	Visual inspection, runout inspection, penetrant test for surface indications
	Impeller	Rotor binding inspection, audible noise inspection	Speed, rotor vibration, developed head, delivered flow, balance return line flow, acoustic emission	Visual inspection, bore measurement, wear surface clearance measurement, penetrant test for surface indications
	Thrust runner	Rotor binding inspection, audible noise inspection	Speed, rotor vibration, temperature, rotor axial position, acoustic emission	Visual inspection, penetrant test for surface indications
	Fasteners	Rotor binding inspection, audible noise inspection, visual inspection, bolt torque measurement	Speed, rotor vibration, rotor axial position, acoustic emission	Visual inspection, bolt torque measurement
Non-rotating internals	Diffusers or volutes	Audible noise inspection	Developed head, delivered flow, rotor vibration, acoustic emission	Visual inspection, penetrant test for surface indications
	Wear surfaces	Rotor binding inspection, audible noise inspection	Developed head, delivered flow, rotor vibration, rotor axial position, balance return line flow	Visual inspection, wear surface clearance measurement
	Fasteners	Rotor binding inspection, audible noise inspection, visual inspection, bolt torque measurement	Rotor vibration	Visual inspection, bolt torque measurement
Pressure containment casing	Casing	Visual inspection, leakage inspection		Visual inspection

Table 8 (continued)

Segment	Part	Non-disassembly	Condition monitoring	Disassembly
Mechanical sub-systems	Bearings	Rotor binding inspection, audible noise inspection, oil level inspection, oil leak inspection, oil purity	Speed, rotor vibration, temperature, rotor axial position, acoustic emission	Visual inspection, wear surface clearance measurement, rotor axial position measurement
	Shaft seals	Visual inspection, leakage inspection, audible noise inspection	Rotor vibration, temperature, acoustic emission	Visual inspection
	Thrust balancer	Rotor binding inspection, audible noise inspection	Rotor vibration, developed head, delivered flow, rotor axial position, balance return line flow, acoustic emission	Visual inspection, wear surface clearance measurement
	Coupling	Rotor binding inspection, audible noise inspection, lubrication, leak inspection	Speed, rotor vibration, acoustic emission	Visual inspection
	Fasteners	Rotor binding inspection, audible noise inspection, bolt torque measurement	Rotor vibration	Visual inspection, bolt torque measurement
Support	Fasteners	Visual inspection, rotor binding inspection, audible noise inspection, bolt torque measurement	Rotor vibration	Visual inspection, bolt torque measurement

Table 9. Periodic inspection, surveillance, and maintenance interval guidelines

Pump segment	Parts	Interval (refueling outages)
Rotating elements	Shaft	3
	Impellers	3
	Thrust runner	3
	Fasteners	3
Non-rotating internals	Diffusers or volutes	3
	Wear surfaces	3
	Fasteners	3
Pressure containment casing	Casing	3
	Suction nozzle	-
	Discharge nozzle	-
	Fasteners	3
Mechanical subsystems	Bearings	1/3[a], 3
	Shaft seals	3
	Thrust balancer	3
	Coupling	3
	Fasteners	3
Support	Fasteners	1-2

[a]Oil analysis (6 month interval).