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LOW-FLOW OPERATION AND TESTING OF PUMPS IN NUCLEAR PLANTS*

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ABSTRACT

Low-flow operation of centrifugal pumps introduces hydraulic instability and other factors that can cause damage to these machines. The resulting degradation has been studied and recorded for pumps in electric power plants. The objectives of this paper are to (1) describe the damage-producing phenomena, including their sources and consequences; (2) relate these observations to expectations for damage caused by low-flow operation of pumps in nuclear power plants; and (3) assess the utility of low-flow testing.

Hydraulic behavior during low-flow operation is reviewed for a typical centrifugal pump stage, and the damage-producing mechanisms are described. Pump monitoring practices, in conjunction with pump performance characteristics, are considered; experience data are reviewed; and the effectiveness of low-flow surveillance monitoring is examined. Degradation caused by low-flow operation is shown to be an important factor, and low-flow surveillance testing is shown to be inadequate.

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1. INTRODUCTION

This paper is an outgrowth of studies on auxiliary feedwater pumps that were conducted under the Nuclear Plant Aging Research Program sponsored by the U.S. Nuclear Regulatory Commission. These studies led to a review of low-flow operation and testing of centrifugal pumps and their consequences; the results are the basis for the discussions herein.

A centrifugal pump is designed for best performance at a specific combination of capacity, head, and speed, that is, the best efficiency point (BEP). At the design or BEP flow rate, the fluid motion is compatible with the physical contours of the hydraulic passages and is therefore well-behaved. However, careful consideration must be given to the operating range for a given application to minimize undesirable effects of off-design flows.

During operation and testing, flow rates can be on the order of 5 to 15% of BEP flow. These flow rates stem from system bypass lines being sized to limit the temperature rise of the pump without regard to hydraulic behavior effects. Deterioration resulting from low-flow hydraulic instability influences was not considered until relatively recently.

For reduced flow, the larger the percentage of BEP flow, the better it is for the pump. In well-engineered pumps, 25 to 35% is sufficient to avoid the dangerous range of off-design operating flow. However, for some pumps, any flow below 50% of BEP capacity may cause severe vibration.

In this paper, the effects of low-flow operation on hydraulic behavior are examined; damage-producing mechanisms and resulting pump degradation are discussed. Centrifugal pump operating experience is summarized, and important aspects of surveillance testing for determining machine health are reviewed.

Pump performance characteristics and the types of degradation incurred must be recognized when designing an effective surveillance program. In addition, hydraulic instability can complicate the data interpretation process. These factors preclude significant reliance on low-flow surveillance testing for operational readiness determinations.

2. LOW-FLOW DEGRADATION

Hydraulic instability is a term used to describe unsteady flow phenomena that become progressively more pronounced as a pump is operated farther away from the best efficiency point (BEP). The hydraulic instability is manifested by flow recirculation in both the suction and discharge regions of an impeller stage when operating below the design flow.[1-5] This recirculation, or hydraulic stall, is the result of disorganization of the internal flow field that occurs at the impeller eye and exit as well as outside the impeller shroud and hub. (See Fig. 1 for nomenclature.[1]) These disorganized flows can be significant contributors to deterioration (i.e., aging and service wear) of pump components because of resultant cavitation, pressure pulsations, unbalanced forces, and vibration. The intensities of any pressure fluctuations accompanying such flows increase with pressure rise or energy level of the pump.

Hydraulic instability associated with low-flow operation can result in cavitation erosion; unstable head-flow characteristics; breakage of impellers, shafts, and cutwaters or diffuser vanes; failures of seals, thrust bearings, and axial thrust balancing devices; and vibration failures. Vibration failures can also result from such things as interactions between pump and driver, foundation, or piping; design deficiencies; or control valve deficiencies. In addition, vibration can be a symptom of bearing failure, internal rubbing, or incipient seal failure.

Cavitation can be caused by entrained gases or flow recirculation in various regions of the pump while operating at off-design flow rates. It can also result from insufficient net positive suction head (NPSH) or combined insufficient NPSH and hydraulic instability. Cavitation, regardless of the source, can cause serious damage to the pump impeller, diffuser or volute, and return vanes.

A properly designed pump stage should have a head-flow curve that is continuously rising as the flow is decreased below the BEP value during constant speed operation. This increase should be continuous with decreasing flow down to recirculation flow, as a minimum. The pump minimum flow should be higher than the onset of system instability however. When the head curve contains a droop or exhibits a flat mid-portion, the head-flow curve is unstable, which is symptomatic of hydraulic instability. Parallel pump operation in the unstable region of the head-flow curve can be difficult.

Impeller breakage is a frequent result of problems such as vibration and hydraulic instability; fluctuating axial forces on impellers contribute to seal, bearing, and axial-thrust balancing device failure. Hydraulic instability, such as rotating stall and cavitation, and high induced vibrations at high frequencies are especially destructive.[6] However, design deficiencies can also be the cause of failure.

To give added perspective on hydraulic instability and its influences, a brief examination of flow behaviors in a pump stage is instructive. A single stage is shown in Fig. 1.

Several factors are associated with low-flow conditions that cause detrimental effects. At these conditions, all impellers develop flow instability in the form of flow reversals in the inlet and discharge regions; these reversals are called suction and discharge recirculation.[7] The attendant recirculation cells are depicted in the upper part of Fig. 2. Part of the liquid flows out of the outer portion of the inlet eye with high rotational velocity and reverses direction to join the main flow into the eye, giving rise to vortex formation. The resultant vortex action induces pressure surges and pulsations that cause rapid deterioration by cavitation erosion of impeller metal in the entrance region.[6]

Likewise, discharge recirculation creates surges and local deterioration by cavitation erosion at the impeller tips. Recirculation in the suction and discharge regions does not necessarily occur at the same flow rate.

Because pumps are designed for BEP flow, off-design conditions, such as low flow, cause a mismatch between the fluid flow angle and the physical angles built into the pump impeller and discharge diffuser or volute vanes. Low-frequency pressure pulsations therefore arise because of internal recirculation within the impeller as well as inside the diffuser or volute. This recirculation stems from flow separation from the metal surfaces and produces stalled areas that eventually wash out and again reform; the phenomena is termed "rotating stall" because of low-frequency cyclic rotation from passage to passage. The lower portion of Fig. 2 illustrates flow behavior inside an impeller.

The geometric relationship between the rotating impeller and the stationary components of the case influences: (1) the attenuation of discharge recirculation effects; (2) reduction of secondary flow circulation in the space between the impeller sidewalls and the casing; (3) the intensity of the vane-passing pulsations at the diffuser inlets or volute cutwaters; and (4) disturbance at the impeller inlet due to leakage return from the impeller eye wear ring clearance.[7] The gap between the impeller periphery and the diffuser vanes or volute cutwater is therefore very important.[5,8,9,10] When the clearance gap is too small, vortices caused by discharge recirculation will tend to collapse near the metal surfaces, causing cavitation.

The pressures acting on the impeller hub and shroud fluctuate; these fluctuations, in turn, give rise to fluctuating net axial forces on the impeller. The impeller will therefore suffer axial position instability, moving back and forth within limits imposed by the thrust bearing and the structure. These fluctuating forces contribute to failure, as noted previously.

Secondary flow circulation in the space between the impeller sidewalls and casing can be controlled by adjusting the clearance gap between the periphery of the impeller and the casing.[5,9] This reduces the unbalanced axial forces.

Cavitation surge can be produced by hydraulic instability, or low NPSH in combination with low-flow recirculation. The latter can be eliminated with sufficiently large NPSH. Cavitation surge also results in damaging pressure pulsations.

Because of increased recognition of the propensity for degradation as described above, operation at off-design conditions with emphasis on low-flow aspects is being given increased attention. Pump manufacturers have developed guidelines for establishing minimum flow limits on pump operation,[3,7] and studies are continuing. Electric Power Research Institute (EPRI) is currently conducting an extensive program on reliability and performance of multistage centrifugal pumps;[8] this program is expected to provide important information on low-flow operation. A study on the influence of surveillance testing at low flow on failure of emergency pumps in nuclear power plants was recently completed by EPRI.[11]

It was noted earlier that intensities of pressure fluctuations accompanying disorganized flows increase with pressure rise or energy level of the pump. Other factors that influence low-flow pump performance and minimum continuous stable flow (MCSF) are specific speed N_s and suction specific speed N_{ss}. The most critical factors are power intensity and N_{ss}.[3] The power intensity is a function of the brake horsepower (bhp) per stage; a power intensity factor F_{pi} can be defined by

$$F_{pi} = (\text{bhp/stage})/(\text{impeller diameter})^3 .$$

Small pumps having low F_{pi} are least likely to suffer damage from hydraulic instability.

N_s is a reference number that describes the hydraulic features of a pump, whether of the radial, semiaxial, or propeller type. The N_s is related to the pump speed N (rpm), the full-capacity flow Q (gpm), and the head per stage H (ft), with each being the BEP value; thus, $N_s = N(Q^{0.5})/H^{0.75}$. N_s affects flow separation from vanes and backflow in the impeller. The backflow driving force increases with increased N_s.

N_{ss} is used to categorize impeller suction design and performance characteristics and is related to the net positive suction head required (NPSHR) rather than H as in the case of N_s. Thus, N_{ss} is given by the following expression:

$$N_{ss} = N(Q_e)^{0.5}/(\text{NPSHR})^{0.75} .$$

The capacity Q_e is per impeller eye, and the quantities in the equation are BEP values. As N_{ss} increases, the impeller tends to become more susceptible to inlet vane flow separation.[3]

3. MONITORING

Pump characteristics. N_s not only influences low-flow pump performance, it is important in characterizing pumps;[12] Fig. 1 demonstrates this fact. Shown are sets of characteristic curves, that is, head H, efficiency E, and power input P, vs flow rate; efficiency (with flow rate as a parameter); and impeller shape (radial to axial flow) as functions of N_s. Reference 13 indicates that pumps used in engineered safety feature systems of pressurized water reactors (PWRs) have an N_s range from 741 to 3080; an examination of high- and low-pressure safety injection, containment spray, and auxiliary feedwater (AFW) pump data for a single PWR plant gave a N_s range from 1000 to 1850. The range of estimated maximum N_s values for pumps in engineered safety feature and safety-related systems of boiling water reactors (BWRs)[14] range from 500 to 4000. Cooper et al[9] gave N_s = 1503 as a typical value for feed pumps discussed in Ref. 15. Hence, for many centrifugal pumps in nuclear plants, it can be assumed that the characteristic curves will approximate those shown on the left and in the center of the upper portion of Fig. 3.

Characteristic curves for an electric-motor-driven AFW pump are given in Fig. 4. The value of N_s is 1174. Note that the characteristic curves tend to correspond to those shown on the left side of Fig. 3, with the head-flow curve being stable.

Pump degradation results in head-flow curves such as those shown in Fig. 4 being altered as shown schematically in Fig. 5(a). The degraded performance curve is depicted by the solid line that is based on the assumption of constant leakage between stages.[12] This assumption also yields the comparison of degraded vs nondegraded performance for high N_s pumps shown in Fig. 5(b). Compare the dashed curve of Fig. 5(b) with the H curve in the upper right of Fig. 3. The latter curve applies to predominantly mixed to axial flow pumps; the indications are that safety-related pumps with high N_s are fewer in number than those having intermediate N_s.

Monitoring Details. The results emphasize the importance of factoring details of centrifugal pump performance into the design of programs for detecting, tracking, and assessing aging and service-wear degradation. Measurements of pressure and flow at flow rates approaching shutoff do not allow meaningful assessment of degradation for pumps with performance curves like those shown in Fig. 5(a). However, it is important that flow as well as pressure measurement be taken at low flows because pressure and flow are essentially independent in such cases. This means that a zero flow condition could otherwise go undetected.

Operation at flow rates above MCSF is required to provide margin for avoiding failure. Reliable operation below this level is not possible.[9] Determinations of the highest flow rates at which off-design recirculating flows occur have been derived from test data.[3] These curves provide relationships between N_{ss} and percent BEP flow for MCSF. Considering the pump examples for one PWR plant cited previously, the MCSF is >30% in all cases. Generally, low-flow operation in nuclear plants is at rates much lower than 30%; flow rates $\leq$10% are often used.

Aging and service wear degradation can be difficult to detect and monitor on the basis of measurements taken during surveillance testing. 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.

Results of an extensive study on understanding and managing aging and service wear in AFW pumps are given in Refs. 2 and 16. Inspection, surveillance, and monitoring methods for detecting and tracking aging and service wear are discussed in detail, and recommendations are made. The recommendations, which are also applicable to other centrifugal pumps, include periodic disassembly and inspection as an essential element.

4. POWER PLANT OPERATING EXPERIENCE

Through EPRI-sponsored projects, a significant amount of information on centrifugal pump performance has been published. This helps to compensate for lack of information on pumps used in nuclear power plants. The most significant summary of data, from the standpoint of this paper, is given in Ref. 15, which gives results from a survey of feed pump outages.

This EPRI survey[15] covered centrifugal pumps used in both fossil- and nuclear-fueled electric power plants. The survey of outages is based on input from 96 utilities covering 240 generating plants; a total of 1327 pumps was covered, with 1204 being feed pumps. The feed pump can be categorized as horizontal or vertical, single or multistage, and low or high head. Pump stages were either diffuser or volute type; the casings were cast or forged; and the pump drivers were electric motors and turbines. Pump types included in the survey are boiler feed, nuclear feed, and feedwater (FW) booster pumps (see Table 1).

The pump types investigated were reduced to five basic frame sizes based on reference pump flow produced at a reference speed of 3570 rpm. To achieve this reduction, the following relationships were used. The reference flow is given by $Q_R = 3570\ (Q/N)$, where Q = design flow and N = design speed. The reference head H_R is given in terms of the design head H by $H_R = H\ (3570/N)^2$. The reference power absorbed per stage (HP_R) is related to the design power by $HP_R = HP\ (3570/N)^3$.

The frame sizes were designated A through E (see Table 2). The A-frame-size boiler feed pumps are also used as AFW pumps for PWR service and as special purpose nuclear pumps. The survey was not extended to that portion of the A-frame pumps, however. Table 3 summarizes the data from the survey.

Data from Ref. 15 were used along with estimates of average number of hours per outage to develop Table 4, which gives relative importance rankings of failures.[6] Cavitation, unstable head curve, impeller breakage, and vibration combine to provide the leading cause or symptom of failure. These elements generally result from hydraulic instability associated with operation at less than BEP flow rates. Hence, this table clearly illustrates the importance of detrimental effects resulting from low-flow operation. Further, since the pump population embraced by the survey includes a significant representation of nuclear-type pumps, the low-flow failure implications for these pumps are inescapable.

The EPRI study[11] on surveillance testing of standby pumps in operating nuclear power plants was to determine whether test-related failures were caused by some aspect of these tests and to identify corrective measures to minimize the occurrence of such failures. This study was instigated in response to concern by pump manufacturers that testing pumps at low flow - on the order of 10% of BEP flow - may lead to premature failure of packing, seals, and rotating element components as a result of higher vibration during low-flow testing. Instances of pump vibration during low-flow testing and of vibration-induced damage to pumps and valves have been reported at both BWR and PWR plants.

Both PWR AFW pumps and BWR residual heat removal service water (RHRSW) pumps were addressed. However, this study neither provides conclusive evidence against nor vindicates the use of low-flow testing practices. It does support, however, the expectation that low-flow test operation will lead to degradation and failure and concludes that prolonged operation of AFW pumps at very low flow (in the range of 10% BEP flow) can cause high vibration, which can manifest itself in bearing- and wear-related failures.

Reports on failures of centrifugal pumps in nuclear power plants include classic examples of deterioration induced by low-flow hydraulic instability. In May 1986, Susquehanna Unit 1 experienced loss of the emergency service water (ESW) system as a result of low-flow cavitation damage to the pumps (LER 86-021-00, May 20, 1986). The suction bell of one pump was damaged so severely that it was severed from the body. The impeller vanes of this pump also were eroded through the thickness.[17] Similar, but less extensive, damage was found in the other three ESW pumps. A later inspection of the RHRSW pumps also revealed similar cavitation damage in each case.

Inspection of the residual heat removal (RHR) pumps in the Vermont Yankee Plant was prompted by NRC Information Notice 86-39.[18] Through-the-wall impeller cracks were found in two pumps, and evidence of low-flow induced cavitation erosion was found in the impeller suction regions of all four pumps.[17]

A locked rotor condition occurred in an electric-motor-driven fire pump at the Haddam Neck Plant (LER-88-003-00, March 3, 1988). This condition resulted from damage to a brass bushing in a stuffing box. The damage was attributed to prolonged low-flow operation of the pump.

Low-flow degradation generally develops slowly, and, in the early stages, does not affect pump performance appreciably. Therefore, the damage produced is not easily detectable. Damage such as erosion, fatigue cracking, and nondisabling breakage in pump stages cannot be observed without disassembly of the pump. Surveillance examination of pumps, as usually practiced, thus leads to high probabilities that this type of degradation will go undetected until pump or system failure occurs and ability to perform the required safety function is lost.

5. CONCLUSIONS

Hydraulic instability from low-flow operation gives rise to degradation mechanisms that, if allowed to persist, will cause damage to the pump internals and eventually lead to failure. The intensities of the degradation mechanisms are functions of the energy per stage and the specific speed. Manifestations of hydraulic-instability-induced effects are cavitation erosion; unstable head-flow characteristics; breakage of impellers, shafts, and cutwaters or diffuser vanes; failures of seals, thrust bearings, and axial-thrust balancing devices; and vibration failures.

The deterioration that occurs develops slowly, and, in the early stages, changes in pump performance are not perceptible. Head and flow data are not reliable indicators of health because head vs capacity curves, in many instances, exhibit very little change at low flows (especially as shut-off flow is approached) because of degradation. Also, damage, such as erosion, cracking, and nondisabling breakage in pump stages, cannot be observed without pump disassembly and inspection. Finally, hydraulic instability can complicate the data interpretation process. These factors combine to preclude placing reliance on low-flow testing for operational readiness determinations and establish periodic disassembly and inspection as a necessary element in surveillance testing programs.

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Table 1. Pumps covered in survey

Type	Description
Boiler feed pumps	Horizontal, multistage, forged outer barrel, welded-on suction and discharge nozzles. Impellers can be in line or opposed (largest percentage in line). Diffusers and volutes equally favored for discharge chambers.
Nuclear feed pumps	Called reactor feed pumps in BWRs and steam generator feed pumps in PWRs. Usually single-stage, double-suction design. Some multistage units, forged casing, diffuser or double-volute discharge chamber.
Feedwater booster pumps	Almost all are horizontal, single-stage, double-suction, cast casing, single- or double-volute outer casing.

Table 2. Pump frame sizes[a]

Frame size	Reference pump flow (gpm)
A	Up to - 2,200
B	2,000 - 4,400
C	4,000 - 9,000
D	8,000 - 16,000
E	15,000 - up

[a]Source: Taken from Ref. 15.

Table 3. Failure rates of utility pumps

Pump Type No.	Pump type	Failures reported from: Total stations	Failures reported from: Total generating units	Number of failed pumps	Number of failures	Total pumps surveyed	Number of failures/ failed pumps	Failure rate (%)
1	Boiler feed	150	203	362	763	1044	2.1	34.7
2	Nuclear feed	20	30	61	133	160	2.2	38.1
3	FW booster	28	40	123	155	123	1.3	100.0
	Subtotal	178	240	546	1051	1327		

Source: Taken from Ref. 15.

Table 4. Pump failure rankings

Pump failures: Components or symptoms	Feedpump outages	Average hours outage[a]	Hours	Percent of grand total	Relative ranking
Cavitation, unstable head curve, impeller breakage, vibration	650	48	31,200	45	1
Seals	602	32	19,264	27.8	2
Wear rings	155	48	7,440	10.7	3
Axial balancing device	337	16	5,392	7.8	4
Shaft broken/damaged	77	48	3,696	5.3	5
Journal bearing	209	8	1,672	2.4	6
Thrust bearing	58	8	464	.57	7
			69,128		

[a]Estimated average hours per outage.

Source: Taken from Ref. 6 and based on data from Ref. 15.

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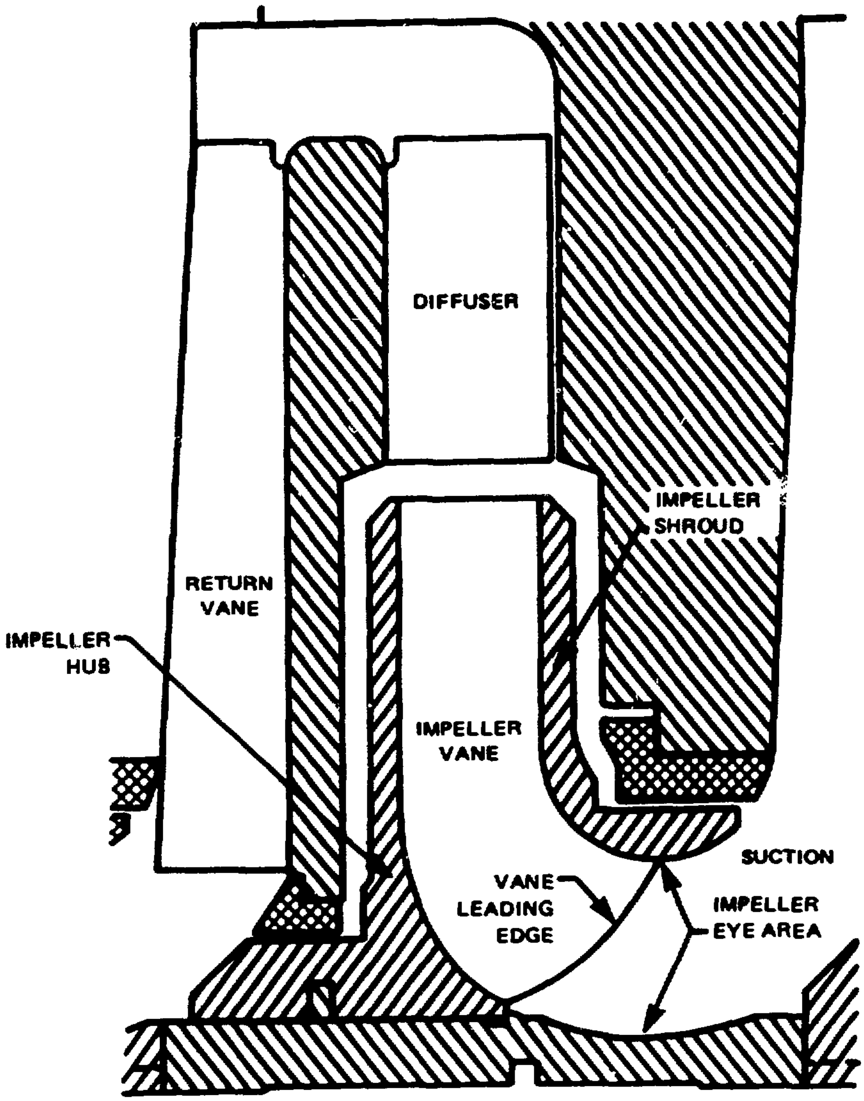

Fig. 1. Pump stage terminology (diffuser-type discharge chamber).

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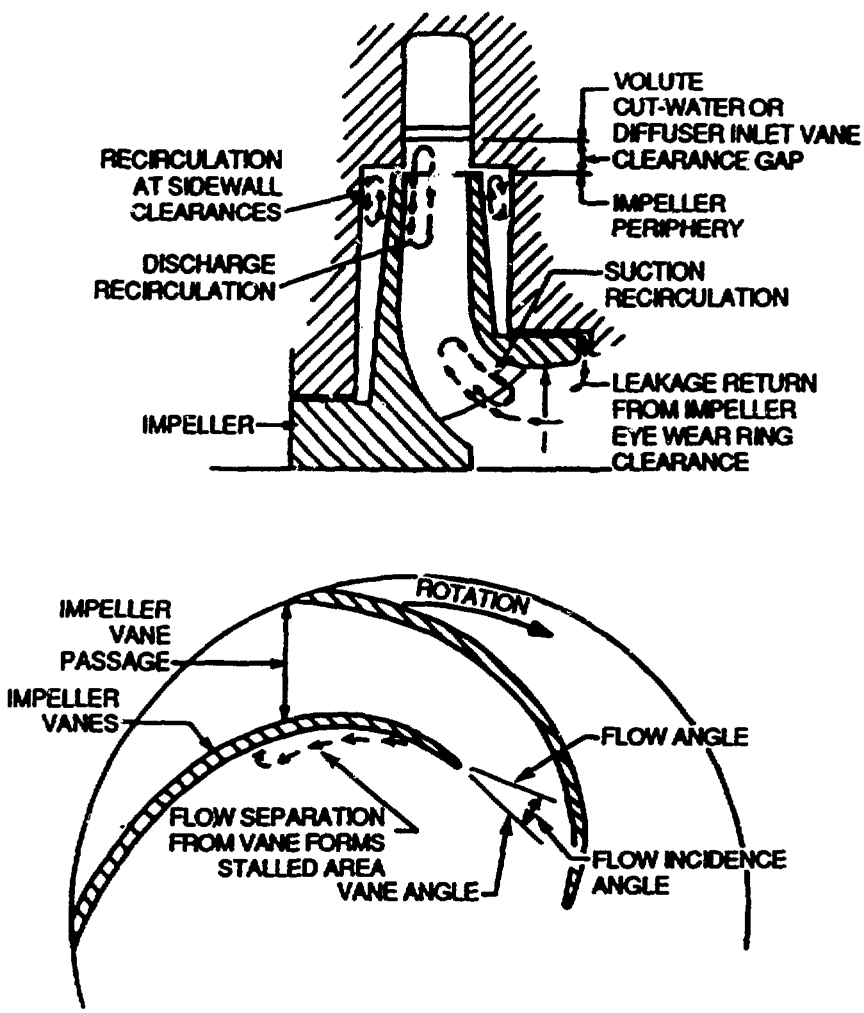

Fig. 2. Hydraulic instability flow phenomena. Redrawn with permission after Ref. 7.

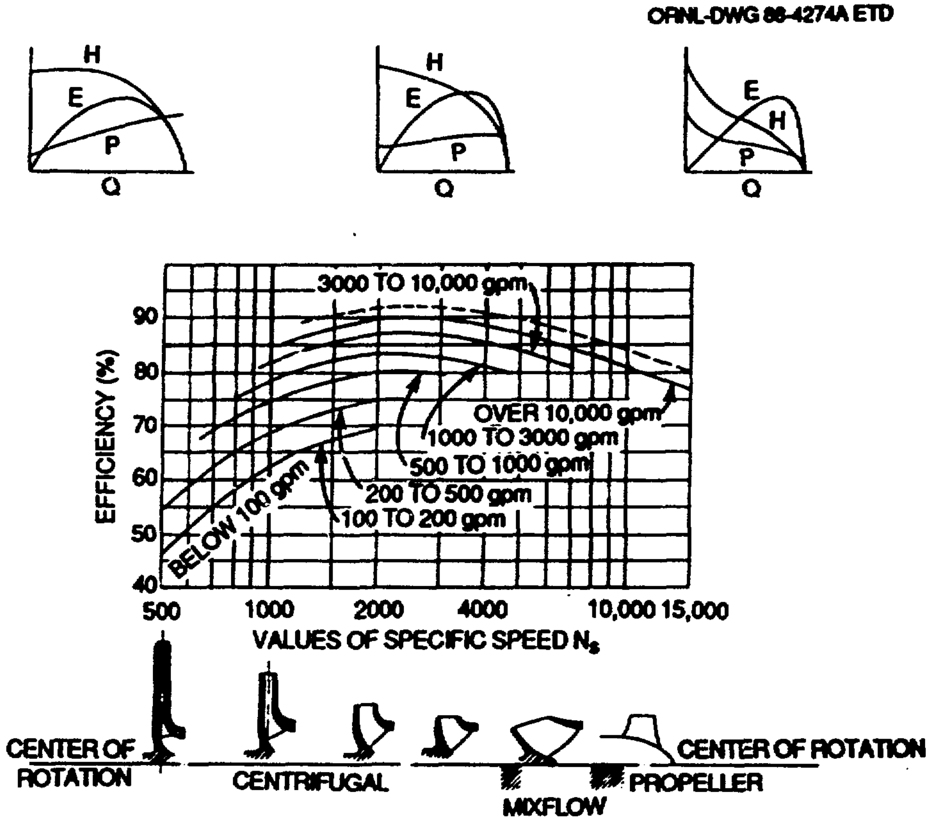

Fig. 3. Approximate relative impeller shapes and performance characteristic variations with specific speed. Reprinted with permission from McGraw-Hill, Ref. 12.

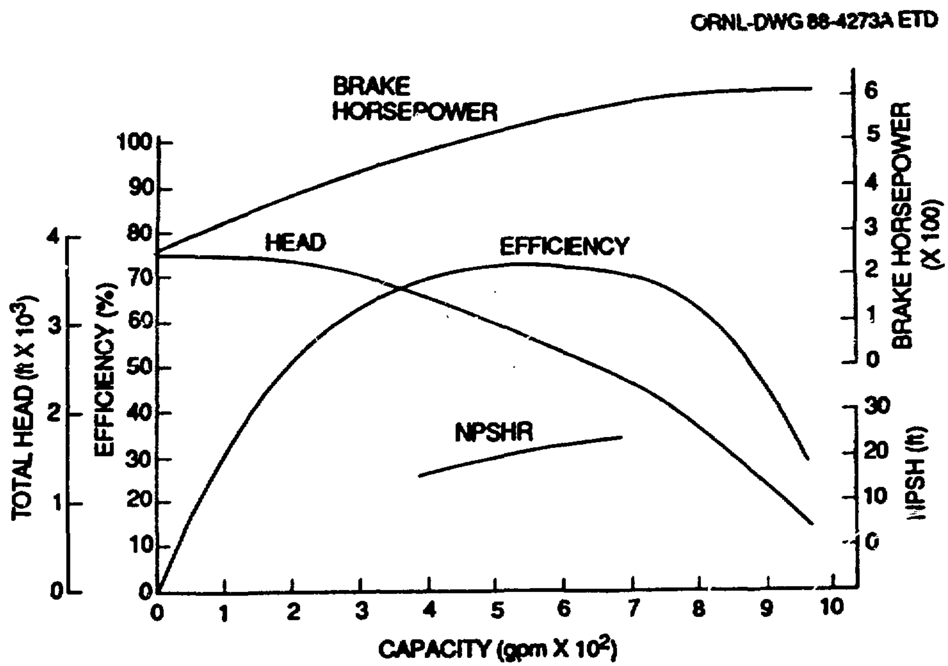

Fig. 4. Characteristic curves for AFW pump.

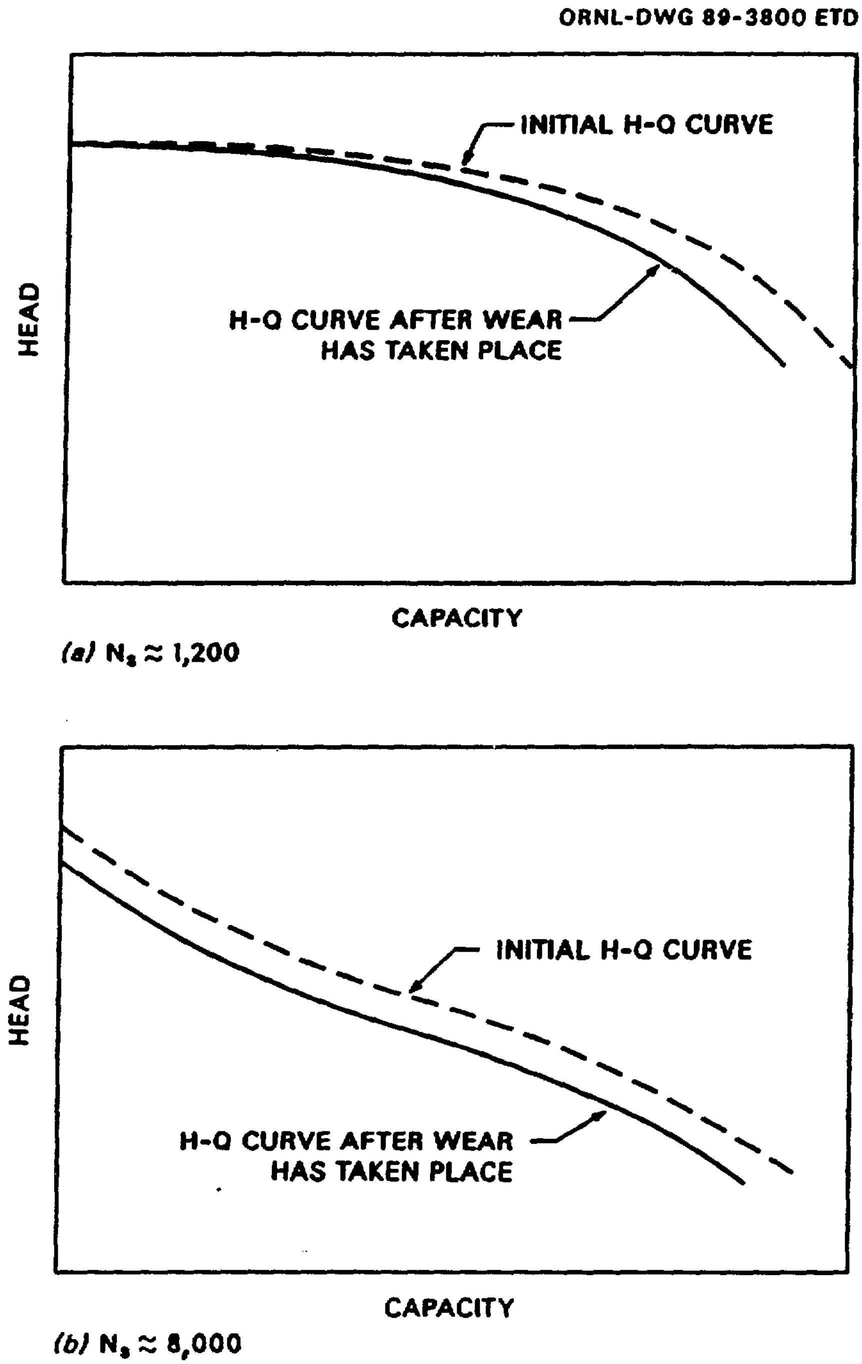

Fig. 5. Effect of wear on head-capacity curves.