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Detection and Effects of Pump Low-Flow Operation*

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ABSTRACT

Operating experience and previous studies performed for the Nuclear Plant Aging Research Program have shown that a significant cause of pump problems and failures can result from low-flow operation. Operation at low-flow rates can create unstable flows within the pump impeller and casing. This condition can result in an increased radial and axial thrust on the rotor, which in turn causes higher shaft stresses, increased shaft deflection, and potential bearing and mechanical seal problems.

Two of the more serious results of low-flow pump operation are cavitation and recirculation. Both of these conditions can be characterized by crackling sounds that accompany a substantial increase in vibration and noise level, and a reduction in total head and output capacity. Cavitation is the formation and subsequent collapse of vapor bubbles in any flow that is at an ambient pressure less than the vapor pressure of the liquid medium. It is the collapse of these vapor bubbles against the metal surfaces of the impeller or casing that causes surface pitting, erosion, and deterioration. Pump recirculation, reversal of a portion of the flow back through the impeller, can be potentially more damaging than cavitation. If located at the impeller eye, recirculation damages the inlet areas of the casing. At the impeller tips, recirculation alters the outside diameter of the impeller. If recirculation occurs around impeller shrouds, it damages thrust bearings. Recirculation also erodes impellers, diffusers, and volutes and causes failure of mechanical seals and bearings. This paper reports on a utility pump failure caused by low-flow induced phenomena.

ORNL has continued to investigate the results of low-flow pump operations by evaluating the types of measurements and diagnostic techniques that are currently used by licensees to detect pump degradation. A new, enhanced application of motor current and power data analysis has been developed that uses a signal comparison methodology to produce an instability ratio indicative of normal or unstable flow conditions. Examples of this type of low-flow detection technique are presented in this paper along with a brief discussion of the various types of technologies currently being used by licensees to evaluate pump operation and determine possible degradation.

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INTRODUCTION

The Nuclear Plant Aging Research (NPAR) Program has sponsored several studies to study the effects of low-flow operations on nuclear plant pumps. The Oak Ridge National Laboratory (ORNL) has just completed the latest NRC-funded study that is documented in the draft report, "Detection of Pump Degradation," NUREG/CR-6089. This research focuses on testing and surveillance methods currently implemented at domestic and overseas nuclear plants to detect pump degradation and assure the operability of safety-related pumps. The primary conclusions of this study reveal that:

1. The routine collection, trending, and analysis of pump vibration spectra is the single most powerful diagnostic tool for the detection of numerous types of pump degradation, such as misalignment, unbalance, looseness, and various bearing anomalies. If vibration spectral analysis was included into required ASME code testing of nuclear plant pumps, it may merit the reduction of the frequency of testing.

2. New advances in thermographic measurement equipment have enabled machinery analysts to detect anomalies not readily identified through other conventional diagnostic techniques.

3. The historical trending of lubricant analysis data can verify normal and abnormal machinery wear and degradation. The recent development of the on-site analysis device could allow maintenance organizations to increase the population of pumps benefiting from lubricant analysis and alleviate administrative burdens associated with off-site transfer and analysis of contaminated samples.

4. Numerous operational problems thought to be caused by pump degradation were found to actually be the result of motor degradation. Recent advances in non-intrusive motor monitoring techniques can be used to detect rotor bar degradation and also provide in-situ information on hydraulically unstable ranges of operation for a pump system.

5. The required monthly-to-quarterly technical specification/ASME testing using minimum flow loops may have created unstable flow configurations that contributed to pump degradation at some nuclear plants. A new analysis technique has been developed using motor current and power data that can assist in revealing a reliable range of pump operation under varying load conditions. The concept of an instability ratio, based on motor power data analysis, is presented to enable the determination of unstable system operational regimes.

This report discusses the possible consequences of low-flow operation and testing of pumps, and how nuclear plants may be able to ascertain if their current testing or operational procedures are inadvertently placing systems in unstable flow regimes that could cause pump degradation.

MINIMUM FLOW TESTING HISTORY

Many of the installed minimum flow lines in nuclear plants were originally intended by manufacturers to be used solely for pump starting and stopping. However, the required ASME code testing as well as the necessity of using specific pumps for plant startup and shutdown support has resulted in a considerable amount of operation at low-flow conditions. Historically, minimum flow capacity for centrifugal pumps was based on ensuring that the temperature rise through the pump would be less than 15°F. The thermodynamic problem that arises when a centrifugal pump is operated at extremely reduced flows is caused by the heating up of the liquid handled. The difference between the brake horsepower (BHP) consumed and the water horsepower developed represents the majority of the power losses in the pump; these power losses are converted to heat and transferred to the liquid passing through the pump. Although temperature rise is important to determining a pump's allowable minimum flow, the flow rate required to achieve hydraulically stable flow conditions may be a more limiting factor, particularly for the high-energy, high-suction specific speed pumps.

Experience has often demonstrated that destructive hydraulic forces, not temperature rise, limit safe minimum flow. Degradation can occur as the result of unstable flow conditions within the pump, which result in substantial radial and axial forces (static as well as dynamic) on both the stationary and rotating parts. Damage can be manifested in a number of ways, including impeller or diffuser breakage, thrust bearing and/or balance device failure due to excessive loading, cavitation damage on suction stage impellers, increased seal leakage or failure, seal injection piping failure, shaft or coupling breakage, and rotating element seizure.[1] In addition to the internal forces generated by unstable flow within the pump itself, interaction between the pump and the system at low-flow conditions can result in substantial surging and vibration that can affect not only the pump, but also other system components and supports.

In a previous research sponsored by the NRC,[2] ORNL and consultant personnel met with representatives of four of the major original equipment manufacturers (OEMs) of pumps who have furnished about 75% of the pumps used in safety-related systems in U.S. nuclear plants. There was consistent agreement among these OEMs that testing pumps under minimum flow conditions was of little value to demonstrating actual hydraulic performance. Two changes they recommended to existing in-service testing practices were:

1. Periodically conduct testing as close as possible to the pump's best efficiency point (BEP) and trend the results to verify that pump performance has not substantially degraded.

2. Minimize or discontinue the practice of routinely testing pumps at minimum flow conditions in order to demonstrate pump operability.

Proposed changes to the ASME O&M Code Subsection ISTB (OM-6) reflect the concerns emanating from minimum flow testing. In the proposed revised standard, testing on minimum flow loops would not be permitted except in rare cases.

LOW-FLOW DEGRADATION CASE HISTORY

In September 1991, Ingersoll-Rand issued a 10 CFR 21 report[3] on broken cast iron diffusers in multistage pumps used in auxiliary feedwater (AFW) applications at an eastern U.S. nuclear plant. Following a reactor trip, low flow to one steam generator was noted. Inspections found that pump diffuser vane pieces had lodged in a venturi, thereby restricting flow.

Subsequent inspections found that cavitation damage to the AFW cast iron diffusers was evident, particularly at the leading edge of the diffuser vanes. Damage was most evident at the first stage diffuser, although deterioration was also seen in other stages. There was also damage found at some areas of diffuser vane to shroud junctions, which was also believed to be the result of low-flow induced cavitation erosion. The utility reported that the pumps had historically been used only for testing and occasionally for hydrotests (and in response to automatic starts following reactor trips and other transients), but were not used in support of normal startup and shutdown activities. This finding prompted the utility to make inspections of all AFW pumps at all its nuclear plants. Additional cavitation-related damage was discovered in other AFW pumps.

Following extensive examination and metallurgical testing of the affected diffuser, Ingersoll-Rand reported that the primary cause of the breakage was cavitation damage at the leading edge of the diffuser vanes which resulted from accumulated operation of the pump at minimum flow. The NRC was notified that this type of degradation could affect AFW pumps at sixteen different nuclear sites.

After finding indications of similar damage in other pumps, Ingersoll-Rand issued the 10 CFR 21 report. It should be noted that in several of the instances in which damage was found, the pumps were "satisfactory," according to technical specifications and ASME Section XI required testing results. This could be anticipated in light of the fact that the pumps are tested at minimum flow conditions using Section XI measurement techniques that cannot detect internal degradation of this nature. Furthermore, utility personnel noted that they had acquired vibration spectral data at both minimum flow and full-flow conditions prior to the failure (as well as measuring hydraulic performance at both conditions), and their analysis of this data did not suggest pump degradation.

The following photographs depict some of the results of the metallurgical analyses. Figure 1 shows the "as received" damaged AFW pump first-stage diffuser vane plate assembly. Figure 2 is a photomicrograph of a section of a different first-stage AFW diffuser plate with two years of service. Shown are a cavitation-related cavity and a microcrack originating from the cavity along a graphite flake. Figure 3 is a photomicrograph of a fatigue crack in the vane transition region of a AFW pump diffuser plate taken from a different plant. The pump was in service for 10 years. Figure 4 is a photomicrograph of a fatigue crack in the vane transition region of an AFW pump diffuser that had been in service for 15 years.

Ingersoll-Rand recommended periodic inspection of the pumps for damage of the diffusers, and replacement of the cast iron parts with stainless steel, if necessary. They further recommended conducting periodic testing at higher flow rates, if possible.

In the aftermath of this 10 CFR 21 report, at least one plant has elected to modify the AFW pumps by changing the impeller/diffuser gap clearances. This type of design change has been successfully employed on a large number of high energy fossil power plant pumps. The potential benefit offered by this change, in lieu of or in addition to the material replacement change, is the fact that the root cause of the diffuser vane damage is being more directly addressed. This action has the benefit of not only mitigating cavitation damage, but also of reducing overall loading on the pump rotating and stationary parts, thereby minimizing other vibration-related problems that have resulted from low-flow operation.

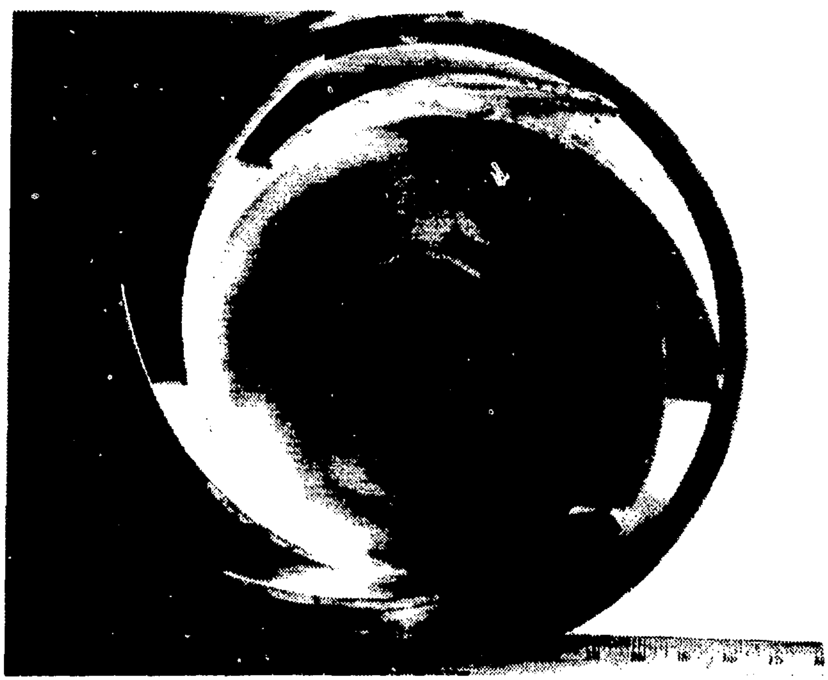

Figure 1. "As received" photograph of damaged AFW pump first-stage diffuser plate assembly.

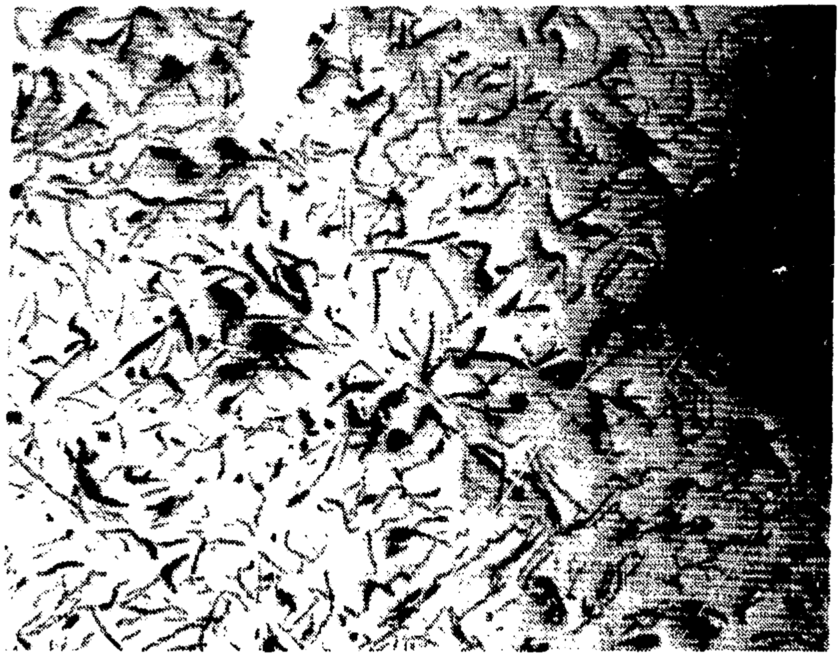

Figure 2. Photomicrograph of a cavitation induced fatigue crack at an AFW pump first-stage diffuser plate after two years of service. Unetched; magnification 50X.

Figure 3. Photomicrograph of a fatigue crack in the vane transition region of an AFW pump diffuser plate from another plant that had been in service 10 years. Unetched; magnification 50X.

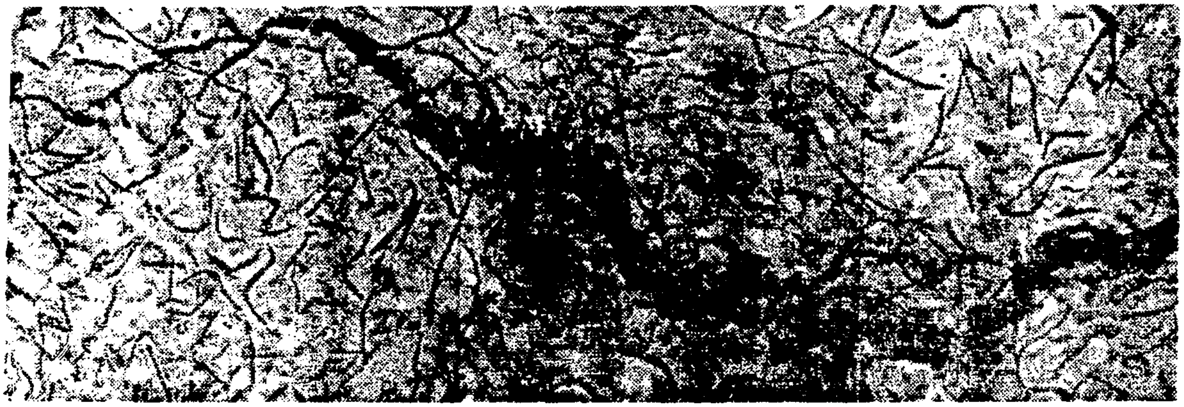

Figure 4. Photomicrograph of a fatigue crack in the vane transition region of an AFW pump that had been in service 15 years. Unetched, magnification 50X.

The phenomenon that caused these cracks is cavitation. Since it is doubtful that the resulting microscopic diffuser vane cracks would have manifested a suspect deviation that could have been discernible through conventional vibration spectral analysis, then to detect this type of degradation, analysis techniques must focus on ascertaining the onset of cavitation itself, or, at least, determining the ranges of unstable flow regimes that can produce such damaging phenomena. The following discussion presents two different methodologies pursued by ORNL researchers to identify unstable hydraulic conditions that could result in pump degradation.

USING POWER DATA ANALYSIS TO DETECT HYDRAULIC INSTABILITY

One objective of the pump degradation research has been to further study conditioned motor current and power data in hopes of developing and/or enhancing analysis techniques that might provide information and insight on abnormal or unstable pump operations. Previous laboratory pump and motor testing have yielded the observation that pump load changes produce power fluctuations in the motor. ORNL researchers have endeavored to determine the relationship between the changing, unstable hydraulic conditions that produce measurable power oscillations in the motor power.

Because motor input power compares almost linearly with motor load (particularly within a small load range), the motor can be used as an effective load transducer. When a pump's hydraulic load changes, the torque load on the motor shaft also changes, and as a result, the motor encounters a variation in its load. These permutations in motor load produce corresponding fluctuations in motor input power that can be quantified.

The instantaneous motor input power for each phase is:

(1) $P_\phi(t) = V_\phi(t) * I_\phi(t)$

where:

$P_\phi(t)$ = Instantaneous power for phase ϕ
$V_\phi(t)$ = Instantaneous voltage for phase ϕ
$I_\phi(t)$ = Instantaneous current for phase ϕ

The total instantaneous input power is the sum of all three phases:

(2) $P_{tot}(t)^* = P_{\phi a}(t) + P_{\phi b}(t) + P_{\phi c}(t)$

The product of the 60-Hz voltage and current ac waveforms results in a 120 Hz waveform with a dc offset; the calculated average of these values for all three phases defines the average input power. By continuously averaging the power over an adequate period (e.g., 1/60th of a second), a running average can be tabulated that realistically characterizes the entire data sample. This running average fluctuates as motor power changes. As noted above, the motor input power varies in response to the input motor load. Therefore, the level of fluctuation of motor input power is a measure of the stability of the motor's load.

Figure 5 shows four illustrations of this concept as it is applied to a pump and motor set operating in a test loop at ORNL. The figures represent normalized power, i.e., the calculated running average power divided by the long-term average for four flow conditions. All of the data was collected at the pump's motor control center by using current and voltage sensors. For simplicity, only one phase of the motor power was analyzed, and power was assumed to be symmetrical for the three phases. At 0 gpm ("shutoff"), relatively significant power fluctuations are experienced by the motor. At the shutoff condition, the pump is essentially stirring the water within or adjacent to the pump casing; there actually is flow within the pump, but no net flow within the system. Clearly, the flow profiles are skewed and unstable at this condition, and produce the observed power fluctuations. At 40 gpm, which is 20% of the manufacturer's best efficiency point (BEP), the normalized fluctuations have reduced slightly; this indicates there are still significant variations in power due to the unstable flow conditions. At 100% of the BEP (200 gpm), the normalized power signal is well defined and has the least overall variation in amplitude; the relatively low level of variation of the power signal indicates that the pump is operating in a relatively stable mode, as expected. At 340 gpm, which is 170% of the BEP, the power fluctuations become erratic again; the flow conditions are becoming increasingly unstable (approaching pump runout), and the instability is reflected in increased normalized motor power variation.

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* If the three motor phases are symmetrical, total power can be assumed to be three times an individual phase's power without incurring significant error.

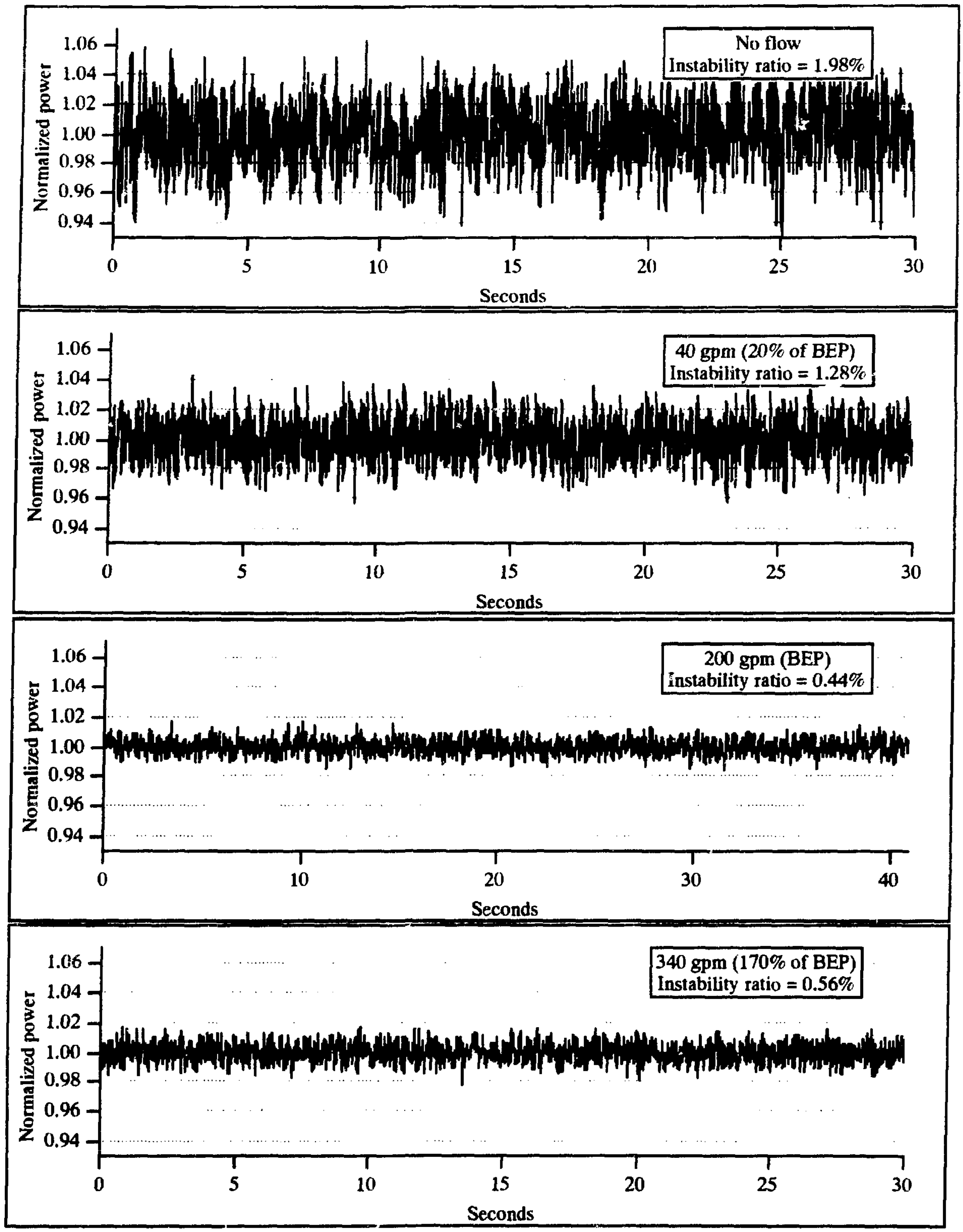

Figure 5. Normalized power at four flow conditions for test loop pump.

A single figure of merit that can be obtained from the normalized power is its standard deviation. ORNL researchers have named the standard deviation of the normalized power the "instability ratio." To further evaluate this quantity, additional testing was conducted on two different hydraulic systems: the test loop pump at ORNL which uses a 7.5 hp motor and a 50 hp motor-driven fire pump owned by a domestic utility. Data was acquired from the motor control center at each pump using current and voltage probes. Measurements were recorded at steady-state conditions that were achieved at various flow rates over the complete range of operation for both pumps.

As displayed in Figure 6, both pumps exhibit their most stable operating characteristics where the instability ratio is at its minimum. For these particular pumps, this occurs over an operating range of approximately 50% to 110% of the BEP. In these flow ranges, the instability ratio is less than 0.5% of the total power being input to the motor; therefore, this interval of flow rates represents the operation range where both pumps are operating stable. Also noteworthy is the shape of the instability ratio curve; it is generally flat from 50% to 110% of the BEP. This indicates a pump system that is relatively unaffected by a wide range of flow rates. For hydraulic applications that must handle a variety of flow rates and loads, the system dynamics would desirably be characterized by a flat instability ratio curve over a wide range of flow rates in order to achieve the maximum efficiency. In addition, the instability ratio may be useful in verifying the design performance specifications (such as BEP) of a particular "as installed" pump.

A final observation of the instability ratio curve is that it provides fairly clear indication of the approach to a range of unstable flow conditions as well as their comparative magnitude. There has been variation in industry practices with regard to acceptable minimum flow rate specifications for pumps. With reference to the data presented in Figure 6, the increasing gradient of the instability ratio curve is more pronounced at flow rates less than 40% of the BEP for the test loop pump and at flow rates less than 20% of BEP for the fire loop pump. This demarcation in slope is where unstable flow conditions are thought to begin for each pump. Extended operation of a pump at these lesser flow rates would possibly cause damage to its components. If these observations made for the tested pumps are found to the applicable to a broader pump population, it may be possible to relatively easily characterize the level of hydraulic load instability for various pumps and flow conditions. Such a characterization could provide a moderately clear indication of the flow regimes to avoid.

To summarize, preliminary studies on pump and motor set power data using instability ratio analysis have yielded the following insights:

1. Enable a measurement of the stable flow range for a specific pump and motor configuration.

2. Establish a stability figure of merit for comparison with other pumps.

3. Provide an alternative indication of relative pump efficiency.

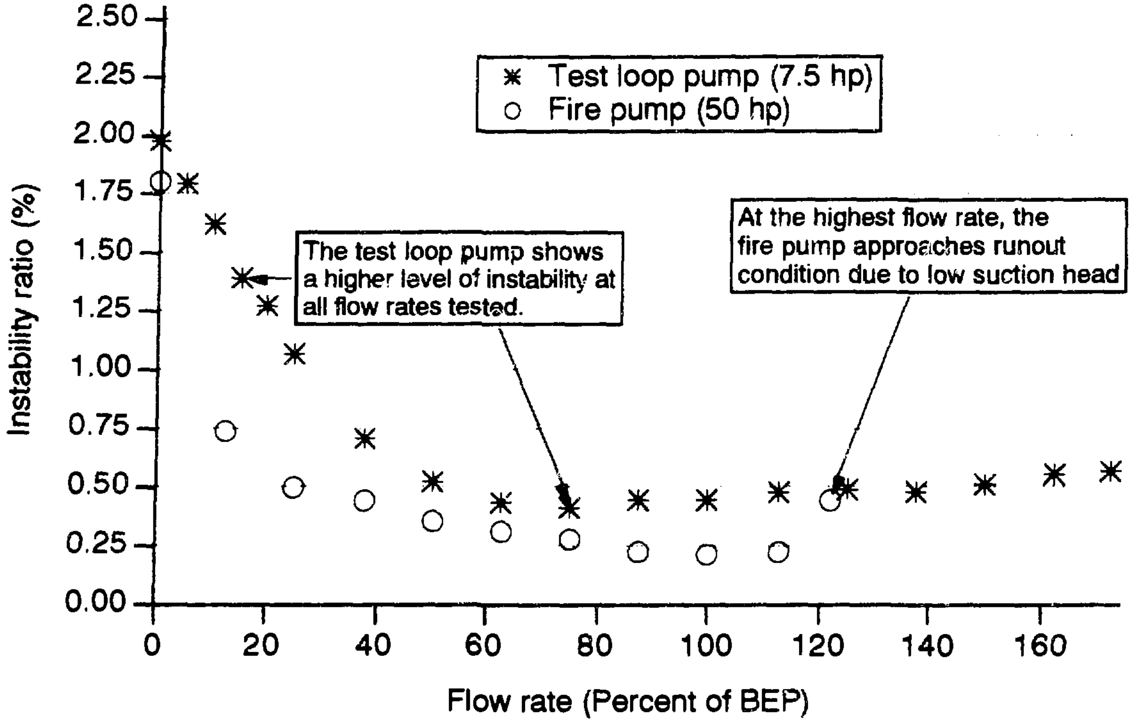

Figure 6. Instability ratio versus flow rate for two pumps

In addition, if preliminary tests are conducted on a particular system prior to planned modifications, such as additional valving or flow restricting devices, it may be possible to quantify the effects of these changes on the overall system's performance. Because the instability ratio is affected by changes in the system load, it is considered to be a sensitive indicator of hydraulic system changes.

CONCLUSIONS

Research into determining the causes and effects of pump degradation has yielded insight regarding damaging phenomena which are characteristic of low-flow pump operation that may be occurring during required ASME code testing on nuclear plant pumps. Testing pumps under low-flow or in minimum flow loops not only fails to provide an assessment of pump operability under off-design emergency conditions but also may prematurely age and degrade pump components. Recently proposed revisions to the ASME pump testing code recognize the deleterious effects of minimum flow testing and have recommended the elimination of this practice. Cavitation, a low-flow phenomenon, has been attributed for the damage of several auxiliary feedwater pumps at two different nuclear sites that have only been operated during required in-service testing via minimum flow loops.

Numerous types of pump degradation can be detected by the routine collection, trending, and analysis of pump vibration spectra. Recent revisions to the ASME testing code allow the use of velocity measurements instead of displacement measurements but make no mention of the benefits of vibration spectral analysis. Because there is a wealth of diagnostic information contained in spectral analysis, its incorporation into the ASME code could merit the reduction of the required testing schedule.

Operational problems once thought to be caused by pump degradation have been determined to be the result of motor degradation. Recent advances in non-intrusive motor monitoring techniques can be used to detect certain types of motor degradation as well as provide in-situ verification of unstable flow regimes. The concept of an instability ratio could provide a measurable assessment of actual minimum flow conditions as well as establish acceptable operational ranges to achieve optimum pump and motor efficiency.

REFERENCES

1. "Aging and Low-Flow Degradation of Auxiliary Feedwater Pumps," M. L. Adams, Proceedings of the Aging Research Information Conference, NUREG/CP-0122, Vol. 1, pp. 365-388, September 1992.

2. "Potential Safety-Related Pump Loss: An Assessment of Industry Data," D. A. Casada, NUREG/CR-5706 (ORNL-6671), NRC Bulletin 88-04, June 1991.

3. Letter to R. Fuhrmeister (USNRC) from G. Young (Ingersoll-Rand), *10 CFR 21 Reportability of A Potential Safety Hazard from Broken Cast Iron Diffuser Pieces in Auxiliary Feed Water Pumps*, September 19, 1991.