PUMP SYSTEM CHARACTERIZATION AND RELIABILITY ENHANCEMENT

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Abstract

Pump characterization studies were performed at the Oak Ridge National Laboratory (ORNL) to review and analyze six years (1990-1995) of data from pump systems at domestic nuclear plants. The studies considered not only pumps and pump motors but also pump-related circuit breakers and turbine drives (i.e., the pump *system*). One significant finding was that the number of "significant" failures of the pump circuit breaker exceeds the number of significant failures of the pump itself. The study also shows how regulatory code testing was designed for the pump only and therefore did not lead to the discovery of other significant pump system failures. Potential diagnostic technologies, both experimental and mature, suitable for on-line and off-line pump testing were identified. The study does not select or recommend technologies but proposes diagnostic technologies and monitoring techniques that should be further evaluated/developed for making meaningful and critically-needed improvements in the reliability of the pump system.

1. INTRODUCTION

The Nuclear Regulatory Commission (NRC)-sponsored characterization of pump failure data for the years 1990 through 1993, inclusively, was prepared at the Oak Ridge National Laboratory (ORNL) and issued in January 1996 [1]. An aging report on turbine drives was also prepared and issued by ORNL in June 1995 [2]. Following these studies, an update report [3] was prepared to characterize data for 1994 and 1995. Most recently, a report [4] on diagnostics was prepared to address technical needs evident in the two characterization studies.

The pump data characterizations consider pumps, pump motors, turbine drives, and pump-related circuit breakers and therefore encompass the entire pump *system*. The characterization made possible the realization (see Fig. 1) that the pump-related circuit breakers in this, their first data analysis, were exhibiting a failure rate (i.e., significant failures only) exceeding that of the pumps themselves [3].

The more recent characterization study showed how the turbine drives for pump systems, though small in number relative to motor drives, are exhibiting a very high failure rate. The study

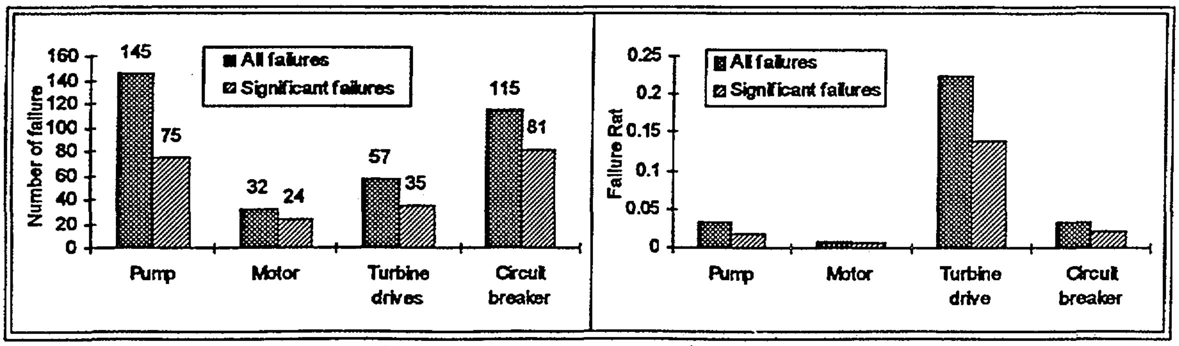

Fig. 1 Failure counts/rates for pumps, motors, turbine drives, and circuit breakers

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also shows how regulatory code testing, that was designed for the pump only, does not lead to the discovery of other significant pump system failures. These findings, coupled with the need to utilize risk-informed methods in development of programs for in-service testing (IST) of components, made clear the need for a pump system diagnostic study.

2. INDIVIDUAL COMPONENTS

2.1. Pumps

Pump failures involve degradation in a number of areas such as internals (e.g., impeller, wear rings) and the bearing. The pump failure data from the two year study is summarized in Table 1 according to plant type and significance.

Pump failures vary widely depending on the pump system. As indicated in Fig. 2, failures are mostly in high-usage systems such as the Emergency Service Water (ESW) system [3]. The system usage in the High Pressure Safety Injection (HPSI) system varies from plant to plant but, in general, usage is high in this system. Failures also vary significantly by age group however, the trend is different for PWRs and BWRs.

TABLE 1 PUMP FAILURES BY AFFECTED AREA AND SIGNIFICANCE

Affected Area	PWR		BWR	
	All	Significant	All	Significant
Internals	34	31	14	12
Bearing	22	13	7	7
Seal, packing	36	8	7	2
Shaft, coupling, keys	10	6	4	3
Other	31	8	5	0

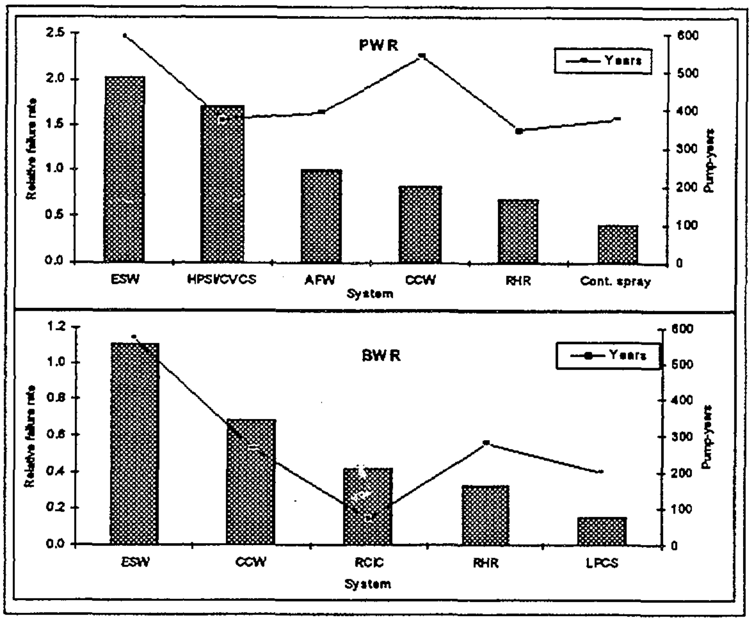

Fig. 2 Distribution of failures by System - PWR & BWR

There is little that needs to be said about motor failure data. The failure rate for motors is relatively low; when failures do occur they are generally severe, and the failures involve primarily bearing and stator degradation.

2.2. Circuit Breakers

As mentioned, circuit breakers experienced more significant failures than pumps themselves (i.e., 81 failures vs. 75 failures) based on the two year study [3]. In a high percentage of cases, the failures are quite severe in that they prevent the pump from performing its intended purpose. In fact, the four most frequent indicators of circuit breaker failure in the two year study are failure of breaker to close (32%), pump stops/spurious trip (13%), failure of the circuit breaker to charge springs (13%), and failure to trip (11%).

The failures are spread over many component areas as indicated in Fig. 3 and involve various types of electro/mechanical components. The failure mechanisms undoubtedly are also diverse. These considerations suggest that it will be a formidable challenge if corrective action or reliability improvement is sought.

2.3. Turbine Drives

The "turbine drive" is defined as an assortment of components (e.g., numerous steam valves and speed control devices) combined with the turbine drive to create a turbine drive *system*. Because of their small population, Code testing of pumps involved turbine drives in only 3% of the cases. The turbine drive failure rate is several times the rate for pumps and circuit breakers. This is of much concern since turbine drive pumps are so important in mitigating accidents involving station blackout failures.

3. PUMP SYSTEM TESTING AND INDUSTRY NEEDS

Significant failures are discovered through Regulatory or Code testing in pumps much more often than in other components of the pump system. In pumps, Code testing reveals 45% of the failures while it reveals only 13% of the failures for motors and 0% for turbine drives and circuit breakers. Even for the pump itself, the testing is of narrow scope. Code testing is effective only in detecting degraded hydraulic performance; its use of pump shaft vibration velocity to detect bearing failure is only effective in cases where bearing degradation is severe.

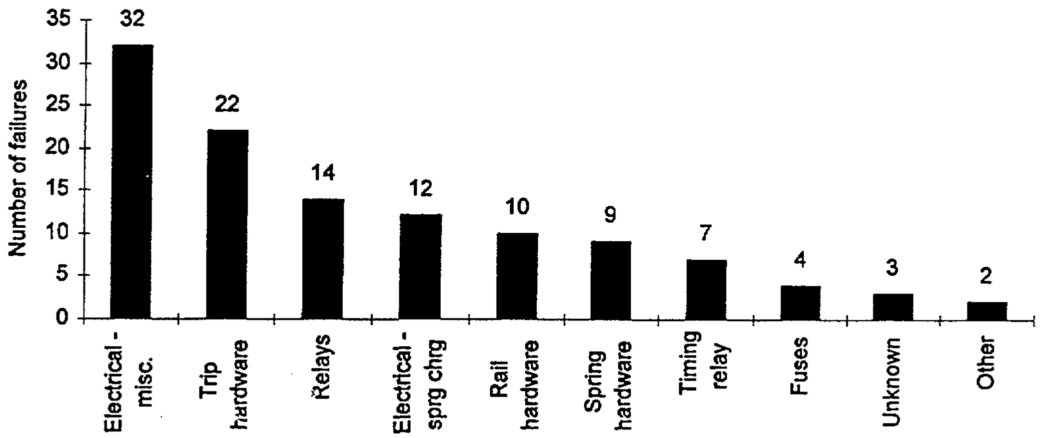

Fig. 3 Circuit breaker failures by affected area

Testing of pump bearing lubrication, motor stator megger tests, turbine drive speed regulation monitoring, maintenance/testing of circuit breakers per manufacturer's, and regulatory code testing of pump vibration and hydraulic performance have been performed in the nuclear industry since the beginning. Newer technologies such as pump motor current signature analysis have seen limited use at certain plants.

Many presently-used tests need to be upgraded or augmented to most effectively support IST. For instance, while the code-specified vibration tests that are performed on pumps as part of the surveillance testing are ineffective in detecting bearing problems, vibration spectral analysis, if performed correctly, *is* effective in the detection of bearing problems and other anomalies as well.

4.0 DIAGNOSTICS/MONITORING NEEDS

4.1 System or root causes of failures

In the diagnostics study [4], care was used not to analyze performance data without appropriate attention being given to system causes (i.e., root causes) of pump system degradation/unreliability. The usefulness of the study would be compromised if various tools for monitoring and diagnosing pump degradation were identified and eventually implemented while the root causes that lead to the degradation continue unchecked. Table 2 presents some potential system causes of certain failures. Examples are shaft misalignment, shaft imbalance, high vibration, poor pump/motor base integrity, and design weaknesses.

The importance of shaft alignment is known to be critical, however it is not possible to determine how many of the bearing and seal/packing failures are related to less-than-desirable precision in the alignment. Most of these system problems and/or root causes need to be precluded early on

TABLE 2 POSSIBLE ROOT CAUSES FOR SIGNIFICANT PUMP SYSTEM FAILURES

Component	Affected area	Possible root causes
Turbine drive	GV stem	Design (i.e., material selection), frequency of testing/low duty cycle resulting in a wet stagnant environment and corrosion
Circuit breaker Circuit breaker Turbine drive Motor	misc. electrical relays governor stator	Environmental stress, normal wear
Circuit breaker Turbine drive Circuit breaker Circuit breaker	trip-related HW trip-related HW Electrical - CS[a] spring hardware	Frequency/quality of maintenance, alignment, environmental stress
Turbine drive	GV	Corrosion, foreign material, normal wear
Pump Motor	bearing bearing	poor shaft alignment, hydraulic instability, high vibration,[b] oil contamination, loss of lubrication, normal wear
Pump	shaft/coupling	poor shaft alignment, hydraulic instability, high casing stresses, hydrogen embrittlement, high vibration[b]
Pump	internals	poor water quality, low suction pressure, off-design operation, normal wear
Pump	seal/packing	poor shaft alignment, hydraulic instability, normal wear

(a) CS = charging spring

(b) caused by a variety of factors, such as hydraulic and mechanical imbalances to the bearing (e.g., material deposition on impeller, cavitation, vane fracture), poor motor base integrity, and/or by stresses transmitted by attached piping (e.g., by the use of precision alignment) and also detected through monitoring or found by inspection (e.g., integrity of pump base plate) in order to reduce the number of significant failures.

4.3 **Diagnostic technology and monitoring techniques**

Diagnostic technology and monitoring techniques that are (1) capable of detecting degradation and (2) useful, in some instances, for trending the aging of components were identified at the completion of the above data analysis. The pump system diagnostic tools suitable for off-line use are presented in Table 3 and the diagnostic tools suitable for on-line use are presented in Table 4.

4.3.1 Timed response and electrical monitoring

Nearly all of the significant failures of the pump-related circuit breakers involved a failure to close or remain closed. The failures were due to ordinary loose fasteners, cracked parts, gummed-up linkages, lack of lubrication, incorrect adjustment, worn hardware, and failed electrical components such as solenoids, switches, relays, etc.

Timed response testing involves a measurement of significant response times in single- or multi-part systems. Response might be measured beginning with a command signal and ending with the completion of the commanded sequence. This sequence can be a sequence of events such as ones brought upon by the rotation of a cam and activation of switches.

Other types of monitoring that may be applied at the same time signals are being obtained for timed response are the monitoring of current, voltage duration, and transition waveforms. Monitoring current or voltage duration for a circuit breaker relay or solenoid can reflect the effort required to activate, force required for full travel, and whether it successfully made the full travel. Transition waveforms are useful as an indicator of degradation of electrical components such as switches and motors. Switch bounce, current-induced arcing, and surge current are examples of anomalies that are evident with such monitoring.

4.3.2 Motor stator testing methods

An important, new, off-line motor stator test for three phase motors is the measurement of inductive imbalance. Inductive imbalance in the windings can be caused by poor manufacturing or rewinding techniques, emerging shorts between turns, partially open windings, phase-to-phase current leakage paths, and internal high resistance joints.

The primary methods of testing the motor stator on-line are electrical signature analysis (ESA), partial discharge tests, and high frequency waveform analysis. ESA uses fast Fourier transform (FFT) analysis of the motor current waveform to identify degradation of the stator windings. This degradation can either be shorted windings or significant changes in the winding capacitance or insulation integrity.

The partial discharge test can be performed on motors that operate on over 4 kv. This test determines whether localized discharges are occurring in the stator windings due to degradation of the insulation.

The high frequency waveform analysis method (developmental) uses special characterization of high frequency spectra to determine the presence of stator winding degradation.

TABLE 3 OFF-LINE DIAGNOSTIC/MONITORING METHODS AND PARAMETERS/CRITERIA

Affected area	Methods	Parameters/Criteria
Circuit breaker misc. electrical Circuit breaker relays	Periodic servicing	Manufacturer's specifications
Motor stator	Megger test and polarization index	Established test parameters - finds moisture
	ac and dc high potential tests	Established test parameters - can cause damage
	Inductive imbalance[a]	Trend and monitor imbalance in windings
Turbine drive governor	Monitor lubrication (flyball)	General oil quality - no dirt/water
	None (electrohydraulic units)	Either failed or not failed
Circuit breaker trip-related HW Turbine drive trip-related HW Circuit breaker electrical - CS[b] Circuit breaker spring hardware	Inspection	Manufacturer's specifications
	Periodic servicing	Manufacturer's specifications
Turbine drive GV	Inspection of valve movement	Stem must move freely
Pump bearing Motor bearing	Inspect lubrication system	Visual
Pump shaft/coupling	Alignment check/monitor	Precision alignment
	Inspection of coupling	Visual - no significant wear
Pump internals	Disassembly and inspection	No erosion, foreign materials, out-of-spec conditions in rotating hardware or wear ring
Pump seal/packing	Inspection	Visual - no leakage while off-line

(a) Development required
(b) CS = charging spring

TABLE 4 ON-LINE DIAGNOSTIC/MONITORING METHODS AND PARAMETERS/CRITERIA

Affected area	Methods	Parameters/Criteria
Circuit breaker misc. electrical Circuit breaker relays Circuit breaker electrical - CS	Timed response Current Transition waveforms	Command to response times Current level as an indicator of effort (circuit breaker motor) Waveform trending as indicator of component degradation
Motor stator	ESA[a,b] (FFT of electrical signals) Partial discharge tests High freq waveform analysis[b]	Most effective on rotor, TBD for stator Detects discharges in winding (for over 4KV motors) Developmental
Turbine drive governor	Monitor speed regulation	Apply limit to or trend speed fluctuations
Circuit breaker trip-related HW Turbine drive trip-related HW Circuit breaker spring hardware	Timed response	Command to response (e.g., latch) times
Turbine drive GV	None	(Minor degradation is apparent when online)
Pump bearing Motor bearing	Vibration/acoustic spectra analysis Thermography Lubrication analysis	Established frequency and acceleration limits Temperature limit at bearing Profile of particle count and size, contamination, viscosity, water limits, etc.
Pump shaft/coupling	ESA (FFT of electrical signals) Standard vibration analysis	Analysis can detect shaft misalignment/crack Limits of imbalance/misalignment
Pump internals	ESA (FFT of electrical signals) or hydraulic performance test	Flow instability measured using ESA or std testing/trending of flow, head, and power parameters - use established criteria
	Vibration spectra analysis Vibration/acoustic	Established frequency and acceleration limits Established vibration limits in the pump casing
Pump seal/packing	Thermal measurement Leak detection	Temperature limit Visual or use of sensors, leakage rate limit pump dependent

(a) Development required

(b) ESA = electrical signature analysis

4.3.3 Speed regulation monitoring

The mechanical flyball drive governors may exhibit minor degradation in the speed regulation of the turbine and may be monitored for speed regulation under start-up, transients, changing pump loads, and, of course, steady state operation. (Not applicable to the electrohydraulic turbine drive governor.)

4.3.4 Electrical signature analysis

ESA was developed, in part, at the Oak Ridge National Laboratory (ORNL) [5,6] and was used in a series of tests where the pump motor acts as a transducer for diagnostics. The motor in certain cases is an effective transducer of torsionally-related load phenomena such as relative precision in shaft alignment, suction conditions, and variation in pump hydraulic conditions. Rotor degradation monitoring is also possible since the amplitude of slip-pole side bands of 60 Hz and harmonics trend upward with increased rotor degradation, especially in larger motors. The technology is not fully developed and absolute determination of the extent of rotor degradation cannot presently be made. However, any technology that shows much promise for the detection of monitoring of diverse phenomena in both the pump and motor merits high emphasis.

4.3.5 Vibration - standard and spectra analysis

Standard vibration analysis is a commonly used tool for the effective monitoring of pump rotor imbalance, misalignment, and instances of severe (i.e., energetic) cavitation. However, vibration analysis is <u>not</u> as effective as ESA for the detection of motor rotor electromagnetic imbalance.

Vibration spectra analysis is an effective tool for the detection of pump and motor bearing defects. Accelerometers are generally placed on the bearing housings however other options can be employed such as eddy current shaft position sensors to sense shaft deflection.

4.3.6 Acoustic monitoring

Acoustic monitoring may be used on pump casings as is performed in a pump monitoring program initiated in Japan in 1993 [5]. Acoustic energy is trended and a spectral analysis is performed and these are analyzed together relative to specific operating conditions (e.g., rotating speed, flow rate, electrical power). High frequency spectral energy and high noise floor are general indicators of cavitation using this technology.

4.3.7 Thermography

IR thermography is the collection and analysis of thermal images to ascertain various types of component degradation. IR inspections are an ideal complement to a comprehensive monitoring program because the technology is noncontacting and analysis results are quickly and easily obtained. One advantage of IR monitoring of bearings is that it can quickly detect early signs of overheating by observing the temperature rises on the rotating shaft.

Post maintenance testing procedures that utilize thermographic analysis have been particularly helpful in diagnosing problems such as packing being too tight, inadequate cooling flows to packing glands, and seal clearances. Data analysis software is then used to catalog the data and develop historical trends.

4.3.8 Lubrication analysis

This analysis methodology has made numerous technological advancements in the past two decades. Nuclear plants use different types of lubricant analyses based on component requirements, and the maintenance goals of the particular organization. The common dilemma is that most plants must send their oil samples, some of which are radioactive, off-site to be analyzed. This is a very expensive and record-intensive. However, recent innovations to the predictive maintenance industry have enabled industries to not only perform their own oil analysis on-site but to collect, store, trend, and correlate the results with vibration analysis data on personal computers [7,8].

At least one utility (Arizona Public Service) has recently found [9] that in-house oil analysis is a powerful enhancement that can be coordinated with vibration monitoring programs for a very significant overall advantage in bearing monitoring. A visual microscope method is used to detect abnormal wear debris in the larger-than-5-micron range (i.e., where most abnormal wear is). This precedes any possible degradation indications by vibration analysis and it is used to determine the frequency of testing by both methods. When both methods are used together in this way, sufficiently early knowledge and confidence of impending failure allows for scheduled repair and frequently the bearing damage is mild enough to facilitate root cause investigation. This is an important example of how the management of a monitoring program (i.e., the integration of testing programs and maintenance) is as important as the choices of technologies and monitoring methods that are employed.

Because of the broad scope of techniques available, the reader is referred to a NUREG [5] that provides a reasonable summary of the more common techniques as well as additional references. The more common techniques are:

Spectrographic analysis
Particle count
Spectrometals analysis
Ferrographic analysis techniques
- direct reading ferrography (DRF)
- analytical ferrography

IR analysis
Viscosity
Total acid number
Total base number

There are additional analytical techniques which are critical to the evaluation of the lubricant condition of reactor main coolant pumps. These pumps present a special problem for a lubricant analysis program, since they operate for extended periods without an opportunity for sample analysis and are generally radiologically contaminated. These additional analyses indicate the effective level of the lubricant additives. With this information, determination of the remaining life of the lubricant can be made. Analyses critical to the evaluation of main coolant pumps include: rotating bomb oxidation test (RBOT), which accelerates oxidation of the lubricant to determine the useful life of the lubricant's anti-oxidation additives, and an anti-rust test, which determines the ability of the lubricant to inhibit rust formation.

5.0 CONCLUSIONS

Aging in the pump system can be monitored and controlled using a combination of the diagnostic and monitoring technologies and techniques combined, of course, with corrective maintenance. Some monitoring tools are simple to apply (e.g., hand-held IR sensor) while others are more difficult in the initial implementation (e.g., hard wiring to various circuit locations in the circuit breaker). This study presented the methods and tools that can be used for monitoring and trending aging effects; what remains are decisions regarding which to use, perhaps on a plant by plant basis.

Recommendations resulting from this study are as follows:

1. A selection of suitable diagnostic and monitoring technologies and techniques, for highly ranked and failure prone component areas, should proceed as part of the IST program;

2. At the same time, consideration should be given to programmatically emphasizing practices that can significantly preclude pump system failures (i.e., root causes);

3. A diagnostic testing and monitoring demonstration facility should be created to support decisions regarding which technologies to use and development of methodologies and techniques;

4. Technology research and development should be performed for critical technologies:

   High frequency waveform analysis,
   Vibration spectra analysis,
   Electrical signature analysis

It is important for diagnostic engineers and technicians to carefully select the *combination* of tools that will be most effective in providing information on risk-important equipment. It is essential that new technologies or technologies that require additional development are given high program emphasis for they clearly will provide essential information and perspectives that cannot be gained from other available alternatives.

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