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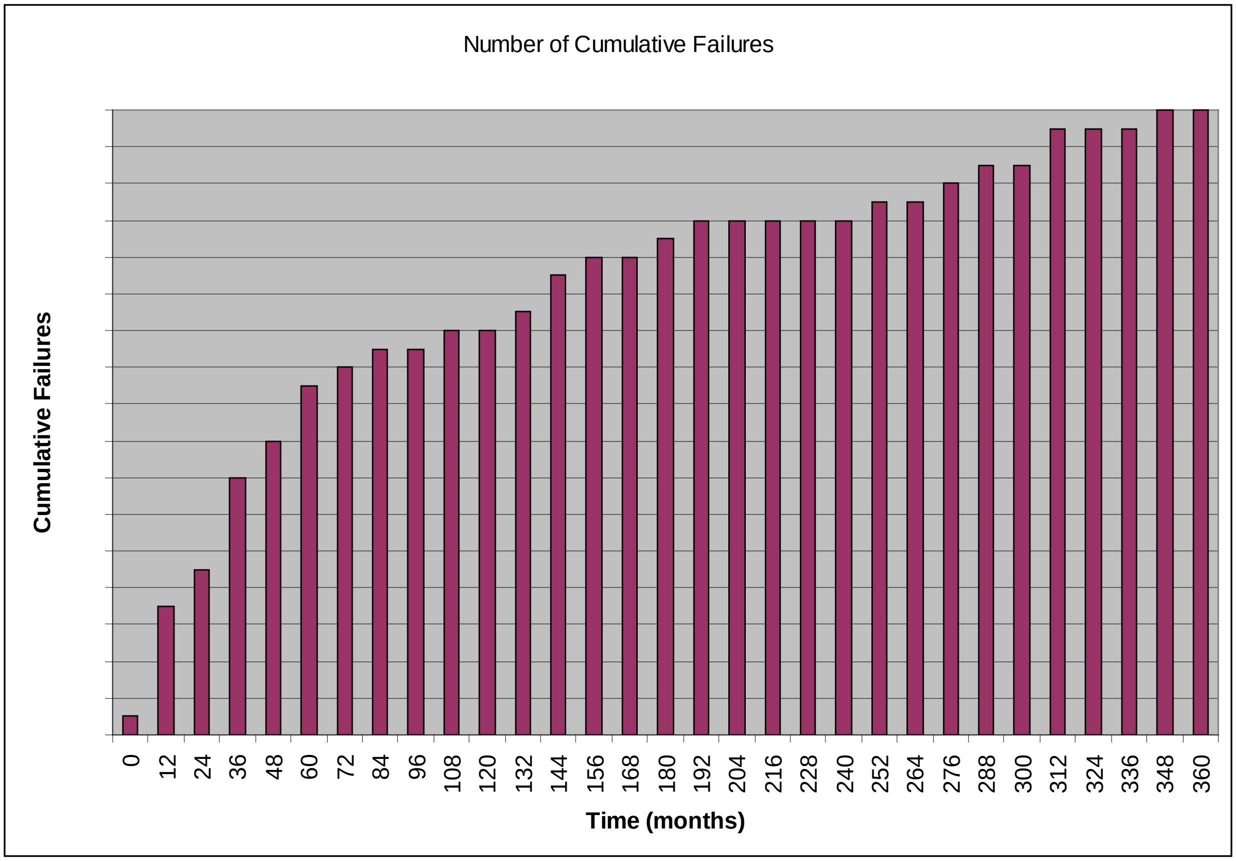
Plant Support Engineering: Large Vertical Pump End-of-Expected-Life Report



Plant Support Engineering: Large Vertical Pump End-of-Expected-Life Report

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PRODUCT DESCRIPTION

The purpose of this report is to provide nuclear power plant managers and component/system engineers with technical guidance regarding end-of-expected-life considerations for large vertical pumps. In particular, the report is intended to assist them in determining the point in the life of a pump when a contingency or refurbishment/replacement plan is desirable to prevent end-of-life failure or to make the impacts of a failure manageable. The report defines actions that can be taken to identify the approach of end-of-life failures or to reduce the costs of responding to an end-of-life failure.

Results and Findings

Large vertical pumps are designed for long-term operation and are intended to be trouble-free over the life of a facility if appropriate maintenance practices are in place. However, there have been many examples of unanticipated plant outages and generation derates due to pump failures. The factors underlying aging of large pumps are numerous and varied, and it is not reasonable to establish generic expectations for pump life that suit all applications, industrywide. Industry data summarized in the report confirm this, showing end-of-life-type failures of large vertical pumps occurring over a wide span of ages ranging from 1 year to 30 years.

When it comes to a given individual pump in a specific application, it is possible to establish expected life. To do so requires evaluation of condition monitoring trends, pump environment, detailed inspection results, plant history, and criticality of the pump. Initial detailed inspections (covering performance, vibration, current, and dimensions of all critical wear parts and clearances) are recommended for new pumps and within five years of installation, to establish trends that can indicate the expected life of a pump and to determine when additional inspections are needed.

Challenges and Objectives

Every pump will eventually reach a point where end-of-life considerations, including the possibility of catastrophic failure, become a primary concern. Due to the function of large vertical pumps, sudden catastrophic failures can significantly impact operation of the plant, and repairs tend to be very expensive compared with costs of a planned repair. This report is intended to support an understanding of pump life expectancy factors that can be combined with long-term planning as a technical basis for the replacement/refurbishment strategy of these major plant assets.

Applications, Value, and Use

Knowledge and planning related to end-of-expected-life considerations are an essential aspect of component life cycle management. Appropriate strategies for dealing with end-of-life issues of large components can reduce the chances of catastrophic failures and significantly lower the costs associated with repairs and replacements. This report provides an analysis of underlying industry data with results and recommendations that will aid users in the identification of end-of-life conditions for large vertical pumps. The target population is nuclear power plant system managers and component/system engineers.

EPRI Perspective

Extension of nuclear plant operating lives beyond their original 40-year licensed term has been granted for over half the existing nuclear fleet in the United States. Industry focus continues to include studies involving system, structure, and component (SSC) aging, supply, obsolescence, refurbishment, and replacement in order to satisfy the regulatory requirements necessary to gain the extended license. Electric Power Research Institute (EPRI) Plant Support Engineering (PSE) provides a standard platform for many of these studies within the Life Cycle Management (LCM) program. Since the inception of the program in the mid-1990s, PSE has provided over 40 studies in the form of SSC sourcebooks, end-of-life guides, and component replacement guides. EPRI nuclear maintenance documents and the EPRI Preventive Maintenance Basis Database (PMBD) outline best practices and recommendations for the implementation of maintenance and condition-based monitoring of large vertical pumps.

Approach

Industry operating experience, EPRI Pump Users Group survey results, vendor recommendations, EPRI maintenance guidance, and industry pump failure data were the foundation for this report. A search of the industry databases was performed to identify actual end-of-life failures and attendant causes. Conditions that accelerate pump life are identified, as are methods to identify these conditions. A brief discussion regarding the logistics associated with pump repair is also included.

Keywords

Large vertical pumps
Expected life
End of life
Life cycle management
Nuclear asset management
Component reliability

ABSTRACT

This report presents information and recommendations related to the end of life of large vertical pumps used at nuclear power plants. The main focus is on how to recognize the approach of end of life of these assets in order to support decisions regarding contingency or replenishment/replacement planning. It is intended primarily for use by nuclear plant system managers and component/system engineers. Major sections are devoted to expected life considerations and condition monitoring. A section on the logistics of component replacement is also provided.

ACKNOWLEDGMENTS

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Purpose

Large vertical pumps are utilized throughout the nuclear industry in a wide variety of applications. Typical applications include, but are not limited to, condensate, service water, circulating water, containment spray, residual heat removal, component cooling, safety injection, and reactor coolant systems.

With license renewal, plants face challenges associated with ensuring that systems and components function properly to meet 60 years of plant operation. Although the life of large vertical pumps varies widely throughout the industry, it is unreasonable to expect any pump to provide 60 years of failure-free operation with little or no pump refurbishment.

Each pump will eventually reach a point where catastrophic failures become a primary concern. In general, due to the function of these pumps, sudden catastrophic failures can significantly impact operation of the plant. Costs of unplanned repairs such as those associated with unanticipated failure of a pump will be very expensive compared with costs of a planned repair.

End of life of a component is the point when the basic periodic maintenance regime of the component needs to be altered to one of major refurbishment or replacement to prevent a situation in which an unplanned **major** repair is required. For large vertical pumps, this includes major subcomponents such as impellers, shafts, and the pump case/bowl. Additionally, a failure of any of these subcomponents constitutes an end-of-life-type failure for this pump (although the pump may be repaired and continue operation). However, failures caused by issues such as manufacturing defects and personnel error are not representative of typical conditions and are not used in predicting typical pump life. Additionally, end of life is reached whenever the present-worth cost of anticipated repairs for the next scheduled outage equals or exceeds the cost of replacement. When confidence in the pump's reliability is diminished and catastrophic failure is a concern, the pump has also reached the end of its life.

This report provides information related to pump failures, a summary of methods to predict end of life, and factors to consider in developing a refurbishment/replacement plan (such as logistics). Guidelines for maintenance practices and condition monitoring currently exist and are referenced; however, no new methods are established by this report. This report provides sufficient information to aid plant management and system/component engineers in determining if the end of life is approaching and if there is a need for long-term plans and additional maintenance and condition-based monitoring (performed more frequently).

1.2 Acronyms and Abbreviations

BEP	best efficiency point
EPIX	Equipment Performance and Information Exchange System
IGSCC	intergranular stress corrosion cracking
IST	in-service testing
NDE	nondestructive examination
NPSH	net positive suction head
NPSHA	net positive suction head available
NPSHR	net positive suction head required
INPO	Institute of Nuclear Power Operations
LCM	life cycle management
NPRDS	Nuclear Plant Reliability Data System
OE	operating experience
OEM	original equipment manufacturer
PM	preventive maintenance
PMT	post-maintenance testing
SCC	stress corrosion cracking

1.3 Scope

The focus of this report is directed toward recognition of approaching end of life of large vertical centrifugal pumps utilized at nuclear power plants. Horizontal pumps are excluded from the scope of this report. For vertical pumps, only the pump is included in the scope; the pump driver (motor, turbine, and so on), support equipment (such as lube oil pumps), and shaft seal/packing are excluded from this report. Items that require extended maintenance (subcomponents such as impellers, bearings, shafts, pump case/bowl, and so on) are the focus of this report because they are the most costly and have greatest cost impact on plant availability.

Feedback provided by industry personnel through the Pump Users Group survey [1] showed that there is no single definition for the term *large pumps*. Criteria identified by respondents as being used for defining the term included the following (the percentage of responses for each is given in parentheses): physical size (7.5%), flow rate (22.5%), operating speed (2.5%), voltage (15%), function (7.5%), and power (45%). Each of these had varying thresholds as well for classifying a pump as a large pump.

This report defines *large pumps* as those with a flow rate of at least 2500 gpm (9464 l/min). Flow rate was utilized to filter failures because it is one of the primary characteristics identified by utility personnel, and pump power is not available for pump failures in the Equipment Performance and Information Exchange (EPIX) database (available only to members of the Institute of Nuclear Power Operations [INPO]). The choice of 2500 gpm was made due to the categories in EPIX, and it represents 75% of the survey responses related to using flow for defining *large pump*.

2
EXPECTED LIFE CONSIDERATIONS

This section discusses factors that could affect pump life, methods to monitor these factors, and typical end-of-life failure modes seen in the field.

2.1 Conditions That Affect Pump Life

Various conditions can have an impact on pump life, such as fluid quality, effectiveness of the preventive maintenance (in terms of its content, frequency, and quality), manufacturing quality, structural support, and so on. Some of these conditions are relatively easy to manage, while some require significant effort. These conditions are discussed in more detail in EPRI documents NP-7413, *Deep Draft Vertical Centrifugal Pump Maintenance and Application Guide* [2], and 1003467, *Vertical Pump Maintenance Guide, Supplement to NP-7413* [3]. The following is a summary of typical conditions that are frequently encountered:

- **Balance.** This includes the initial balance of the pump as well as changes occurring during operation that are caused by debris, erosion, cavitation, and so on.
- **Alignment.** Alignment of the line shaft components and alignment of the pump to the driver are critical to maximizing the life of a pump.
- **Mechanical looseness.** Looseness can result from human error, corrosion, thermal cycles, or normal pump operation.
- **Resonance.** Pump resonant frequencies can change over the life of the pump as a result of normal wear, adjustments in operating speed, or changes to the environment. Structural resonant frequency aligned with pump rotational frequency is a common industry problem with vertical pumps.
- **Hydraulic instability.** The hydraulic conditions of the system can change based on the fluid quality (and temperatures), presence of large debris, silt deposition, pump degradation, and so on. This also includes vortex formation at the pump suction caused by sump design, varying water levels, filter/screen condition, and so on.
- **Environment.** The quality of the fluid can be difficult to manage, but it can have a tremendous impact. Chemistry control (affecting corrosion), sandy/brackish environment (affecting erosion), biological parameters, and so on can have a large impact on the life of the pump.

- **Impeller clearance changes.** Pump performance of semi-open impellers can be greatly reduced if impeller vane-to-liner/shroud clearance is set too high. On the other hand, high hydraulic friction or damage from contact can occur if the clearance is not set high enough. Adjustments to the clearance may be required several times throughout the year to account for expansion/contraction of the pump shaft due to changes in fluid temperature. The fluid quality can also influence the clearance by causing wear of the impeller vane ends and the liner/shroud. The clearance is adjusted by means of a “lift test.” The lift test is also used for adjusting the clearance in the enclosed impeller pumps; however, the adjustment is not as critical as with semi-open impeller pumps.
- **Cavitation.** Pump design, sump design, variations in suction pressure, multipump operating variations, pump operating conditions, liquid levels and temperature, and operation at runout flows can have an impact on pump cavitation. Small changes in the pump (operating speed, impeller design, and so on) can significantly impact the amount of cavitation-related damage.
- **Preventive maintenance (PM) effectiveness.** The frequency, extent, and type of PM performed can enhance or reduce the life of a pump. Each time the pump is disassembled, opportunities are created to allow other factors (misalignment, looseness, imbalance, and so on) to become more or less prevalent than otherwise would have been the case.
- **Manufacturing defects.** Flaws in the manufacture of a pump may go unnoticed for several years. However, in the presence of additional stressors, manufacturing defects can result in major pump failures.
- **Manufacturing tolerances.** Inadequate tolerances in the pump design can result in an increased severity of many of the above listed conditions.

If not addressed in a timely manner, each of the above factors can eventually lead to premature degradation of the pump. The resulting degradation could range from the pump operating beyond its normal parameters to catastrophic damage. Table 2-1 presents common degradation indications related to failure mechanisms that involve some of the above factors.

Table 2-1
Typical Large Vertical Pump Degradation Indications and Mechanisms

Failure Mode	Failure Mechanism
High vibration	Balance
	Misalignment
	Mechanical looseness
	Resonance
	Hydraulic instability
	Cavitation
	Environment
	Internal rubbing
	Manufacturing defect
Loss of performance	Hydraulic instability
	Pump clearance changes
	Cavitation
	Worn casing vanes
	Impeller wear
High motor current	Misalignment (severe)
	Internal rubbing
	Manufacturing defect
	Operation outside the intended flow range

2.2 Normal Aging Mechanisms/Effects

There are various failure mechanisms that cannot reasonably be altered. Although actions can be taken to minimize the effect of these mechanisms, there comes a point when it becomes too costly to pursue corrective measures. These aging effects, mechanisms, and diagnostic methods have been identified in the EPRI PM Basis Database [4] and are provided in Table 2-2 with some additional information based on experience.

Details on the pump diagnostic methods can be found in EPRI documents *Deep Draft Vertical Centrifugal Pump Maintenance and Application Guide* [2] and *Vertical Pump Maintenance Guide*, *Supplement to NP-7413* [3].

When replacement or major refurbishment of the pump's major components (impellers, shafts, and the pump case/bowl) would be required to correct issues listed in Table 2-2, the pump is considered to be approaching its end of life. This is discussed further in Section 2.3.

Table 2-2
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Impeller	Wear—reduced outer diameter	Fluid quality Debris Impeller material Motor thrust bearing wear Operating outside of design conditions Improper impeller clearance	Performance trending Maintenance inspection Vibration trending Motor current trending	Methods for trending and inspection are well established.	May be weld repaired if base metal is suitable, or replace impeller.	Planned: 2 days to 7 days Unplanned: 3 days to 15 days	Entire pump internal assembly must be removed and dismantled for the inspection and repair.
	Wear—vane thinning or erosion	Fluid quality Debris Impeller material Operating conditions	Maintenance inspection	Methods for trending and inspection are well established. Trending vane measurements provides the most accurate indication.	If amount of thinning is less than the corrosion allowance, no action needed. Replace impeller if corrosion allowance is violated.	Planned: 2 days to 7 days Unplanned: 3 days to 15 days	

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Impeller (cont.)	Wear—rubbing face and liner/shroud	Large change in temperature Loose coupling Corrosion—coupling Line shaft bearing wear or failure	Maintenance inspection Vibration trending Audible noise Pump lift check	Methods for trending and inspection are well established.	Restore dimensions by welding and grinding, or metal spray, or chrome plating.	Planned: 2 days to 7 days Unplanned: 3 days to 15 days	
	Wear—from cavitation	System configuration Operating outside of design conditions Low net positive suction head available (NPSHA) Low intake water level	Maintenance inspection Vibration trending Audible noise Performance trending Borescope	Methods for trending and inspection are well established.	May be weld repaired if base metal is suitable. Replace impeller if wear is extensive.	Planned: 2 days to 7 days Unplanned: 3 days to 15 days	

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Impeller (cont.)	Wear—from vortexing	Sump design Low intake water level	Oscillating motor current Oscillating flow Performance trending Vibration trending Maintenance inspection Audible hammering noise	Methods for trending and inspection are well established.	Replace impeller if vane breakage or cracking occurs. No repair needed if no visible damage.	Planned: 2 days to 7 days Unplanned: 3 days to 15 days	Check condition of bearings, shaft seal, wear rings and bushings/ sleeves for collateral damage.
	Wear—from recirculation at impeller	Operating outside of design conditions	Maintenance inspection Vibration trending Audible noise Performance trending Borescope	Methods for trending and inspection are well established.	May be weld repaired if base metal is suitable. Replace impeller if wear is extensive.	Planned: 2 days to 7 days Unplanned: 3 days to 15 days	Check condition of bowl casings and inlet bell and discharge vanes for collateral damage.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Impeller (cont.)	Physical damage	Stress corrosion Cracking Fatigue from corrosion Internal rubbing Hydraulic thrust reversal System water hammer Manufacturing defect Debris	Vibration trending Maintenance inspection Borescope	Methods for trending, inspection, and NDE are well established.	If cracks or breakage exists, replace impeller.	Planned: 2 days to 7 days Unplanned: 3 days to 15 days	Check shaft, bearings, seals, bowls, wear rings, bushings/ sleeves, and motor thrust bearing for collateral damage.
	Loose or failed impeller key or locking rings	Vibration Corrosion Installation error Improper material Excessive fit tolerance Hydraulic transients	Performance trending Vibration trending Maintenance inspection Motor current trending	Trending methods are effective only after key has failed.	Machine keyways and ring grooves to be oversized, replace keys and rings to suit. If not feasible, replace impeller, shaft, keys, and rings. Consider use of “keyless” hubs.	Planned: 2 days to 7 days Unplanned: 3 days to 15 days	Manufacturer to be consulted about permissible machining of keyways.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Discharge head and motor mount	Cracked welds	Vibration Stress corrosion cracking Manufacturing/ design defect Installation/ removal stresses Pressure impulses/ startup transients	Maintenance inspection Vibration trending	Methods for trending, inspection and NDE are well established.	Welds should be ground out, repair welded, and stress relieved.	Planned: 2 days to 7 days Unplanned: 3 days to 10 days	Use care to avoid overheating while welding. Dimensions should be checked after repair to ensure proper alignments are maintained.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Discharge head and motor mount (cont.)	Corrosion of motor mount flange	Environment Too-frequent intrusive maintenance Loose motor mounting bolts Improper installation	Maintenance inspection Vibration trending Operator rounds	Methods for trending and inspection are well established.	Clean off corrosion material. If motor to pump fit-up dimensions are violated, use shims to restore fit-up. If corrosion is severe, cut and replace flange (if weldable).	Planned: 2 days to 7 days Unplanned: 3 days to 10 days	If flange material is not weldable, a plastic trowel-on and machinable repair material may be used to restore fit-up dimensions. Avoid overheating while welding. Check final dimensions to ensure proper alignment is maintained.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Discharge head and motor mount (cont.)	Deformation	Installation/ removal stresses Nozzle loads	Maintenance inspection Dial indicator measurements during startup	Methods for inspection are well established.	Cut, bend, weld, and stress relieve to restore fit-up of motor to pump, if base metal is suitable. If not weldable, replace discharge head.	Planned: 2 days to 7 days Unplanned: 3 days to 20 days	Cause of the deformation should be determined. Additional stiffeners may be needed on the discharge head, or the discharge may need to be restrained. Look for collateral damage at the bearings and sleeves.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Line shaft coupling	Worn keyway	Torsional vibration Manufacturing tolerances Improper material	Maintenance inspection Vibration trending	Methods for inspection are well established. Vibration may only show signs after a failure has occurred.	Machine keyways and ring grooves to be oversized, replace keys and rings to suit. If not feasible, replace shaft, keys, and rings. Consider utilizing couplings with keyless hubs.	Planned: 2 days to 7 days Unplanned: 3 days to 20 days	Manufacturer should be consulted about permissible machining of keyways.
	Stripped threads	Torsional vibration Manufacturing tolerances Improper material	Maintenance inspection Vibration trending	Methods for trending and inspection are well established.	Rethread shaft and coupling. If they cannot be rethreaded, replace shaft and couplings.	Planned: 2 days to 7 days Unplanned: 3 days to 20 days	Manufacturer should be consulted about permissible amount of rethreading.
	Corrosion	Type of material Pumped fluid	Maintenance inspection	Methods for inspection are well established.	Replace couplings with upgraded material.	Planned: 2 days to 5 days Unplanned: 3 days to 8 days	Shaft may also need to be replaced with upgraded material.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Line shaft coupling (cont.)	Locking split ring failure	Improper installation Manufacturing tolerances Hydraulic transient	Pump lift check Vibration trending	Methods for trending and inspection are well established.	Replace coupling.	Planned: 2 days to 5 days Unplanned: 3 days to 8 days	May cause major collateral damage requiring complete overhaul.
Pump/motor coupling	Improper fit	Corrosion Manufacturing tolerances Installation error Misalignment	Maintenance inspection Vibration trending Thermography	Methods for trending and inspection are well established.	Replace coupling.	Planned: 2 days to 4 days Unplanned: 3 days to 5 days	Replacement coupling should be balanced by manufacturer when purchased. Corrosion may be caused by stray electrical currents and should be investigated.
	Imbalance	Improper installation Improper key size Mismatched coupling halves/bolts	Vibration trending Abnormal noise	Methods for trending are well established.	If the coupling properly aligns the pump and motor shafts, it need only be balanced.	Planned: 2 days to 3 days Unplanned: 3 days to 4 days	The key and keyway should be compatible.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Pump/motor coupling (cont.)	Damage to adjustment nut or plate	Galled threads on nut or plate Corrosion	Maintenance inspection	Methods for inspection are well established.	The nut or plate screw to the shaft—the nut or plate and shaft may be rethreaded. Corrosion should be cleaned off and the part reused if there remains sufficient thickness. The parallel surfaces should be restored.	Planned: 2 days to 4 days Unplanned: 3 days to 5 days	The manufacturer should be contacted to determine the allowable amount of rethreading on the shaft and nut or plate, or the minimum thickness of the nut or plate. If minimum conditions cannot be met, the coupling and possibly the shaft may need to be replaced.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Shaft	Cracking	Shaft whip, running at > 10% off-BEP Stress corrosion cracking Inadequate design margin Manufacturing defect Thermal fatigue Cyclic/torsional fatigue Cyclic bending Bound shaft	Vibration trending Impact testing Maintenance inspection Ultrasonic testing	Methods for trending and inspection are well established.	Surface cracks can usually be tolerated but should be ground smooth. Penetrating circumferential cracks require replacement of the shaft.	Planned: 2 days to 7 days Unplanned: 3 days to 20 days	If cracks occur at corners of fillets, keyways, or ring grooves, the radius of the corner should be increased by machining to reduce stress concentrations.
	Loss of shaft diameter	Misalignment Corrosion Bearing wear Packing wear	Vibration trending Maintenance inspection	Methods for trending and inspection are well established.	Worn or corroded surfaces should be ground smooth. If remaining diameter is acceptable to the manufacturer, the shaft may be reused.	Planned: 2 days to 7 days Unplanned: 3 days to 20 days	Straightness of the shaft should be checked as possible collateral damage.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Shaft (cont.)	Wear	Misalignment Corrosion Bearing wear Packing wear	Vibration trending Maintenance inspection	Methods for trending and inspection are well established.	Worn or corroded surfaces should be ground smooth. If remaining diameter is acceptable to the manufacturer, the shaft may be reused.	Planned: 2 days to 7 days Unplanned: 3 days to 20 days	Straightness of the shaft should be checked as possible collateral damage.
	Bent	Misalignment Thermal shock Improper storage Improper installation Foreign material Water hammer Inadequate manufacturing heat treatment process Internal rubbing	Vibration trending Maintenance inspection	Methods for trending and inspection are well established.	If the bend is a fairly uniform bow and has not caused cracks, the shaft may be straightened and stress relieved. If it remains straight, it can be reused. A sharp bend typically causes cracks and requires shaft replacement.	Planned: 2 days to 7 days Unplanned: 3 days to 20 days	Collateral damage to bearings, wear rings, shaft seal, sleeves and bushings should be checked.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Bearings—sleeve (product lubricated)	Wear	Fluid quality Pump run dry Bearings run dry excessively prior to flow establishment Suction vortexing Misalignment Excessive mechanical or hydraulic loading Cavitation Improper assembly Excessive tolerance (design) Rough journal	Vibration trending Motor current trending Audible noise	Methods for inspection are well established. Vibration and motor current effective only if failure is imminent.	Worn bearings should be replaced. Condition of journals should be inspected and ground smooth if needed.	Planned: 2 days to 5 days Unplanned: 3 days to 10 days	In pumps with an inner column, the adequacy of the lubricating system should be reviewed. If accelerated wear occurs, the cause should be investigated and corrected.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Bearing retainers and spiders	Cracking	Fatigue from corrosion Improper installation Excessive tolerance (design) Manufacturing defect	Maintenance inspection Vibration trending	Methods for trending and inspection are well established.	If the materials are weldable, the cracks can be weld repaired. If not, the retainer and spider assembly should be replaced.	Planned: 2 days to 5 days Unplanned: 3 days to 10 days	The cause of cracking should be investigated and corrected. Care should be taken to ensure proper shaft alignment with the repair.
	Corrosion	Fluid quality Improper material	Maintenance inspection	Methods for inspection are well established.	The retainers and spiders should be replaced with upgraded materials.	Planned: 2 days to 5 days Unplanned: 3 days to 10 days	Check the bearings for collateral damage.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Wear rings	Wear	Fluid quality Improper fits/ tolerances Misalignment Excessive mechanical or hydraulic loading Improper clearance Setting Material selection Improper installation Bent shaft	Vibration trending Performance trending Maintenance inspection Audible noise Hand rotation Motor current trending	Methods for trending and inspection are well established.	Wear rings should be replaced when the diametric clearance approaches twice the as-built clearance. If the pump has both casing and impeller wear rings, both should be replaced. The impeller ring can be trimmed smooth and an oversized case ring installed. If the pump only has a casing wear ring, the mating impeller surface should be trimmed smooth and an oversized casing ring installed to restore proper clearance.	Planned: 2 days to 6 days Unplanned: 3 days to 14 days	If wear on the stationary part is elliptical in shape, misalignment is indicated.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Wear rings (cont.)	Galling	Fluid quality Improper fits/tolerances Misalignment Excessive mechanical or hydraulic loading Improper lift setting Material selection Improper installation Bent shaft Debris	Vibration trending Performance trending Hand rotation Maintenance inspection Motor current trending	Methods for trending and inspection are well established.	Roughened surfaces should be machined smooth. If the resulting diametric clearance approaches twice the as-built clearance, the rings should be replaced.	Planned: 2 days to 5 days Unplanned: 3 days to 10 days	Galling is usually caused by a heavy sustained internal rub or material more susceptible to galling and can cause collateral damage to the rotor and bearings. The cause should be investigated and corrected.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Gaskets and O-rings	Leaks from erosion	Improper fit Surface condition of shaft and stationary fluid boundary seals Improper material	Performance trending Maintenance inspection Operator rounds	Methods for trending and inspection are well established.	Damaged seating surfaces should be ground smooth and parallel, and the surfaces coated with stainless weld and ground smooth, or chrome plated.	Planned: 2 days to 7 days Unplanned: 3 days to 15 days	The gasket or o-ring should be in a compressed state when torqued as specified by vendor.
	Leaks from corrosion	Improper material Age Contamination High temperature Improper installation	Performance trending Maintenance inspection Operator rounds	Methods for trending and inspection are well established.	Damaged seating surfaces should be ground smooth and parallel then coated with a material that is resistant to the corrosion mechanism.	Planned: 2 days to 7 days Unplanned: 3 days to 15 days	The gasket or o-ring should be in a compressed state when torqued as specified by the vendor.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Gaskets and O-rings (cont.)	Leaks from incorrect material	Improper material Age/radiation Contamination High temperature Improper installation	Performance trending Maintenance inspection Operator rounds	Methods for trending and inspection are well established.	Clean up seating surfaces and restore surfaces by machining and coating if needed. Replace gaskets or o-rings with upgraded materials.	Planned: 2 days to 5 days Unplanned: 3 days to 10 days	The service conditions including pressure, temperature, fluid velocity and quality, and exposure to radiation should be considered in determining material upgrades.
	Deformation	Warped surface Improper installation	Performance trending Maintenance inspection	Methods for trending and inspection are well established.	Seating surfaces should be machined smooth, flat and parallel to each other. If dimensional requirements are violated, they may be restored by coating the surfaces with weld and grinding smooth, or by chrome plating.	Planned: 2 days to 7 days Unplanned: 3 days to 15 days	The gasket or o-ring should be in a compressed state when torqued as specified by the vendor.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Bowls	Corrosion	Environment Fluid quality Improper material Loss of protective coating Galvanic activity	Performance trending Maintenance inspection	Methods for trending and inspection are well established.	Clean off the corrosion material. If remaining thickness has not violated the corrosion allowance, reuse the bowl. A trowel-on machinable casting repair material may be used on small locally damaged areas if the pump service permits.	Planned: 2 days to 7 days Unplanned: 3 days to 20 days	Manufacturer should be contacted for corrosion allowance data. If corrosion is accelerated, replacement of bowls of upgraded material should be considered. External coating, if used, should be repaired with an upgraded coating if available.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Bowls (cont.)	Erosion	Fluid quality Improper material Loss of protective coating High flow velocities Improper impeller fit	Performance trending Maintenance inspection	Methods for trending and inspection are well established.	Weld repair if the base material permits. If not weldable, a trowel-on machinable casting repair material can be used if the pump service permits. Replace bowl if erosion is extensive and the corrosion allowance is violated.	Planned: 2 days to 7 days Unplanned: 3 days to 20 days	Replacement bowls may be available in materials that are more erosion resistant and should be evaluated.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Bowls (cont.)	Cavitation or impeller recirculation	Operating outside of design conditions Improper NPSHA Low intake water level Plugged suction screen or traveling screen System configuration—poor sump design	Vibration trending Audible noise Maintenance inspection Performance trending	Methods for trending and inspection are well established.	Cavitation and recirculation damage are similar. The main difference is where the damage occurs. Treat as stated above for erosion.	Planned: 2 days to 7 days Unplanned: 3 days to 20 days	The cause should be investigated and corrected to avoid expensive recurrence.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Column piping	Corrosion	Environment Fluid quality Improper material Loss of protective coating	Performance trending Maintenance inspection	Methods for trending and inspection are well established.	Clean corrosion material off and determine if the corrosion allowance has been violated. Replace column if excessive thinning has occurred. If damage is localized, repair may be made by welding or using a trowel-on machinable repair material if pump service permits.	Planned: 2 days to 7 days Unplanned: 3 days to 20 days	Replacement column may be of upgraded material, or of the original material except having thicker corrosion allowance. Use of protective coatings should be investigated if pump service permits their use.

Table 2-2 (continued)
Aging Mechanisms and Effects of Large Vertical Pumps

Pump Subcomponent	Aging Effect	Aging Mechanism	Diagnostic Methods	Diagnostic Effectiveness	Reparability	Repair Time	Repair Issues
Column piping (cont.)	Loose bolting	Installation error Inadequate material selection Galvanic corrosion Vibrations Vortex formation	Maintenance inspection	Methods for inspection are well established.	Tighten bolts using torque values prescribed by vendor. If the problem is extensive and caused by operating conditions, bolt locking devices should be considered.	Planned: 2 days to 3 days Unplanned: 3 days to 4 days	Look for collateral damage such as worn bearings and wear rings if the column sections go out of alignment as a result of the loose bolting. If operating conditions are the cause, the problem should be addressed.
	Weld or joint failure	Vibration Manufacturing error Vortex formation	Maintenance inspection Vibration trending Performance trending Motor current trending	Methods for trending and inspection are well established.	If a welded joint is cracked, the weld can be repaired, making sure that bearing alignment is maintained. If the joint fails completely the pump may need to be rebuilt.	Planned: 2 days to 7 days Unplanned: 3 days to 20 days	Collateral damage should be investigated as a cracked weld can cause the column to go out of alignment resulting in bearing and wear ring wear, and possible galling.

2.3 Primary End-of-Life Failure Modes

2.3.1 Identification of Failures

Industry failure databases were reviewed for the period from January 1997 to April 1, 2009, to identify the major failures experienced by large vertical pumps at nuclear plants. These failures are typically only related to systems within the scope of the Maintenance Rule or those that cause power reductions/transients, so the reported failures may be fewer than actual. However, the types of failures are expected to be representative of all large vertical pumps.

Table 2-3 identifies the keyword searches performed to identify failures of various types of pumps and the number of relevant failures for each. Results of the searches were filtered to ensure that only relevant failures were reviewed. Failures were filtered out based on:

- Pumps that were not centrifugal
- Failures that impact operation of a pump but were not a pump failure (failures associated with instrumentation, valves, procedural issues, and so on)
- Support equipment (such as pump lube oil pumps, seal water injection systems, and so on)
- External leakage caused by corroded fasteners/plugs
- Pump flow <2500 gpm (9464 l/min)
- Failures such as an air-bound pump, foreign material contamination, human performance issues, and issues identified and corrected during post-maintenance testing (PMT), and so on

Following this review, 34 failures were identified pertaining to large vertical pumps, as shown in Table 2-3. Each of these failures required either replacement or relatively major rebuilding to return the pump to service. Figure 2-1 shows the progression in number of cumulative pump failures versus pump life.

Table 2-3
EPIX Searches (full search results are available only to INPO members)

Search	Number of End-of-Life Large Vertical Pump Failures
Reactor coolant pump	1
Service water pump	20
Circulating water pump	5
Residual heat removal pump	0
Safety injection pump	1
Component cooling water	0
Containment cooling	0
Containment spray pump	1
Condensate pump	6
Total	34

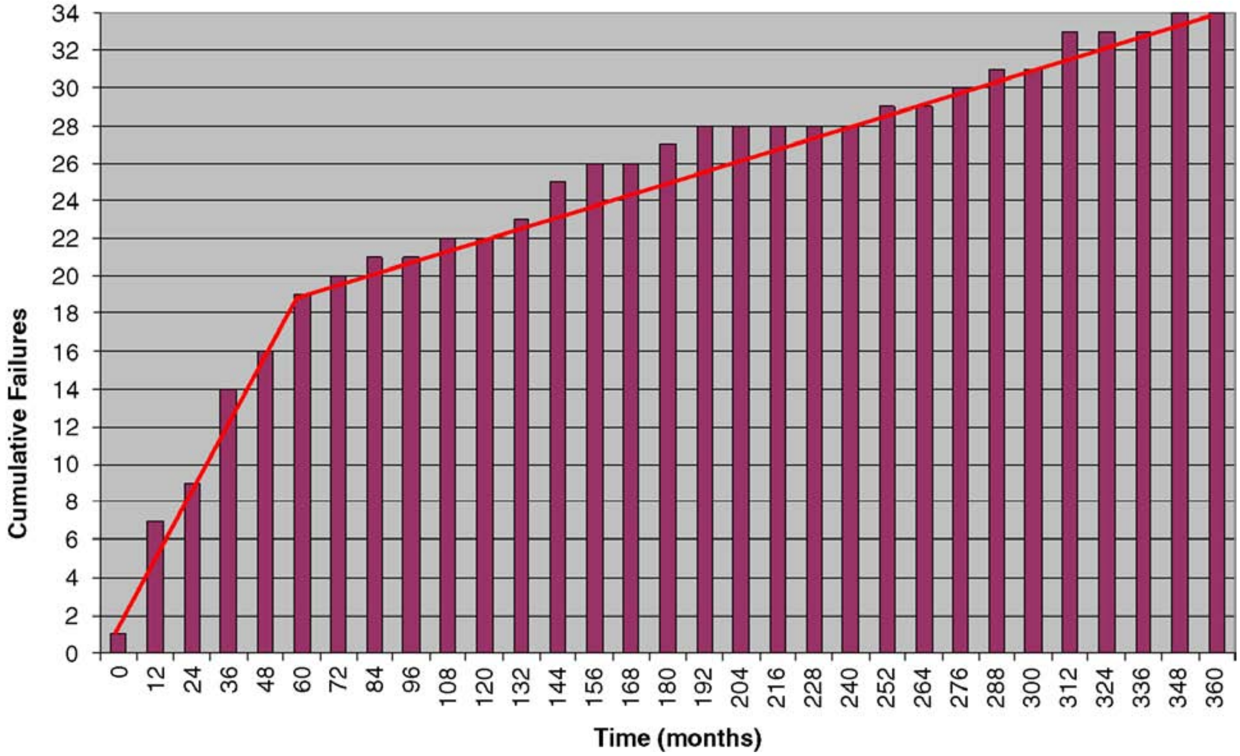


Figure 2-1
Number of Cumulative Failures

2.3.2 Failure Analysis

The failures identified through the process discussed in Section 2.3.1 were reviewed to determine the cause. A review of the results shows that the majority of the major failures (19 out of 34) occurred within the first five years of pump life. The number of cumulative failures increased rapidly for the first five years; then the rate of failures per year reduced dramatically. All failures that occurred prior to one year of service were attributed to maintenance (improper assembly, misalignment, manufacturing defect, design errors, and so on) and are considered infant mortality. The remaining twelve failures that occurred within five years of installation/rebuild were due to various causes; three of these twelve are considered to have been caused by personnel error and are not considered indicative of typical pump life. As for the remaining nine failures that occurred between one year and five years, a common mode of failure could not be identified (each pump failed in different ways). However, the common thread in these relatively short-lived pumps was inadequate design, improper application, and/or a harsh environment (fluid quality).

The failures are summarized in Table 2-5 (at the end of Section 2), which contains the time that it took for the failure to occur (based on pump installation or last refurbishment). As can be seen, there is a wide range of lifetimes related to the pumps that did fail. For this reason, an accurate prediction of expected lifetime that would apply to the entire industry is not possible. However, failure data shows that if special conditions (design or application flaw, personnel error, or harsh environment) do not exist that would cause the pump to fail within the first five years of operation, a failure rate of ~0.6 pumps per year (15 pumps over 25 years) exists for the entire industry. The failure rate for all pumps (excluding infant mortality and special-cause failures) less than five years is 1.8 pumps per year (nine pumps over five years) for the entire industry.

2.3.3 Monitoring Effectiveness

Table 2-5 also contains valuable information related to the effectiveness of methods to help evaluate pump condition. A review of the failure indications shows that vibration monitoring was useful in predicting approximately one-third of all failures. In addition, pump performance data (pressure and flow) was useful in predicting approximately one-third of all failures (some failures were indicated by both vibration and pressure/flow). However, of the failures reported, 70% (24 of 34) likely could not have been predicted prior to the actual failure by relying on vibration monitoring and performance trending. After the first five years, 53% (8 of 15) likely would not have been seen. Degradation leading to many of these failures could only have been seen by performing detailed internal pump inspections.

For example, Item 9 in Table 2-5 was identified by erratic pump motor current and vibration. Although these parameters are typical parameters for pump diagnostics, the failure was not predicted by the trends seen previously. As a result of the significant change and erratic parameters, an inspection by divers identified the disconnected bellmouth (disconnection between casing and barrel). Had a detailed inspection of the pump been performed, the degradation might have been evident, and repairs could have been made prior to the failure. Item 33 in Table 2-5 was identified by high motor current. The failure was attributed to erosion of the pump impeller bolts and bushing that was not identified by condition monitoring. Had a detailed inspection of the pump been performed, the degraded fasteners and bushing would have been evident.

2.3.4 Determining Pump Life

As mentioned in Section 2.3.2, a generic pump life cannot be predicted; however, determining the estimated life for each pump (on an individual basis) can be accomplished. If a detailed inspection is performed at the beginning of life and then again within the first five years of pump life, the data collected (performance, vibration, current, and dimensions of all critical wear parts, pressure retaining parts, and clearances) could provide for correlation between diagnostic test method results and pump condition.

Performing the second inspection at five years is based on an initial high failure rate (as shown in Figure 2-1). The beginning-of-life inspection could utilize vendor data; however, the data should be actual measurements and not nominal values. Use of nominal values for new pumps can lead to erroneous trends with regard to wear rates. In cases when pumps have been installed for long periods and measurements for the original pump installation (when new) are not available, current measurements could be compared to original nominal values to obtain a general trend; however, the margin for error is higher. Applications with a more harsh environment should perform a second inspection earlier than five years. However, sufficient time to provide an adequate change in parameters must be allowed for more accurate results. The correlation developed between these inspections allows for a higher confidence that condition monitoring results provide an indication of pump condition and remaining life. The trend developed by these diagnostic methods could allow for a prediction of the point at which parameters would reach their limits from normal operation (wear, flow, pressure, vibration, and so on). At this predicted point, the pump would be considered to be approaching its end of life because increased maintenance inspections and possibly refurbishment or replacement would be required to keep the pump operating within specification. If the estimated cost of maintenance or repairs meets or exceeds the cost of replacement, then the pump is considered to have reached the end of its feasible life. Each plant must perform its own analysis of operating conditions and past history to identify an expected life related to an individual pump.

This does not mean that condition monitoring replaces detailed internal inspections throughout the life of the pump. As discussed in Section 2.3.2, there are degradation parameters that are not detectable through condition monitoring techniques. A balance with regard to frequency of detailed inspections must be achieved by evaluating condition monitoring trends, pump environment, initial inspection results, pump history, and criticality of the pump to establish a point at which detailed inspections are implemented. A pump installed in a system with an abrasive fluid may require relatively frequent internal inspections compared to a pump installed in a "clean" system. As shown in Table 2-3, service water pumps exhibit the highest failure rates and should be inspected more frequently than others. At a minimum, for pumps that have a significant cost or plant operation impact, at least one additional detailed inspection should occur after the recommended five-year inspection and prior to the pump reaching its predicted end-of-life point.

2.3.5 Example of End-of-Life Determination

The following example uses hypothetical data to illustrate a method for estimating end of life. This example is greatly simplified. For instance, over the course of the five-year period there will typically be numerous performance tests that provide results of flow. So, by the time the five-year inspection is performed, the trend for flow may be better represented by a curve (based on the numerous data points collected) rather than a straight line.

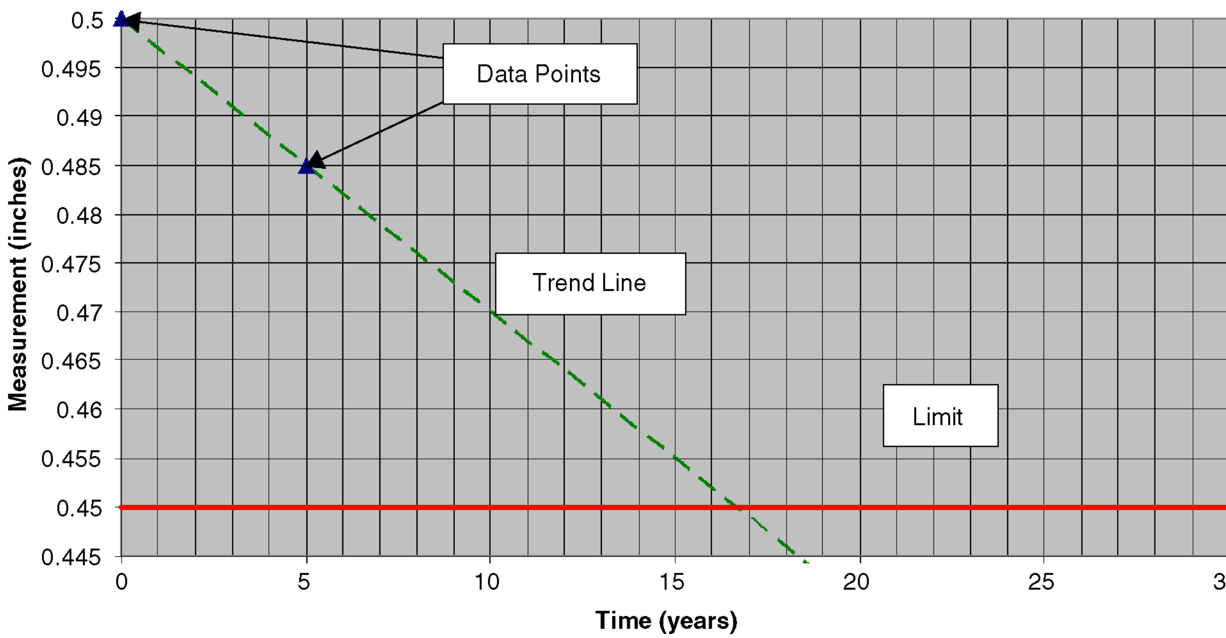
Data collected at the beginning of life included measurement of the casing thickness and pump flow at rated speed. Additional measurements such as impeller vane thicknesses, shroud thicknesses, and running clearances at bearings, bushings, and wear rings should be collected but are ignored here for simplicity of the example. This data was collected again at a five-year inspection. Results were analyzed to evaluate the expected life of the pump and are shown in Table 2-4.

Table 2-4
Hypothetical Measurements for End-of-Life Determination Example

	Data at Beginning of Life	Data at 5 Years	Limit
Casing thickness	0.500 inch	0.485 inch	0.450 inch
Flow at rated speed	5000 gpm	4940 gpm	4850 gpm

1 inch = 25.4 mm
1 gpm = 3.79 l/min

This data can be plotted and a trend developed to evaluate when the parameter would reach its limit for an estimation of the life of the pump. Figures 2-2 and 2-3 show the plots from the data in Table 2-4. The data points (shown as triangles and diamonds) represent the measurement, the dashed line represents the trend, and the thick solid line represents the limits. The figures show that the casing thickness reaches its limit at 16.5 years, whereas the flow limit is reached at 12.5 years. Based on these results, another detailed inspection should be done at between 10 and 12 years to evaluate the status of the trend and to provide a new estimate (from the latest trend) on the life expectancy of the pump.



1 inch = 25.4 mm

Figure 2-2
Casing Thickness

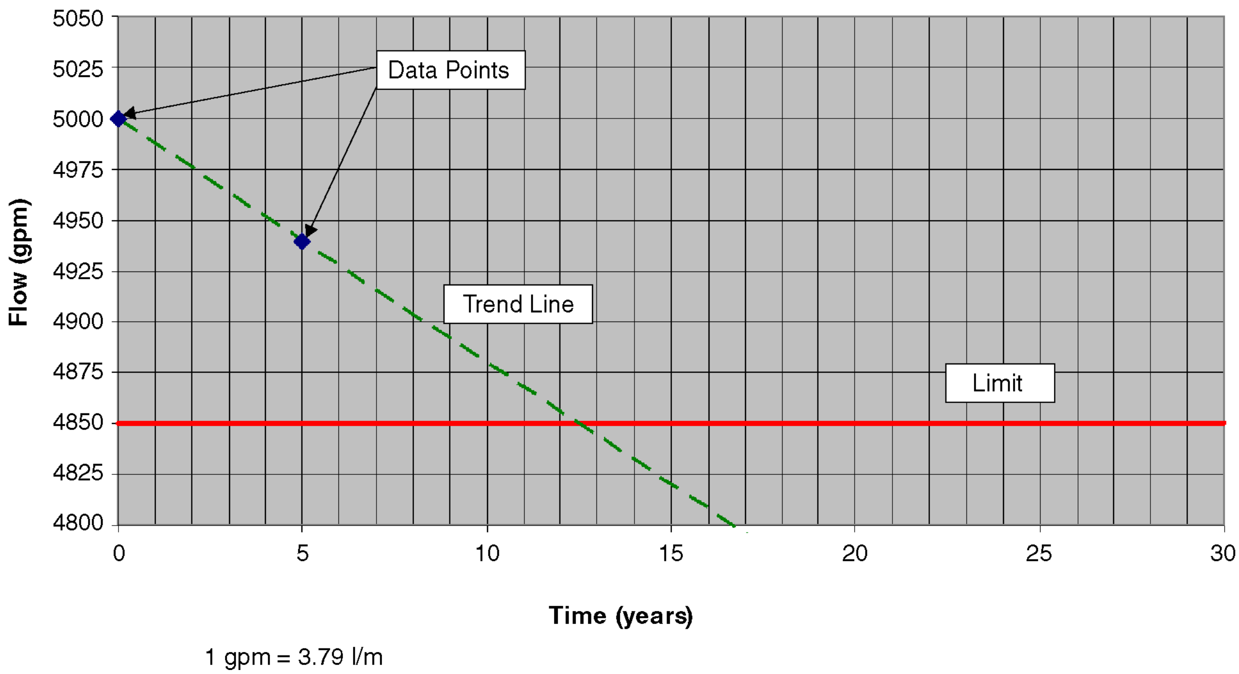


Figure 2-3
Flow Measurement

In addition to the trends viewed in the data, additional relationships should also be reviewed. For instance, the casing thickness in this example reduced by 0.015 inch (0.381 mm) or 3%, while flow reduced by 60 gpm (227 l/min) or 1.2%. If the casing wear could be related directly to flow, then another method exists to determine when the casing reaches its limit of a 10% reduction (0.050 inch [1.27 mm] wear). This casing reduction would not be directly measured until the next scheduled inspection; however, a 4% flow reduction could indicate a 10% casing thickness reduction. Care must be taken when analyzing relationships to ensure that they are valid. It is recognized that as normal wear progresses, the rate of wear slows, so that the straight-line approach may be conservative.

2.3.6 Comparison to Current EPRI Documents

Other EPRI resources exist that discuss periodicity for various maintenance practices for large vertical pumps. These include the EPRI PM Basis Database [4] and the report *Condensate Pump Application and Maintenance Guide* [5]. These two resources recommend pump overhaul on an "as required" basis, but neither references detailed internal inspections. Items in the EPRI resources should continue as currently listed, with the additional detailed inspections discussed in Section 2.3.4.

Table 2-5
EPIX Failure Summary (full search results are available only to INPO members)

Item Number	Failed Component	General Failure	Failure Indication	Description of Cause	Contributing Factors	PM Supporting Expected Life	Time from In-Service to Failure (Months)	Failure Predictable Using Vibration, Performance, Motor Current, or Thermography?
1	Bearing	Seized	Pump tripped during start.	Failure attributed to bushing degradation caused by improper installation.	Improper installation	Post-maintenance testing Vibration monitoring	0	No
2	Bearing	High vibration	Routine pump vibration data collection showed excessive vibrations.	Failure attributed to impeller imbalance, believed to have been caused by debris.	Design Wear from operation	Detailed inspection Vibration monitoring	0.07	No
3	Shaft	Operated, but not within specified parameters	High packing temperatures followed by high pump vibrations.	Failure attributed to a warped shaft caused by improper maintenance practices during recent repairs.	Improper maintenance practices Vibration	Detailed inspection Vibration monitoring	0.15	No
4	Bearing	High vibration	Following installation, vibration levels above alarm limits but below required action limits.	Failure attributed to improper assembly.	Improper assembly	Vibration monitoring	0.5	Yes

Table 2-5 (continued)
EPIX Failure Summary (full search results are available only to INPO members)

Item Number	Failed Component	General Failure	Failure Indication	Description of Cause	Contributing Factors	PM Supporting Expected Life	Time from In-Service to Failure (Months)	Failure Predictable Using Vibration, Performance, Motor Current, or Thermography?
5	Suction bell	Operated, but not within specified parameters	Pump motor current and vibration were erratic. Inspection by divers identified disconnected bellmouth (between casing and barrel).	Failure attributed to improper pump design for its application.	Design/ environment Inadequate instructions Vibration	Detailed inspection Vibration monitoring	1	No
6	Shaft	Seized	Pump tripped shortly after start; several flags dropped on breaker.	Failure attributed to a seized shaft caused by improper installation/ misalignment.	Improper installation Imbalanced impeller	Detailed inspection Alignment instructions	1	No
7	Shaft	Cracked	Pump discharge pressure dropped and abnormal noise noted while pump was running.	Failure attributed to a broken shaft. Shaft repaired during previous maintenance; previous repairs were inadequate.	Inadequate repairs from previous work	Detailed inspection Performance trending Rebuild plan	10	No

Table 2-5 (continued)
EPIX Failure Summary (full search results are available only to INPO members)

Item Number	Failed Component	General Failure	Failure Indication	Description of Cause	Contributing Factors	PM Supporting Expected Life	Time from In-Service to Failure (Months)	Failure Predictable Using Vibration, Performance, Motor Current, or Thermography?
8	Impeller	Operated, but not within specified parameters	During IST, pump discharge pressure exceeded required action limit for pump.	Failure attributed to impeller contact with casing due to pump running condition (causing shaft to stretch) and casing design. Condition was previously identified in a different report but action had not yet been implemented.	Design Operating below design point	Performance trending Detailed inspection	20	Yes
9	Suction bell	Operated, but not within specified parameters	Pump motor current and vibration were erratic. Inspection by divers identified disconnected bellmouth (disconnection between casing and barrel).	Failure attributed to improper pump design for its application.	Design/ environment Inadequate PM (recently increased inspection frequency) Vibration	Detailed inspection Vibration monitoring	20	No
10	Casing	Pump tripped	Pump tripped shortly after start; several flags dropped on breaker.	Failure attributed to increased loading on pump caused by distortion of the casing from pipe loading.	System loading (mechanical stress)	Detailed inspection	29	No

Table 2-5 (continued)
EPIX Failure Summary (full search results are available only to INPO members)

Item Number	Failed Component	General Failure	Failure Indication	Description of Cause	Contributing Factors	PM Supporting Expected Life	Time from In-Service to Failure (Months)	Failure Predictable Using Vibration, Performance, Motor Current, or Thermography?
11	Bearing	Operated, but not within specified parameters	Pump discharge pressure and motor current dropped while pump was running.	Failure attributed to bearing support assembly caused by fatigue.	Inadequate design Vibration	Detailed inspection Vibration monitoring Rebuild plan	34	No
12	Suction bell	Operated, but not within specified parameters	Pump discharge pressure dropped while pump was running.	Failure attributed to pitting corrosion combined with a defect in the parts utilized for the previous rebuild.	Cavitation/ erosion Vibration	Detailed inspection Performance trending Rebuild plan	36	No
13	Shaft	High vibration	While pump was operating, excessive lateral motion was witnessed by personnel.	Failure attributed to cracked shaft coating installed during the last maintenance period.	Vibration Wear from operation Design (material)	Design (materials) Vibration monitoring Detailed inspection	36	No
14	Bearing	High vibration	During IST, pump vibration levels exceeded the action required limits.	Failure attributed to worn bearings caused by wear due to normal operation.	Vibration Wear from operation Design (material)	Detailed inspection Vibration monitoring Rebuild plan	36	No

Table 2-5 (continued)
EPIX Failure Summary (full search results are available only to INPO members)

Item Number	Failed Component	General Failure	Failure Indication	Description of Cause	Contributing Factors	PM Supporting Expected Life	Time from In-Service to Failure (Months)	Failure Predictable Using Vibration, Performance, Motor Current, or Thermography?
15	Bearing	High vibration	Abnormal noise noticed during rounds.	Failure believed to have been caused by hard particles (debris) or electrolysis (inadequate grounding).	Vibration Wear from operation Foreign material Inadequate grounding	Detailed inspection Vibration monitoring	42	No
16	Shaft	Cracked	Pump discharge pressure and motor current dropped while pump was running.	Failure attributed to fatigue failure of shaft caused by an imbalance leading to excessive vibrations. Pump design (no lower bearing) contributed to the failure.	Design Vibration Misalignment	Detailed inspection Vibration monitoring	43	No

Table 2-5 (continued)
EPIX Failure Summary (full search results are available only to INPO members)

Item Number	Failed Component	General Failure	Failure Indication	Description of Cause	Contributing Factors	PM Supporting Expected Life	Time from In-Service to Failure (Months)	Failure Predictable Using Vibration, Performance, Motor Current, or Thermography?
17	Bearing	High vibration	During IST, pump vibration levels noted to have significantly increased above action required limits.	Failure attributed to inadequate structural support combined with normal wear. Over time, caused pump to operate at/near resonance peak (resonance point decreases as bearing clearances increase/stiffness decreases).	Structural support design Wear from operation	Vibration monitoring	51	Yes
18	Bearing	Excessive wear/ cracking	Excessive packing leakage noted while pump was operating; packing adjustments failed to stop leak. Packing was replaced and then ejected during pump operation.	Failure attributed to a cracked upper bearing sleeve. Crack formation was a result of H_2 embrittlement due to a chemical attack resulting from previous excessive release of sulfuric acid into the system.	Environment (excess sulfuric acid introduction) Wear from operation	Detailed inspection	60	No

Table 2-5 (continued)
EPIX Failure Summary (full search results are available only to INPO members)

Item Number	Failed Component	General Failure	Failure Indication	Description of Cause	Contributing Factors	PM Supporting Expected Life	Time from In-Service to Failure (Months)	Failure Predictable Using Vibration, Performance, Motor Current, or Thermography?
19	Coupling	Cracked	During system surveillance testing, pump discharge pressure and motor current dropped significantly.	Failure attributed to cracked coupling. Crack formation was caused by IGSCC.	Environment Corrosion Vibration	Visual inspection Vibration monitoring	60	No
20	Shaft	Pump tripped	Pump tripped.	Failure attributed to cracked shaft from inadequate design and failure to implement approved design change.	Inadequate design Vibration Inadequate change management	Detailed inspection Vibration monitoring Rebuild plan	71	No
21	Impeller	Operated, but not within specified parameters	Pump discharge pressure and flow were below acceptable levels during a surveillance test.	Failure attributed to impeller wear caused by environment (sandy water).	Wear from operation Frequent impeller lift adjustments Known condition, modification prepared to correct but not installed	Detailed inspection Performance trending	84	Yes

Table 2-5 (continued)
EPIX Failure Summary (full search results are available only to INPO members)

Item Number	Failed Component	General Failure	Failure Indication	Description of Cause	Contributing Factors	PM Supporting Expected Life	Time from In-Service to Failure (Months)	Failure Predictable Using Vibration, Performance, Motor Current, or Thermography?
22	Shaft	Cracked	Pump tripped due to electrical fault.	Failure attributed to shaft failure caused by SCC/manufacturer's defect.	Environment Corrosion Vibration	Detailed inspection Vibration monitoring Performance trending	105	No
23	Casing	Operated, but not within specified parameters	Pump discharge pressure decreased with abnormal noise evident.	Failure attributed to high cycle fatigue of the diffuser vanes.	Design Vibration	Detailed inspection Vibration monitoring Performance trending	127	No
24	Bearing	Operated, but not within specified parameters	Pump high vibrations and high O_2 concentration.	Failure attributed to cracked pump shell at lower bushing due to fatigue in heat-affected zone.	Vibration	Detailed inspection Vibration monitoring Rebuild plan	142	No

Table 2-5 (continued)
EPIX Failure Summary (full search results are available only to INPO members)

Item Number	Failed Component	General Failure	Failure Indication	Description of Cause	Contributing Factors	PM Supporting Expected Life	Time from In-Service to Failure (Months)	Failure Predictable Using Vibration, Performance, Motor Current, or Thermography?
25	Casing	Operated, but not within specified parameters	IST previously performed at partial flow point. Test point changed to pump reference point; results showed pump performance significantly lower than expected.	Failure attributed to normal wear of the pump internals. Pump passed at lower flows, but not at higher flows (reference point) where effects of increased internal clearances are more pronounced.	Wear from operation Corrosion (pipe scale) Test method	IST trending Detailed inspection Rebuild plan	144	Yes
26	Shaft sleeve	Cracked	Routine vibration data collection indicated a potential crack in the shaft.	Failure attributed to a cracked shaft sleeve for the journal bearing. Exact cause was not determinable but is believed to have been a fatigue failure.	Operation Environment Vibration	Detailed inspection Vibration monitoring	156	Yes
27	Suction bell	Operated, but not within specified parameters	Suction bell bolts found loose during an inspection (loose bolts between bellmouth and barrel).	Failure attributed to inadequate PM instructions.	Environment Inadequate PM	Detailed inspection Vibration monitoring	174	Yes

Table 2-5 (continued)
EPIX Failure Summary (full search results are available only to INPO members)

Item Number	Failed Component	General Failure	Failure Indication	Description of Cause	Contributing Factors	PM Supporting Expected Life	Time from In-Service to Failure (Months)	Failure Predictable Using Vibration, Performance, Motor Current, or Thermography?
28	Bearing	Pump tripped	Pump tripped while running.	Failure attributed to loss of lubrication to the lower bearing.	Inadequate lubrication	Oil analysis Vibration monitoring Motor current trending Rebuild plan	192	No
29	Shaft	Cracked	During IST, pump discharge pressure and flow at the required action limit.	Failure attributed to cracked shaft due to IGSCC.	Environment Corrosion Vibration Inadequate review of OE Repeat decisions to delay overhaul/ inspection of pump	Detailed inspection Vibration monitoring	252	Yes

Table 2-5 (continued)
EPIX Failure Summary (full search results are available only to INPO members)

Item Number	Failed Component	General Failure	Failure Indication	Description of Cause	Contributing Factors	PM Supporting Expected Life	Time from In-Service to Failure (Months)	Failure Predictable Using Vibration, Performance, Motor Current, or Thermography?
30	Impeller	Operated, but not within specified parameters (air bound)	During IST, pump discharge pressure and flow below acceptance criteria with slightly higher motor current and vibrations.	Failure attributed to pieces of wood in pump suction well left from a design change installation 18 years earlier.	Foreign material in suction	Visual inspection after maintenance Performance trending	276	Yes
31	Coupling	Cracked	Pump discharge pressure and motor current dropped while pump was running.	Failure attributed to a cracked coupling. Pump operation at resonant point led to loosening of diffuser bearing assembly, causing contact with the impeller. This condition led to fatigue failure of the coupling.	Vibration Operating below design point	Vibration monitoring Operating procedures	288	No
32	Bearing	High vibration	During IST, pump vibration levels significantly exceeded the action required limits.	Failure attributed to improper installation of upper bearing.	Vibration Wear from operation	Detailed inspection Vibration Monitoring	312	No

Table 2-5 (continued)
EPIX Failure Summary (full search results are available only to INPO members)

Item Number	Failed Component	General Failure	Failure Indication	Description of Cause	Contributing Factors	PM Supporting Expected Life	Time from In-Service to Failure (Months)	Failure Predictable Using Vibration, Performance, Motor Current, or Thermography?
33	Impeller	Operated, but not within specified parameters	Pump motor current noted to be pegged high.	Failure attributed to erosion of the pump impeller caused by incorrect material being used.	Design (material selection) Erosion	Detailed inspection Vibration monitoring Performance trending	312	No
34	Bearing	High vibration	During IST, vibration levels were above alarm limits but below required action limits. Follow-up testing was performed indicating vibrations in the acceptable range.	Vibrations attributed to wear from normal operation.	Vibration Wear from operation Design (material)	Detailed inspection Vibration monitoring	342	Yes

Note: Shaded rows represent end-of-life-type failures that are not indicative of typical pump life; failures were caused by personnel error or operation in the presence of a stressor such as a manufacturing defect, improper application, or environment that does not normally exist. The data associated with these failures is included in the analysis to help identify the point at which "special cause" failures are less prevalent—in this case at approximately five years (see Figure 2-1).

3
CONDITION MONITORING

3.1 On-Line Monitoring

Effective methods of condition monitoring have been developed and are discussed in detail in various EPRI documents. A brief summary of these methods can be found in Table 3-1. Detailed discussion regarding data collection and analysis can be found in the following documents:

- *Deep Draft Vertical Centrifugal Pump Maintenance and Application Guide* [2]
- *Vertical Pump Maintenance Guide, Supplement to NP-7413* [3]
- *Condensate Pump Application and Maintenance Guide* [5]
- *Pump Troubleshooting, Volume 1* [6]

Table 3-1
Typical Condition Monitoring Techniques

Condition Monitoring Technique	Factors Affecting Severity	General Cause	Comments
Vibration monitoring and trending	Unbalance	Inadequate dynamic balance of subcomponents (after maintenance/ refurbishment/ commissioning of new pump) Component material loss or damage Bowing of the shaft	Frequency corresponding to 1x rotational speed, primarily in radial direction. Amplitude increase with speed.

Table 3-1 (continued)
Typical Condition Monitoring Techniques

Condition Monitoring Technique	Factors Affecting Severity	General Cause	Comments
Vibration monitoring and trending (cont.)	Misalignment	Dimensional clearance and concentricity of alignment fits Perpendicularity of alignment faces to the shaft axis Parallelism of the alignment faces to each other	Frequency corresponding to 1x rotational speed and its harmonics. Amplitude increases with speed.
	Mechanical looseness	Rabbet fits loose Loose or inadequate bolting Loose pump foundation joint (improper or broken grout) Lack of crush between the bearing and its support Increased clearance between the bearing and journal	Frequency corresponding to 1x rotational speed and its harmonics, possibly including ½ harmonics (1½x, 2½x, etc.). Amplitudes in radial and axial directions.
	Resonance	Pump/structural issues	Must identify ways to alter the natural frequency of either the structure or the rotating equipment.
	Hydraulic instability	Cavitation	Broadband vibration in the 3–5 kHz range.
		Flow separation at the impeller inlet; often accompanied by cavitation	4–10 Hz and 0.55x–0.90x. Also signs of cavitation.
		Recirculation at the impeller outlet and casing inlet	4–10 Hz and 0.55x–0.90x. Vane pass frequency.
		Impact loading of the exiting impeller flow on the stationary casing vanes	Vane pass frequency.

Table 3-1 (continued)
Typical Condition Monitoring Techniques

Condition Monitoring Technique	Factors Affecting Severity	General Cause	Comments
Vibration monitoring and trending (cont.)	Hydraulic instability (cont.)	Flow separation at the discharge elbow	4–10 Hz and 0.55x–0.90x.
		Operation in the unstable portion of the pump curve	Random vibration frequency and widely varying amplitudes.
		Hydraulic resonance in the piping system	Discharge pipe natural frequency (flow resonance).
	Sump-induced vibration	Inadequate sump design	Additional guidance and references provided in Appendix D of *Deep Draft Vertical Centrifugal Pump Maintenance and Application Guide* [2].
Pump performance testing/trending	Head variation	Incorrect initial specifications Wear Operation at unstable point on head/flow curve Subcomponent damage	Parameters to monitor (ideal would be to monitor all): • Flow • Suction pressure • Suction temperature • Discharge pressure • Discharge temperature • Motor Input power • Motor voltage • Motor current • Motor speed • Bearing temperature Thermodynamic performance testing has significant potential to improve knowledge of pump condition.

Table 3-1 (continued)
Typical Condition Monitoring Techniques

Condition Monitoring Technique	Factors Affecting Severity	General Cause	Comments
Motor current trending	High motor current	Operation at lower flow rates Increased motor thrust bearing friction Internal rubbing Incorrectly adjusted packing	Combination of general causes could result in pump trip due to motor over-current condition.
Thermography (if bearing accessible) or direct temperature measurement (if available)	High temperature	Inadequate lubrication/cooling to bearings Increased bearing load Improper bearing materials	High temperature typically accompanied by additional indications (such as higher vibrations, higher motor current, or reduced performance).

Other methods of monitoring include external and internal inspections. These methods require the pump to be taken out of service to allow adequate access. Maintenance and inspection methods have been developed over the years. A key practice is to trend the results of inspections (especially dimensions, presence of pitting, and so on) through use of databases, photographs, videos, and so on, and compare these results with the trending data from condition monitoring results. Correlation between the results obtained in condition monitoring and inspections must be developed to provide the best indication of the pump's overall condition and prediction of pump life.

3.2 Off-Line Monitoring

Off-line monitoring consists primarily of inspections but may consist of specific pump testing and condition monitoring for some plants. A number of plants have the flexibility to take one pump out of service at a time without any impact on plant operation. However, certain inspections (such as use of divers) may require plant shutdown to allow personnel entry.

If detailed pump inspections cannot be performed on-line, then detailed off-line inspections are highly recommended. Internal inspections can confirm/diagnose indications seen in condition monitoring, quantifying the extent of the condition and identifying deterioration that is not shown in condition monitoring. As shown in Table 2-5, 70% of the failures reported were not predicted by normal condition monitoring methods. Although many of failures showed indications identified by normal condition monitoring, the failure was not predicted. Internal inspections would have been required to identify the degradation mechanism. A combination of condition monitoring (such as vibration, performance, motor current, and thermography) with internal inspection provides the best approach for predicting failures and evaluating pump life.

4
LOGISTICS OF COMPONENT REPLACEMENT

There is wide variation among large vertical pump manufacturers and pump models found throughout the industry. Table 4-1 provides a list of some of them.

The main aging effects in large vertical pumps are wear and erosion/cavitation. Unfortunately, these mechanisms are applicable to a majority of the pump subcomponents. Plant history would be a decent indicator of which subcomponents are most limiting for a given application. History along with criticality of the pump should be taken into consideration when evaluating the need for spare parts and/or spare pumps as well as the overall approach to take concerning the end of life for the pump.

Table 4-1
Large Vertical Pump Manufacturers/Models

Pump Manufacturer	Model	Pump Manufacturer	Model
Allis Chalmers Corp.	42x24WMCE	Ingersoll-Rand	30APKD-12
Allis Chalmers Corp.	H16X12-VTMC3	Ingersoll-Rand	30APKD-2
Allis Chalmers Corp.	VTMC-2	Ingersoll-Rand	30APKD-3
Aurora Pump	20KM	Ingersoll-Rand	30APKD-7
Aurora Pump	5K6286XH42A	Ingersoll-Rand	30APKD-8
Babcock & Wilcox Canada, Ltd.	42083	Ingersoll-Rand	30APKD-9
Babcock & Wilcox Canada, Ltd.	642157	Ingersoll-Rand	32APKD-10
Babcock & Wilcox Canada, Ltd.	10X12X21 KSMK	Ingersoll-Rand	32APKD-3
Babcock & Wilcox Canada, Ltd.	10X14X22-NHSH	Ingersoll-Rand	32APKD-4
Babcock & Wilcox Canada, Ltd.	2650-40	Ingersoll-Rand	32APKD-6
Babcock & Wilcox Canada, Ltd.	6X8X13 SMK	Ingersoll-Rand	32APKD-8

Table 4-1 (continued)
Large Vertical Pump Manufacturers/Models

Pump Manufacturer	Model	Pump Manufacturer	Model
Babcock & Wilcox Canada, Ltd.	78BN	Ingersoll-Rand	32APKD-9
Baldwin-Hamilton Co.	SAFV	Ingersoll-Rand	34APKD-3
Byron-Jackson	1549-3LF	Ingersoll-Rand	34APKD-4
Byron-Jackson	18CKXH	Ingersoll-Rand	34APKD-6
Byron-Jackson	24KXH	Ingersoll-Rand	34APKD-7
Byron-Jackson	28DX 18.5CKXL	Ingersoll-Rand	34APKD-8
Byron-Jackson	28DX18CKXL	Ingersoll-Rand	36APKD-2
Byron-Jackson	28DX21CKXL	Ingersoll-Rand	36APKD-3
Byron-Jackson	28HC FIG 6927	Ingersoll-Rand	36APKD-4
Byron-Jackson	30DX19CKXLH-13STG	Ingersoll-Rand	36APKD-6
Byron-Jackson	30DX19CXL12-13STG	Ingersoll-Rand	36APKD-7
Byron-Jackson	30-DX20CKXCH2	Ingersoll-Rand	47APM
Byron-Jackson	30DX-20-CKXH	Ingersoll-Rand	69APMA
Byron-Jackson	30DX21CXKL	Ingersoll-Rand	6UC
Byron-Jackson	32KXH	Ingersoll-Rand	6UCL
Byron-Jackson	32RXL	Ingersoll-Rand	6X17LP
Byron-Jackson	37KXL	Ingersoll-Rand	6X23WD
Byron-Jackson	43DX-28	Ingersoll-Rand	73APS
Byron-Jackson	43DX-30KXH	Ingersoll-Rand	79APMA
Byron-Jackson	6X10X18V-DSM	Ingersoll-Rand	80APH
Byron-Jackson	DVSS	Ingersoll-Rand	83APMA
Byron-Jackson	DWT	Ingersoll-Rand	8X20 W
Byron-Jackson	SMJ	Ingersoll-Rand	8X20 WD
Byron-Jackson	VCT-12X12X17 DVSS 1	Ingersoll-Rand	8X20 WDF
Byron-Jackson	VCT-16GH	Ingersoll-Rand	8X21 ALH
Byron-Jackson	VCT-20KXL	Ingersoll-Rand	8X23 WDF
Byron-Jackson	VCT-24 BXF	Ingersoll-Rand	APKD
Byron-Jackson	VCT-24KXH 2-STG	Ingersoll-Rand	INLINER 1 ½ VK-3

Table 4-1 (continued)
Large Vertical Pump Manufacturers/Models

Pump Manufacturer	Model	Pump Manufacturer	Model
Byron-Jackson	VCT-28KXH-1STG	Ingersoll-Rand	Type APKC
Byron-Jackson	VCT-28RXL-2STG	Ingersoll-Rand	Type W
Byron-Jackson	VCT-30KXE-1STG	Ingersoll-Rand	Type WDF
Byron-Jackson	VCT-32RXL-28KXL-2STG	Johnston Pump Co.	1226
Byron-Jackson	VCT-33WX-1STG	Johnston Pump Co.	12DC-5STG
Byron-Jackson	VCT-36RXL-2STG	Johnston Pump Co.	16PS
Byron-Jackson	VCT-37KXH-2STG	Johnston Pump Co.	18 DC-7STG
Byron-Jackson	VCT-37KXL-1STG	Johnston Pump Co.	18-CC-6
Byron-Jackson	VCT-80VX	Johnston Pump Co.	18DC
Byron-Jackson	VCT-81PMR	Johnston Pump Co.	2-27CC
Byron-Jackson	V-DSM-6X10X18	Johnston Pump Co.	22NMC
Byron-Jackson	VMT	Johnston Pump Co.	24 EC, 3STG
Byron-Jackson	VMT-16R-14R-8STG	Johnston Pump Co.	24EC
Byron-Jackson	VMT-18CKXH	Johnston Pump Co.	24QXC/QMC
Byron-Jackson	VMT-18X24X38	Johnston Pump Co.	27CC
Byron-Jackson	VMT-20CKX-H0-L13-14STG	Johnston Pump Co.	27CC 2 STG
Byron-Jackson	VMT20CKXH-H7L6	Johnston Pump Co.	27DC-24QMC
Byron-Jackson	VMT-24CKX-H0-H9-10STG	Johnston Pump Co.	28NMC 3STG
Byron-Jackson	VMT-24KX-6STG	Johnston Pump Co.	3-CC-42
Byron-Jackson	VMT-24KX-8STG	Johnston Pump Co.	30C5-2
Byron-Jackson	VMT-24KXH-10STG	Johnston Pump Co.	30-CC-2
Byron-Jackson	VMT-24KXH-7STG	Johnston Pump Co.	30-CS
Byron-Jackson	VMT-24KXH-H6-7STG	Johnston Pump Co.	30IN DC 2STG
Byron-Jackson	VMT-24KXHOH76-7STG	Johnston Pump Co.	33CMC
Byron-Jackson	VMT-24RXL-16KXH-7STG	Johnston Pump Co.	GB-2558-64
Byron-Jackson	VMT-28CKX-H0-8STG	Johnston Pump Co.	NE2374

Table 4-1 (continued)
Large Vertical Pump Manufacturers/Models

Pump Manufacturer	Model	Pump Manufacturer	Model
Byron-Jackson	VMT-28CKXH-8STG	KSB (Klein Schanzlin and Becker Pumpen GmbH)	R01
Byron-Jackson	VMT-28-H0-3STG	Layne & Bowler	16EHH-7STG
Byron-Jackson	VMT-28KX-2STG	Layne & Bowler	16FHH-2STG
Byron-Jackson	VMT-28KXFH	Layne & Bowler	18FXH
Byron-Jackson	VMT-28KXH	Layne & Bowler	24RKMC
Byron-Jackson	VMT-28KX-H0-7STG	Layne & Bowler	25RHHL2
Byron-Jackson	VMT-28KX-H0-H2-8STG	Layne & Bowler	28SK
Byron-Jackson	VMT-28KX-H0-H6-7STG	Layne & Bowler	28SKK-3STG
Byron-Jackson	VMT-28KXH-2STG	Layne & Bowler	350SW20K2
Byron-Jackson	VMT-28KXH-8STG	Layne & Bowler	91F-3472-01-02
Byron-Jackson	VMT-32KXF1H2	Layne & Bowler	S/0 D26081
Byron-Jackson	VMT-32KX-H0-3STG	Pacific Pumps Division/Dresser Industries	8X20-SFP
Byron-Jackson	VMT-32KXL	Pacific Pumps Division/Dresser Industries	8X24-SPF
Byron-Jackson	VMT-33DX-21CKXH-4STG	Pacific Pumps Division/Dresser Industries	SAC
Byron-Jackson	VMT-40DX-28KXH	Pacific Pumps Division/Dresser Industries	SPF
Byron-Jackson	VMT-43DX-30CKX-6STG	Pacific Pumps Division/Dresser Industries	SPF-8X20-1STG
Byron-Jackson	VMT-5RL	Pacific Pumps Division/Dresser Industries	WYR-20X31M
Byron-Jackson	VMT-DSJH	Pacific Pumps Division/Dresser Industries	WYRF-10X16

Table 4-1 (continued)
Large Vertical Pump Manufacturers/Models

Pump Manufacturer	Model	Pump Manufacturer	Model
Byron-Jackson	VTP	Pacific Pumps Division/Dresser Industries	WYRF-6X10
Byron-Jackson Pumps Division/Borg Warner	18CKXFL9 10STG	Peerless Pump	18HH
Byron-Jackson Pumps Division/Borg Warner	33WX 1-Stage VCT	Peerless Pump	24HH-1
Byron-Jackson Pumps Division/Borg Warner	DFSS	Peerless Pump	24HXB-1(PE1X2X8)
Byron-Jackson Pumps Division/Borg Warner	KX	Peerless Pump	24MA
Byron-Jackson Pumps Division/Borg Warner	RX	Peerless Pump	36HXB
Byron-Jackson Pumps Division/Borg Warner	VHT	Peerless Pump	36HXB
Colt Industries, Inc.	HC FIG 6927	Peerless Pump	9LA
Fairbanks-Morse	5712	Peerless Pump	VT-18HH-2STG
Fairbanks-Morse	34 HC FIG 7000	Peerless Pump	VT-18HH-2STG
Foster Wheeler	TVKH 40 D4	Sulzer Bingham Pumps, Inc.	10X12X14.5 CVDS
Foster Wheeler	VKH 40 D4	Sulzer Bingham Pumps, Inc.	10X12X18B-VCR
General Electric	5K831166A7	Sulzer Bingham Pumps, Inc.	10X18B-J-VCR
Goulds Pumps, Inc.	10AHX-AHC	Sulzer Bingham Pumps, Inc.	10X18B-VCR
Goulds Pumps, Inc.	VIT	Sulzer Bingham Pumps, Inc.	12X14X14.5 CVDS
Goulds Pumps, Inc.	VIT-12X16DHLC	Sulzer Bingham Pumps, Inc.	12X16X14.5 CVDS
Goulds Pumps, Inc.	VIT-20X30BLC-2STG	Sulzer Bingham Pumps, Inc.	12X18X28 CVIC
Goulds Pumps, Inc.	VIT-8X12JMC	Sulzer Bingham Pumps, Inc.	16X20X29

Table 4-1 (continued)
Large Vertical Pump Manufacturers/Models

Pump Manufacturer	Model	Pump Manufacturer	Model
Goulds Pumps, Inc.	VIT-8X14JMC	Sulzer Bingham Pumps, Inc.	18X24X28X-1STG CVIC
Goulds Pumps, Inc.	VIT-FF	Sulzer Bingham Pumps, Inc.	18X27BVCM
Goulds Pumps, Inc.	VITX-SD-10X14JHC	Sulzer Bingham Pumps, Inc.	18X34B-VCM-1STG
Goulds Pumps, Inc.	VIT-XSD12X18HMC-2	Sulzer Bingham Pumps, Inc.	20X30X34A-5STG
Goulds Pumps, Inc.	VIT-XSD20X28BHC-2STG	Sulzer Bingham Pumps, Inc.	24X36 VLTM
Goulds Pumps, Inc.	VIT-XSD-24X30BLC	Sulzer Bingham Pumps, Inc.	30X44C-VTM-2STG
Goulds Pumps, Inc.	VIT-XUD 24X30 BHC/1	Sulzer Bingham Pumps, Inc.	8X14AVCM
Hayward-Tyler Pump Co.	166RW	Sulzer Bingham Pumps, Inc.	CVDS
Hayward-Tyler Pump Co.	18X23 VSN	Sulzer Bingham Pumps, Inc.	CVDS M1JJ-49-1
Hayward-Tyler Pump Co.	24VSN	Sulzer Bingham Pumps, Inc.	CVIC
Hayward-Tyler Pump Co.	32X42 VS01	Sulzer Bingham Pumps, Inc.	VCM
Ingersoll-Rand	106APH	Sulzer Bingham Pumps, Inc.	VCR
Ingersoll-Rand	115APH	Sulzer Bingham Pumps, Inc.	VLTM-1D471
Ingersoll-Rand	12 NA	Sulzer Bingham Pumps, Inc.	VTM
Ingersoll-Rand	12X20 KD-8	Sulzer Bingham Pumps, Inc.	VTR
Ingersoll-Rand	25 APK-2	Sulzer Bingham Pumps, Inc.	VTR-18X30X26B
Ingersoll-Rand	25APKD-6	Westinghouse	W-11006-A1 93A
Ingersoll-Rand	25APKD-7	Worthington Pump	10M50-W-3
Ingersoll-Rand	25APKD-8	Worthington Pump	14QL-18

Table 4-1 (continued)
Large Vertical Pump Manufacturers/Models

Pump Manufacturer	Model	Pump Manufacturer	Model
Ingersoll-Rand	25APKD-9	Worthington Pump	15H-277-6S
Ingersoll-Rand	25APKD-10	Worthington Pump	15HH-410-2S
Ingersoll-Rand	26 APK-1	Worthington Pump	15HH-410-6
Ingersoll-Rand	27APKD-5	Worthington Pump	20H-500-W-2
Ingersoll-Rand	27APKD-7	Worthington Pump	20QL-26
Ingersoll-Rand	27APKD-8	Worthington Pump	22HH670W
Ingersoll-Rand	27APKD-9	Worthington Pump	24-NA-38 HD
Ingersoll-Rand	28APKD-2	Worthington Pump	28HH-1475
Ingersoll-Rand	29APKD-3	Worthington Pump	28QEC-8
Ingersoll-Rand	29APKD-5	Worthington Pump	330EAC4VTP
Ingersoll-Rand	29APKD-6	Worthington Pump	33QEAC4
Ingersoll-Rand	29APKD-9	Worthington Pump	Type H
Ingersoll-Rand	30APKD-10	Worthington Pump	Type WGID

4.1 Parts Availability

Availability of parts is a major issue when repairs are needed on large vertical pumps. Some subcomponents may be stocked by vendors. However, the larger, more expensive subcomponents are typically manufactured on an as-needed basis, and spares are not readily available. Lead times for new subcomponents could be several months to over a year. Although costly, an agreement could be reached with a vendor to expedite the order and reduce the lead time by a few weeks. Reliance on expediting parts should be avoided, because it cannot always be accomplished. This applies to complete pump assemblies as well, especially for more unique pumps. Because pump manufacturers typically obtain subcomponents from other vendors, they too have lead-time issues, which would cause even longer lead times for a plant to order a new pump than to obtain subcomponents. Many pump vendors, both OEM and aftermarket shops, offer reverse engineering services. Long lead times and high costs can be reduced by using the reverse engineering option. The same quality standards required of the OEM should be applied to reverse engineering options.

As shown in Table 4-1, there are many varieties of pumps in service in the nuclear power industry. That being said, the same manufacturer and model pump installed at one plant is very possibly also in service at a different plant. When responding to a pump failure, the fastest way to obtain parts may be to purchase used parts, purchase parts from a different facility, or refurbish the current parts.

4.2 Repair Times

Repair times for failures that are end-of-life failures can range from days to months. Long repair times may be considered acceptable, depending on the pump application. If an excess capacity (both physical excess and in terms of the technical specifications) exists, there may be no direct plant impact other than the increased risk associated with a train being out of service.

Table 4-2 compares repair time considerations for planned and unplanned repairs.

Table 4-2
Repair Time Considerations

	Planned Repair	Unplanned Repair
Lead time for parts	Up to several months. Parts procured in advance of maintenance to eliminate impact on repair time.	Up to several months. Repairs delayed while awaiting parts. If possible to expedite, cost of parts for repair is greatly increased.
Vendor support	Vendor support is available.	Vendor support difficult to obtain and more costly.
Rigging equipment	Equipment is readily available either on-site or by leasing.	If leasing required, equipment typically available but may be more costly.
Work instructions	Sufficient time exists for creation of work instructions.	Although work instructions can be completed in a relatively short time for emergent issues, an increased risk of error is created. One way to minimize risk is to preplan emergent work items based on plant history and industry OE.
Maintenance qualification	Sufficient time exists for maintenance personnel to review work instructions and become familiar with infrequent items by walkdowns and/or training.	Although qualified maintenance personnel and vendors are typically available, due to an aging workforce experienced personnel are being lost to retirement. The loss of skilled craft has a particularly big impact when there are unplanned repairs because newer workers may be less equipped to undertake repairs without an ample amount of preparation time. Lack of preparation time can increase the time needed to perform the actual work.

Table 4-2 (continued)
Repair Time Considerations

	Planned Repair	Unplanned Repair
Repair location	Several plants have the capability to perform an in-house refurbishment of any pump. However, depending on the work required, a larger number ship the pump to a vendor for complete refurbishment.	Several plants have the capability to perform an in-house refurbishment of any pump. However, depending on the work required, a larger number ship the pump to a vendor for complete refurbishment.
Plant impact	Minimal impact. Work planned as required to prevent impact to generation.	Unknown until failure occurs and extent of condition evaluated.

4.3 Shipping/Storage Issues

As discussed above, spare parts and/or pumps should be maintained on-site depending on pump criticality and plant history. Several parts may be stored with the intention of never using them. Long-term storage presents challenges associated with various factors such as temperature, humidity, dust, damage from adjacent parts, damage due to improper support, and so on. While in storage, parts should still be maintained (lubricated, cleaned, rotated, provided with elastomer replacement, and so on).

Shipping parts (subcomponents and pumps) presents the same challenges as long-term storage, along with some additional ones. Besides a need for providing physical support for storage, there is a need for additional physical support during shipping to account for increased load from the transit (turns, bumps, acceleration, and so on). When pumps have been installed in contaminated systems, radiological controls add increased complexity. This must be taken into consideration in both shipping and determining the facility's ability to handle the radiological components upon receipt.

4.4 Refurbishment

Refurbishment of pumps entails several options that affect cost and risk. Some of these items were discussed in Section 4.2, such as where the repairs will be performed and who will perform the repairs. Additional consideration should also be given to the parts utilized. A determination must be made about using new parts, refurbishing existing parts, or utilizing used parts. Methods of repair for parts (such as weld repairs, use of epoxy, and so on) already exist and are discussed in the following documents:

- *Deep Draft Vertical Centrifugal Pump Maintenance and Application Guide* [2]
- *Vertical Pump Maintenance Guide, Supplement to NP-7413* [3]
- *Condensate Pump Application and Maintenance Guide* [5]

Utilization of used parts introduces risk stemming from the unknown condition and previous operating history of the parts. This risk should be carefully considered prior to utilizing these parts in critical pumps that could affect plant safety or operation. Inspection, testing, and nondestructive examination can be used to reduce the risks associated with utilization of used parts.

5
CONCLUSIONS

Industry failure information was reviewed to identify failures that are typical of end of life of large vertical pumps. Table 2-5 shows the results of this search and indicates that end-of-life-type failures may occur between one year and thirty years into the pump life; however, failures that occur prior to the five-year point typically share a special cause such as a harsh environment. This wide range is due to a variety of aging factors that can be found in Table 2-1. Methods that are useful in evaluating the pump condition are identified in Table 3-1. Details regarding pump maintenance methods, condition monitoring techniques, and troubleshooting can be found in various EPRI documents. The following documents present methods that should be reviewed and implemented to aid in evaluating the pump's condition:

- *Deep Draft Vertical Centrifugal Pump Maintenance and Application Guide* [2]
- *Vertical Pump Maintenance Guide, Supplement to NP-7413* [3]
- *Condensate Pump Application and Maintenance Guide* [5]
- *Pump Troubleshooting, Volume 1* [6]
- *Pump Troubleshooting, Volume 2* [7]

Since 1997, there have been only 24 end-of-life-type failures (34 were reported; 10 of those were considered either infant mortality or failures due to abnormal circumstances). Existing maintenance and condition monitoring methods, as described in the above sources, are effective, but it is recommended to perform a detailed visual inspection within the first five years (sooner in known harsh environments) of pump life to ensure that a special cause is not contributing to reduced pump life and to develop a correlation between actual pump condition and condition monitoring parameters. This correlation can be useful in estimating the individual pump life expectancy. In addition, because over half of the end-of-life-type failures that occurred would have had no direct indication from condition monitoring alone, a detailed inspection should be performed at some point that is determined based on condition monitoring trends, pump environment, initial inspection results, plant history, and criticality of the pump.

Each pump will eventually reach the end of its life. The point at which a plant should shift from basic condition monitoring to more detailed monitoring including internal inspection and measurements varies from plant to plant and from pump to pump. This point is dependent on trends established through condition monitoring, presence of aging factors (pump environment), and plant history. Once the pump life expectancy is determined, then more detailed maintenance should be scheduled (such as more frequent detailed inspections) as that time approaches. In addition, a contingency plan and pump refurbishment/replacement plan should be developed along with arrangement for parts based on the criticality of the pump and the cost associated with each path.

6
REFERENCES

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6. *Pump Troubleshooting, Volume 1*. EPRI, Palo Alto, CA: 2000. TR-114612-V1.
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A
TRANSLATED TABLE OF CONTENTS

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Electric Power Research Institute (EPRI)

プラントサポートエンジニアリング: 大型縦置きポンプ予想耐用年数報告書

1019154

最終報告 2009年12月

製品説明

本報告書の目的は、原子力発電所マネージャーおよび構成部品 / システムのエンジニアに大型縦置きポンプの耐用年数の検討に関する指針を提供することです。特に、耐用年数による故障を防ぐため、または故障の影響を管理可能にするために緊急事態対応または改修 / 交換計画が必要な場合に、ポンプの寿命の判定を支援することを意図としています。本報告書は、寿命の接近を識別するため、または耐用年数による故障に対応するコストを削減するために講じることができる措置を明確にしています。

結果と研究成果

大型縦置きポンプは長期運転のために設計されており、適切な保全方法が実施されている場合には施設の寿命以上に故障がないことが意図されています。ただし、ポンプ故障による予期せぬプラント停止、および発電出力レベルの低下の例は多数ありました。大型ポンプのエージングの根底にある要素は多様で多数あり、業界全体、すべての適用に適合するポンプ寿命の一般的な予想を設定することは合理的ではありません。本報告書にまとめられている業界のデータはこれを裏付けており、1～30年の幅広いエージングの期間に発生する大型縦置きポンプの耐用年数による故障が示されています。

特定の適用の個別の特定のポンプに関して言えば、予想される寿命を設定することは可能です。そうするためには、状態監視の傾向、ポンプ環境、詳細な検査結果、発電所の履歴、およびポンプの重大性を評価する必要があります。5年以内に設置された新しいポンプの場合、ポンプの予想寿命の兆候となる傾向を設定するため、および追加的な検査が必要な時期を決定するために、初回の詳細な検査（性能、振動、電流、および重大な磨耗部品と間隙）が推奨されています。

課題と目的

ポンプは最終的には耐用年数の検討（壊滅的な故障の可能性を含む）が一番の関心事になる時点に近づきます。大型縦置きポンプの機能のために、突然の壊滅的な故障が発電所の運転に重大な影響を及ぼす可能性があり、修理は計画されている修理のコストと比較して極めて高価になる傾向があります。本報告書は、これらの主要なプラント資産の改修 / 交換の戦略のための技術基盤として長期の計画に組み込むことができる、ポンプ寿命予想の要素の理解を支援することを目的としています。

応用、値、および使用

予想耐用年数の検討に関連する知識と計画は、構成部品の寿命サイクル管理の重要な側面です。大型構成部品の耐用年数問題に対処するための適切な戦略は、壊滅的な故障の可能性を削減し、修理と交換に関連するコストを大幅に引き下げます。本報告書は、基礎的な業界データの解析から、大型縦置きポンプの耐用年数条件を識別する際に役立つ結果および推奨事項を提供しています。対象とする読者は、原子力発電所のシステムマネージャーおよび構成部品 / システムのエンジニアです。

EPRIの観点

最初の40年の許認可条件以上に存続している原子力発電所の運転の延長は、既存の米原子力発電所群の半分以上に許可されてきました。業界の焦点には、延長ライセンスを得るために必要な規制要求事項を満たすために、システム、構造、および構成部品（SSC）のエージング、供給、陳腐化、改修、および交換に関する研究が引き続き含まれています。電力研究所（EPRI）プラントサポートエンジニアリング（PSE）は、寿命サイクル管理（LCM）プログラム内のこれらの多数の研究に標準的基盤を提供します。1990年代半ばのプログラムの検査以来、PSEは40以上の研究を、SSCソースブック、耐用年数ガイド、および構成部品交換ガイドの形をとって提供してきました。EPRI原子力保全文書およびEPRI予防保全ベースデータベース（PMBD）は、大型縦置きポンプの保全の実施および状態監視のための最優良事例および推奨事項の概要を示しています。

方法

業界の運転経験、EPRIポンプユーザグループの調査結果、ベンダーの推奨事項、EPRI保全指針、および業界のポンプ故障データは、本報告書の根幹です。業界のデータベースの研究は、実際の耐用年数による故障および付随する原因を識別するために行われました。ポンプ寿命を加速する条件とこれらの条件を識別する方法が明確にされています。ポンプの修理に関連する手配業務に関する簡潔な議論も含まれています。

キーワード

大型縦置きポンプ
予想寿命
耐用年数
寿命サイクル管理
原子力資産運用
構成部品の信頼性

要約

本報告書では、原子力発電所で使用される大型縦置きポンプの耐用年数に関連した情報および推奨事項が提示されています。主な焦点は、緊急事態対応または改修 / 交換の計画に関する決定を支援するために、これらの資産の耐用年数の接近を認識する方法に関するものです。原子力発電所のシステムマネージャーおよび構成部品 / システムのエンジニアによる使用を主に意図しています。主要なセクションが、予想される寿命についての考察および状態監視に当てられています。構成部品交換の手配業務についてのセクションも含まれています。

目次

図リスト

表リスト

발전소 지원엔지니어링: 대형 수직펌프의 예상수명말기 보고서

1019154

최종보고서, 2009. 12

보고서 개요

이 보고서는 원자력발전소의 계통관리자 및 기기/계통 기술자들에게 대형 수직펌프의 예상 수명말기 고려사항에 대한 기술지침(guidance)을 제공하기 위한 것이다. 특히 이 보고서는 수명말기 고장을 예방하고 고장에 의한 영향을 관리하기 위해 긴급계획 또는 정비/교체계획이 필요한 경우, 펌프가 수명주기에서 어느 위치에 있는지를 기술자들이 결정할 수 있도록 지원하기 위한 것이다. 또한 보고서는 수명말기 고장에 근접하고 있는지를 확인하거나, 수명말기 고장에 소요되는 비용을 감소시키기 위해 취할 수 있는 조치들을 명확히 하고 있다.

결과 및 소견

대형 수직펌프는 장기운전을 할 수 있도록 설계되어, 적합하게 정비를 할 경우에는 설비 수명기간 동안에 고장이 발생하지 않을 것으로 예상한다. 그러나 펌프 고장으로 인해 예상하지 못한 발전정지와 출력감발 사례가 많이 있었다. 대형 펌프의 노화인자들이 매우 많고 다양하므로, 모든 용도와 전체 산업계에 적합한 보편적 펌프 수명의 기대치를 마련하는 것은 합리적이지 않을 것이다. 이 보고서에 요약되어 있는 산업계 데이터가 이를 뒷받침하고 있다. 이러한 산업계 데이터가 1년에서 30년에 이르는 광범위한 노화기간에 걸쳐 발생하는 대형 수직펌프의 수명말기 고장을 나타내고 있기 때문이다.

특정 용도에 사용하는 개별 펌프일 경우에는 예상 수명을 수립할 수 있다. 이를 위해 상태감시추이, 펌프가동환경, 세부검사결과, 발전소 이력 및 해당 펌프의 위험도 평가가 필요하다. 새로운 펌프 및 설치 후 5년 이내 펌프의 예상 수명을 보여줄 수 있는 추이를 확립하고, 언제 추가 검사가 필요한지 결정하기 위해 초기에 세부적인 검사(성능, 진동, 전류 및 주요한 마모 부품의 치수와 유격)를 실시하도록 권장한다.

도전과 목적

모든 펌프는 궁극적으로 재난성 고장 가능성을 포함하여 수명말기에 대한 고려사항이 주된 관점이 되는 시기에 도달하게 될 것이다. 대형 수직펌프의 기능을 고려해 볼 때 갑작스런 고장이 발생할 경우 발전소 운전에 심각한 영향을 미칠 수 있으며, 수리 비용은 계획된 수리에 비해 매우 많은 비용이 소요될 수 있다. 이 보고서는 이러한 발전소 주요 자산의 교체/정비 전략을 수립하기 위한 기술적 기반으로서, 장기계획에 연관될 수 있는 펌프수명 예측인자들을 이해하는데 도움을 주기 위한 것이다.

용도, 가치 및 활용

예상 수명말기 고려사항에 대한 지식 및 계획은 기기 수명주기를 관리하는데 필수 요소이다. 대형 기기의 수명말기 문제를 다루는 전략은 재난적 고장발생 가능성을 감소시킬 수 있으며, 수리와 교체 비용을 크게 줄일 수 있다. 이 보고서는 대형 수직펌프의 수명말기 상태를 식별하는데 있어 사용자를 지원하기 위해 결과와 권고사항 및 산업계 기초자료의 분석 내용을 제공한다. 이 보고서는 원자력발전소 계통관리자와 기기/계통 기술자들을 주요 대상으로 하고 있다.

EPRI 전망

미국의 기존 원자력발전소 전체설비의 절반이상은 이미 초기 운영허가 기간인 40년을 초과하여 계속운전을 허용하고 있다. 산업계에서는 운영허가 기간 연장을 위해 규제요건을 충족시킬 수 있도록 계통, 구조물 및 기기(SSC)의 노화, 공급, 단종, 정비 및 교체와 관련한 연구를 계속하는데 초점을 두고 있다. EPRI의 발전소엔지니어링지원(PSE) 조직에서는 이러한 연구를 수행하기 위해 수명주기관리(LCM) 프로그램 내에서 표준기반을 제공하고 있다. 1990년대 중반에 이 프로그램을 시작한 이후 PSE 조직에서는 계통, 구조물 및 기기(SSC) 관련 기초자료, 수명말기 지침서 및 기기교체 지침서의 형태로 40건 이상의 연구 결과물을 발행하였다. EPRI의 원자력 정비관련 문서 및 예방정비 기반 데이터베이스(PMDB)를 통해 대형 수직펌프에 대한 정비 및 상태기반 감시를 실시하기 위한 최우수 사례와 권장사항들을 제시하고 있다.

접근방법

이 보고서에서는 산업계 운전경험, EPRI 펌프사용자그룹의 조사결과, 제작자 권장사항, EPRI 정비지침 및 산업계의 펌프고장데이터를 기초자료로 활용하였다. 실제 수명말기 고장 및 부수적 원인을 확인하기 위해 산업계 데이터베이스를 조사하였다. 이러한 수명조건을 확인하기 위한 수단을 통해 펌프의 수명을 단축시키는 조건을 확인하였다. 또한 이 보고서에서는 펌프 수리와 연관된 실행계획을 간략하게 논의하고 있다.

핵심용어

대형 수직펌프
기대수명
수명말기
수명주기관리
원자력자산관리
기기 신뢰도

요 약

이 보고서는 원자력발전소 대형 수직펌프의 수명말기에 관련된 정보와 권장사항들을 제시하고 있다. 긴급 또는 정비/교체계획에 대한 의사결정을 지원하기 위해, 이러한 설비의 수명말기에 대한 접근방법을 어떻게 할 것인지에 대해 중점을 두고 있다. 이 보고서는 주로 원자력발전소 계통관리자 및 기기/계통 기술자들이 활용하기 위한 것이다. 대부분의 장에서는 예상 수명에 대한 고려사항과 상태감시를 다루고 있으며, 기기 교체를 위한 실행계획에 대해서도 하나의 장을 할애하고 있다.

목 차

그림 목록

표 목록

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