UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

May 1, 1997

MEMORANDUM TO: Richard H. Wessman, Chief
Mechanical Engineering Branch
Division of Engineering, NRR

FROM: Michael E. Mayfield, Chief
Electrical, Materials and Mechanical
Engineering Branch
Division of Engineering Technology, RES

SUBJECT: ORNL FINAL LETTER REPORT

Attached for your information is a copy of the ORNL final letter report ORNL/NRC/LTR-96/37, "Improved Diagnostics and Monitoring Methods for Pumps and Related Equipment."

This report was prepared in response to NRR user need requests to support the current work on motor operated valve, check valve, and pump performance as related to recorded operational failures in order to access longer intervals between inservice tests. NRR has requested that this report be made publicly available. Therefore, the final letter report has been placed in the PDR for public access.

The RES project manager for this activity is Jerry Jackson, who can be reached at 415-6656.

Attachments: As stated

ORNL/NRC/LTR/96-37

Improved Diagnostics and Monitoring Methods for Pumps and Related Equipment

Letter Report

R. H. Staunton
Oak Ridge National Laboratory
Oak Ridge, Tennessee

April 1997

Research sponsored by the Office of Nuclear Regulatory Research, U. S. Nuclear Regulatory Commission under Interagency Agreement DOE DE-AC05-840R21400 with the U. S. Department of Energy under contract No. 1886-8632-4W with Lockheed Martin Energy Systems, Inc.

Contents

List of Figures

List of Tables

1.0 Background

Early phases of a program to utilize risk-informed methods in development of programs for in-service testing (IST) of components to monitor the reliability of critical components and systems are now being developed by plants with approval from the Nuclear Regulatory Commission (NRC). The risk-informed IST program relies on risk analysis for categorization of specific plant component safety significance and it relies on component testing to establish the health of the component and to determine its margin relative to design goals as does the traditional prescriptive method of testing at more-frequent intervals. However, the risk-informed IST program relies more heavily on effective diagnostic and/or monitoring technologies and techniques than programs of the past. Where testing is to be performed less frequently, it is necessary to have monitoring tools that are more effective or sensitive in detecting various levels of degradation and incipient failures. It is also necessary to know what are the most likely failure mechanisms, the affected sub-components, and the best means of monitoring them. This letter report focuses on pumps and related equipment and attempts to address many of these needs.

2.0 Scope

A characterization of pump failure data for the years 1990 through 1993, inclusively, was prepared and issued in January 1996 [1]. An aging report on turbine drives was also prepared and issued in June 1995 [2]. Following these studies, an update report[1] was prepared to characterize data for 1994 and 1995. The present study on diagnostics will be based, in large part, on this update study. The update study was of much interest since the data indicated a rather dramatic improvement in pump system reliability when compared to the earlier four-year study. This improvement in reliability began in the late 1980's and has continued through the 1990's to the present. The improvement is apparently broad-based and includes a large number of pump and valve types throughout the domestic nuclear industry [3].

The data characterization upon which this analysis is based, considers pumps, pump motors, turbine drives, and pump-related circuit breakers and therefore encompasses the entire pump system. The criteria used to obtain failure data is described in the update study and, briefly, includes the following:

1. Safety-related pumps, motors, and turbine drives
2. Circuit breakers with pump applications
3. Only centrifugal pumps (i.e., no positive displacement pumps)
4. Inclusion of the following generic pump applications (by common name):

PWR Plants	BWR Plants
Auxiliary feedwater (AFW)	Component cooling water (CCW)
Component cooling water (CCW)	High pressure coolant injection (HPCI)
Containment spray (Cont. spray)	Emergency service water (ESW)
Charging/high pressure safety injection (CVCS/HPSI)	Low pressure coolant injection/residual heat removal (RHR)
Emergency service water (ESW)	Reactor core isolation cooling (RCIC)
Low pressure safety injection/residual heat removal (RHR)	Low pressure core spray (LPCS)

These systems generally account for approximately 15 pumps at a typical plant and represent about 53% of the IST pumps.

5. Only pumps and motors for which the Nuclear Plant Reliability Data System (NPRDS) application code was provided were included in the analysis (eliminating less safety significant safety-related pumps).

The above characterization study made possible the methodical identification of failure-prone areas in the pump system for which parameters and indicators can be monitored or trended to establish aging rates in support of IST. These areas were ranked in importance and matched to potential technologies/techniques that might be used for diagnostic monitoring. These technologies are briefly discussed in Sect. 4 and additional considerations pertaining to root causes and preventative maintenance considerations are discussed in Sect. 5. Recommendations are provided in Sect. 6 and an overview of typical circuit breaker periodic maintenance is illustrated in Appendix A.

---

[1] R. H. Staunton, A Characterization Update of Pump and Related Equipment Failure Experience in the Nuclear Power Industry (1994-1995), ORNL/NRC/LTR/96-32, Oak Ridge National Laboratory, Oak Ridge TN (October 1996 - DRAFT)

3.0 Identification of pump system component diagnostic need

The following sections summarize selected pump, pump motor, turbine drive, and circuit breaker failure data obtained during 1994 and 1995 from PWR and BWR plants in the U. S. These data are being presented to establish where the need exists for diagnostic and monitoring technologies or techniques for improving/maintaining the reliability of the pump system. Note that where number of failure indications are provided, these numbers may exceed the number of failures since many failures produced more than one indication.

Method of detection refers to the general activity in the plant that was being performed (e.g., testing, maintenance, normal operations) at the time when the failure was detected. The method of detection will be used in this section to show both strengths (e.g., detection of degradation by regulatory code testing) that de-emphasize the need for diagnostics and weaknesses in detection that suggest areas where diagnostics may be needed.

The three methods of detection are, (1) *regulatory/code* - where failures or degradation are detected by the criteria associated with regulatory/code required monitoring, (2) *plant programmatic* - where failures are detected as the result of a monitoring processes that are used as part of the plant's routine operation or predictive/preventative maintenance programs that are voluntarily implemented, and (3) *inoperable* - where failures are not detected before the component becomes inoperable. For the purposes of this study, "inoperable" is not defined as it is in the plants where a technical specification definition is used, but rather, it is defined more conventionally where it simply means that the component will not function as required.[2] The "inoperable" classification strongly suggests a need for more effective diagnostics or monitoring and, although "plant programmatic" is preferred to it, plant programmatic is still weak in that such detection relies on a voluntary programs that can vary significantly from plant to plant.

3.1 Pumps

Table 3.1 shows the number of failure indications by reactor type and significance. The failure indications for overall PWR failures were varied with poor hydraulic performance and external water leakage being the most predominant. For significant failures, all of the poor hydraulic performance failures remain and "noise/vibration" and "failure to run/start" are other significant indicators. Significant BWR failures had similar indicators[3] except for the absence of failures to start.

The first chart in Figure 3.1 shows the number of failures by affected area and method of detection. For comparison, the second chart in the figure shows only significant failures. The number of inoperable pump failures is the same in the two charts since they are all significant. Of special interest are the bearing failures where plant programmatic actions detected 9 significant failures and 7 were not detected before the pump became inoperable. Code testing discovered only 3 bearing failures (16%). The code standard is to use vibration velocity of the pump shaft as the diagnostic parameter. Numerous studies have shown this method unable to detect bearing defects until the bearing is almost totally degraded which accounts for the 16% effectiveness. For internals, which corresponds closely with "poor hydraulic performance" in Table 3.1, code testing was very successful having detected 74% of the significant failures however in 8 (19%) instances the pump became inoperable before detection was made. All 10 of the shaft and coupling related failures lacked detection and 5 seal and packing failures (all significant) also lacked detection.

---

[2] In almost all cases, "inoperable" was applied to pumps that would not start, could only run briefly before tripping, and/or fluctuated widely in speed due to turbine drive problems.

[3] The draft report referenced in Sect. 2 shows generally lower failure counts for BWRs due mainly to smaller plant populations and better performance.

Table 3.1 Failure indication by reactor type and significance

Indicator	PWR All	PWR Significant	BWR All	BWR Significant
Poor hydraulic performance	28	28	12	11
Noise or vibration	14	12	4	4
Fail to run/start	7	7	0	0
Hot bearing	5	4	2	2
Other	15	4	3	1
External water leakage	37	3	10	1
Lube oil anomaly	14	3	1	0
Hot packing	2	2	1	1

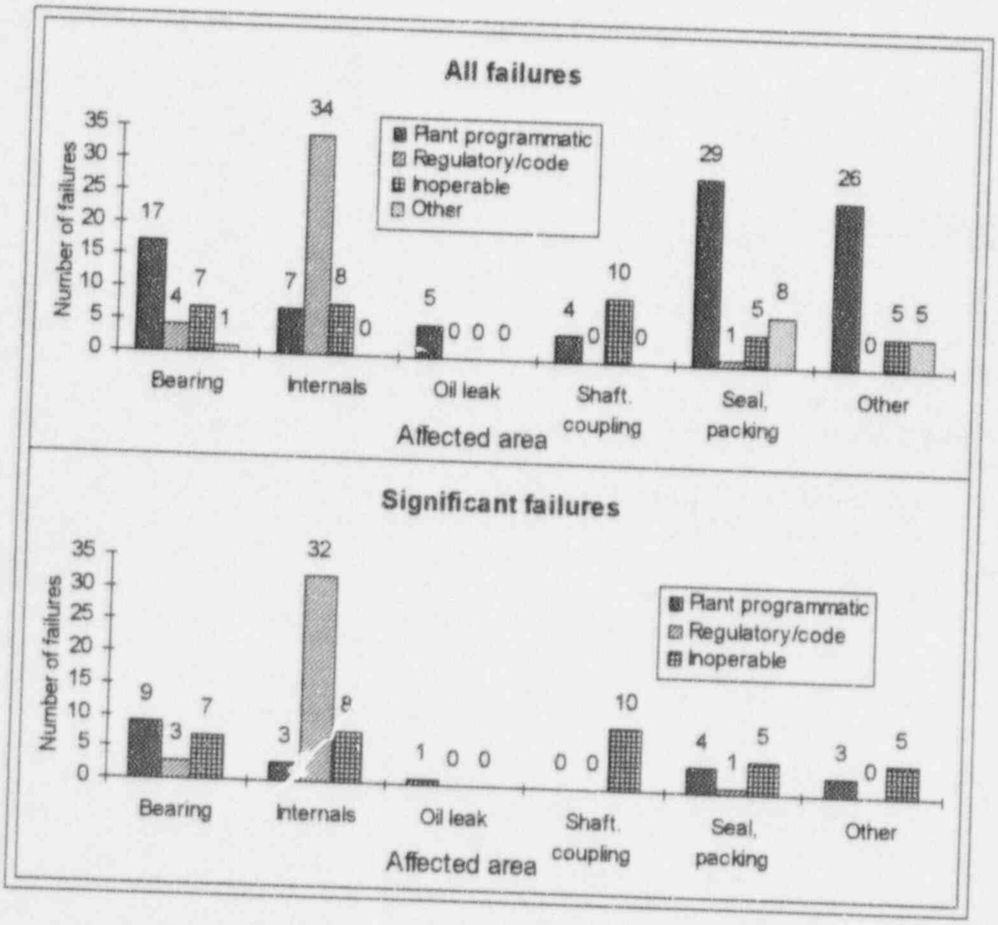

Figure 3.1 Failures by affected area and method of detection - all failures/significant failures

Having reviewed the above relevant pump failure data, the weaknesses and needs for failure detection/diagnostics are summarized in Table 3.2. The pump areas comprised of the bearings, internal components (e.g., impeller), shaft and/or coupling, and seal and/or packing are all candidates for improved diagnostics and/or monitoring. These needs will be further addressed in Section 3.5.

Table 3.2 Summary of pump component areas potentially needing improved diagnostics

	Bearing	Internals	Shaft/coupling	Seal/packing
Significant failures lacking any means of detection	7	8	10	5
Additional significant failures relying only on plant programmatic detection	9	3	0	4

It is acknowledged that a high number of failures that are not significant exists for the seal/packing and "other" pump areas (Figure 3.1). These represent needs that may potentially improve plant maintenance however the savings, if any, are not likely to justify improved monitoring and diagnostic programs. For instance, installing a system to detect water dripping from a seal might speed maintenance but would not reduce costs or significantly improve either pump reliability or availability.

3.2 Pump motors

Figure 3.2 shows the number of motor failures for each major component area; bars indicate significant failures and the line plot indicates all failures. In contrast to pumps, motor failures are most often detected after they become inoperable (64% of significant failures) and all stator, wiring, and rotor failures are significant (also, six of the eight bearing failures are classified as significant). The stator and bearing are the most common sources of failure as one might expect. The highest stresses that the motors must endure are the load stresses in the bearing and the thermal, high voltage, and magnetically-induced mechanical stresses in the stator.

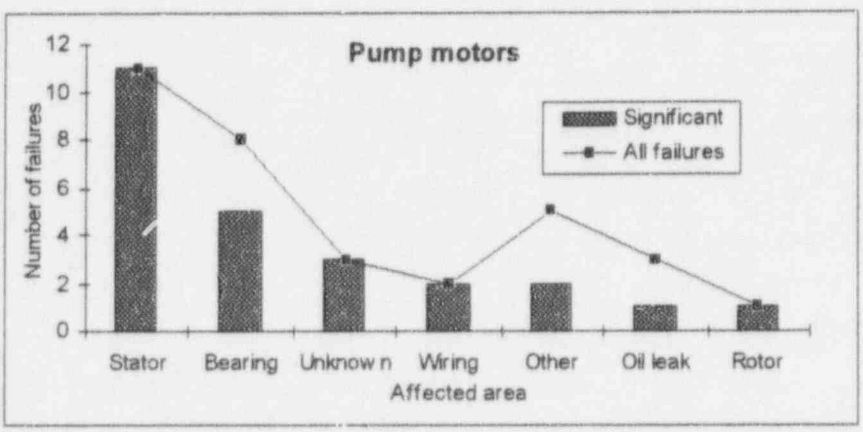

Figure 3.2 Number of motor failures by affected area

Table 3.3 lists the methods of detection for significant pump motor failures. As indicated above, many (i.e., 15 or 63%) of the failures were not detected before the pump motor had become inoperable and thus no method of detection is assigned to those 15 failures. Table 3.4 shows the motor component areas that are candidates for improved diagnostics. Although the number of motor failures are small for the 2 year study, the stator and bearing are believed to have the greatest need for monitoring and diagnostics. In the previous study [1], stator and bearing areas were the affected area in 78% of the significant failures. Although the percentage is also high (64%) in the present study, the real contrast is that there were 61

combined failures in stators and bearings in the previous 4 year study while there were only 16 in the current study (i.e., the failure rate was half the failure rate recorded during the 4 year study). This reliability improvement is presently a relatively short trend and therefore the need for improved diagnostics, based mainly on the prior study, remains for now.

Table 3.3 Method of detection for pump motor failures

Method of detection	No. of significant failures
Inoperable	15
Plant programmatic	6
Regulatory Code	3

Table 3.4 Summary of pump motor component areas potentially needing improved diagnostics

	Stator	Bearing
Significant failures lacking any means of detection	10	2
Additional significant failures relying only on plant programmatic detection	1	1

3.3 Turbine drives

The detection of turbine drive failures has depended on indications of trips, visual evidence of anomalies, alarms/visual indicators, indications of degraded speed regulation, and other indicators or symptoms as indicated in Table 3.5. None of the indicators listed present unusual challenges in applying some type of monitoring scheme.

Table 3.5 Turbine drive failures by indicator/symptom

Failure indicator	Significant failures	All failures	Failure indicator	Significant failures	All failures
Trips	20	20	Indicator (alarm)	1	6
Visual	5	9	Hot bearing	1	1
Speed regulation	4	5	Fails to trip	1	4
Fails to start	2	2	Lube oil	0	2
Other	1	7	Vibration	0	1

The first chart in Figure 3.3 shows the number of failures by affected area for both significant failures (bars) and all failures (line plot). The affected areas, as listed from left to right, are governor valve (GV) stem, the governor, trip-related hardware, other or miscellaneous components, the GV (other than stem) and operator, trip and throttle valve (TTV), shaft bearing, turbine piece parts, lubricant, and the steam admission valve (SAV).

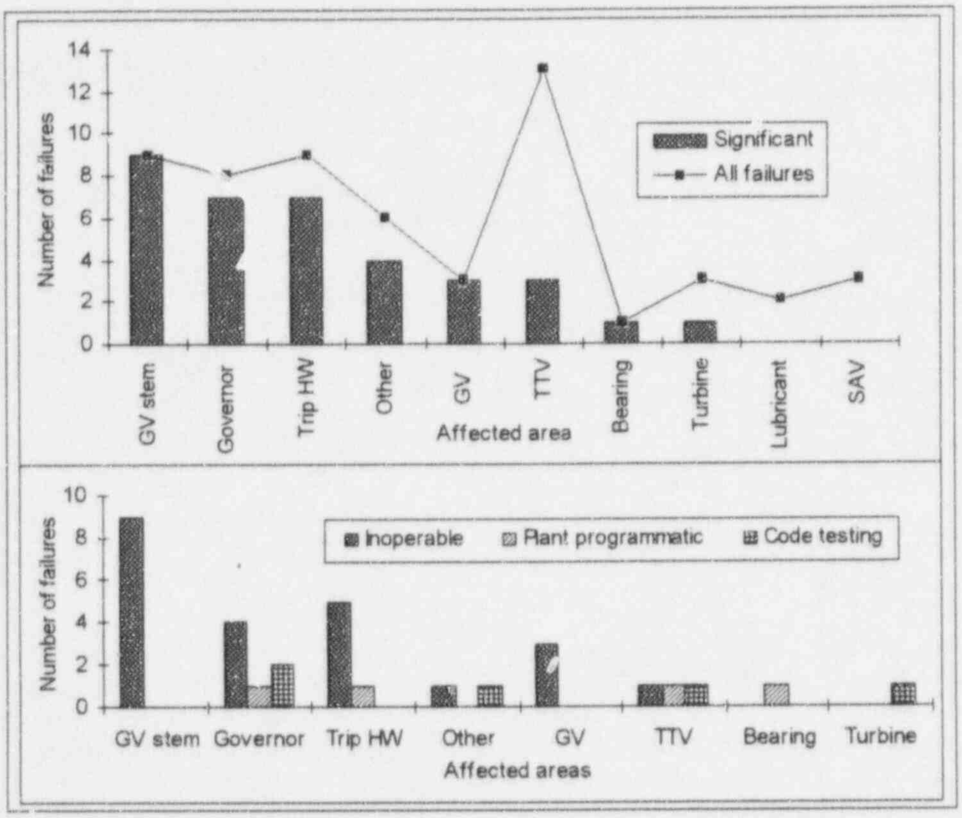

Figure 3.3 Turbine drive failures by affected area and method of detection

The second chart in Figure 3.3 shows the significant failures by affected areas further broken down by method of detection. The turbine drive was found to be inoperable at the time of detection for failures involving the GV stem and GV and in most failures of the governor and trip-related hardware. All other methods of detection are spread over the various turbine drive areas in instances of only one or two failures per area. However, it is noteworthy that code testing successfully detected five failures before the failures incapacitated the turbine drive. The regulatory code does not require *any* monitoring of the turbine drive (or of the pump motor and pump-related circuit breakers). There is generally only one or, at most, two turbine-driven pumps in any IST program. Therefore, turbine-driven pumps only represent about 3% of all pump IST.

Table 3.6 summarizes the causes/conditions at ibuted to the significant turbine drive failures. Aside from perhaps "corrosion," the major causes (e.g., worn part, out-of-adjustment) should not preclude possible detection through diagnostic and/or monitoring techniques.

Table 3.6 Causes/conditions attributed to significant turbine drive failures

Cause	No.	Cause	No.
Worn Part	9	Human error	3
Corrosion	8	Other	3
Unknown	6	Gummed-up or lack of lubrication	1
Out-of-adjustment	5	Loose part (mechanical)	1

Based on the above results, Table 3.7 summarizes the turbine drive component areas that are candidates for improved diagnostics. The table indicates the number of significant "inoperable" failures for the turbine drive component areas. These are the areas that need diagnostic or monitoring

technologies/practices for detecting degradation *before* the turbine drive becomes inoperable. The governor valve stems experienced corrosion in nearly all of the instances shown indicating that improved design might be much more effective than enhanced diagnostics in improving reliability.

Table 3.7 Summary of turbine drive component areas potentially needing improved diagnostics

Turbine drive area	Significant failures lacking means of detection
Governor valve stem[a]	9
Trip-related hardware	5
Governor	4
Governor valve	3

(a) design problem

3.4 Circuit breakers

There were 115 (81significant) circuit breaker failures comprising a population of breakers whose voltage rating distribution is: 55% 4160 volt, 32% 480 volt, 6% 600 volt, and 7% miscellaneous higher voltages. As shown in Table 3.8, circuit breakers exhibit a variety of failure indicators including failure to close, failure to charge springs, spurious trip ("pump stops") racking difficulties, alarms, and others. These indicators, nine categories in all, exemplify the complexity of the circuit breaker system of electrical and mechanical mechanisms that must all work together. The motor-driven mechanical system of rotating shafts, gears, and cams drive a number of springs and electrical switches that are controlled by electrical commands and mechanical push buttons and levers. Although some functions have limited redundancy or mechanical back-up controls, the system is frequently unforgiving of degradation involving a single loss of adjustment, critical lubrication, failed switch, etc.

Table 3.8 Circuit breaker failures by specific indication

Indicator	Significant failures[a]	All failures[a]
Failure to close	35	37
Fail to charge spring	15	15
Pump stops	14	15
Rack difficulties	6	8
Alarm	6	9
Other, unknown	5	8
Fail to trip	2	13
Visual	1	6
Load timing	0	7

(a) Total exceeds failure count due to multiple indicators in many failures.

The first chart in Figure 3.4 shows numbers of significant failures (bars) and all failures (line plot) for each affected area of the circuit breakers. The three areas most affected are electrical areas, trip-related hardware, and electrical components related to the spring charging mechanism. Also significant are failures involving electrical relays, rail-related hardware, and spring charging hardware.

The second chart in Figure 3.4 shows the significant failures by affected areas further broken down by method of detection. The chart indicates that there are primarily five degraded areas that were responsible for the circuit breakers being found inoperable at the time of detection. These areas are miscellaneous

electrical areas, trip-related hardware, electrical components related to the spring charging mechanism, electrical relays, and spring charging hardware. There also was a dependence on plant programmatic activities to detect failures in the first three of these areas as well as for the rail hardware. Note that regulatory code testing did not detect any significant failures in circuit breakers (as would be expected since there is no required testing of breakers).

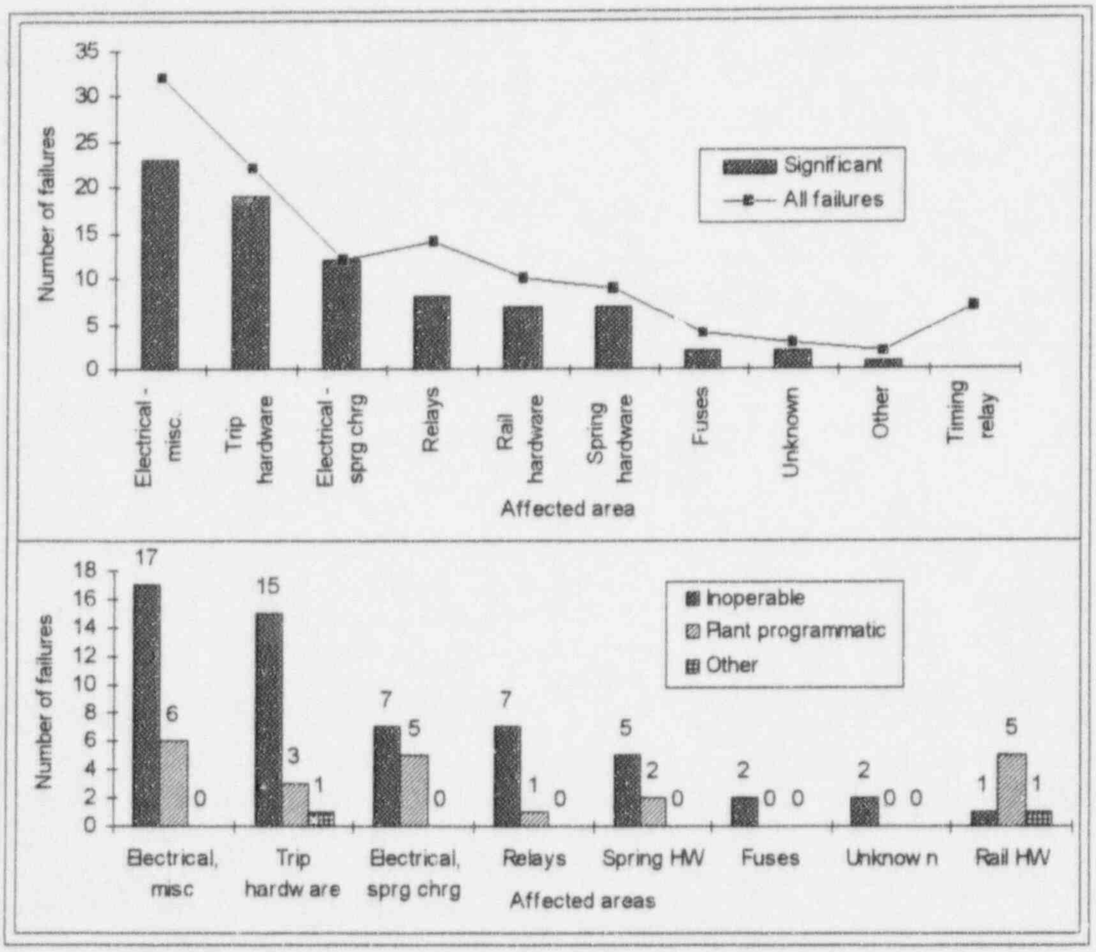

Figure 3.4 Circuit breaker failures by affected area

Table 3.9 shows the numbers of significant failures of circuit breakers by cause/condition. Diagnostic and monitoring systems or techniques are needed that would be able to detect circuit breaker failures due to a wide variety of causes including degradation in various electrical components, lack of required adjustment, loose fasteners, fractured parts, etc. The monitoring system would have to monitor one or more operations of the circuit breaker system and/or sense the condition of various mechanical and electrical devices.

Table 3.10 summarizes the candidates for diagnostic and monitoring systems or techniques and is based on the number of inoperable failure and failures detected by plant programmatic activities. Diagnostics and/or monitoring systems are needed for a total of three electrical systems and two hardware systems. All but one (i.e., trip hardware) of these five systems have some relationship to circuit breaker closure. The table does not include hardware associated with the circuit-breaker-to-cubicle racking in and out operations since nearly all of these hardware problems were detected at the time (i.e., no need for improved diagnostics).

Table 3.9 Significant failures of circuit breakers by cause/condition

Cause/condition	Significant failures	Cause/condition	Significant failures
Electrical component	22	Design	6
Out-of-adjustment	12	Human error	5
Loose part/fastener	11	Worn part	5
Fractured or cracked	9	Gummed up/lack of lube	4
Defective contacts	9	Missing item	2
Unknown	7		

Table 3.10 Summary of circuit breaker component areas potentially needing improved diagnostics

	Electrical misc.	Trip hardware	Elect. Spring charging	Electrical Relays	Spring hardware
Significant failures lacking any means of detection	17	15	7	7	5
Additional significant failures relying only on plant programmatic detection	6	3	5	1	2

3.5 Final ranking of diagnostic need

Figure 3.5 shows the significant failure counts (bars) and rates (line plot) for pumps, pump motors, turbine drives, and circuit breakers. In establishing the ranking of diagnostic needs for the various components, it is important to note that the incident of motor failures is quite low and, while the number of turbine drive failures is also low, its rate is far higher than that of the other components due to its small population (and service time). Clearly, less priority can be given to motor-related diagnostics but the

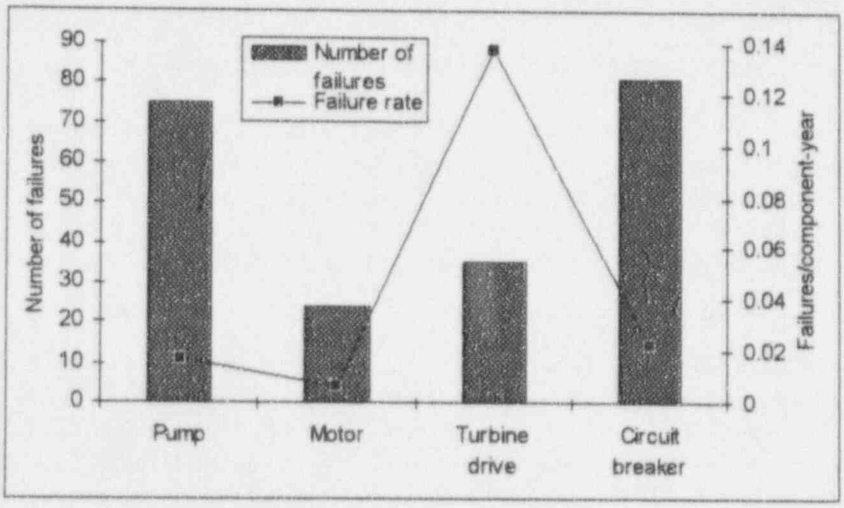

Figure 3.5 Failure count/rate of pumps and related equipment

decision is not so clear for the turbine drive. For turbine drives, the overall failure count and maintenance burden is low but, more importantly, the reliability is quite low and this should not be acceptable for a non-electrical pump drive that is so critical during station blackouts. Thus, diagnostic needs pertaining to turbine drives will be emphasized over other components but not quite as much as the relative failure rates would suggest.

Table 3.11 Final ranking of diagnostic need for component affected areas

		3	4	5	6	7
Component	**Affected area**	**Not detected prior to failure**	**Plant programmatic**	**Number not detected plus 1/2 plant programmatic**	**Component-related multiplier**	**Final Ranking**
Turbine Drive	GV stem	9	0	9	10	90
Circuit Breaker	Misc. electrical	17	6	20	3.4	68
Circuit Breaker	trip-related HW	15	3	16.5	3.4	56
Turbine Drive	trip-related HW	5	1	5.5	10	55
Turbine Drive	governor	4	1	4.5	10	45
Circuit Breaker	electrical - CS[a]	7	5	9.5	3.4	32
Turbine Drive	GV	3	0	3	10	30
Pump	bearing	7	9	11.5	2.5	29
Circuit Breaker	relays	7	1	7.5	3.4	26
Pump	shaft/coupling	10	0	10	2.5	25
Pump	internals	8	3	9.5	2.5	24
Circuit Breaker	spring hardware	5	2	6	3.4	20
Pump	seal/packing	5	4	7	2.5	18
Motor	stator	10	1	10.5	1	11
Motor	bearing	2	1	2.5	1	3

(a) CS = Charging spring

Table 3.11 shows the final ranking of affected areas for the various pump system components. The higher the ranking, the greater the need for improved diagnostics/monitoring. The ranking is based on a process that is dependent on diverse factors such as, (1) how successfully the failure detection was, (2) the method of detection (e.g., regulatory versus the "optional" plant programmatic), and (3) the failure rate of the main component (i.e., pump, motor, turbine drive, or circuit breaker). Thus, the ranking worsens by the number of applicable failures that were not detected and it worsens if the main component has a high failure rate. In contrast, the ranking will be favorable for components whose failures were discovered by the required code testing and where the main component is reliable (e.g., motor).

This method was selected because it uses available information pertinent to the need for diagnostics and/or monitoring to perform an initial, quantitative ranking of the specific failures as identified by the affected areas. This methodology is deemed adequate for ranking diagnostic needs for the purposes of this report and it presumes that current monitoring requirements will continue. This ranking method is based only on needs for improved diagnostics. The number of turbine drives is much smaller than the number of motor drives (approximately 1:30 ratio). Therefore, a more detailed cost-benefit analysis should be completed to adjust the rankings.

Numerical columns in the table are described as follows:

Column 3 - Number of failures not detected prior to the pump system becoming inoperable
Column 4 - Number of failures detected only by plant programmatic activities
Column 5 - Column 3 value added to half Column 4 value (second value halved since plant programmatic, although not regulated or consistent from plant to plant, is not as serious a failure detection concern as failure to detect before the system becomes inoperable).
Column 6 - Scaling factors based on failure rates (Figure 3.6) with the turbine drive factor being adjusted by a 0.5 factor [due to concerns (e.g., cost) for developing monitoring for a component with a relatively small population].
Column 7 - Column 5 multiplied by the scaling factors (Column 6)

Many of the affected areas in the table failed due to system problems and/or root causes such as shaft misalignment, shaft imbalance, high vibration, poor pump/motor base integrity, and design weaknesses. Table 3.12 relates the list of failed affected areas to possible root causes. Many of these root causes will be further discussed in Sect. 5.

Table 3.12 Possible root causes for established significant pump system failures

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

(a) CS = charging spring
(b) caused by a variety of factors, such as hydraulic and mechanical imbalances to the bearing (e.g., material deposition on impeller, cavitation, vane fracture), poor motor base integrity, and/or by stresses transmitted by attached piping

The importance of shaft alignment is known to be critical, however it is not possible to determine how many of the bearing and seal/packing failures were related to less-than-desirable precision in the alignment. Most of these system problems and/or root causes need to be precluded early on (e.g., by the use of precision alignment) and also detected through monitoring or found by inspection (e.g., integrity of pump base plate) in order to reduce the number of significant failures. The ranked listing in Table 3.11 has the advantages of being identified in a methodical process, of being absolutely pertinent, and ranked; however the system problems and root causes need to be highlighted and likewise considered for diagnostic and monitoring technologies (Section 5).

4.0 Diagnostic and monitoring technologies

The application of diagnostic and monitoring technology and practices in the nuclear pump system is not new. Testing of pump bearing lubrication, motor stator megger tests, turbine drive speed regulation monitoring, maintenance/testing of circuit breakers per manufacturer's specifications (see Appendix A), and, of course, regulatory code testing of pump vibration and hydraulic performance have been performed in the nuclear industry since the beginning. Newer technologies such as pump motor current signature analysis have seen limited use at certain plants.

Some of the conventional testing and monitoring that has been used historically has been of less than optimal design. These are the types of tests that need to be upgraded to most effectively support IST. For instance, the code-specified vibration tests that are performed on pumps as part of the surveillance testing program are ineffective in detecting bearing problems. Vibration spectral analysis, if performed correctly, *is* effective in the detection of bearing problems and other anomalies as well (see Sect. 4.6).

4.1 Potential methods and parameters for trending aging effects in the pump system

Diagnostic testing and monitoring can be performed on components in the pump system using a variety of technologies and techniques and what can be used effectively varies depending on whether the pump is off-line or on-line. Table 4.1 summarizes diagnostic/monitoring methods and parameters for off-line testing of pump system components by the affected areas that were determined most significant in Sect. 3.5. Because a test is listed in the table does not necessarily mean that it is recommended for use in connection with an IST program for the pump system. The table also, in the last column, provides a reference to sections that provide additional details. Table 4.2 summarizes the same types of information for *on-line* testing of pump system components.

The technologies shown in the tables are generally suited for monitoring pump operation, diagnostic analyses of anomalies, and trending the aging of the components (i.e., pump, motor, turbine drive, and circuit breaker) and the overall pump system. The rate of aging can be determined through the trending of the pertinent indicators generated by the diagnostic/monitoring devices. The technologies shown in the tables are available for application unless otherwise noted. In some cases the technology is quite conventional although it may not have been commonly applied as described. These cases are <u>not</u> noted since they do not present a significant obstacle or represent significant product development.

The GV stem is not shown in either of the tables in spite of it being ranked highest in significance. The reason for this is that it is a design- and application-related corrosion problem that needs corrective action more than diagnostics. Furthermore, the problem does not lend itself well to detection prior to complete failure (i.e., becoming pitted and stuck where it enters the packing). Because of the infrequent operation of the turbine drives in nuclear industry service, the valve stem sees a corrosive environment that is not encountered in applications in other industries. In nuclear service, the valve may see hot steam for fifteen minutes and then cool temperatures for an extended period (e.g., a month) before exposure to hot steam for another fifteen minutes and so on. The valve stem and packing were not designed for such low duty cycles and an effective correction has not been implemented to date (see Sect. 6).

Table 4.1 Off-line diagnostic/monitoring methods and parameters/criteria

Affected area	Methods	Parameters/Criteria	Ref. Sect.
Circuit breaker misc. electrical Circuit breaker relays	Periodic servicing	Manufacturer's specifications	(self explanatory)
Motor stator	Megger test and polarization index	Established test parameters - finds moisture	Standard tests (except inductive imbalance described in Sect. 4.3)
	ac and dc high potential tests	Established test parameters - can cause damage	
	Inductive imbalance[a]	Trend and monitor imbalance in windings	
Turbine drive governor	Monitor lubrication (flyball)	General oil quality - no dirt/water	(self explanatory)
	None (electrohydraulic units)	Either failed or not failed	
Circuit breaker trip-related HW Turbine drive trip-related HW	Inspection	Manufacturer's specifications	(self explanatory)
Circuit breaker electrical - CS[b] Circuit breaker spring hardware	Periodic servicing	Manufacturer's specifications	
Turbine drive GV	Inspection of valve movement	Stem must move freely	
Pump bearing Motor bearing	Inspect lubrication system	Visual	(see Table 4.2, lubrication analysis)
Pump shaft/coupling	Alignment check/monitor	Precision alignment	5.1
	Inspection of coupling	Visual - no significant wear	
Pump internals	Disassembly and inspection	No erosion, foreign materials, out-of-spec conditions in rotating hardware or wear ring	(self explanatory)
Pump seal/packing	Inspection	Visual - no leakage while off-line	(self explanatory)

(a) Development required

(b) CS = charging spring

Table 4.2 On-line diagnostic/monitoring methods and parameters/criteria

Affected area	Methods	Parameters/Criteria	Ref. Sect.
Circuit breaker misc. electrical Circuit breaker relays Circuit breaker electrical - CS	Timed response	Command to response times	4.2
	Current	Current level as an indicator of effort (circuit breaker motor)	
	Transition waveforms	Waveform trending as indicator of component degradation	
Motor stator	ESA[a,b] (FFT of electrical signals)	Most effective on rotor, TBD for stator	4.3, 4.5
	Partial discharge tests	Detects discharges in winding (for over 4KV motors)	
	High freq waveform analysis[b]	Developmental	
Turbine drive governor	Monitor speed regulation	Apply limit to or trend speed fluctuations	4.2
Circuit breaker trip-related HW Turbine drive trip-related HW Circuit breaker spring hardware	Timed response	Command to response (e.g., latch) times	4.2
Turbine drive GV	None	(Minor degradation is apparent when online)	NA
Pump bearing Motor bearing	Vibration/acoustic spectra analysis	Established frequency and acceleration limits	4.6
	Thermography	Temperature limit at bearing	4.8
	Lubrication analysis	Profile of particle count and size, contamination, viscosity, water limits, etc.	4.9
Pump shaft/coupling	ESA (FFT of electrical signals)	Analysis can detect shaft misalignment/crack	4.5
	Standard vibration analysis	Limits of imbalance/misalignment	4.6
Pump internals	ESA (FFT of electrical signals) or hydraulic performance test	Flow instability measured using ESA or std testing/trending of flow, head, and power parameters - use established criteria	4.5, surveillance testing or derivative
	Vibration spectra analysis	Established frequency and acceleration limits	4.6
	Vibration/acoustic	Established vibration limits in the pump casing	4.6, 4.7
Pump seal/packing	Thermal measurement	Temperature limit	4.8
	Leak detection	Visual or use of sensors, leakage rate limit pump dependent	(Self explanatory)

(a) Development required

(b) ESA = electrical signature analysis

4.2 Timed response and electrical monitoring of components

Nearly all of the significant failures of the pump-related circuit breakers involved a failure to close or remain closed. The failures were *not* due to defective arc contacts, main contacts, interrupters, vacuum breakers, arc chutes, or high voltage dielectrics, but to ordinary loose fasteners, cracked parts, gummed-up linkages, lack of lubrication, incorrect adjustment, worn hardware, and failed electrical components such as solenoids, switches, relays, etc.

Visual observations of indicators, marks, indicator lights, gauges, whether performed at the breaker or remotely, are not effective means to monitor the degradation of these types of components. The circuit breaker may be said to contain a "clock works" of mechanical shafts, gears, springs, cams, etc. and several electrical components (e.g., relays, switches). The electrical components can be monitored, often separately or in small groups, and mechanical parts can be monitored in groups or subsystems (e.g., charging of closing spring). Electrical parts that can be monitored individually include solenoids/relays, the motor, and switches that support breaker closing and tripping.

Timed response testing involves a measurement of significant response times in single- or multi-part systems. Response might be measured beginning with a command signal and ending with the completion of the commanded sequence. This sequence can be simple (i.e., a solenoid movement) or a sequence of events such as ones brought upon by the rotation of a cam and activation of switches. The more events included in a sequence, the larger the number of potential problem locations making the timed sequence anomalous. Timed response testing may be simple to implement especially where signals are readily available [e.g., at a motor control center (MCC)] but difficult to implement in instances where there are several sequences to monitor (e.g., circuit breaker opening, trips, opening spring charging, closing spring charging).

Timed response *limits* can be specified for pieces of equipment once they are established or where determined by a vendor. Where greater sensitivity is needed or complexity is greater, it may not be possible to specify a limit but, instead, the timing trended for significant changes in response times. Generally a limit can still eventually be developed/specified with experience as a percent increase relative to initial value(s).

Other types of monitoring that may be simple to apply at the same time signals are being obtained for timed response are the monitoring of current, voltage duration, and transition waveforms. Monitoring current or voltage duration for a circuit breaker relay or solenoid can reflect the effort required to activate and whether it successfully made the full travel. For circuit breaker trip and close spring charging, the determination of the minimum motor voltage for operation is an indicator of the force required (i.e., an indicator of degradation) for the spring to reach full compression. Alternatively, monitoring motor current level can be used as the indication of force required. Transition waveforms are useful as an indicator of degradation of electrical components such as switches and motors. Switch bounce, current-induced arcing, and surge current are examples of anomalies that are evident with such monitoring.

Of course, when the breaker is out of service, several tests recommended by the manufacturer can be performed. These tests are comprehensive in scope and offer high confidence that the electrical components are functional and that the mechanical systems are adjusted and free to operate. Many dynamic characteristics are also covered that can only be measured during operation with the mains energized.

More advanced or comprehensive diagnostics that are both non-intrusive and, at least partially permanently installed, will permit the diagnostic monitoring of trip spring charging current, close spring charging current,

relay contacts, auxiliary contacts, trip initiation, and close initiation. As described in an IEEE publication focusing specifically on circuit breaker diagnostics and failure investigation [4], parameters that can be measured for these items include slow moving linkages, changes in current signatures, open coils, defective contacts, contact bounce, event timing (e.g., relays, solenoids), motor current draw, and others. The IEEE publication presents qualitative "effort" and "benefit ratings" for many diagnostic options.

4.3 Motor stator testing methods

An important, new, off-line motor stator test for three phase motors is the measurement of inductive imbalance. Inductive imbalance in the windings can be caused by poor manufacturing or rewinding techniques, emerging shorts between turns, partially open windings, phase-to-phase current leakage paths, and internal high resistance joints. Although new and experimental, equipment is available[1] on the market for measuring inductive imbalance and other parameters which, when trended, show the present and predicted condition of a motor. Research is underway to develop this technology for on-line applications.

The primary methods of testing the motor stator on-line are electrical signature analysis (ESA), partial discharge tests, and high frequency waveform analysis. ESA uses fast Fourier transform (FFT) analysis of the motor current waveform as described in Section 4.5 to identify degradation of the stator windings. This degradation can either be shorted windings or significant changes in the winding capacitance or insulation integrity.

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

The high frequency waveform analysis method uses special characterization of high frequency spectra to determine the presence of stator winding degradation. Although this is a developmental technology, it holds promise of becoming a useful diagnostic tool in the next couple years if research continues.

4.4 Speed regulation monitoring

The electrohydraulic turbine drive governor cannot be monitored effectively using available technology. This electronic device usually fails to an inoperable state and does so without producing unusual electrical or drive performance precursors. In contrast, the mechanical flyball drive governors may exhibit minor degradation in the speed regulation of the turbine and may therefore be monitored using speed regulation monitoring where the stability of the turbine speed is monitored under start-up, transients, changing pump loads, and, of course, steady state operation. Electrical speed sensors/indicators already exist necessitating only the addition of enhanced monitoring and perhaps provisions for the trending of the data.

4.5 Electrical signature analysis

Electrical signature analysis (ESA) has been developed, in part, and used at the Oak Ridge National Laboratory (ORNL) [5,6] in a series of tests where the pump motor is used as a transducer for diagnostics.

---

1 PdMA Corporation, 5909-C Hampton Oaks Pkwy, Tampa, Florida

The motor in certain cases is an effective transducer of torsionally-related load phenomena such as relative precision in shaft alignment, suction conditions, and variation in pump hydraulic conditions. Rotor degradation monitoring is also possible since the amplitude of slip-pole side bands of 60 Hz and harmonics trend upward with increased rotor degradation, especially in larger motors. The technology is not fully developed and absolute determination of the extent of rotor degradation cannot presently be made. However, any technology that shows much promise for the detection of monitoring of diverse phenomena in both the pump and motor merits high emphasis and a brief summary discussion follows:

> In a recent study [6] where hydraulically-related energy was analyzed in three pumps to gain some perspective on the usefulness of motor data in assessing flow stability, flow rates were varied from shutoff to equal or greater than the best efficiency point (BEP). It was observed that as flow rate was reduced from the BEP, the level of low frequency noise in the power spectrum increased for all motors. Significant differences were observed in the spectral noise levels for horizontal, single suction pumps and the double suction pump. The same study presented the results of an on-line motor current monitoring system used to trend motor data on pumps and other equipment in a utility system at ORNL. Motor power spectrum data monitored in this study has been used to successfully detect blockage in the pump suction strainer.
>
> Portions of the current spectrum associated with rotor bar and stator slot pass frequencies show a clear potential for indications of rotor, and possibly, stator condition. The greatest usefulness here is not in making comparisons to an absolute criterion, but in trending the data to identify degradation patterns. Advanced motor models hold promise for improving on-line degradation detection, but work remains to be done.

Research also shows that ESA is not as effective as spectral vibration analysis for the detection of bearing defects or mechanical imbalance.

4.6 Vibration - standard and spectra analysis

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

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

4.7 Acoustic monitoring

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

4.8 Thermography

IR thermography is the collection and analysis of thermal images to ascertain various types of component degradation. IR inspections are an ideal complement to a comprehensive monitoring program because the technology is noncontacting and analysis results are quickly and easily obtained. Thermography has always been recognized as an effective monitoring technique for electric and steam systems, but it should not be overlooked in evaluating the operating conditions of pumps and motors.

One advantage of IR monitoring of bearings is that it can quickly detect early signs of overheating by observing the temperature rises on the rotating shaft. This information is particularly beneficial during start-ups since it enables the monitoring of heat propagation through the shaft. This technology has also proven invaluable in assessing the true operational conditions of equipment that have no temperature sensors or where existing instrumentation is considered to be faulty.

Post maintenance testing procedures that utilize thermographic analysis have been particularly helpful in diagnosing problems such as packing being too tight, inadequate cooling flows to packing glands, and seal clearances.

Thermographic data can be acquired with a portable IR scanner and subsequently interfaced with a computer where the IR data are downloaded. Data analysis software is then used to catalog the data and develop historical trends. Plots of component temperature vs time for the various types of equipment have been successfully utilized in the prevention of operation problems by numerous industrial and utility predictive maintenance programs.

4.9 Lubrication Analysis

4.9.1 New innovations in testing

Lubrication analysis has been utilized as a form of predictive maintenance in the nuclear power industry since the first plants were built. This analysis methodology has made numerous technological advancements in the past two decades. It can be as simple as evaluating the oil in a sight glass to determine if it has changed color or level, or as advanced as using a scanning electron microscope to study the particles in an oil sample. Nuclear plants use different types of lubricant analyses based on component requirements, and the maintenance goals of the particular organization. The common dilemma is that most nuclear plants must send their oil samples, some of which are radioactive, off-site to be analyzed. This is a very expensive and record-intensive procedure due to regulatory requirements. However, recent innovations to the predictive maintenance industry have enabled industries to not only perform their own oil analysis on-site but to collect, store, trend, and correlate the results with vibration analysis data on personal computers [7,8].

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

investigation. This is an important example of how the management of a monitoring program (i.e., the integration of testing programs and maintenance) is as important as the choices of technologies and monitoring methods that are employed.

4.9.2 Testing methodologies

Analyses performed to determine the quality and suitability of the oil for continued usage are commonly known as *oil analysis* (OA) techniques. Analyses performed to determine the mechanical condition of the lubricated components are commonly known as WPA techniques. While hundreds of different analyses can be performed on oil samples, a limited number are routinely used in predictive maintenance programs. Many of these techniques are also valuable in the evaluation of greases.

Spectrographic analysis is a technique also referred to as trace metals, spectrochemical, or wear metals analysis. This analysis provides information on the condition of the lubricated components by monitoring concentrations of wear metals such as iron, lead, tin, copper, etc. Coolant and dirt contamination are detected by monitoring the concentration of elements such as silicon, sodium, and boron. Lubricant consistency is monitored by trending concentrations of lubricant additives such as phosphorous, calcium, zinc, etc.

Particle count is a technique that provides a distribution of particles present in the oil sample. Particle count complements spectrometals analysis by monitoring particles greater than 10 microns, which are beyond the spectrometer's detection capabilities. This analysis technique is critical to systems that are extremely sensitive to particulate contamination. On the other hand, certain systems, such as gearboxes, generate particles in such quantities that particle count information is virtually useless.

There are two types of *ferrographic analysis* techniques: direct reading ferrography (DRF) and analytical ferrography (AF). DRF provides a ratio of large-to-small magnetically influenced particles and can provide insight into the wear rate of the lubricated component. AF is usually employed when other analyses indicate the presence of a potential problem: ferrous particles are examined by a trained analyst who can determine possible particulate source and wear severity. AF should be used when adverse wear trends are noted and before a decision is made to conduct a visual inspection of the component.

IR analysis monitors the chemical composition of the oil in certain key wavelengths. Contaminants such as glycol, fuel, and water can be detected as well as lubricant degradation products, such as oxidation and nitration.

There are also more commonly recognized lubricant analysis techniques. *Viscosity*, the most important property of an oil, provides a measure of its load bearing and lubricating properties. Solids content indicates the gross particulate contamination and can reveal potential mechanical and lubricant-related problems. *Total acid number* (TAN) is a measure of the amount of acidic agents present and indicates lubricant oxidation or contamination. *Total base number* (TBN) monitors the acid neutralization reserves of the lubricant.

In addition to these analyses previously discussed, there are analytical techniques which are critical to the evaluation of the lubricant condition of reactor main coolant pumps. These pumps present a special problem for a lubricant analysis program, since they operate for extended periods without an opportunity for sample analysis and are generally radiologically contaminated. These additional analyses indicate the effective level of the lubricant additives. With this information determination of the remaining life of the lubricant can be made. A decision can then be made to change the lubricant or extend its use through another cycle. Analyses critical to the evaluation of main coolant pumps include: rotating bomb oxidation test (RBOT), which

accelerates oxidation of the lubricant to determine the useful life of the lubricant's anti-oxidation additives, and an anti-rust test, which determines the ability of the lubricant to inhibit rust formation on lubricated components. Further information pertaining to the lubrication testing of main coolant pumps is available in NUREG/CR-6089 [5].

Selection of the types of analyses to be performed on each unit must take several factors into consideration: potential savings of the program in terms of radiation exposure, maintenance expense, lubricant changes, and downtime must be evaluated with the types of analyses and periodicity of sampling.

5.0 System problems/root causes

System problems that may be the root causes or next-level-down causes for a number of the significant pump system failures include shaft imbalance, high vibration, poor pump/motor base integrity, and design weaknesses. Those failures identified earlier by affected area may be due to these conditions or combination of conditions in a high percentage of cases.

5.1 Shaft alignment

As mentioned in Sect. 3.5, system problems and/or root causes such as poor shaft alignment are critical and, if not attended to properly, can undermine the effectiveness of many diagnostic/IST programs in supporting the lengthening of test intervals for pump systems. Precision alignment of pump and motor or pump and turbine drive shafts is a process that cannot be rushed and one that the maintenance supervisor must appreciate and support. Laser alignment is presently the most common method for establishing and monitoring shaft alignment. A laser-based shaft monitoring systems is a convenient means to use presently available technology to ensure that alignment is being maintained.

Precision aligned shafts are accomplished with attention given to soft foot, bracket sag (in the case of mechanical dial alignments), and thermal growth of casings. Descriptions and details of these concerns are as follows:

Soft foot is a condition that may be encountered during initial alignment where a mounting support of a pump or motor may not rest on the support base when the other three do and are bolted in place. A soft foot must be carefully shimmed and shimmed in a stepped fashion (see Figure 5.1) if the surface of the foot is not parallel to the support base. Failure to shim a soft foot will create high casing and bearing stresses and poor reliability of bearings and seals.

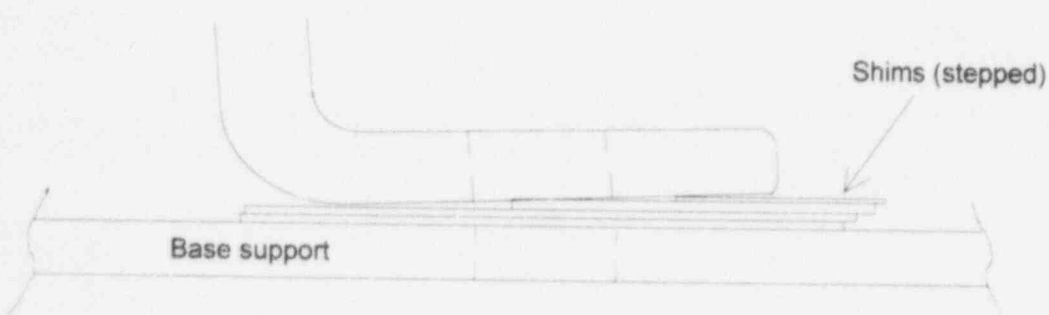

Figure 5.1 Correction for angled soft foot mount

Bracket sag refers to a condition that can exist in a mechanical dial indicator shaft alignment device. The dial indicator itself is generally mounted at the end of a metallic shaft and the weight of the indicator can place a small but significant bending moment on the dial indicator shaft. It is easy to test for and compensate for this bending but the maintenance worker must be trained to do it and be permitted to devote time to the procedure even during high work load times. One advantage of laser alignment is that it precludes this potential introduction of error.

Thermal expansion in the pump and motor casings may differ significantly degrading the shaft alignment in a predictable manner. For a true precision alignment, this must be compensated for. This is especially important for pumps in the residual heat removal (RHR) system that may operate with water temperatures ranging from 50° to 350° F. The turbine-driven pumps are another important application since the temperature can increase from approximately 70° F when idle to 550° F in operation.

The methodology for compensating for thermal expansion is straightforward, (1) the two casings' average cold and steady-state hot temperatures are measured at different heights above the front and rear mounts, (2) the average temperature change at the front and rear of both casings is calculated and, (3) these are multiplied by the height to casing centerline distances and the coefficients of expansions for the casing materials. The results are the thermal growth distances for the fronts and rears of both casings. Shims are installed under the appropriate mounts to compensate for the differences in the thermal expansions of the two casings.

5.2 Imbalance and vibration

Clearly, rotating assembly imbalance and vibration will increase stresses and wear in bearings and seals. The imbalance may occur over time in the pump due to erosion, build-up of foreign material, or cavitation to the pump impeller. Vibration may have similar causes and may occur due to shaft damage (e.g., bending).

5.3 Pump/motor support

The integrity of the motor and pump support base often depends on the quality of grouting performed in the area between the base plate and the concrete support. A quality job will not only reduce vibration and the potential loss of precision shaft alignment, but often prevent very high noise levels which can discourage, at very least, incidental attention from operators and maintenance personnel.

5.4 Common design problems

Lastly, design weaknesses such as in the turbine drive governor valve stem (a corrosion-prone area) should be corrected. This particular example does not lend itself well to the application of any current diagnostic or monitoring applications. Another design problem involves operation of a pump at an off-design point that results in hydraulic instability. Operation of pumps at flow conditions sufficiently above or below the BEP will result in instability that may cause degradation to pump internals and will almost certainly cause significantly shorter bearing and seal life.

6 Conclusions and Recommendations

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

Regulatory/Code testing is effective in the detection of internal (i.e., hydraulic-related) pump failures and, to a lesser extent, bearing, seal, and packing failures. It is not effective in detecting failures in the broader pump *system* since this method detected very few or no failures in the pump motor, turbine drive, or circuit breakers. Of the ranked failures, 37 were detected by plant programmatic activities, however three times as many (i.e., 114) were *not* detected prior to failure. These data point to a need for improved testing, diagnostics, and/or monitoring in the pump system.

Candidate diagnostic/monitoring methods, suitable for off-line or on-line usage, are available to detect many of the failure modes occurring in the pump system. In other cases, technology development is needed (see below) and in the case of GV stem corrosion, corrective action is needed possibly to provide a material/design change. The diagnostic/monitoring methods presented in this study include activities as routine as periodic servicing, lubrication analysis, inspection, and alignment or as specialized as timed response, high frequency waveform analysis, ESA, vibration spectra analysis, and other electrical, thermal, and vibration tests. Innovations in lubrication analysis and programmatic applications (e.g., correlation of results to vibration analysis data) are also specialized and show much promise in predicting pump bearing failures based on early applications.

Improved diagnostic/monitoring methods can help to justify the lengthening of testing intervals as long as fundamental root causes and good installation/maintenance practices are given proper emphasis. Precision shaft alignment, control of imbalance, and the use of sound pump/motor base supports will ensure that pump system performance, utilizing improved monitoring, is not undercut by the inattention to fundamentals.

When a recent draft study[2] revealed that the number of significant failures of the pump circuit breaker exceeded the number of significant failures of the pump itself, much attention shifted toward the circuit breakers. The present study also shows that regulatory code testing of the pump did not lead to the discovery of a single significant circuit breaker failure before the breaker had become inoperable. In short, only minimal efforts (i.e., infrequent preventative maintenance) are directed toward the discovery of circuit breaker degradation.

Circuit breaker designs have changed significantly over the years and various plants have breakers spanning many years or decades. The electro/mechanical control portion of the breakers have been improved during this time and consolidated to a compact assembly located at the bottom of the breaker underneath the main contacts and arc chutes. Furthermore, breaker design also varies significantly by manufacturer. For instance, maintenance on one manufacturer's design may require complete (and laborious) disassembly while a breaker

---

[2] R. H. Staunton, A Characterization Update of Pump and Related Equipment Failure Experience in the Nuclear Power Industry (1994-1995), ORNL/NRC/LTR/96-32, Oak Ridge National Laboratory, Oak Ridge TN (October 1996 - DRAFT

from another manufacturer in the same voltage class may require the simple removal of the cover followed by cleaning of contacts that is facilitated by swing-down arc chutes (see Appendix A). These types of time- and manufacturer-related differences are postulated to create significant differences in performance and reliability. It is recommended that this be further explored since there is a realistic potential for the replacement of the poorest circuit breaker designs to be a cost-effective approach to justifying longer test intervals.

Additional recommendations resulting from this study are as follows:

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

2. At the same time, consideration should be given to programmatically emphasizing practices that can significantly preclude pump system failures as discussed in Sect. 5;

3. Corrective action(s) to address/solve the corrosion problem in the GV stem should be carefully considered;

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

5. Preparation of a detailed plan for monitoring major components of the pump system should be prepared and;

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

   High frequency waveform analysis,
   Vibration spectra analysis,
   ESA.

The move toward condition-based and risk-based maintenance continues not only in the nuclear industry but in a broad spectrum of industries that are interested in minimizing unplanned outages and unnecessary maintenance. To this end, it is important for diagnostic engineers and technicians to carefully select the *combination* of tools that will be most effective in providing information on risk-important equipment. It is envisioned that programs in the years to come will include combinations of periodic and on-line monitoring techniques that will provide an independent means of assessing those conditions that are most likely manifestations of equipment degradation. It is essential that new technologies or technologies that require additional development are given high program emphasis for they clearly will provide essential information and perspectives that cannot be gained from other available alternatives.

References

1. D. A. Casada, "A Characterization of Pump and Pump Motor Degradation and Failure Experience in the Nuclear Power Industry," USNRC Letter Report ORNL/NRC/LTR/95-24, Oak Ridge National Laboratory, Oak Ridge, TN, January 1996

2. D. F. Cox, "Aging of Turbine Drives for Safety-Related Pumps in Nuclear Power Plants," USNRC Report NUREG/CR-5857 (ORNL-6713), Oak Ridge National Laboratory, Oak Ridge, TN, June 1995

3. "Reactors Annual Report, 1994-FY95," NUREG-1272, Vol. 9, No. 1, U.S. Nuclear Regulatory Commission, Office of Analysis and Evaluation of Operational Data, July 1996

4. "IEEE Guide for Diagnostics and Failure Investigation of Power Circuit Breakers," IEEE Std C37.10-1995, IEEE Power Engineering Society, Institute of Electrical and Electronics Engineers, Inc., New York, NY, September 1996

5. R. H. Greene, D. A. Casada, "Detection of Pump Degradation," NUREG/CR-6089, ORNL-6765, Oak Ridge National Laboratory, Oak Ridge, TN, August 1995

6. D. A. Casada, Oak Ridge National Laboratory, *Using the Motor to Monitor Pump Conditions*, presented July 1996 in Washington, DC, published in "The Proceedings of the Fourth NRC/ASME Symposium on Valve and Pump Testing," NUREG/CP-0152, Board of Nuclear Codes and Standards of the ASME and the U. S. Nuclear Regulatory Commission, Washington, DC, July 1996

7. T. Spettel and R. Garvey, *"On-site Oil Analysis: A New Tool for the Vibration Analyst,"* pp. 49-54 in Proceedings of the 17th Annual Meeting of the Vibration Institute, Willowbrook, Ill., June 8-10, 1993

8. Computational Systems, Inc., "PC-Based Integration of Spectrographic, Ferrographic and Vibrational Analysis data," P/PM Technology 4(1), 21-23 (Jan-Feb 1991)

9. B. Johnson, Arizona Public Service, *Part 2 - Current Program Integrating Strategies and Lubrication Technology*, presented July 1996 in Washington, DC, published in "The Proceedings of the Fourth NRC/ASME Symposium on Valve and Pump Testing," NUREG/CP-0152, Board of Nuclear Codes and Standards of the ASME and the U. S. Nuclear Regulatory Commission, Washington, DC, July 1996

Appendix A
Routine maintenance of a 4160 volt breaker

Although the majority of pump system breaker failures involve 4160 volt units, the design similarities end there considering that the designs span decades and several manufacturers are involved each with significantly different designs. Workers involved in the maintenance of 4160 volt circuit breakers may maintain file cabinets filled with manufacturer specifications, maintenance manuals, and part diagrams and lists. The primary components, however, remain the same - the breakers consists of certain key contacts (to be described), arc chutes, railing hardware and switches, and the electromechanical system designed to provide opening and closing that is either by (1) command, (2) automatic (i.e., tripping), or (3) manual.

As indicated in Sect. 1, the primary circuit breaker areas that were affected (i.e., failed) in nearly all of the significant failures were located in the electro/mechanical control portion that is designed to perform opening, closing, and automatic tripping functions. This Appendix seeks to provide the reader with an understanding of the overall physical breaker layout, the degree of maintenance performed based on manufacturer guidelines, and what maintenance is performed on this electro/mechanical control portion of the breaker.

This Appendix describes standard maintenance on an air breaker. Other types of common breakers are the older magne-blast breakers and the relatively new vacuum breakers. The magne-blast breaker is fundamentally the same as the air breaker but much more difficult to perform maintenance on as will be pointed out later in this appendix. The vacuum breaker relies on contacts inside three vacuum bottles to make and break connections. The contacts in the vacuum bottles are moved via a plunger that enters the bottles and a plunger drive mechanism. The adjustment for contact position is critical and factory-adjusted. Maintenance requires testing the vacuum in each bottle and replacing all three if loss of vacuum is discovered in any one. The vacuum bottles make arc chutes unnecessary and, as a result, make the overall size of the breaker much smaller than for other designs.

Text pertaining to Figures A.1 through A.9 is located with the figures on the following pages.

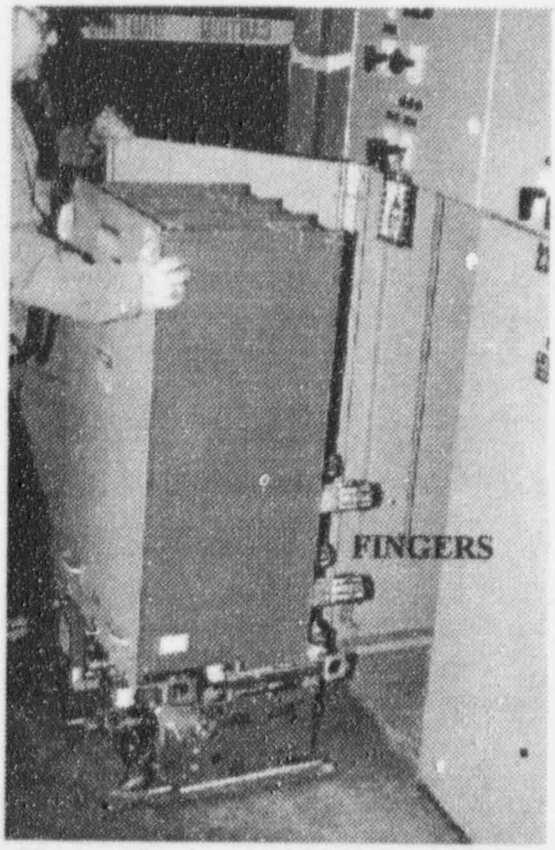

Fig A.1 Removal of 4160 volt breaker ("rack out")

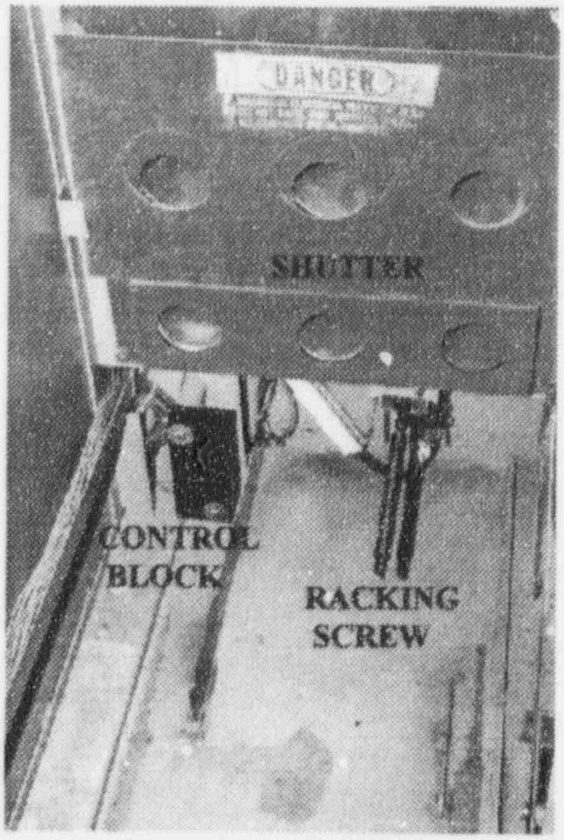

Fig. A.2 Empty Cubicle

The breaker maintenance begins when it is deenergized and removed from the cabinet or specific cubical location as shown in Fig. A.1. To remove a breaker, the drive bar to the racking screw nut is turned counterclockwise and a rack lock foot lever is depressed. This mechanically frees the breaker so it can be rolled out or racked out of the cabinet. The rack out breaks connections at the six stab-to-finger connections through which the three phase 4160 volt circuit is made. A control block terminal also breaks contacts with the control block shown in Fig. A.2. The stabs are located behind the sliding safety shutter shown at the back wall of the cabinet in the figure.

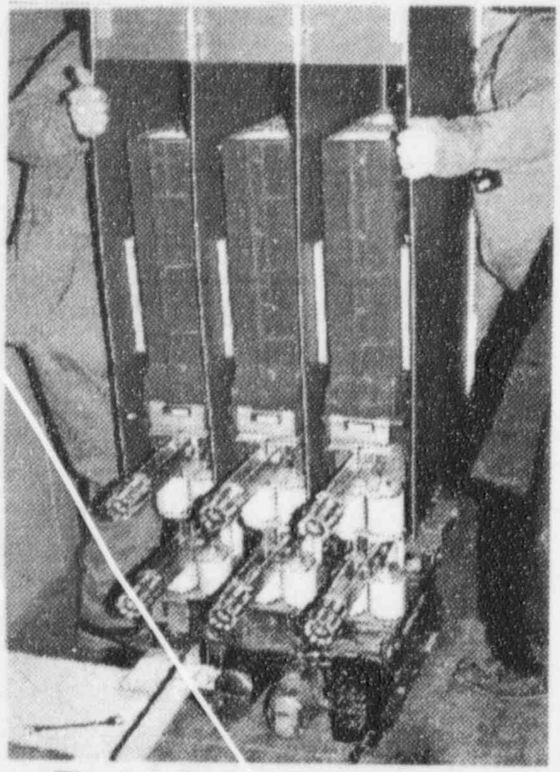

Fig. A.3 Removal of main cover

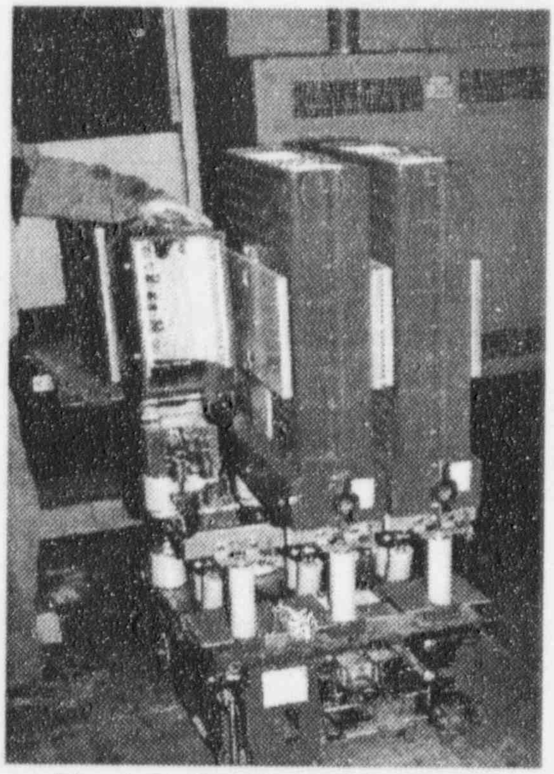

Fig. A.4 Opening left arc chute

Once the circuit breaker is in position for maintenance, the main cover is removed (Fig. A.3) and set aside. For air breakers of this type, the hinged arc chutes can be conveniently lowered as shown in Fig. A.4, exposing the main contacts for cleaning. In magne-blast breakers, a lengthy disassembly operation must take place to perform maintenance on the contacts, insulating surfaces, and arc chutes. In magne-blast breakers, the physically-larger electro/mechanical control system is located just behind a large front panel and the arc chutes are located at the rear of the breaker.

For the depicted air breaker, the removed cover is wiped down as are essentially all exposed insulating surfaces. Each arc chute is inspected for the presence of carbon on the internal surfaces. This inspection includes a megger test which may indicate a need for cleaning (i.e., a failed test). If cleaning is required, the arc chutes are removed and the surfaces are sand blasted. This operation can only be performed a limited number of times (e.g., three) before the chutes must be replaced.

Fig. A.5 Shining main contacts

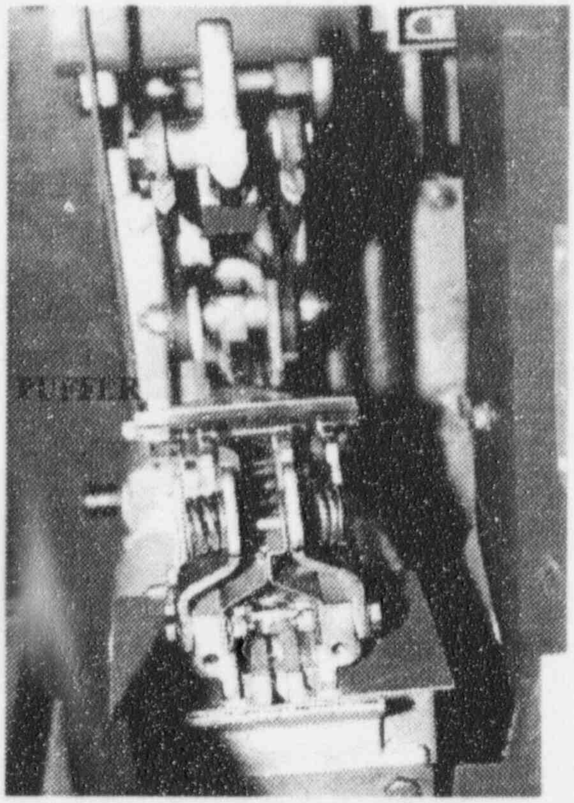

Fig. A.6 Contacts and puffer details

As shown in Fig. A.5, a metal brush is used to clean or shine the arcing and main contacts. Figure A.6 shows the contacts and mating fingers as well as the clear plastic housing of the puffer. The piston-driven, pressure air blast is emitted from the puffer pushing the arc into the arc chutes where an inductor creates a field that pulls the arc further up between a series of insulting baffles, thus elongating the arc until it breaks. The main contact is shown as the light object on the top of Fig. A.6. Note the wedge shaped point and how arcing contacts are located to either side and slightly below the point of the main contact.

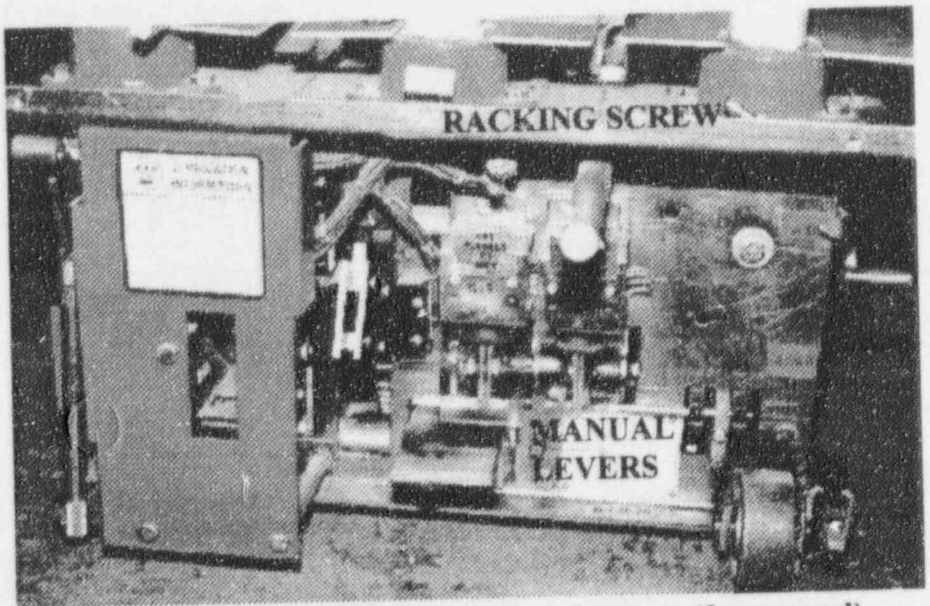

Fig. A.7 Electro/mechanical control system (front panel)

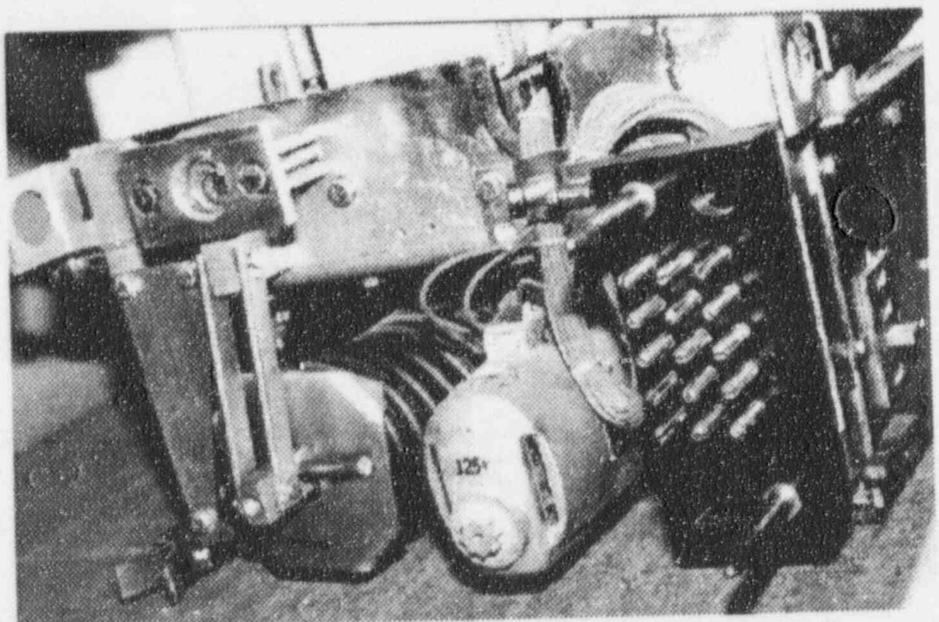

Fig. A.8 Electro/mechanical control system (rear panel)

The electro/mechanical control unit front panel is shown in Fig. A.7. The racking screw drive is shown where a drive crank is connected for racking in and out. Two manual controls, one for opening the breaker and one for closing are also shown. Only a suggestion of the elaborate gear box and wiring is visible. Fig. A.8 shows the rear panel of the breaker where the charging spring for closing and charging motor are clearly visible. Also shown is the location of the racking nut (upper left-hand corner) and the control block (opposite corner) with guide pins at the upper left and lower right corners. As opposed to magne-blast breakers which use several

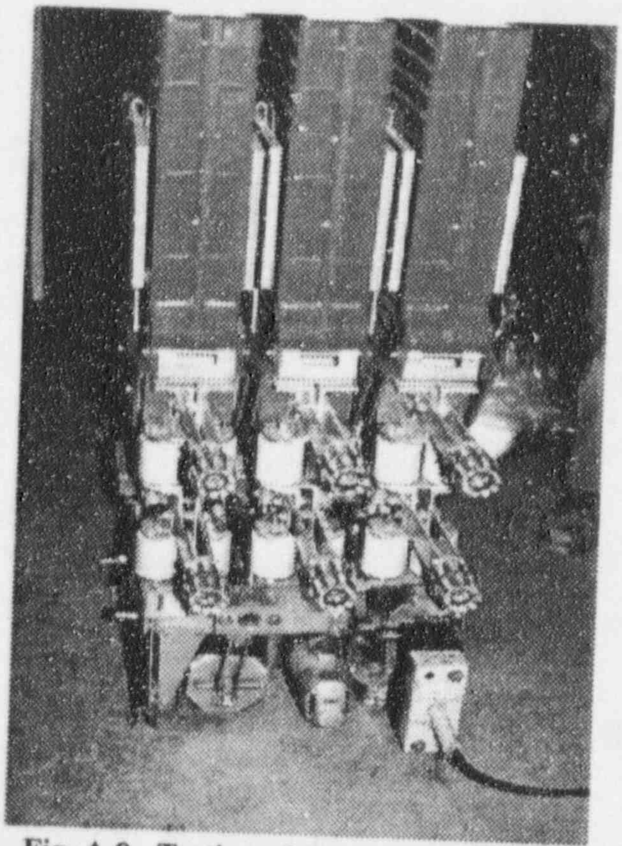

Fig. A.9 Testing of the spring charging mechanism before installing cover and completion of maintenance

large springs, the air breaker design depicted uses a large closing spring shown next to the motor and two much smaller opening springs.

The electro/mechanical control unit is not convenient to work on being located at the bottom of a breaker weighing well over 1000 lbs. The standard periodic maintenance performed on the unit is spraying a lubricant down into it through small opening to lubricate moving parts. Approximately 90% of the maintenance is performed on other areas of the breaker.

Fig. A.9 shows a test block plugged onto the breaker for final testing. The signal through this connection charges the spring and then tests the closing mechanism. This may be performed several times to assure proper operation of the charging mechanism. Following this test the breaker cover is fastened in place and the breaker is racked in for operation.