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PRELIMINARY ASSESSMENT OF PUMP IST EFFECTIVENESS[1]

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ABSTRACT

A preliminary review of Inservice Testing (IST) effectiveness for Code Class 1, 2, and 3 pumps at nuclear power plants was performed. IST requirements are specified by ASME Section XI, and the Operations and Maintenance Standard (OM Part 6). The INPO NPRDS database was used to provide failure reports for these components for 1988 to 1992. This time frame coincides with the issuance of Generic Letter 89-04, which resulted in a more consistent application of the requirements by the licensees.

For this time period, 2585 pump failures were reported. A review of these failures indicated that the majority (71.6%) were due to external leakage, and were excluded from this study since these events typically do not affect pump operability and are not detected by the measurement of IST parameters. Of the remaining 733 events, a review was performed to identify the primary failure causes, failure modes, and method of detection. Plant testing programs, consisting of IST, surveillance testing, and special testing, detected approximately 40% of these occurrences. Others were detected through operational abnormalities, routine and incidental observations, alarms, and while performing maintenance. This paper provides a discussion of the results of the study (Ref. 1).

INTRODUCTION

As per the requirements specified in 10 CFR 50.55a(f), all operating nuclear power plants are required to develop and maintain a formal inservice testing (IST) program. These programs are designed to ensure the operational readiness of Code Class 1, 2, and 3 pumps and valves. Specific testing requirements and acceptance criteria are defined by Section XI of the ASME Boiler and Pressure Vessel Code. 10CFR50.55a(b) provides the latest editions and addenda of Section XI approved for use. Licensees are required to update their IST programs every 10 years to the edition and addenda referenced in paragraph (b). Currently, Section XI editions through 1989 are referenced in paragraph (b).

Section XI first introduced pump and valve testing requirements in the 1971 Edition, Summer 1973 Addenda. The 1988 Addenda of Section XI omitted specific requirements and specified that the rules for pump and valve IST shall meet the requirements set forth in ASME Operations and Maintenance Standards Part 6 (OM-6), "Inservice Testing of Pumps in Light-Water Reactor Power Plants," and Part 10 (OM-10), "Inservice Testing of Valves in Light-Water Reactor Power Plants." In 1990, the ASME issued the OM Code which was written to replace the pump and valve requirements contained in Section XI. The NRC staff is currently evaluating the OM Code for inclusion into the regulations, 10CFR50.55a(b).

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[1]Work performed under the auspices of the U.S. Nuclear Regulatory Commission.

The US Nuclear Regulatory Commission has also provided additional guidance to licensees regarding compliance with specific IST requirements in Generic Letter 89-04 (GL 89-04) and, very recently, in Draft NUREG-1482.

Licensees prepare specific IST programs for their plants, and update the program every ten years as discussed above. This program provides the specific testing requirements and test frequency for each pump and valve included in the program.

Brookhaven National Laboratory (BNL), under contract with the U.S. Nuclear Regulatory Commission (NRC), is conducting a review of the IST effectiveness at nuclear power plants. The results will be used to identify and recommend potential Code changes and revisions to improve existing IST programs in identifying component degradations before failure.

IST effectiveness may be defined and assessed in several ways. For example, the following issues may be evaluated in making the assessment:

a) What type of pump and valve failures are occurring, and how many are being detected by IST? Are any of the failures found by other means potentially detectable by IST?
b) Does the IST program identify component degradation prior to failure?
c) Are safety-significant failures and degradations being identified?
d) To what extent does the program duplicate other required testing programs (i.e., Appendix J leak testing, Technical Specification testing, PIV testing, MOV GL 89-10 testing)?
e) Is the program cost effective?

For this initial, limited scope review, it was decided to review the pump and valve failure occurrences to determine the specific types of failures occurring, and to what degree the IST program is identifying these failures. For this study, the Nuclear Plant Reliability Data System (NPRDS), which is a computerized information retrieval system maintained by the Institute of Nuclear Power Operations (INPO) was used. The NPRDS contains specific information (failure mode, symptom, cause and system effect, and the method of detection) on component failures submitted by the nuclear utilities. Failures are reported to NPRDS when degradation of a component, part, or associated device has occurred and one function of the component (e.g., to produce the specified flow or differential pressure) has been lost or degraded, such that the performance criterion for at least one of the component's functions is not met. The performance criterion may be based on Technical Specification limits, ASME Code limits, or system design limits, for example. The NPRDS data also encompasses those events reported as Licensee Event Reports (LERs) as specified by 10 CFR 50.73.

All Safety Class 1, 2, and 3 pump and valve failure events from 1988 to 1992 contained in the NPRDS were reviewed for applicability to this study. As defined in NPRDS, the Safety Class of components is determined using ANSI/ANS 51.1 (PWRs) or 52.1 (BWRs). Although the scope of the new OM Standards includes all safety-related pumps and valves, the current regulations require IST in accordance with Section XI only for ASME Code Class 1, 2, and 3 pumps and valves. NPRDS only provides the Safety Class, and not the Code Class, of components. Therefore, the scope of our study was limited to Safety Class 1, 2, and 3 components. There may be some discrepancy between Safety Class and ASME Code Class 1, 2, or 3, although this is not expected to be significant. Many plants include all safety-related pumps and valves in their IST programs. The 5 year time frame was chosen to coincide with the issuance of Generic Letter 89-04, which provided specific, detailed instructions to licensees regarding IST. This has resulted in a more consistent application of the Code requirements by the individual licensees. A secondary benefit resulting from this guidance has been an improved and more consistent reporting of operating pump failures to the NPRDS. This paper discusses the results of the evaluation of pump failures.

REVIEW OF CODE REQUIREMENTS FOR PUMPS

Section XI, Subsection IWP of the ASME Boiler & Pressure Vessel Code, OM Standard Part 6, and the OM Code, Subsection ISTB define the rules and requirements for the preservice and inservice testing of Class 1, 2, and 3 centrifugal and positive displacement type pumps to assess their operational readiness. The test quantities required to be measured and compared to reference values to detect degradation include pump speed, differential pressure, flow rate, and vibration amplitude (measured as either displacement or velocity). The test frequency, acceptance criteria, corrective action, and records requirements are also specified. Also included are rules and requirements on defining acceptable instrumentation, including accuracy, range, calibration, and instrument location.

As discussed in 10CFR50.55a(f)(6)(i), when testing in accordance with the Code is impractical, relief may be requested. Additionally, licensees may propose alternatives to the Code, as allowed by 10CFR50.55a(a)(3). The following are requirements of the Code for which licensees commonly ask for relief from:

- pump vibration frequency range requirements for low speed pumps (e.g., pumps that would require the instrument range to be less than 10 hz.) (Section XI, ¶ IWP-4520(b)).
- pump vibration acceptance criteria for pumps with normally high vibration levels (Section XI, ¶ IWP-3210).
- pump inlet pressure measurement for pumps that take suction from a bay or tank (Section XI, ¶ IWP-3100).
- test instrument ranges (Section XI, ¶ IWP-4120).
- quarterly measurement of flowrate for pumps without an adequate test loop (e.g., Containment spray pumps in PWRs) or normal plant operation does not allow the required test configuration (e.g., service water pumps) (Section XI, ¶ IWP-3400(a)).
- the use of reference values for pumps with variable system resistance based on demand loads (e.g., component cooling water pumps) (Section XI, ¶ IWP-3110).

Additionally, some licensees have requested to measure vibration velocity in root mean square (rms) rather than peak, as required by the Code, and to use specific provisions of OMa-1988 Part 6.

OPERATING DATA REVIEW

As discussed in the Introduction, the NPRDS database was used to review the pump operating failures which occurred between 1988 and 1992. Pump failure records were reviewed for specific failure modes, effects, and detection methods in order to provide an overview of the failures, and assess the effectiveness of the IST in detecting these failures. Failures related to the pump driver (e.g., motor or turbine) were not evaluated since IST does not directly assess these components.

For the 1988 to 1992 time period, there were 2585 reported failures affecting Class 1, 2, and 3 pumps (Figure 1). Of these, 1852 failures (71.6%) were due to external leakage (i.e., packing failures). Typically, external leakage failures do not affect the pump operability, and are not detected by the required IST test parameters. Therefore, they were excluded from our study. The remaining 733 pump failure events were used for the evaluation.

Failure Causes

The six most frequently occurring failure causes for those pump failures not due to external leakage are shown in Figure 2. These included:

a) normal/abnormal wear (NPRDS Code AD),
b) caused by previous repair (NPRDS Code AM),
c) mechanical damage/binding (NPRDS Code BB),
d) out of mechanical adjustment (NPRDS Code BC),
e) aging (NPRDS Code BD), and
f) blocked or obstructed flowpath (NPRDS Code BF).

These six failure causes accounted for 559 (76%) of the pump failures. An additional 22 failure causes contributed to <3.7% each to the total, and were considered isolated occurrences and based upon the programs scope, were not evaluated. Pump wear (normal and abnormal) (44%), mechanical damage/binding (13%), and mechanical adjustment problems (7%) were the three most common failure causes. The system effect of these failure causes is also shown in Figure 2 and is discussed later in this paper.

A review of the six most frequent failure causes has shows that each can be detected by IST as shown on Table 1. The time-dependant failure causes (i.e., aging, wear, and mechanical degradation), should be detectable by trending specific plant operating parameters.

Failures due to previous component repairs are also addressed by both Section XI and the OM Code. Both Codes specifically require pump operation and the re-establishment of reference values following maintenance, repairs, or replacement. Still, 40 (7%) pump failures were attributed to previous repairs. The need for adequate post-maintenance testing is essential to assure the proper condition of the component after maintenance. Human related problems from the maintenance (i.e., improper installation, wrong parts) can be discovered at this time. Improper maintenance, if not detected, may accelerate aging degradation, or result in failure. A recent review of insights obtained from a review of NRC Maintenance Team Inspection reports, also concluded that post maintenance testing was an area which required improvement at many plants (Ref. 2). This fact, as well as the 40 failures attributed to previous maintenance, highlight the need for thorough post-maintenance testing.

Figure 3 shows the actual method of detection for each of the failure causes. The majority of the failures were detected by surveillance tests (32%), followed by routine observation (26%), and operational abnormalities (15%). As reported by the licensees to NPRDS, only 26 (5%) failures with these failure causes were detected by IST. However, a review of a sampling of the failures detected by surveillance testing indicate that many were also probably IST related. Plant Technical Specifications require IST in accordance with Section XI, therefore, utilities may input IST detected failures as surveillance testing. Since the scope of the study did not allow for a detailed review of each individual failure, it was decided that for purposes of this evaluation, no distinction would be made between the three testing methods (IST, surveillance, and special testing) included in the

Table 1 Failure Cause Detectable by Current IST Requirements

Failure Cause	Potentially Detectable by IST				
	Pump Speed	Differential Pressure	Flow Rate	Vibration	Post-Maintenance Testing
Normal/Abnormal Wear[1]	Y	Y	Y	Y	NA
Caused by Previous Repair[2]	Y	Y	Y	Y	Y
Mechanical Damage/Binding	Y	Y	Y	Y	NA
Out of Mechanical Adjustment	N	N	N	Y	NA
Aging[3]	Y	Y	Y	Y	NA
Blocked or Obstructed Flowrate	Y	Y	Y	Y	NA
External Leakage	N	N	N	N	NA
Others[4] (e.g., dirt, lack of lubrication, particulate contamination, electrical, human-related)	-	-	-	-	-

1 Depending on wear part (e.g., impeller, bearing).
2 Depending on extent of repair.
3 Depending on what part is subject to aging. Note aging is often used as a catchall failure cause.
4 Not evaluated due to their limited frequency.

NPRDS database. This assumption is conservative because the surveillance tests (i.e., Technical Specification Tests) require system testing in addition to Section XI component testing. These three testing and inspection methods accounted for 222 (40%) of the failure causes. The remaining 60% were detected by operational abnormalities, maintenance, audio-visual alarm, routine or incidental observations, or corrective maintenance.

The number of failure occurrences detected through testing for the six most frequent failure causes is shown in Table 2. Of these six failure causes, the most critical are those which would result in the inoperability of a pump which could have affected plant operation and safety, namely mechanical damage/binding and blocked/obstructed failures. Specific examples of failures attributed to these causes included bearing failure and cracked shaft. As discussed previously, failures due to previous repairs also should have been detected by IST. A sampling of the 25 failures attributed to this cause not detected by testing includes packing adjustment, missing parts, air binding, bearing installed 180 degrees out, and wrong bearings installed. Most pump failures were attributed to normal wear and aging, the majority of which were not detected by testing.

A review of the normal wear and aging failures indicate that mechanical wear of the rotating assemblies and bearing failures were the dominate failure causes. The majority of these failures were preceded by an increase in temperature and vibration. Mechanical vibration is a parameter specifically addressed by the Code. Interpretation of the data to determine the cause for increased vibration levels is often difficult. Increases in vibration could be due to many factors (e.g., upstream flow cavitation and building structure vibration, as well as specific pump problems), and if the pump

Table 2 Pump Failure Cause Detection

Failure Cause Description	Detected During Testing	Not Detected During Testing
Normal/Abnormal Wear (NPRDS Code AD)	137 (43%)	181 (57%)
Caused by Previous Repair (NPRDS Code AM)	15 (38%)	25 (62%)
Mechanical Damage/Binding (NPRDS Code BB)	17 (19%)	74 (81%)
Out of Mechanical Adjustment (NPRDS Code BD)	34 (65%)	18 (35%)
Aging/Cyclic Fatigue (NPRDS Code BO)	8 (26%)	23 (74%)
Blocked/Obstructed (NPRDS Code BF)	11 (41%)	16 (59%)

is not disassembled and inspected, the exact cause may not be readily apparent. If the levels are not large enough to exceed the Code required action or alert levels, the pump may be returned to service, regardless of the trend. Given the frequency of pump failures which experienced increased vibrations, a change to the Code to require that an engineering evaluation is done if these trends are observed may be warranted. These evaluations could be done without removing the pump from service, and if the cause is isolated, it could be fixed prior to pump failure. The OM Code Committee is considering a change that would allow the use of vibration spectrum analysis (which requires analysis of trends), in lieu of doubling the test frequency, when vibration deviations fall within the alert range. It should be noted that most plants, in addition to the Code required vibration measurements, perform spectral analysis as preventive maintenance and trend the results. As demonstrated by the two utilities recently visited by BNL to review the IST programs, maintenance vibration programs can be effective in identifying degraded conditions. The Code committees and NRC are increasingly relying on the use of vibration to detect degradation over hydraulic monitoring, as evidenced by the changes made in OMa-1988, Part 6 (Ref. 3) and Generic Letter 89-04, Position 9. Based upon this reliance, and the art of interpreting vibration data, increased controls on personnel training and qualifications may be warranted.

Unlike vibration, bearing temperature monitoring is no longer required by the Code. Previously, temperature was required to be monitored yearly. The primary reason for deleting this requirement was that the ASME committees felt it was unlikely that a yearly test would coincide with the failure, which is the only time an increase in temperature would be expected. Only if the temperature is continuously monitored could impending pump bearing failure be detected. However, given the amount of failures due to increased temperatures, it may be warranted to do a further detailed review of these failures. Considering the potential economic and safety ramifications which could result from the failure of certain risk significant, continuously running pumps, a continuous temperature monitoring system may be desirable.

Failures resulting from blocked or obstructed flow paths are an example of events which may not always be detectable by IST. Several failures were noted to result from foreign objects (e.g., wood) obstructing pump intakes, and damaging impellers. These occurrences happen quickly, and chances are IST testing would not coincide with these occurrences. This is not to say that all of these failure causes are undetectable. Blockage due to the buildup of sand over time at the service water intake potentially would be detectable through a gradual decrease in output flow and differential pressure. The trending program for specific pumps should be reviewed to ensure that changes in these parameters are investigated before failure. The OM committees are presently considering Code changes to address pump trending.

Failure Symptoms

In addition to ensuring that the most common failure causes were addressed by Code requirements, a review of the failure symptoms is also important. These symptoms are the first indications of an actual, or imminent pump failure. The five failure symptoms for the failures reviewed included:

a) physical fault-failure due to a changed physical condition or configuration (NPRDS Code A),
b) out of specification-failure characterized by pump operation outside of permissible ranges (NPRDS Code B),
c) demand fault-failure of pump to operate upon demand (NPRDS Code C),
d) abnormal characteristic-pump failure characterized by a response which is not normal or anticipated (NPRDS Code D), and
e) Contained leakage-leakage of the pumped fluid along the system flow path (NPRDS Code F).

The majority of the pump failures exhibited out of specification or abnormal parameters (Figure 4).

Figure 5 shows the method of detection for these failure symptoms. Of the 733 pump failures not due to external leakage, 40% (293) were detected through the testing programs. A particular concern was the 62 pumps which failed on demand. It is essential that a pump be available to perform the designed safety function when needed, particularly those which are normally in standby. A review of these events showed that 41 failures affected operating pumps, and 21 failures affected standby pumps. Of the 21 instances which affected the standby pumps, 12 were detected through testing. Of the 9 occurrences, 7 represent events of standby components which would not have operated upon demand if required, and were found by chance. Though these types of events were not frequently observed in the data, they highlight the importance of IST to detecting degradations which could affect the operability of standby pumps.

Failure Modes

A review of the particular failure mode for pumps which failed due to causes other than external leakage, was also performed to determine if the IST requirements were effective in identifying each. The failure modes describe how a problem or deficiency affected the function of a component when the failure was discovered. For pumps, the NPRDS database identified four specific modes:

a) failure to start upon demand (NPRDS Code FS),
b) failure to continue running (NPRDS Code FR),
c) other incipient failures found during inspection, surveillance, testing, or maintenance (NPRDS Code MO), and
d) failures unable to classify (NPRDS Code UA).

Figures 6 and 7 show failure modes as a function of both failure cause and symptom, respectively. Failure to start on demand was the predominant failure mode for standby pumps, while pumps which failed to run exhibited abnormal and out of specification pump characteristics. Pump wear was the main cause for both of these failure modes. Incipient failures were primarily due to pump wear, and though they did not affect the starting or running capability, they did affect the ability of the pump to operate as designed. A sensitive trending of IST pump quantities would be required to detect these occurrences before actual pump failure.

Figure 8 shows the method of detection for these failure modes. Plant testing discovered 53% of the reported failures to start, and 38% of the failures to run. Figure 9 shows the pump operating status for each failure mode. The majority of pump failures were related to operating pumps failing to continue running. Testing has not been successful at detecting these failures prior to occurrence. This highlights the importance of pump operation and performing quarterly testing, if possible. Though the plant effect is minimal, the loss of redundancy may be safety significant for some systems. Licensees may consider rotating these alternate pumps into operation if possible, since it appears that operation is the prime way to detect these failures and degradation. Again, it is essential that the trending program be sensitive enough to detect operating abnormalities before failures occur. The probability of detecting these failures due to increased operating time, would be greater.

Failure Effects

The pump failure occurrences, which were not due to external leakage, affected over 40 different systems (in both BWR and PWR plants). Table 3 lists the systems most frequently affected by these failures. Service water (21%) and chemical and volume control (20%) systems were most frequently affected. The seven systems listed in Table 3 accounted for 65% of the reported failures. The remaining failures affecting other plant systems did not exceed 3% for any one system.

Table 3 Systems Affected By Pump Failures

System	% of Occurrence
Service Water	21
Chemical Volume and Control	20
Auxiliary Feedwater	6
Reactor Coolant	6
Control Rod Drive	5
Component Cooling Water	4
Reactor Recirculation	3

A review of these failures was also made to determine if the pumps affected were in the operating or standby mode. The majority of the failures affected normally operating pumps (Figure 10). This distinction is important since it is essential that standby pumps, important to plant safety, be available to operate as designed upon demand, and that IST be used to detect and correct degrading conditions before failure during operation.

Typically, these pump failures had no significant effect on plant operations (Figure 11). Only 7% of the failures resulted in the plant being removed from service, reduced power, or a plant trip. This is not surprising since many of the plant systems contain redundant pumps so as to minimize any disruption to power production. However, the effect on the individual systems was greater (Figure 12), as only 27% of the pump failures resulted in no system effect. Degraded system train (44%) and loss of redundancy (loss of one or more train function(s)) (23%) were the most frequent effects.

PUMP CONCLUSIONS AND RECOMMENDATIONS

This evaluation of operational data for Class 1, 2, and 3 pumps demonstrated that a significant number of failures have occurred, resulting in significant system affects (i.e., component loss, loss of redundancy, etc.), but have not resulted in significant plant affects. Numerous systems have been affected by these pump failures, with the service water and chemical and volume control systems being the most frequent. Over 75% of the failures affected operating pumps. However, the failures to standby pumps are significant since it may have resulted in the pump being unable to perform its safety function in the event of an emergency. Table 4 shows the effectiveness of IST in detecting the six most commonly occurring failure causes. Plant testing was only effective in detecting 40% of the failures.

Pump aging, due to normal and abnormal wear of the internal components, was the most common failure cause. However, in addition to those degradations detected through testing, a significant number were discovered through routine observations. Examples of these occurrences indicate that leaks, high vibration levels, or variations in pump motor current readings alerted operators to impending failure. While not every degradation is detectable through testing, it is essential that the results from these tests be trended, and those which continue to approach Code specified Alert and Required Action Ranges be evaluated. The Code currently only requires licensee corrective action after the Required Action level is reached. It is also essential that the trending program be sensitive enough to detect such trends. Not to be lost in this evaluation is the importance of system walkdowns and observations by operating personnel. Without these observations, other failures would have occurred. An example of this are the pumps which failed due to blocked or clogged inlets. If this was occurring over time, it may have been detectable through trending flow or pressure measurements. The use of trending should be included in the Code.

Based upon the limited review of failures not detected by IST, the increased use of non-intrusive inspection techniques may help to detect degradations. Techniques such as motor current signature analysis have proven useful in correlating current variations to specific component degradations.

Table 4 Effectiveness of Testing in Detecting Pump Failures

Failure Cause	Total Number of Failures	Detected by Testing	Not Detected by Testing
Normal/Abnormal wear	318	137 (43%)	181 (57%)
Caused by previous repair	40	15 (38%)	25 (62%)
Mechanical damage/binding	91	17 (19%)	74 (81%)
Out of mechanical adjustment	52	34 (65%)	18 (35%)
Aging/cycle fatigue	31	8 (26%)	23 (74%)
Blocked/obstructed	27	11 (41%)	16 (59%)
Other causes	174	272 (41%)	102 (59%)
Total	733	294 (40%)	439 (60%)

Some component aging due to wear may only be detectable by periodic pump teardown and inspection. Though such a practice is required by the Code every 10 years as part of the inservice inspection program (i.e., ISI) for Class 1 components, this may not be adequate for certain risk significant pumps which have shown a tendency to this type of degradation. A more thorough analysis would be required to identify specific pumps and systems, since such a maintenance practice is not without risks, and may lead to additional failures.

The NRC has recommended for the next generation of nuclear power plants (i.e., the ALWRs), that a disassembly and inspection program be developed for all safety-related pumps to detect unacceptable degradation which cannot be detected through the use of advanced non-intrusive techniques. Periodic disassembly and inspection would be performed based on historical performance, analysis of trends, service life of parts (e.g., o-rings) and non-intrusive results (Ref. 4).

Continuous monitoring of temperature and vibration levels on some pumps may be warranted given the history of bearing failures. The Code is increasing the emphasis on vibration monitoring.

An important part of the testing program is post maintenance testing. Failures attributed to previous maintenance were seen, which may have been preventable if thorough tests were performed prior to operation.

Testing provides one of the only ways to determine the operability of standby pumps. A significant number of standby pumps failed to continue to run after starting. If redundant pumps are available in a system that is normally operating (e.g., service water), it may be useful to rotate these into service periodically. This practice would tend to detect pump degradation which could be addressed before the pump possibly failed on demand.

Our study highlighted the failures of Safety Class 1, 2, and 3 pumps, as reported by the licensees through the INPO NPRDS database. A significant number of pumps failures were seen. Numerous occurrences were discussed highlighting failures which resulted from worn internals which were not detected by plant testing. However, a qualitative examination of these failures indicated that a significant portion may have been detectable if the trending program was sensitive enough.

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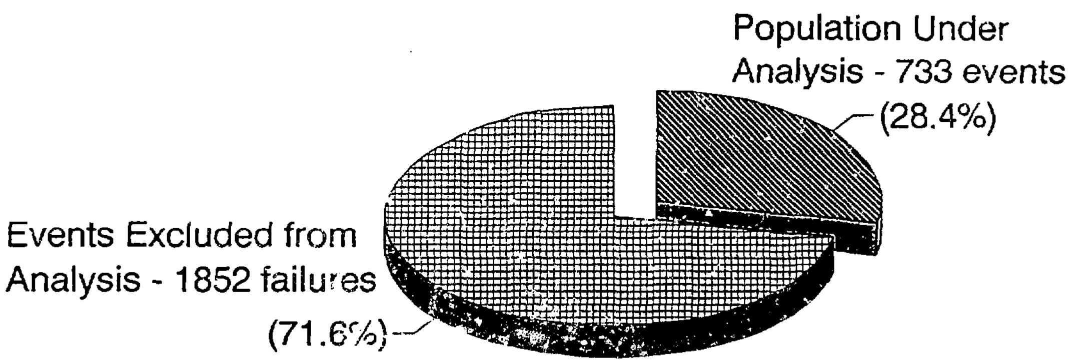

Figure 1 Class 1, 2, and 3 pump failures (1988-1992)

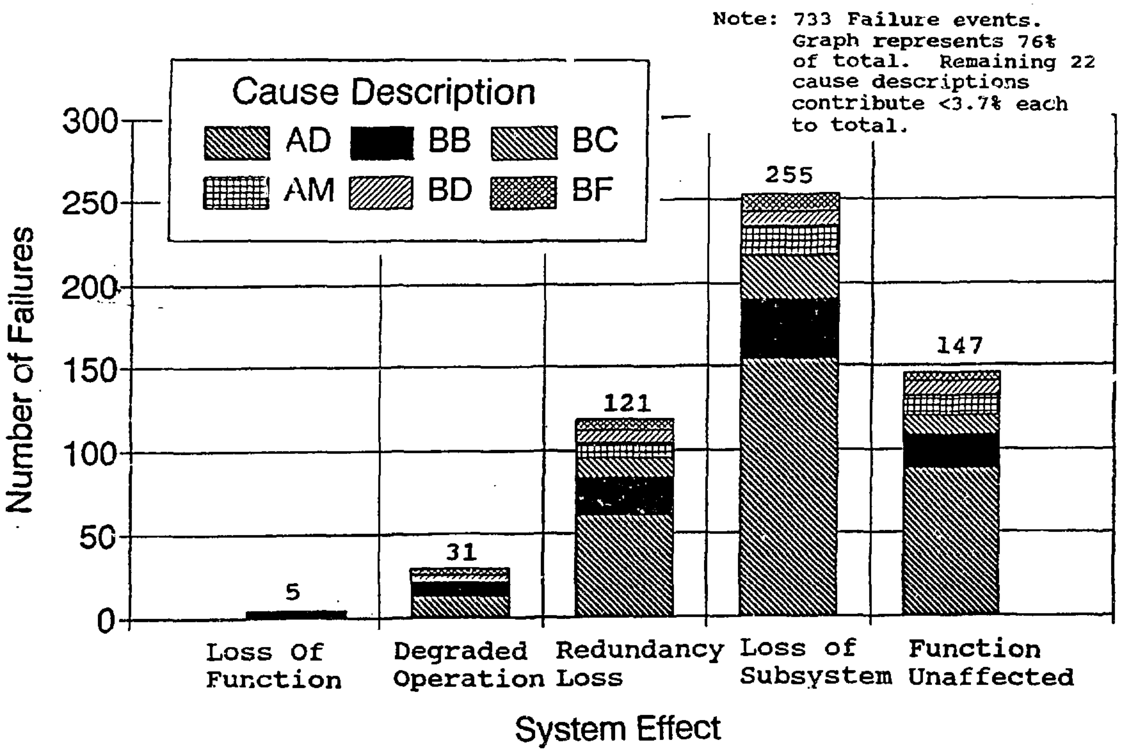

Figure 2 Pump failure cause and system effect

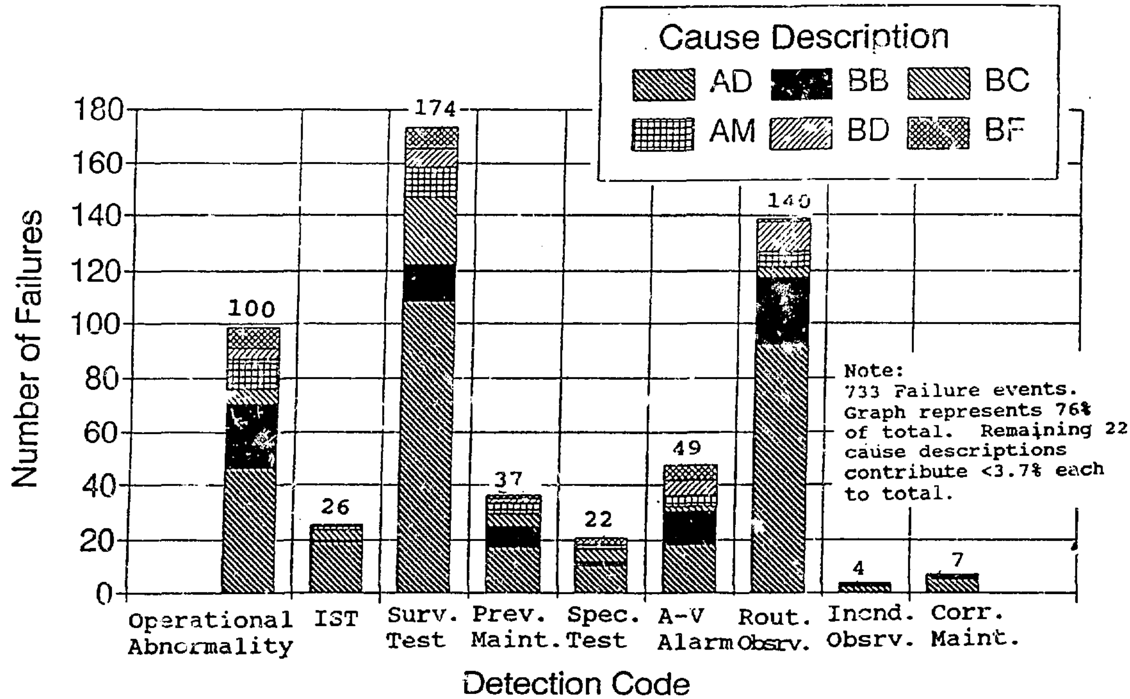

Figure 3 Pump failure cause and detection method

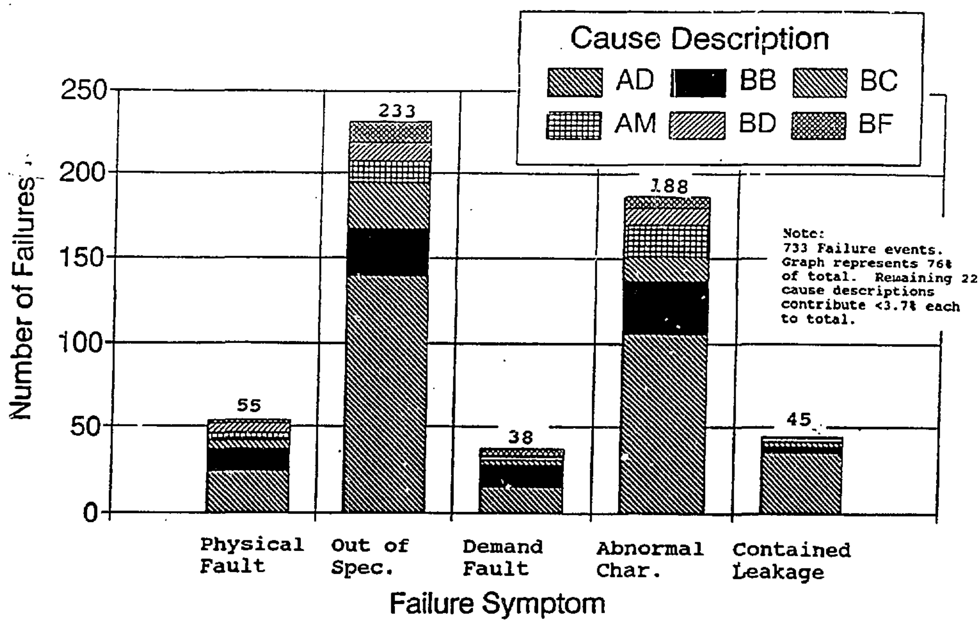

Figure 4 Pump failure symptom vs. failure cause

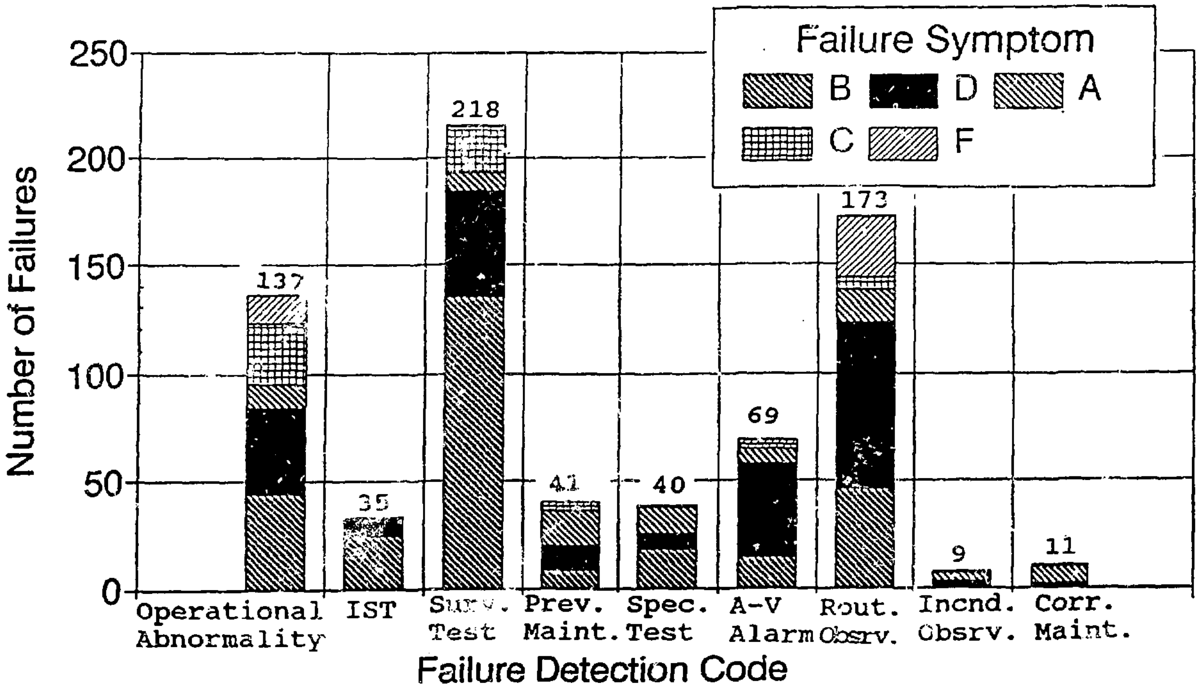

Figure 5 Pump failure symptoms vs. detection method

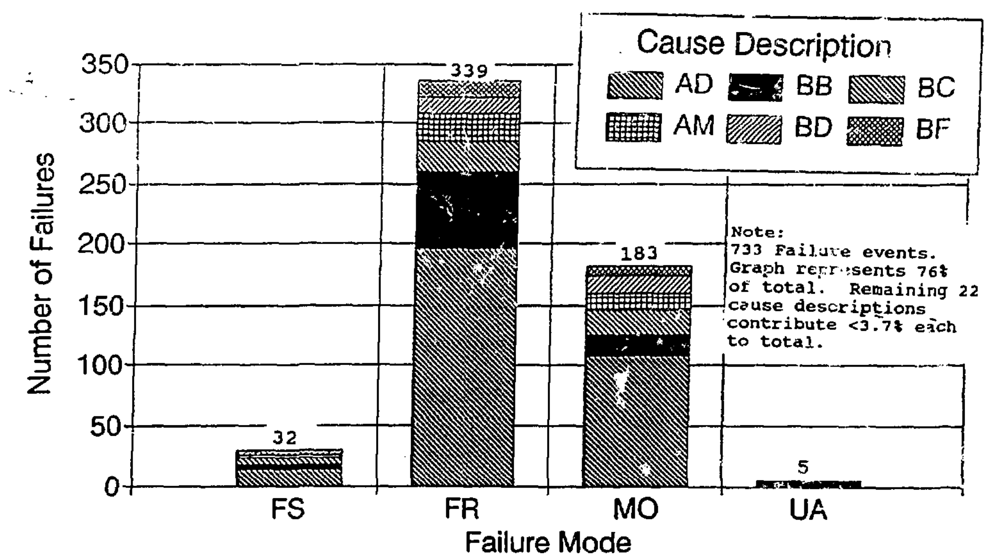

Figure 6 Pump failure mode vs. failure cause

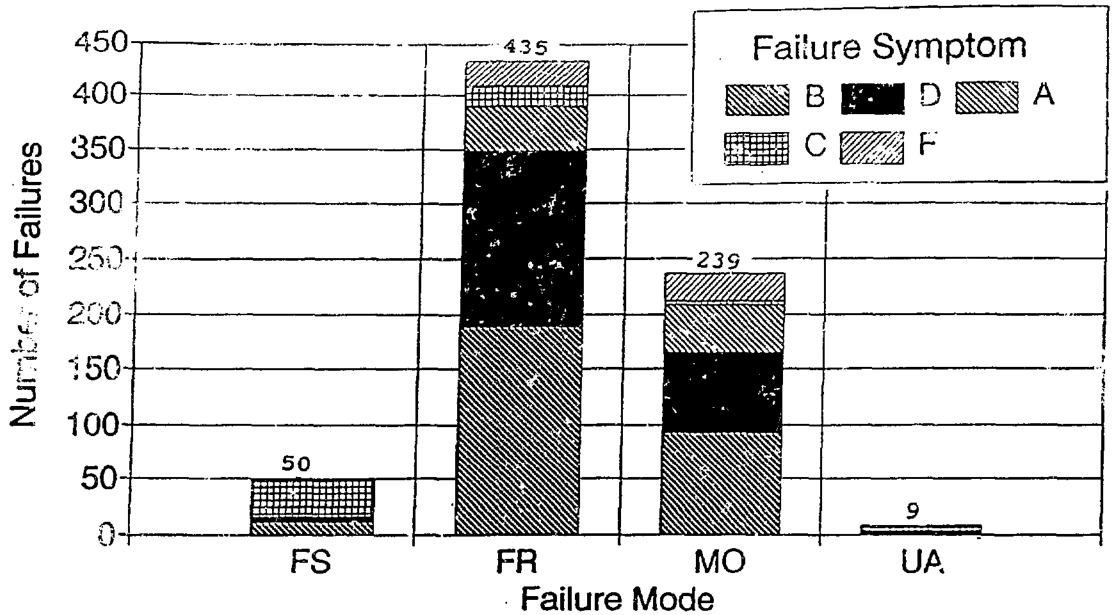

Figure 7 Pump failure mode vs. failure symptom

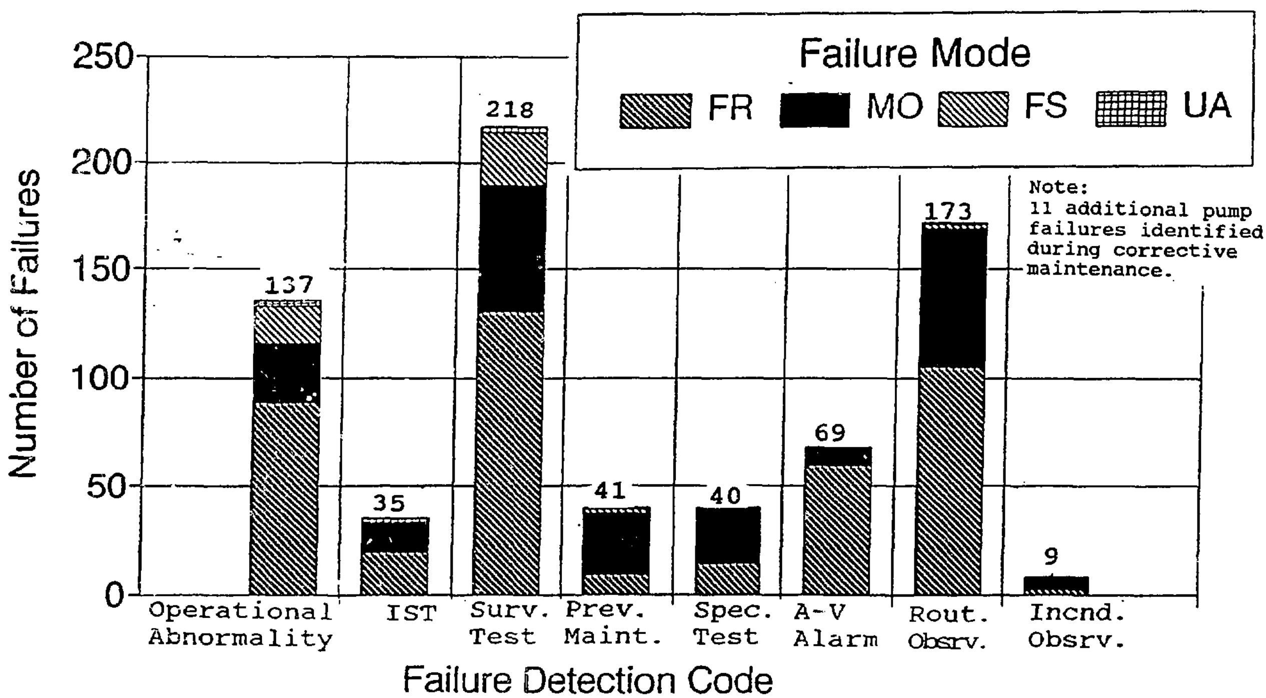

Figure 8 Pump failure mode vs. detection method

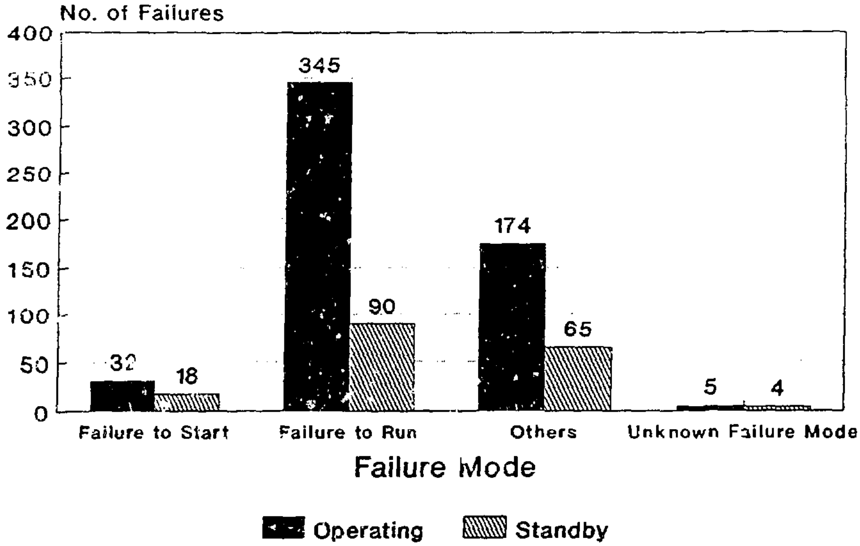

Figure 9 Plant operating status vs. failure mode

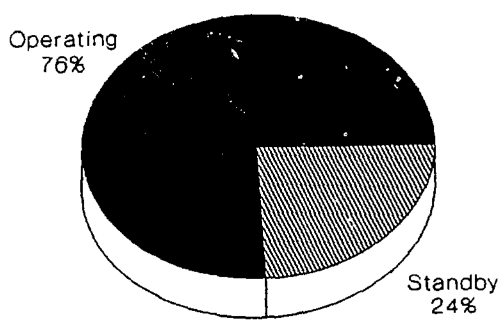

Figure 10 Pump operating status

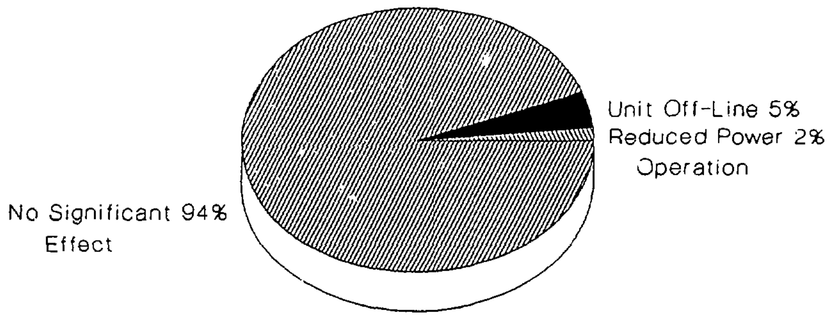

Figure 11 Plant effects from pump failures

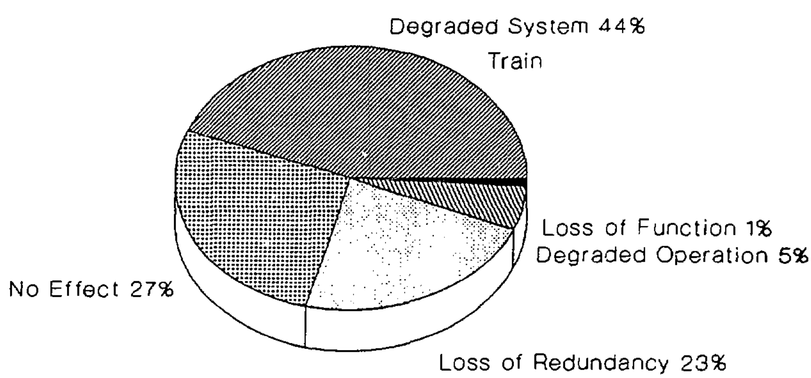

Figure 12 System effect from pump failures