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OPERATING PUMPS ON MINIMUM FLOW*

D. A. Casada, Oak Ridge National Laboratory
Y. C. Li, U. S. Nuclear Regulatory Commission

Abstract

The Nuclear Regulatory Commission (NRC) regulations in Appendix A to 10 CFR 50 require that components important to safety be designed and tested to quality standards commensurate with the importance of the safety functions to be performed. The NRC regulations in 10 CFR 50.55a reference the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code for criteria in conducting inservice testing of pumps. The ASME Code allows the performance of pump inservice testing using mini-flow bypass loops. Operating experience and studies performed for the Nuclear Plant Aging Research Program (NUREG/CR-4597 Vols. I and II) showed that a leading cause of pump problems and failures is associated with hydraulic instability phenomena induced by low flow operation.

The NRC staff issued Information Notice (IN) 87-59 to alert all licensees to two miniflow design concerns identified by Westinghouse. The first potential problem discussed in this IN involves parallel pump operation. If the head/capacity curve of one of the parallel pumps is greater than the other, the weaker pump may be dead-headed when the pumps are operating at low-flow conditions. The other problem relates to potential pump damage as a result of hydraulic instability during low-flow operation. In NRC Bulletin 88-04, dated May 5, 1988, the staff requested all licensees to investigate and correct, as applicable, the two miniflow design concerns. The staff also developed a Temporary Instruction, TI 2515/105, dated January 29, 1990, to inspect for the adequacy of licensee response and follow-up actions to NRC Bulletin 88-04.

Oak Ridge National Laboratory has reviewed utility responses to Bulletin 88-04 under the auspices of the NRC's Nuclear Plant Aging Research Program, and participated in several NRC inspections. Examples of actions that have been taken, an assessment of the overall industry response, and resultant conclusions and recommendations are presented.

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OPERATING PUMPS ON MINIMUM FLOW

Background

Historically, minimum flow capacity for centrifugal pumps was based on ensuring that the temperature rise through the pump was not excessive. As a general rule of thumb, the minimum flow rate was specified so that the temperature rise through the pump would be less than 15°F (it should be noted that this rule of thumb was not universally applied, and temperature rises greater than 50°F have been used for some pump applications).

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

As the effects of low-flow operation have become better understood by pump technologists, design modifications that can reduce unsteady flow conditions have been developed. Modifications to pump geometries have been demonstrated to allow operation at lower flow rates with substantially reduced impact[2]. Some pump original equipment manufacturers (OEM) and non-OEM repair shops now offer design options or retrofits that allow pumps to be operated acceptably at reduced minimum flow. However, there remain in service a large number of pumps that were not designed specifically to allow operation under low-flow conditions and for which no modifications have been made.

In May of 1988, the Nuclear Regulatory Commission (NRC) issued Bulletin 88-04, "Potential Safety-Related Pump Loss." The Bulletin addressed two general concerns:

- The potential for dead-heading one of two pumps when operated in parallel
- The adequacy of pump minimum flow protection provided by the installed minimum flow lines.

With regard to the first concern, the Bulletin specifically discussed the potential problem of parallel pump operation during miniflow operation, noting that the stronger of two pumps can dead-head the weaker pump. It was also noted that the strong/weak pump situation is not a problem at moderate to high flow conditions because of the shape of pump head-capacity curves in those regions. Relative to the second item, the Bulletin noted that pump manufacturers now advise that desired minimum flow capacity is greater than was originally specified for some pumps. The Bulletin required that all plants conduct a review of all safety-related pumps.

Oak Ridge National Laboratory (ORNL), under the auspices of the NRC's Nuclear Plant Aging Research Program, reviewed industry responses to the issues identified in the Bulletin[3]. The principal purpose of the study was to provide a general assessment of the type and extent of actions taken in response to the Bulletin. The review consisted of several elements:

- Discussions with representatives of several pump manufacturers
- General review of all utility correspondence to the NRC responding to the Bulletin
- Review of the distribution of pump suppliers whose pumps are used in selected systems
- Detailed on-site review at selected plants

The results of this study are summarized in this paper.

ORNL also participated in individual plant inspections in support of NRC's Nuclear Reactor Regulation activities. The inspections were conducted to review the adequacy of the specific plants' responses to the Bulletin. Some observations made during the inspections are presented.

Discussions with Pump Manufacturers

ORNL met with representatives of four of the major manufacturers of pumps used in safety-related service in U.S. plants. These four manufacturers together have furnished about 75% of the pumps used in the safety-related systems of primary concern.

Three of the principal areas of discussion, and the results of the discussions are provided below.

- *Which types of pumps are most susceptible to low-flow degradation?*

The pumps noted to be most susceptible to low-flow degradation were high energy and high suction specific speed (high flow, low NPSH required) pumps.

- *What are the associated failure modes?*

Failure/degradation modes associated with low-flow operation that were most often mentioned were seal failure, occasional shaft breakage, bearing failure, excessive wear of wear rings, and cavitation damage.

- *What are some possible means for demonstrating a pump's ability to successfully operate under low-flow conditions?*

The OEMs identified a couple of correlations that can provide some very general insights into the relative requirements for pump minimum flow[4,5]. However, the use of the generic correlations to address 88-04 was discouraged.

There was fairly uniform agreement that there was a need to be able to measure the forces present (for example, radial thrust) in order to predict component life. It was recognized, however, that this is not practical for field-installed pumps. There was a general consensus that with the current state of understanding, a properly conducted field test could verify that particular pump's capability under the test conditions. One manufacturer noted that tolerance stack-ups and pre-test service life could play major roles in the results of such testing. Another manufacturer noted that in tests conducted by their company overseas, the hydraulically induced forces associated with several pumps of the same model varied by a factor of three to four.

Several of the manufacturers emphasized the need for a test program to address intermittent operation at low flow, in light of the fact that there is no objective data related to such operation.

The subject of the suitability of current monitoring practices was discussed. There was consistent agreement that testing pumps under miniflow conditions was of little value, from a hydraulic performance demonstration standpoint. The vendors observed that of the means that are currently practicable, spectral vibration monitoring and trending was the best indicator of potentially damaging conditions. However, it was noted that monitoring capability for some pumps (specifically deep-well pumps) was limited. It was also noted that the parameter that most needed to be measured was force on pump components, and that could only be accurately monitored currently using intrusive means. Two changes to current in-service testing practices were recommended:

- Periodically conduct testing at close to the pumps best efficiency point (BEP) to verify that the pump performance has not substantially degraded.
- Minimize or discontinue practice of routinely testing pumps at minimum flow conditions in order to demonstrate pump operability.

Assessment of Written Plant Responses

General Discussion

The correspondence from all plants to the NRC on Bulletin 88-04 was reviewed to provide an indication of the range of actions taken in response to the Bulletin. The review evaluated the licensees' analyses and data for low-flow operation presented in their response and determined what actions, in terms of design changes, procedure changes, special inspections, etc., have been or will be made.

The level of information provided in the correspondence varied substantially. For some plants, there was a fairly detailed discussion of original and current minimum flow recommendations and existing system configuration, as well as an identification of specific design, procedural, or other changes made to address Bulletin concerns. There were also a number of responses that provided only an indication that the issues had been reviewed, with little or no system/pump specific information provided.

Procedural and Design Changes and Special Testing

An attempt was made to determine the extent and types of procedural and design changes made in response to the Bulletin, as well as special tests that were conducted.

The distribution of identified changes, by system, for both pressurized water reactors (PWRs) and boiling water reactors (BWRs) is provided in Figures 1 and 2. It should be recognized that it is likely that there were procedural or other administrative actions taken that were not identified in the written responses, and are thus not reflected in these figures.

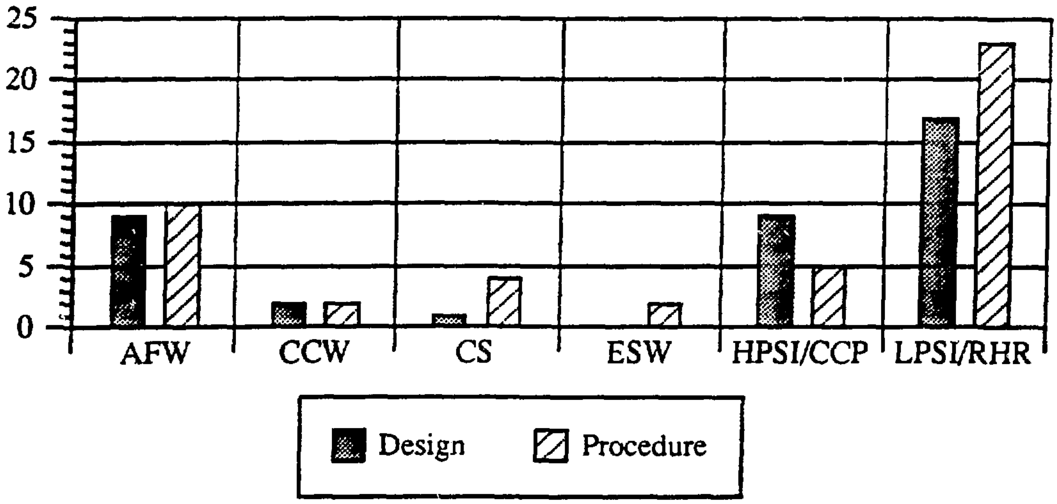

Figure 1. Number of PWR units in which design and procedure changes were made

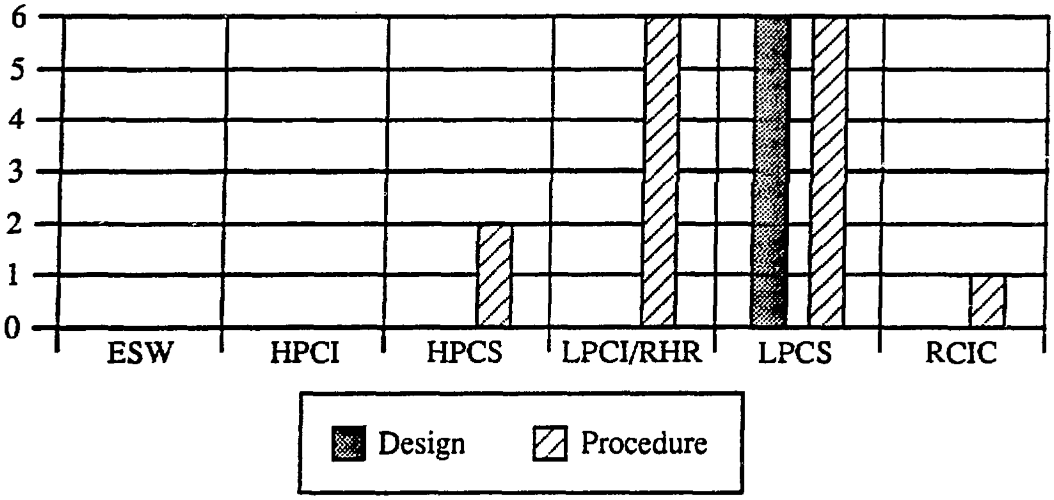

Figure 2. Number of BWR units in which design and procedure changes were made

Several different types of design changes were identified in the responses. These are indicated in Figure 3. The majority of the design changes involved either increasing the size of the orifice in the miniflow line or otherwise modifying the minimum flow line. It is noteworthy that no modifications to pump design were identified in the written responses. Subsequent to the completion of the review, verbal discussions have revealed one plant that is in the process of modifying auxiliary feedwater pump impeller vane and diffuser clearances to minimize low-flow operation problems.

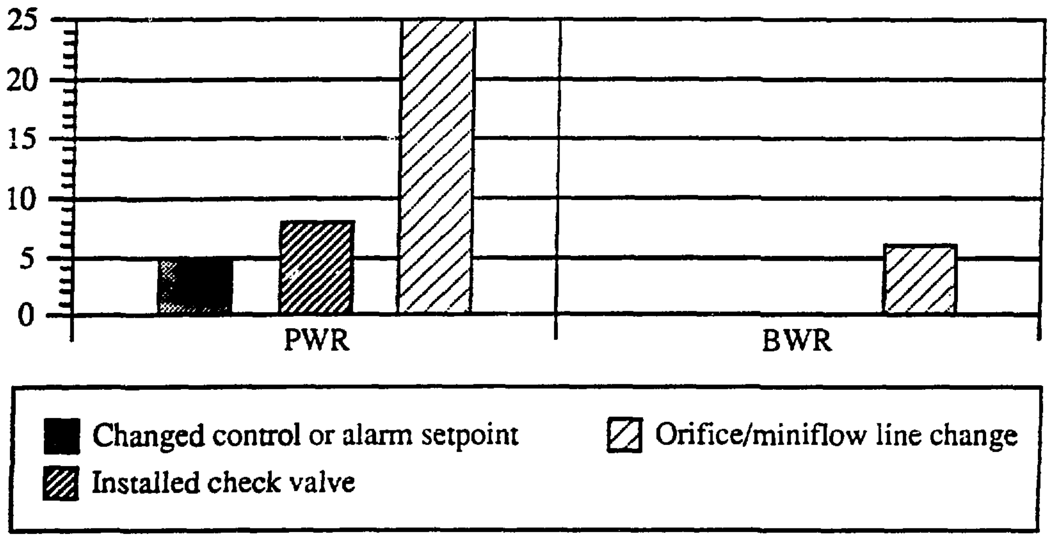

Figure 3. Distribution of design changes, by type of change

A total of 44 special tests or inspections that either had been conducted or would be conducted to monitor pump condition were identified. About $^2/_3$ of these tests were associated with either low pressure core spray (LPCS), low pressure coolant injection/residual heat removal (LPCI/RHR), low pressure safety injection/residual heat removal (LPSI/RHR), or containment spray (CS) systems.

A number of types of special analyses were also identified. Most of these involved parallel pump competition. A total of 48 such analyses were specified. Almost half of these involved the LPCI/RHR or LPSI/RHR systems. Twenty-one of the analyses were minimum acceptable flow calculations, based on either a published correlation or on other undesignated bases. Note that these analyses were performed by the utility (not by the pump manufacturer).

It was noted during the review that a substantial fraction of the design and procedural changes were made by a relatively small portion of the industry. Figure 4 indicates that 80% of the changes were made by about 30% of the plants. All noted changes were made by less than half of the plants.

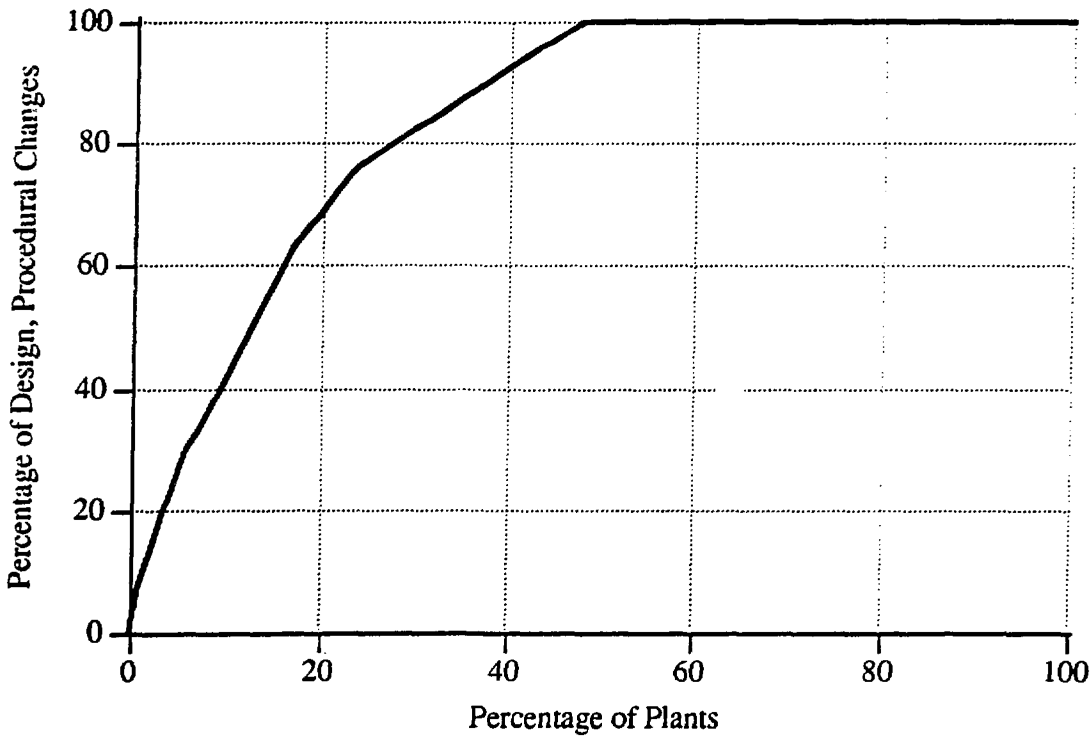

Figure 4. Distribution of procedural or design actions taken in response to NRC Bulletin 88-04

Summary

The written response review made two principal observations:

- There are no generic guidelines for determining the acceptability of a pump for operation under the various modes and times required in support of both normal and emergency conditions, and
- The low-flow issue was not adequately addressed by all plants.

It was observed that the lack of generic guidelines essentially guaranteed that the issue would not be uniformly and adequately addressed.

Individual Plant Inspections

The NRC has conducted inspections of several plants to review plant responses in more detail than was possible through the correspondence review discussed above. ORNL participated, primarily under the auspices of the Mechanical Engineering Branch, in four inspections conducted at a single unit Combustion Engineering plant, a General Electric twin-unit plant, a single-unit Westinghouse plant, and a three-unit facility comprised of a single Westinghouse unit and two Combustion Engineering units. In addition, ORNL assisted the NRC in the review of another plant's pump test and subsequent disassembly/examination program. These inspections served to confirm the observations made during the review of the written responses. Some pertinent observations made during the inspections are provided below.

Parallel Pump Competition

Personnel at one of the plants inspected had identified that parallel pump competition existed in the RHR system, and was in the process of installing check valves to preclude competition in the future. The actions being taken by the utility to address the pump competition were judged to be appropriate.

During another inspection, the inspectors noted the potential for parallel pump interaction to exist during a pump switch-over sequence. In this case, two RHR[†] pumps share a common minimum flow line, and normally only one pump is operated. The concern primarily exists during

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† The RHR pumps in this plant are used solely for residual heat removal, unlike the dual function RHR/low pressure injection pumps in most plants.

the process of switching over from one pump to the other. The utility agreed that the potential exists, and is in the process of identifying corrective actions.

The other two inspections also found situations in which it was not intuitively obvious that pump competition would be precluded. In one case, personnel contracted by the plant to review the Bulletin concerns had failed to note the absence of orifices in the minimum flow lines of the core spray pumps for one unit (the orifices did exist on the other). The minimum flow lines from two pumps joined into a common header, and it was not clear that the head losses prior to the common header connection were sufficient to prevent pump competition. Subsequent hydraulic analyses showed that competition should not occur. For the other plant, several minimum flow lines, each of which carried several hundred gallons per minute, joined in a common header. There had been no analysis performed to verify the absence of pump competition prior to the inspection.

While the latter two situations have subsequently been found to be acceptable, they had not been considered prior to the inspections, and are indicative of a somewhat superficial review.

It appears that the primary generic parallel pump competition concern (affecting several RHR systems) has been adequately identified and addressed. The only new parallel pump competition concern identified in the four inspections is specific to a single unit. It is unlikely that there are additional pumps that are generically within any of the four NSSS scopes of supply, including the emergency core cooling system pumps, for which a parallel pump competition problem exists that has not been identified. This conclusion is based on the facts that no other parallel pump competition situations were identified, and that most NSSS systems are reasonably similar in design. However, the fact that three of the four plants inspected had conditions for which potential competition existed, but had not been identified by the utilities, leaves some residual uncertainty.

Minimum Flow Adequacy

Most of the inspection activities were oriented toward the adequacy of minimum flow provisions. At three of the four facilities, the majority of the OEMs had been contacted to determine the current recommended minimum flow rate. None of these three plants had contacted the service water pump OEM*. At the fourth facility (the three unit plant), however, the OEM for only one pump had been contacted.

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* Note that, generally speaking, the service water system pumps would normally be run at a substantial fraction of design flow, and most likely minimum flow adequacy would not be a concern.

For the fourteen pump applications at the four facilities which had been reviewed relative to the manufacturer's current recommended minimum flow rate, the distribution of the level of conformance with supplier recommendations shown in Table 1 was found.

Table 1. Level of Conformance to OEM Recommended Minimum Flow

Number of pumps	Level of Conformance to OEM Minimum Flow Recommendations
4	Fully meet current recommendations with existing configuration.
1	Meet current recommendations after completing system modification.
3	Nominally meet OEM recommendations (available flow is essentially equal to that recommended).
2	Meet current recommendations, for most plant conditions. Some off-normal (non-emergency) conditions could lead to operation outside the recommendations.
4	Do not meet current recommendations.

The observations made during the on-site inspections relative to parallel pump competition and the potential inadequacy of minimum flow supported the conclusion reached during the review of the written responses that, generally speaking, the response to the low-flow degradation issue has been relatively superficial. There was a considerable variation in the approaches taken by individual plants involved in the inspection to address the Bulletin concerns.

Methods which were judged to be appropriate means of assuring adequate pump reliability that were noted during both the written response review and during the inspections included:

- Verification that the pump minimum flow line supports a flow rate that meets the vendor recommendations for continuous operation
- Verification that although the pump minimum flow line does not support a flow rate that meets the vendor recommendations for continuous operation, it does support a flow rate that meets a time-restricted flow rate, along with a verification that there are adequate administrative controls to ensure that the pump is not operated for a time in excess of the vendor recommendations
- For pumps which did not meet the vendor recommendations during regular operation, a commitment by the plant to carefully monitor pump performance and to periodically disassemble and examine the pump for signs of damage

Approaches that have been taken in addressing the issue that were judged to not be adequate or which had other weaknesses included one or more of the following:

- Reliance on static modeling of pumps
- Reliance on the absence of low-flow-attributed failures (i.e., not the absence of failures, rather the fact that none of the failures that had occurred had been attributed by plant personnel to low-flow operation)
- Reliance on non-spectral vibration data from in-service testing
- Dependence upon instrumentation whose accuracy at test conditions was insufficient to form solid conclusions
- Failure to have in place administrative controls which would assure compliance with pump manufacturer recommendations
- The assumption of orifices being present in minimum flow lines when there were none
- Failure to recognize that off-normal procedural controls created situations where the pumps would be operated outside the manufacturer recommendations (even though the plant had determined that pump operation would fully comply with the recommendations when operated under normal conditions)

While some of the above approaches are not without merit, the extent to which they were relied upon (in various combinations) did not provide an adequate level of assurance that the pump would operate reliably.

The site inspections revealed varying levels of appreciation for the types of damage that could be manifested from operation of pumps at low flows. Some plant personnel had an excellent understanding of the damage mechanisms and appropriate means of monitoring, while others were not well aware of the potential problems.

Most plants had reviewed at least the historical failure data for the pumps at their plant; however, there had been little done in the way of reviewing failure data more generically. For example, one plant used an auxiliary feedwater (AFW) pump of the same model and with similar minimum flow rates as another plant which had found substantial low-flow related damage when the AFW pumps were disassembled and examined* . The plant personnel were not aware of the experience at the other plant, even though the information was available through the Nuclear Plant Reliability Data System.

All of the plants inspected were using, or were in the process of developing, a pump spectral vibration monitoring program which goes beyond ASME Code requirements. There appeared to

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* The damage found ultimately resulted in the issuance of a 10CFR21 report from the manufacturer. See discussion below under "A Postscript."

be a need for improved monitoring and trending of the data, however. As an example, an auxiliary feedwater pump at one plant showed substantial increases in vibration at vane passing frequency during the two most recent tests. However, there was no programmatic monitoring and trending practice to note the change; as a result, no actions were being taken to more carefully monitor the pump. It should be noted that the ASME Code-required testing results did not reflect the increased vibration at this frequency due to the fact that the in-service test program only monitored overall displacement.

General Conclusions

Based upon the review of the written responses and the individual plant inspections, pump competition concerns appear to have been adequately addressed by the utility reviews. However, it appears that additional efforts are needed to resolve low-flow-related issues. Fundamentally, there is a need for a better definition of how a pump could be qualified for low-flow operation. In order to achieve the required level of definition, additional insights into the parameters that influence a pump's ability to operate successfully at low-flow are needed. Also needed is a better understanding of design or monitored parameters that could be used to make the necessary determinations.

This issue is currently in the NRC potential generic issue prioritization process. The purpose of the prioritization is to assess the safety significance of the issue and the need for additional NRC guidance on evaluating and correcting miniflow deficiencies.

A Postscript

In September, 1991, at the time that the individual plant inspections were being completed, Ingersoll-Rand issued a 10 CFR 21 report[6] on broken cast iron diffusers in multistage pumps used in AFW applications. The problem was initially identified at Surry Unit 2 in 1988. Following a reactor trip, low flow to one steam generator was noted. Inspections found that pump diffuser vane pieces had lodged in a venturi, thereby restricting flow.

Subsequent inspections found that cavitation damage to the AFW cast iron diffusers was evident, particularly at the leading edge of the diffuser vanes. Damage was most evident at the first stage diffuser, although damage was also seen in other stages. There was also damage found at some areas of diffuser vane to shroud junctions, which was also believed to be the result of low-flow induced cavitation erosion. Ingersoll-Rand noted that the primary cause of the breakage was cavitation damage at the leading edge of the diffuser vanes which resulted from accumulated operation of the pump at minimum flow.

After finding indications of similar damage at other plants, Ingersoll-Rand issued the 10 CFR 21 report. It should be noted that in several of the instances in which damage was found, the pumps were satisfactory, according to technical specification and ASME-Code-required testing results. This could be anticipated in light of the fact that the pumps are tested at minimum flow conditions where internals degradation of this nature would not be detectable.

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

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

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List of Acronyms

AFW	auxiliary feedwater
ASME	American Society of Mechanical Engineers
BEP	best efficiency point
BWR	boiling water reactor
CCP	centrifugal charging pump
CCW	component cooling water
CS	containment spray
ESW	emergency service water
HPCI	*high pressure coolant injection*
HPCS	high pressure core spray
HPSI	high pressure safety injection
LPCI	low pressure coolant injection
LPCS	low pressure core spray
LPSI	low pressure safety injection
NPSH	net positive suction head
NRC	U.S. Nuclear Regulatory Commission
OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
PWR	pressurized water reactor
RCIC	reactor core isolation cooling
RHR	residual heat removal