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Potential Safety-Related Pump Loss: An Assessment of Industry Data

NRC Bulletin 88-04

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Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

Nuclear utility plants are required to periodically test safety-related pumps to demonstrate proper functioning of the pump. Historically, a substantial number of these pumps have been routinely tested at the flow rate available through the pump's minimum flow recirculation flow path, which in many cases was sized to avoid overheating only. It has become more widely recognized that operation of a pump under low-flow conditions can result in hydraulically unstable conditions that can damage the pump, even though the rate of flow is adequate for heat removal.

Nuclear Regulatory Commission (NRC) Bulletin 88-04 required utilities to examine (1) the potential for dead-heading of pumps due to parallel pump competition and (2) the adequacy of the minimum flow rate provided for each safety-related pump. Utilities have reviewed the currently recommended minimum flow rates with pump vendors and have examined existing system design provisions, operating controls, and historical maintenance experience.

Under the auspices of the NRC's Nuclear Plant Aging Research Program, Oak Ridge National Laboratory has reviewed utility responses to Bulletin 88-04. An assessment of the industry response and resultant conclusions and recommendations are presented.

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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
IST	in-service testing
LOCA	loss-of-coolant accident
LPCI	low-pressure coolant injection
LPCS	low-pressure core spray
LPSI	low-pressure safety injection
NPRDS	Nuclear Plant Reliability Data System
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
RWST	refueling water storage tank

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The contributions of Dave Eissenberg, Bill Greenstreet, Bill Farmer, Renee Li, and Ted Sullivan, Jr., in providing guidance and organizational direction are appreciated.

Bob Clark undertook the difficult task of reviewing and providing an independent assessment of all of the industry responses to the Bulletin. The insights he provided, as well as those offered by Jimi Yerokun, were important "calibration" points.

The hospitality and cooperation of pump manufacturer experts, including Jeff Bartholomew, Lloyd Hanson, and S. (Gopal) Gopalakrishnan of Byron-Jackson; Dennis Bowman, Martin Prescott, Bill Marscher, and Bruno Schiavello of Dresser (Pacific & Worthington); Philip Nagengast, Donald Sloteman, and Tim Wotring of Ingersoll-Rand; and David Eddy, Earl Gordon, Stan Pace, and Donald Spencer of Sulzer-Bingham are greatly appreciated.

Finally, the technical expertise and common sense approach to the study of pumps provided by Mike Adams was instrumental to the project.

1. BACKGROUND AND SCOPE

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 has not been universally applied and that 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. Degradation can occur as the result of unsteady flow conditions within the pump, which result in substantial radial and axial forces (static as well as dynamic) on both the stationary and rotating parts. 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 well.

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.[*] Some pump original equipment manufacturers (OEMs) and non-OEM repair shops now offer design options or retrofits that allow pumps to be operated acceptably at reduced minimum flow. However, a large number of pumps remain in service which were not designed specifically to allow operation under low-flow conditions and for which no modifications have been made.

In May of 1988, the U.S. 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 (miniflow) 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 (e.g., higher head at same flow) 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

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[*] E. Makay and J. A. Barrett, "Changes in Hydraulic Component Geometries Greatly Increased Power Plant Availability and Reduced Maintenance Costs: <u>Case Histories</u>," presented at the First International Pump Symposium, Texas A&M University, May 1984.

minimum flow capacity is greater than was originally specified for some pumps. The Bulletin required that all plants conduct a review of the safety-related pumps, including the following specific requirements:

"All addressees are requested to do the following:

1. Promptly determine whether or not its facility has any safety-related system with a pump and piping system configuration that does not preclude pump-to-pump interaction during miniflow operation and could therefore result in dead-heading of one or more of the pumps.

2. If the situation described in Item 1 exists, evaluate the system for flow division taking into consideration (a) the actual line and component resistances for the as-built configuration of the installed system; (b) the head versus flow characteristics of the installed pumps, including actual test data for "strong" and "weak" pump flows; (c) the effect of test instrument error and reading error; and (d) the worst case allowances for deviation of pump test parameters as allowed by the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) Section XI, Paragraph IWP-3100.

3. Evaluate the adequacy of the minimum flow bypass lines for safety-related centrifugal pumps with respect to damage resulting from operation and testing in the minimum flow mode. This evaluation should include consideration of the effects of cumulative operating hours in the minimum flow mode over the lifetime of the plant and during the postulated accident scenario involving the largest time spent in this mode. The evaluation should be based on best current estimates of potential pump damage from operation of the specific pump models involved, derived from pertinent test data and field experience on pump damage. The evaluation should also include verification from the pump suppliers that current miniflow rates (or any proposed modifications to miniflow systems) are sufficient to ensure that there will be no pump damage from low flow operation. If the test data do not justify the existing capacity of the bypass lines (e.g., if the data do not come from flows comparable to the current capacity) or if the pump supplier does not verify the adequacy of the current miniflow capacity, the licensee should provide a plan to obtain additional test data and/or modify the miniflow capacity as needed."

A copy of Bulletin 88-04 is included as Appendix A.

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. The principal purposes of the study were to provide a general assessment of the type and extent of actions taken in response to the Bulletin and to determine whether additional research is needed to resolve the issues. 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 documented in this report. It should be noted that NRC review of this issue is ongoing, in that individual site inspections will continue well into 1991. Site-specific reviews offer a superior means for acquiring a proper perspective on exactly what the industry response has been. However, it is critical that the reviews be conducted and reported in a consistent manner in order to achieve this benefit.

2. DISCUSSIONS WITH PUMP MANUFACTURERS

ORNL and consultant personnel met with representatives of four of the major manufacturers of pumps used in safety-related service in U.S. plants. Firms visited included Byron-Jackson, Dresser Pump Division (Pacific & Worthington), Ingersoll-Rand, and Sulzer-Bingham. These four manufacturers together have furnished about 75% of the pumps used in the safety-related systems of primary concern.

The manufacturers' representatives were very cooperative and interested in discussing low-flow-related concerns. Each had developed responses to utility requests associated with the Bulletin. The focus of the conversations was on what types of pumps (not on specific models or plants) would be most susceptible to low-flow problems, how degradation might be manifested, and the general approach taken by the manufacturers in responding to requests from utilities.

The vendors, in general, did not have readily available for review historical failure data that could provide new insights into failures and degradation related to operation at low flow. There are few or no test data related to intermittent operation of the pumps. Several of the vendors noted that although information such as replacement parts ordered for specific pumps could be a useful indicator of the nature of historical problems and could potentially provide some insights into the extent to which low-flow operation was a factor, they either did not have the data compiled in a structure that would lend itself to easy use or were naturally reluctant to share such information.

In response to a query as to what general types of pump designs would be most susceptible to low-flow degradation, most pointed to high-energy and high-suction specific speed [high-flow, low-net positive suction head (NPSH) requirement] pumps. It was noted that pump/system interaction can be a dominant source of damaging pulsation/vibration.

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. It is important to recognize that the OEM is not involved in a comprehensive root cause analysis of every pump failure. Also, the OEM may be contacted for a replacement or spare part by a customer other than the party that experienced a failure (for example, where one utility buys a replacement part from another utility in order to expedite pump repair, and the supplying utility repurchases another spare). As a result, the OEM may not be made aware of the circumstances involved in the failure. There is no data base of pump failures that have been caused by low-flow degradation.

The issue of what would be appropriate means to qualify a pump for service at low-flow conditions was discussed. Although there was some diversity of how to practically do this, there was fairly uniform agreement that what needed to be done was to measure the forces present (e.g., radial thrust) in order to predict component life. The value of field testing a pump to verify its ability to withstand certain conditions was discussed. There was a general consensus that a successful test would only verify <u>that</u> pump's capability under the test conditions. In other words, as-installed testing would demonstrate the performance of the specific rotating element/stationary part configuration, when operated at the specific system test conditions. One manufacturer noted that tolerance stack-ups and pretest 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 3 to 4.

The potential value of conducting a test program to better quantify the significance of some of the important design and service factors to low-flow degradation was discussed. Some of the pump manufacturers observed that because of the broad spectrum of pumps, it would be very difficult to bound all concerns for all pumps with a testing program that involved only a few pump designs; however, there was agreement that a relatively small, but well controlled and monitored, test could contribute substantially to a clearer understanding of the important parameters related to this issue. Several of the manufacturers emphasized the need for such a test program to address intermittent operation at low flow, in light of the fact that there are 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 (head and flow) standpoint. The vendors observed that of the means that are currently practicable, vibration monitoring and trending were the best indicators 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 (IST) practices were recommended:

1. periodically conduct flow, head, and vibration measurements when operating at close to the pump's best efficiency point (BEP) in order to verify that pump performance has not substantially degraded and
2. minimize or discontinue the practice of routinely testing pumps at minimum flow conditions in order to demonstrate pump operability.

Some generalized methods for determining acceptable minimum flow rates have been published by individuals, including employees of the pump manufacturers.[2,*] These methods, which are empirical/analytical in nature, have been used to provide general guidance on the establishment of acceptable flow regimes. The methods, however, are geared toward continuous operation rather than the intermittent duty conditions under which many of the safety-related pumps are used. Furthermore, one of the manufacturers cautioned against using the generic correlation* for Bulletin 88-04 purposes.

The recommended minimum flow rates suggested by the manufacturers to utilities appear, for the most part, to provide reasonable, conservative guidelines for safe operation of the pumps. In most cases, the vendors notified utilities that more detailed assessment of

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[*] S. Gopalakrishnan, "A New Method for Computing Minimum Flow," presented at the Fifth International Pump Symposium, Texas A&M University, 1988.

a particular pump application could be made if the pump did not fall within the general guidelines.

A variety of flow requirement structures was provided by the OEMs. Most typical of these structures was a recommended minimum flow for continuous operation along with lower flow requirements for briefer operating periods. An example is provided below.

Example
Pump BEP conditions: 4100 gal/min @ 325 ft head.
Minimum flow for continuous operation: 1500 gal/min.
Minimum flow – short-term operation (defined as less than 2 h in 24 h): 1100 gal/min.

In some cases, the manufacturers provided a very short term flow rate, principally for start/stop operation (e.g., less than 15 min). The fraction of BEP flow recommended and the structure of the recommendations depended on the methodology used by the OEM, the pump design, and, to a certain extent, utility operating practices.

3. ASSESSMENT OF PLANT RESPONSES

3.1 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 was made to evaluate the licensees' analyses and data for low-flow operation presented in their response and to determine 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 in response. 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.

Prior to conducting the plant-by-plant review, several systems whose pumps were to be included in the study were identified. Some of the systems with smaller safety-related pumps, such as diesel fuel oil transfer and boric acid transfer pumps [pressurized water reactors (PWRs)] were not included. The systems considered are listed in Table 1.

Table 1. Systems included in assessment

System[a]	Acronym
Auxiliary feedwater (PWR)	AFW
Component cooling water (PWR)	CCW
Containment spray (PWR)	CS
Emergency service water (PWR and BWR)	ESW
High-pressure coolant injection (BWR)	HPCI
High-pressure core spray (BWR)	HPCS
High-pressure safety injection/centrifugal charging pump (PWR)	HPSI/CCP
Low-pressure coolant injection/residual heat removal (BWR)	LPCI/RHR
Low-pressure core spray (BWR)	LPCS
Low-pressure safety injection/residual heat removal (PWR)	LPSI/RHR
Reactor core isolation cooling (BWR)	RCIC

[a] PWR = pressurized water reactor; BWR = boiling water reactor.

The actual system designs vary from plant to plant. For example, some PWR plants have combination charging/high-pressure safety injection pumps, while others have both a centrifugal charging pump (often in addition to positive displacement pumps) and high-pressure safety injection pumps. Thus, the individual plant systems that provide the general functions associated with the generic systems listed in Table 1 were considered.

3.2 PROCEDURAL AND DESIGN CHANGES

The responses were reviewed to determine if the plant indicated that procedural changes had been or were being implemented. There were 29 PWR units (at 18 sites) that identified a total of 56 procedure changes and 38 design modifications made in response to the Bulletin. There were 8 BWR units (at 6 sites) that identified a total of 17 procedure changes and 6 design modifications made as a result of the Bulletin. Several of the units that identified changes noted changes to design or procedures in several different systems. The distribution of identified changes, by system, is provided in Table 2. Figures 1 and 2 depict this information graphically.

Table 2. Distribution of procedural and design changes by system

Plant type	System	Number of plants changing procedures	Number of procedures changed[a]	Number of plants changing design
PWR	AFW	10	12	9
PWR	CCW	2	2	2
PWR	CS	4	4	1
PWR	ESW	2	2	0
PWR	HPSI/CCP	5	5	9
PWR	LPSI/RHR	23	31	17
BWR	ESW	0	0	0
BWR	HPCI	0	0	0
BWR	HPCS	2	2	0
BWR	LPCI/RHR	6	7	0
BWR	LPCS	6	7	6
BWR	RCIC	1	1	0
	Total	61	73	44

[a] More than one type of procedure was changed at some plants.

It should be noted that the numbers of changes identified above are the numbers of plants whose response identified that one or more procedure or design changes associated with the particular system had been or would be made. It is likely that there were other procedural or administrative actions taken that were not specifically identified in the responses. Also, several plants noted procedural controls that were in existence prior to issuance of the Bulletin.

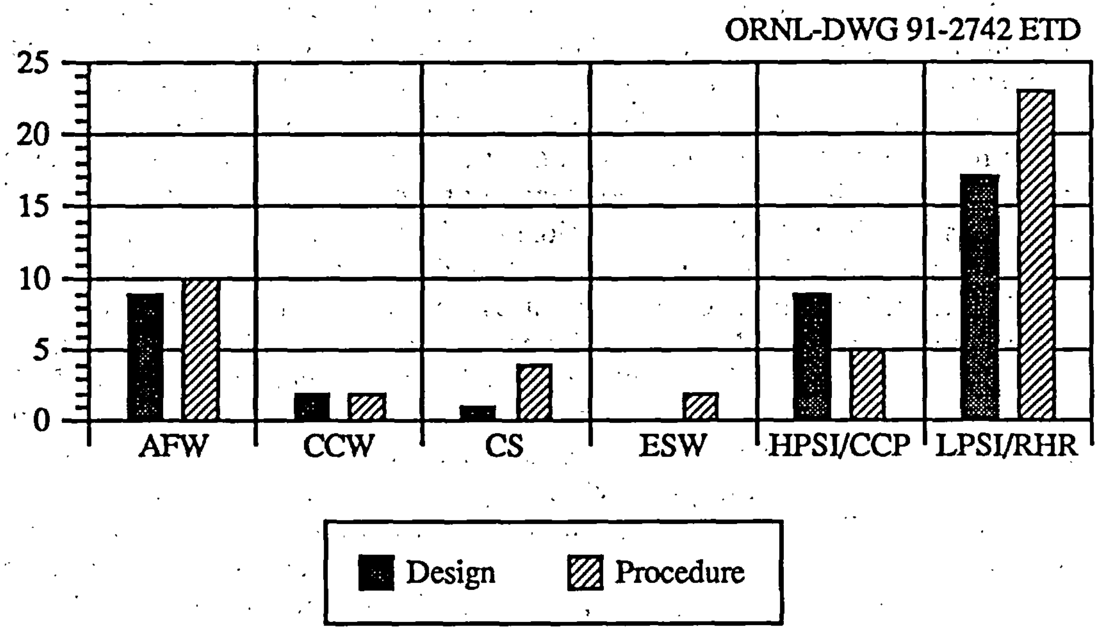

Fig. 1. Number of PWR units in which design and procedure changes were made.

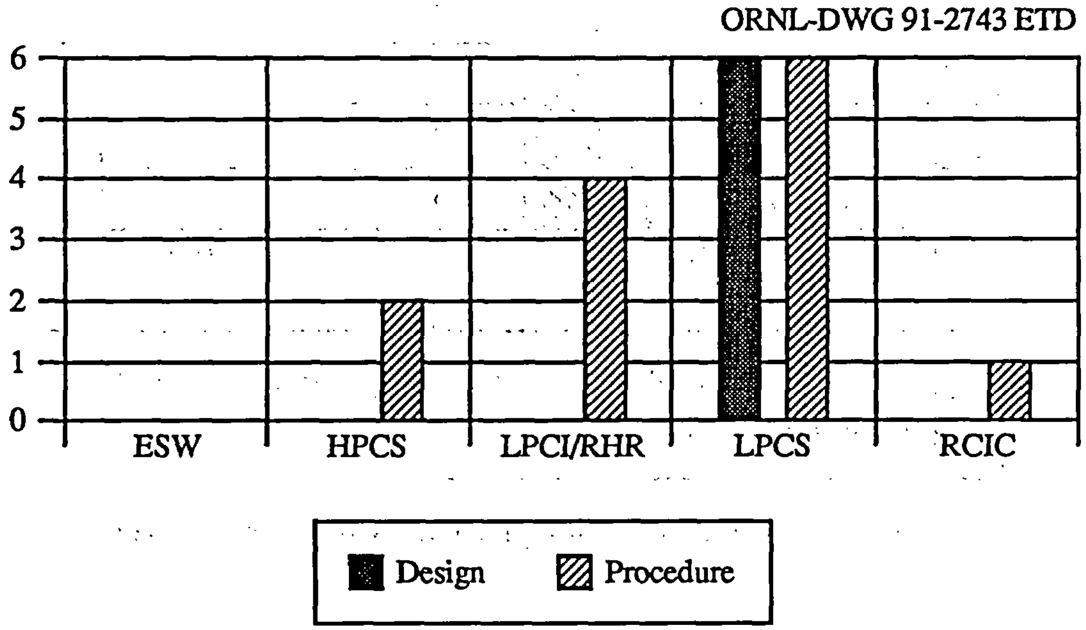

Fig. 2. Number of BWR units in which design and procedure changes were made.

In this respect, operating procedures for several systems from one plant (not one of the three plants discussed in Sect. 5) were reviewed. It was found that all of the safety-related system procedures reviewed included precautions relative to minimum allowable flow for pump protection. The systems that are not safety related did not include such precautions, indicating that the precautions had been placed in the procedures in response to the Bulletin (or in response to some earlier operating experience feedback activity). In this utility's response to the NRC, there was no mention of the procedural precautions. This is an indication that the individuals responsible for the Bulletin response may not have been intimately familiar with operating procedural requirements and precautions.*

Several different types of design changes were identified in the responses. These are summarized in Figure 3. Most of the design changes involved either increasing the size of the orifice in the miniflow line or otherwise modifying the minimum flow line. Eight plants committed to install check valves downstream of pump discharge miniflow line connections in order to ensure that pumps could not be dead-headed. Five commitments involved a change to a control or alarm system related to pump minimum flow protection.

Figure 4 indicates the distribution of the types of procedures that were changed in response to the issues discussed in the Bulletin. Note that some plants changed more than one type of procedure for a given system; thus the total number of procedure changes indicated by Figure 4 is greater than that indicated by Table 2 and Figs. 1 and 2.

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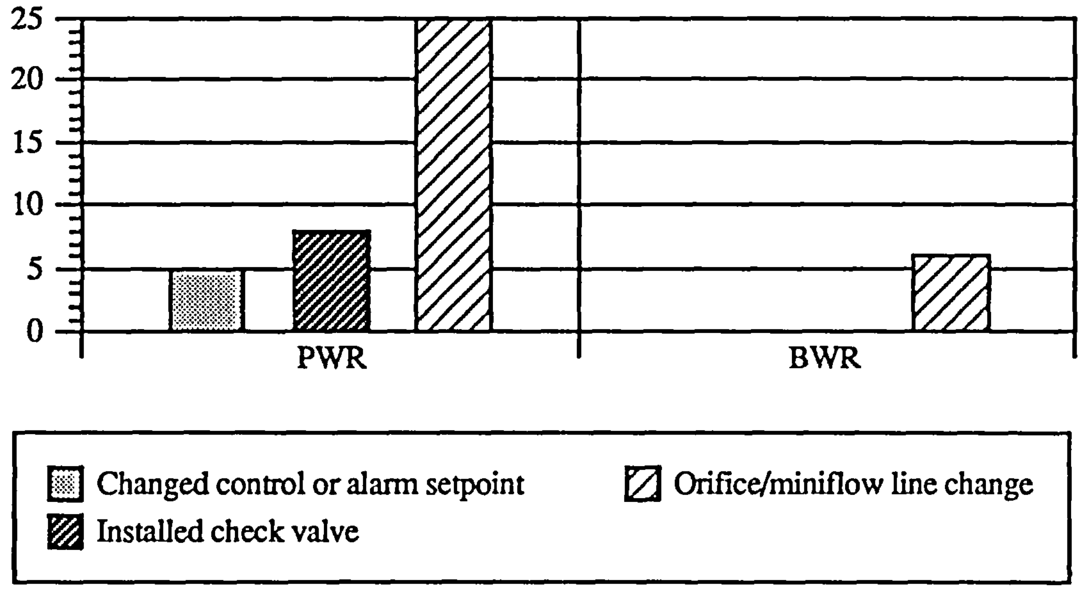

Fig. 3. Number of design changes by type of change.

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* In the author's experience, this is frequently a reflection of the fact that general office staff, as opposed to operating plant staff, are often responsible for these types of responses (as was the situation in this case).

ORNL-DWG 91-2745 ETD

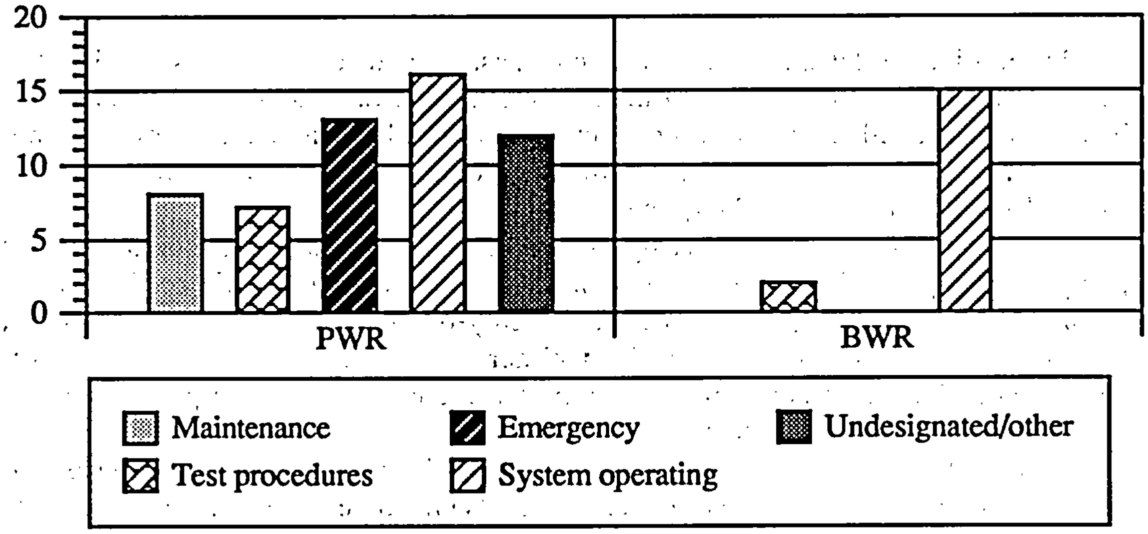

Fig. 4. Number of procedure changes by type of procedure.

A majority of the procedural and design changes indicated in the responses were made by a relatively small number of plants. Figure 5 demonstrates that all of the indicated changes were made by just less than half of the plants. Half of the corrective actions discussed in the plant responses were made by about 10% of the plants. Note that this plot is structured such that Plant 1 made the most changes, Plant 2 the second most, and so forth. About half of the plants did not identify changes that had been or would be made.

ORNL-DWG 91-2746 ETD

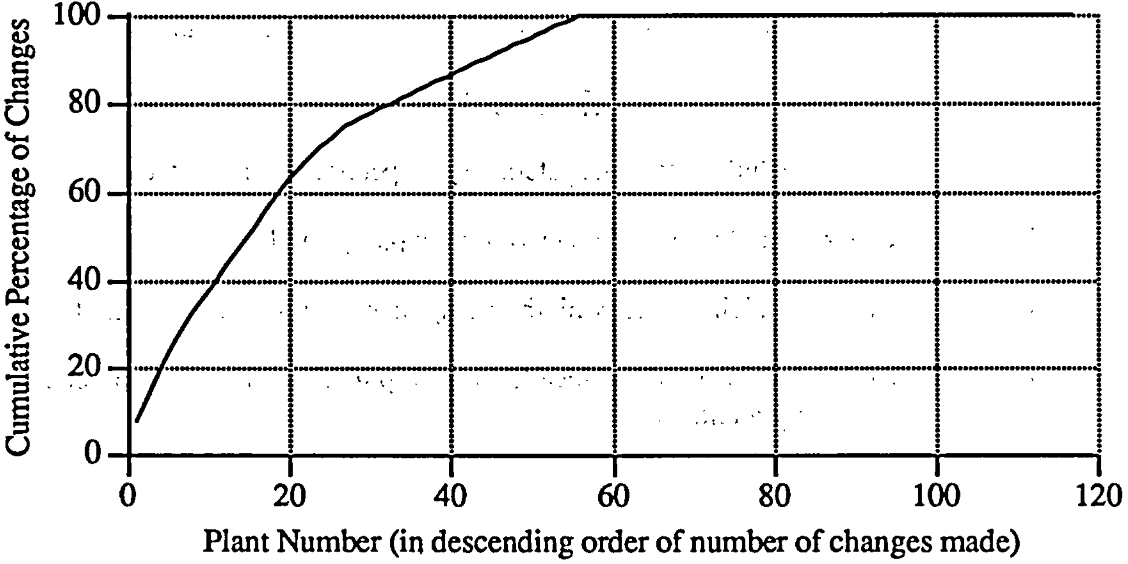

Fig. 5. Distribution of procedural or design actions taken in response to NRC Bulletin 88-04.

3.3 OTHER RESPONSE ACTIONS

In addition to design or procedure changes, special tests and/or special analyses performed in conjunction with the Bulletin were identified. A total of 44 special tests or inspections that either had been conducted or would be conducted to monitor pump condition were identified. About two-thirds of these tests were associated with either LPCS, LPCI/LPSI/RHR, or CS systems.

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

Fifteen of the analyses involved hydraulic flow balance-type calculations performed to verify that pump competition was not a concern. While there were many examples where there was an assertion that pump competition was not a concern because of individual miniflow orifices, the 15 analyses indicated a more in-depth review. However, it should be noted that one of the plants conducting such a review subsequently found that the pumps for which the review had been performed did, in fact, compete to the extent that one of the pumps was dead-headed during actual operation.

Three analyses involved static/dynamic force calculations (see discussion on this in Sect. 5). The remainder were categorized as "other/undesignated."

3.4 RESPONSE LEVEL OF DETAIL

The level of detail included and the general completeness of the information included in the individual plant responses were assessed. Four categories were considered:

<u>Category</u>	<u>Description</u>
a	Extent to which pertinent systems were specifically identified
b	Level of detail provided concerning the pumps and systems
c	Extent to which contact with the pump manufacturers was verified
d	Extent to which conformance to the pump manufacturer recommendations was clearly identified

The following rating levels were established:

Rating	**Description**
1	Extensive review, which included all appropriate information. For example, for Category a, if all appropriate systems were noted as having been reviewed, this rating would be given.
2	Marginal to generally adequate response, which included most appropriate information. For example, for Category a, if all but one or two systems were specifically identified as having been reviewed, this rating would be given.
3	Insufficient data provided. For example, for Category a, if only one or two systems were specifically identified as having been reviewed, this rating would be given.

Each of the four categories was assessed for each plant. While the rating of the level of information provided in a response is not necessarily a perfect indicator of what was actually done during the plant's review, it does provide a secondary measure of the extent to which the Bulletin concerns were addressed.

Most plants either identified at least those systems noted in Table 1 or at least the majority of them. Many plants did not specifically address systems such as ESW or CCW, which for some plants do not include miniflow lines in the design but rather depend upon system alignment to always ensure proper minimum flow.

A substantial variation between BWR and PWR responses was noted in the areas of contact with the pump vendors and compliance with pump vendor recommendations. It appears that many of the BWR plants relied primarily upon the BWR Owner's Group generic response and either did not contact the pump vendors or at least did not indicate such contact. However, it should also be noted that, in general, BWR plants include provision for full-flow testing of at least the pumps provided under the nuclear steam supply system scope of supply and would be less likely to incur pump degradation associated with routine low-flow operation of these pumps.

Figures 6 and 7 graphically provide the results of this portion of the assessment.

ORNL-DWG 91-2747 ETD

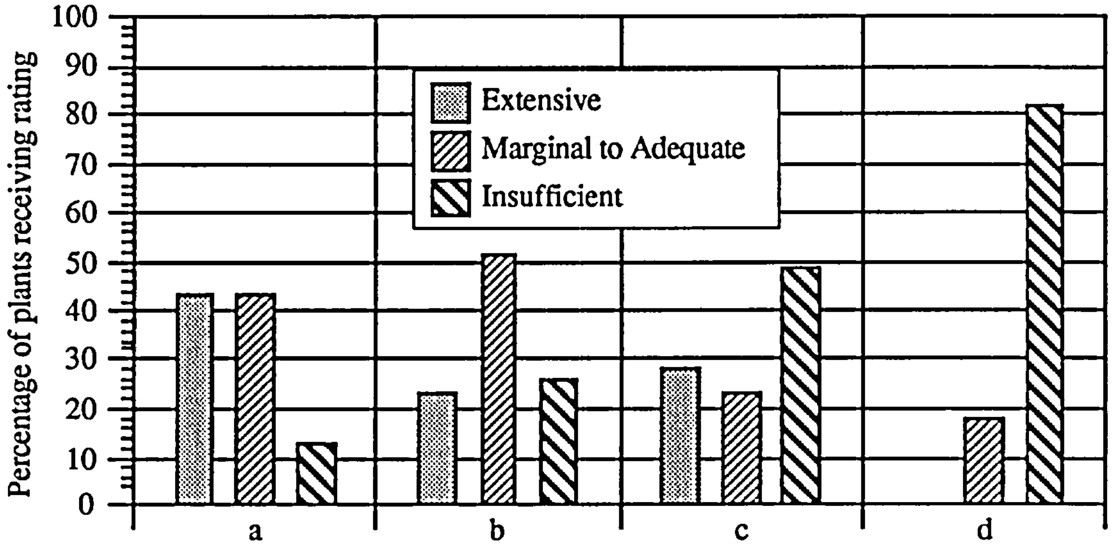

Fig. 6. Distribution of BWR plant ratings. Number of plants receiving specified response rating by category (see categories below).

Categories

a: Extent to which pertinent systems were specifically identified.
b: Level of detail provided concerning the pumps and systems.
c: Extent to which contact with the pump manufacturers was verified.
d: Extent to which conformance to the pump manufacturer recommendations was clearly identified.

ORNL-DWG 91-2748 ETD

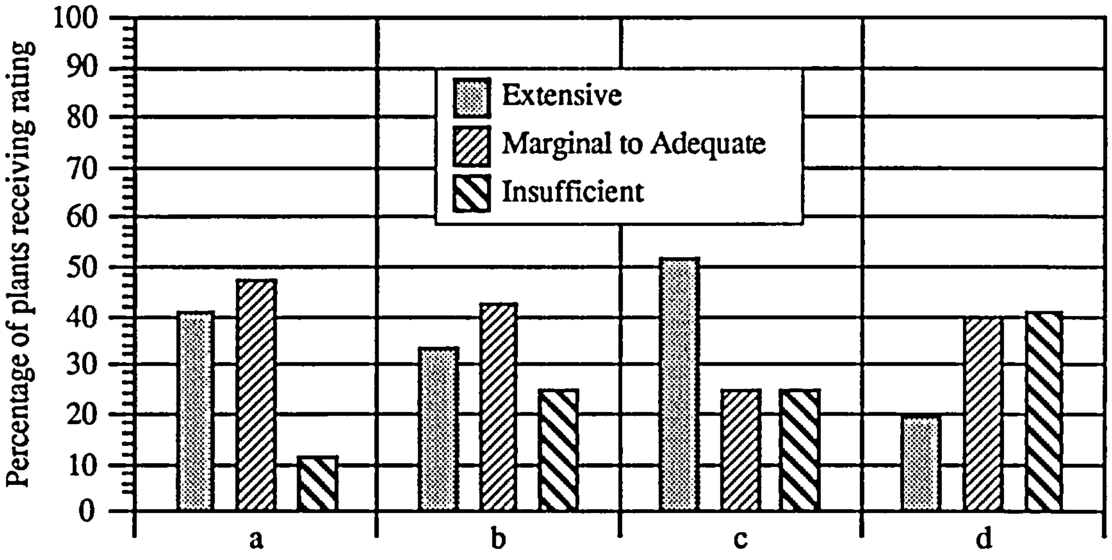

Fig. 7. Distribution of PWR plant ratings. Number of plants receiving specified response rating by category (see categories above).

4. DISTRIBUTION OF PUMPS BY TYPE

A review was conducted of Nuclear Plant Reliability Data System (NPRDS) information on pumps in use in safety-related systems considered. According to the NPRDS data base, there are 2061 Safety Class 1, 2, or 3 centrifugal pumps in service in the systems considered in this review. A total of 30 different manufacturers are identified as suppliers; however, almost three-fourths of the pumps were supplied by 5 manufacturers. It should be noted that a few of the pumps included in the above figures are small, auxiliary support pumps.

Specific pump models may be used in different applications. For example, Byron-Jackson type DVMX pumps (horizontal, multistage pumps) are used in AFW, HPCI, and HPSI systems. The individual DVMX pump ratings vary substantially (e.g., there may be an order of magnitude difference in BEP flow), depending upon number of stages, impeller size, etc. For this reason, as well as the fact that there may be considerable differences in behavior under low-flow conditions, even for essentially identical pumps (as noted in Sect. 2), a review of failure experience by model was deemed inappropriate for this generic study.

A tabulation of the single leading and the top five suppliers of pumps (by number of pumps in service) for the systems considered is provided in Table 3. Because of the similarity in design service conditions for certain systems (e.g., AFW and RCIC), some of the systems were considered jointly with other systems.

Table 3. Distribution of pump suppliers (pump suppliers for specified system)

System(s)	Number of pump suppliers	Fraction of pumps supplied by leading supplier for system	Fraction of pumps supplied by top five suppliers
AFW/RCIC	9	0.36	0.94
CCW	15	0.39	0.83
CS	11	0.36	0.89
ESW	19	0.16	0.66
RHR/LPCI/LPSI/LPCS	11	0.41	0.93
HPSI/HPCI/HPCS	18	0.42	0.84
All above systems	30	0.25	0.73

For several of the pump suppliers, there are also a number of styles of pumps in service within a given type of system. Furthermore, other features of the system and general plant design and operating procedures can substantially affect how pumps are operated within given systems. Thus, it is extremely difficult to generalize about historical problems for pumps of a certain style or pumps used within a general class of system.

5. ON-SITE REVIEWS OF PLANT DATA

To gain a better understanding of the issue of low-flow concerns addressed in the Bulletin, on-site reviews at three PWR plants were conducted. One of the reviews was made in conjunction with a one-week NRC inspection of the utility's actions taken relative to the Bulletin; another was a shorter duration, smaller scope review that was not performed in conjunction with an inspection activity; and the third was associated with a special inspection of a specific pump. All of the reviews proved to be beneficial in terms of providing detailed insights as to the level of attention focused on this subject at these plants. Some examples of strengths and weaknesses noted during these reviews are provided in the discussion below.

Normal and emergency operating procedures, as well as maintenance and surveillance procedures, were reviewed at all three of the plants visited. Considerable variations in operating and surveillance practices relative to pump minimum flow provisions were found.

5.1 PLANT A

5.1.1 Strengths

Plant A conducted most of its normal surveillance testing near the BEP and had conducted special testing of several pumps. The vibration monitoring program appeared to be thorough, and some of the plant personnel contacted demonstrated a good understanding of the concerns over low-flow operation.

In general, this plant's systems were well designed from the standpoint of testability – that is, normal testing is conducted near the BEP. This should help reduce long-term degradation. It appeared that the plant had done a thorough job of reviewing normal operating procedures to ensure that pumps are not operated in a damaging mode during routine operations.

5.1.2 Weaknesses

An analysis performed for pumps in one of the systems did not provide an adequate basis for conclusions reached. The pumps in the affected system may be operated at minimum flow conditions following certain design-basis accident conditions. As a result, special testing of these pumps was conducted. The pumps experienced significant vibration during the tests, which were of short duration and were performed under minimum flow conditions specifically for the purpose of collecting vibration data. The utility appropriately identified the concern associated with the high vibration level, notified the NRC, and initiated a review of possible corrective measures. However, a nuclear industry consulting organization subsequently performed a simplified analysis of the pump and determined that it was satisfactory for long-term operation, even under the high vibration levels. The utility accepted this analysis and used it as the basis for resolving the concern. The analysis was judged by ORNL not to be adequate for its intended purpose, in that it translated a complex dynamic problem into a simplistic static problem and drew inappropriate conclusions from the results.

A second weakness identified in Plant A was that utility personnel had apparently not as carefully considered operation under the guidance of their emergency procedures as they had operation under normal operating procedures. A review of a separate system's pumps at Plant A indicated that there are certain operating conditions [e.g., following a small-break loss-of-coolant accident (LOCA)] where the HPSI pumps could potentially be dead-headed because of their minimum flow line to the refueling water storage tank (RWST) being isolated following switchover to the containment sump. The system realignment for this mode of operation had not been considered by the personnel reviewing system procedural controls in conjunction with the Bulletin response.

5.2 PLANT B

5.2.1 Strengths

Plant B appeared to have done a thorough review of both their normal, test, and emergency procedures relative to pump low-flow operation. A potential problem with one pump (RHR) was identified, and a pump test and inspection program was developed in an attempt to qualify the pump's ability to operate satisfactorily under low-flow conditions. This test involved running the pump at low flow for what was then estimated to be a conservative period of time (relative to the time that the pump would have to operate following an accident) and subsequently disassembling and inspecting the pump. Vibration, flow, and head data were collected during the test. As far as is discernible from the review of all plant responses, this is the only plant to conduct this level of both testing and inspection on a particular pump.

Plant B appeared to have carefully reviewed all their pump applications and had taken actions (both procedural and design change) to alleviate areas of concern.

5.2.2 Weaknesses

The vibration data collected from the special test conducted by Plant B were developed and reviewed in a format that provided little useful information. There were considerable uncertainties associated with the flow measurements during the test. Subsequent reviews of emergency operating procedures by ORNL indicated that the test duration (and other parameters) may not have bounded the limiting postaccident requirements. As a result, an analysis involving simplified assumptions was performed by a nuclear industry consulting organization to attempt to address the duration issue and other factors.

A review of the analysis (performed for Plant B by the same organization used at Plant A) by ORNL found that it attempted to reduce complicated dynamic problems to simplified static conditions for evaluation. It was concluded that the method used by the consultant was inadequate and inappropriate for the intended purpose. This conclusion was validated during subsequent discussions with pump vendors, including the manufacturer of the RHR pump used at Plant B.

5.3 PLANT C

The review of the Plant C response was completed in conjunction with an NRC inspection. The review focused on four systems – HPSI, RHR, CS, and AFW. A summary of the observations follows. A more detailed discussion of the review results is provided in Appendix B.

5.3.1 Strengths

Plant C had implemented a program to provide main control board indication when pumps were being operated under conditions that were below continuous acceptable minimum flow (the indication consisted of labels placed on pump motor current indicators). While pump motor running current indication is only a crude indication of pump operating conditions, it was a consistent type of data available for all affected pumps (most of the pumps did not have individual pump flow indication).

5.3.2 Weaknesses

This plant had several pumps with relatively low minimum flow rates, and testing is normally conducted at or near minimum flow.

For one system (RHR), the minimum flow rates were substantially less than current vendor recommendations. The utility's evaluation essentially relied on the fact that the good operating experience for the pumps in question indicated that the pumps were not being adversely affected. The corrective maintenance on the RHR pumps had, in fact, been minimal. However, the periodic testing for these pumps was done under miniflow conditions and thus would not have been capable of detecting hydraulic degradation.

The minimum flow lines for RHR and CS at this plant shared a common return header downstream of the miniflow orifices. The utility had not performed an analysis of the common line frictional head loss (which, in turn, affected the individual pump flow). Preliminary calculations performed during this visit indicated that the common line loss was not negligible (from the standpoint of its impact upon individual pump flow rate) if all the pumps were operated in parallel. The utility plans to perform detailed analyses on this subject.

In another system (AFW), the 20-gal/min flow rate available through the miniflow line met the vendor recommendation for very short term, start/stop type of operation (defined by the vendor as 15 min or less). However, there were no procedural or administrative controls in place to ensure that the pump was operated within this criterion nor within the vendor-defined minimum flow requirement of 55 gal/min for short-term operation (3 h or less). Disassembly and inspection of the same model pumps, used in the same service, and with similar minimum flow provisions at another utility revealed considerable wear of a nature that indicated low-flow degradation (scoring of the balance drum, cracked diffusers, excessive wear of wear rings, and thrust bearing damage). Plant C was not aware of the results of the other plant's inspections.

For the HPSI/CCP system, the condition under which the system was operated was depended upon to maintain flow above vendor recommendations. However, a review of procedures revealed that when the chemical and volume control system was operated according to plant procedures in the alternate letdown mode, the total charging flow would be less than vendor recommendations.

6. CONCLUSIONS

Generally speaking, the response of the industry to the low-flow degradation issues discussed in Bulletin 88-04 appears to be relatively superficial. There are some exceptions to this general observation. Furthermore, a superficial response for a specific system and pump does not necessarily equate to the existence of a problem for that system/pump. Given the facts that (1) low-flow degradation is, to a large extent, a common-mode failure concern and (2) that failure of a pump cannot be readily overcome by manual operator action (as is the case for many valve/valve operator failures, for example), it is important that more detailed attention be focused on low-flow concerns.

Two specific conclusions can be drawn. First, 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. Currently, ASME pump testing requirements are used by the industry to verify pump operational readiness. However, the ASME requirements are not geared toward demonstrating satisfactory low-flow operating capability.

Second, the low-flow issue was not adequately addressed by all plants. It is judged that the very fact that there has been no generic guidance on how to assess the suitability of pumps under given conditions effectively guaranteed that this would be the case, since utilities were essentially on their own to determine how to qualify individual pumps that were questionable.

7. RECOMMENDATIONS

The following recommendations are based on the review of the issue discussed in previous sections. During 1991, ORNL will be involved in additional activities related to Bulletin 88-04. These recommendations are thus preliminary in nature and are subject to modification as additional insights are gained.

1. It is recommended that the industry be encouraged to develop pump qualification criteria and processes. The program should provide a generic procedure for validating the satisfactory application of individual pumps for all potential operating modes.
2. Consideration should be given to the development and/or implementation of new diagnostic techniques, such as motor current signature analysis (employing advanced signal analysis techniques), which would provide more meaningful information about important pump operating parameters than is currently available (outside of the use of intrusive monitoring involving elaborate test configurations).
3. A small-scale pump test program should be considered. The purpose of the program should be to identify and quantify, at least relatively, the important parameters associated with low-flow degradation of at least one pump model. The testing would be partially destructive in nature since it should provide for accelerated aging of the pump parts.
4. Additional utility review of pumps should be encouraged but should be preceded by the completion of tasks recommended in items 1 and 2.

Recommendations 1, 2, and 3 are not unrelated. If better means of readily assessing pump condition existed, the task of developing qualification criteria would be simplified. Qualification criteria and process would help focus diagnostic development and application. Test program results would help identify the parameters that are most important to monitor. Thus, these areas should be worked in parallel and coordinated. The overall goal of these activities should be to provide the basis for determining the acceptability of a given pump for the conditions at which it may be required to operate.

REFERENCES

1. M. L. Adams and E. Makay, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., "Aging and Service Wear of Auxiliary Feedwater Pumps for PWR Nuclear Power Plants," USNRC Report NUREG/CR-4597, Vol. 1 (ORNL-6282/V1), July 1986.*

2. C. C. Heald and R. Palgrave, "Backflow Control Improves Pump Performance," *Oil and Gas Journal*, pp. 96–105 (February 25, 1985).†

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* Available from the National Technical Information Service, Springfield, VA 22161.

† Available in public technical libraries.

Appendix A

NRC BULLETIN 88-04

OMB No.: 3150-0011
NRCB 88-04

UNITED STATES
NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REACTOR REGULATION
WASHINGTON, D.C. 20555

May 5, 1988

NRC BULLETIN NO. 88-04: POTENTIAL SAFETY-RELATED PUMP LOSS

Addressees:

All holders of operating licenses or construction permits for nuclear power reactors.

Purpose:

The purpose of this bulletin is to request all licensees to investigate and correct as applicable two miniflow design concerns. The first concern involves the potential for the dead-heading of one or more pumps in safety-related systems that have a miniflow line common to two or more pumps or other piping configurations that do not preclude pump-to-pump interaction during miniflow operation. A second concern is whether or not the installed miniflow capacity is adequate for even a single pump in operation.

Description of Circumstances:

Westinghouse Electric Corporation recently notified all utilities with Westinghouse-designed nuclear steam supply systems (NSSS) of the two concerns noted above. NRC Information Notice 87-59 forwarded a summary of these concerns to all holders of operating licenses or construction permits for nuclear power reactors and indicated that further staff evaluation might result in a request for specific licensee actions. Several licensees have confirmed the existence of these concerns in their plants (Turkey Point, H. B. Robinson, Vermont Yankee). This bulletin is the result of the staff's evaluation.

Discussion:

When two centrifugal pumps operate in parallel and one of the pumps is stronger than the other (i.e., has a higher developed head for the same flow), the weaker pump may be dead-headed when the pumps are operating in the minimum flow mode. The phenomenon is manifested at low flow rates because of the flatness of the pump characteristic curve in this range. The head difference is not a problem at moderate to high flow conditions because of the shape of the pump characteristic curve in these regions.

Traditionally, the required miniflow for these pumps was established solely on the basis of pumped fluid temperature rise. Today, however, it is generally understood that temperature rise is not the only factor influencing safe continuous minimum flow operation. Centrifugal pumps will demonstrate a flow condition that has been described as hydraulic instability or impeller recirculation at some point below the best efficiency point (BEP) on their characteristic curve. These unsteady flow phenomena become progressively more pronounced as the flow is further decreased and can result in pump damage from pump vibration, excessive forces on the impeller, and cavitation. It is now generally recommended that the limitations associated with these hydraulic phenomena be considered when specifying minimum flow capacity.

The first potential problem involves parallel pump operation with both pumps recirculating through a common miniflow recirculation line or with a piping configuration that does not preclude pump-to-pump interaction during miniflow operation. The problem was identified on a plant whose licensee requested that Westinghouse determine if parallel operation while on miniflow is acceptable. Westinghouse reviewed the plant's residual heat removal (RHR) system configuration. The review determined that the potential exists for the stronger pump to dead-head the weaker pump during low flow, parallel pump operating conditions while on miniflow only. In addition, it was determined that even without pump interaction the recirculation flow available was not adequate to ensure continuous operation of even a single RHR pump on miniflow. Although these issues are based on an evaluation of RHR pumps at a particular plant, the first concern may exist at other plants configured with a common pump recirculation flow path and the second concern may also exist at other plants independent of whether or not there is a common recirculation pump flow path.

The NRC staff believes that these issues may be relevant to all water-cooled reactor designs, regardless of the pump application or the NSSS manufacturer. This is based on the belief that miniflow lines have traditionally been designed for only 5% to 15% of pump design flow. Some pump manufacturers now are advising that their pumps should have minimum flow capacities of 25% to more than 50% of best efficiency flow for extended operation to protect against hydraulic instability or impeller recirculation problems.

Actions Requested:

All addressees are requested to do the following:

1. Promptly determine whether or not its facility has any safety-related system with a pump and piping system configuration that does not preclude pump-to-pump interaction during miniflow operation and could therefore result in dead-heading of one or more of the pumps.

2. If the situation described in Item 1 exists, evaluate the system for flow division taking into consideration (a) the actual line and component resistances for the as-built configuration of the identified system; (b) the head versus flow characteristics of the installed pumps, including actual test data for "strong" and "weak" pump flows; (c) the effect of test instrument error and reading error; and (d) the worst case allowances for deviation of pump test parameters as allowed by the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) Section XI, Paragraph IWP-3100.

3. Evaluate the adequacy of the minimum flow bypass lines for safety-related centrifugal pumps with respect to damage resulting from operation and testing in the minimum flow mode. This evaluation should include consideration of the effects of cumulative operating hours in the minimum flow mode over the lifetime of the plant and during the postulated accident scenario involving the largest time spent in this mode. The evaluation should be based on best current estimates of potential pump damage from operation of the specific pump models involved, derived from pertinent test data and field experience on pump damage. The evaluation should also include verification from the pump suppliers that current miniflow rates (or any proposed modifications to miniflow systems) are sufficient to ensure that there will be no pump damage from low flow operation. If the test data do not justify the existing capacity of the bypass lines (e.g., if the data do not come from flows comparable to the current capacity) or if the pump supplier does not verify the adequacy of the current miniflow capacity, the licensee should provide a plan to obtain additional test data and/or modify the miniflow capacity as needed.

4. Within 60 days of receipt of this bulletin, provide a written response that (a) summarizes the problems and the systems affected, (b) identifies the short-term and long-term modifications to plant operating procedures or hardware that have been or are being implemented to ensure safe plant operations, (c) identifies an appropriate schedule for long-term resolution of this and/or other significant problems that are identified as a result of this bulletin, and (d) provides justification for continued operation particularly with regard to General Design Criterion 35 of Appendix A to Title 10 of the Code of Federal Regulations (10 CFR 50), "Emergency Core Cooling" and 10 CFR 50.46, "Acceptance Criteria for Emergency Core Cooling System for Light Water Nuclear Power Reactors."

5. Within 30 days of completion of the long-term resolution actions, provide a written response describing the actions taken.

6. An evaluation of your actions in response to this bulletin should be documented and maintained at the plant site for a minimum of two (2) years. That evaluation should, as a minimum, address the piping system configuration in accordance with Item 1 above, each of the four factors discussed in Item 2, pertinent test data and field experience on minimum flow operation, and verification of the adequacy of current miniflow capacity by the pump manufacturer.

The written reports, required above, shall be addressed to the U.S. Nuclear Regulatory Commission, ATTN: Document Control Desk, Washington, D.C. 20555, under oath or affirmation under the provisions of Section 182a, Atomic Energy Act of 1954, as amended. In addition, a copy shall be submitted to the appropriate Regional Administrator.

This requirement for information was approved by the Office of Management and Budget under clearance number 3150-0011. Comments on burden and duplication should be directed to the Office of Management and Budget, Reports Management, Room 3208, New Executive Office Building, Washington, D.C. 20503.

If you have any questions about this matter, please contact the technical contact listed below or the appropriate NRR project manager.

Charles E. Rossi

Charles E. Rossi, Director
Division of Operational Events Assessment
Office of Nuclear Reactor Regulation

Technical Contact: T. Collins, NRR
(301) 492-0897

Attachment: List of Recently Issued NRC Bulletins

Appendix B

PLANT C RESPONSE TO NRC BULLETIN 88-04

During the on-site visit at Plant C, design features; operating, testing and maintenance procedures; and plant analysis relative to Bulletin 88-04 were reviewed. This review was done in conjunction with an NRC inspection of the plant response to the Bulletin. Appropriate excerpts from the report prepared are provided below.

B.1 GENERAL OBSERVATIONS

B.1.1 Written Response Evaluation

Essentially all of the utility responses to NRC Bulletin 88-04 have been reviewed by ORNL personnel. The range of responses has been broad, both in the context of the quantity and quality of useful information contained in the responses, as well as in the indicated actions taken to address the concern.

The response of Plant C provided design information, simplified drawings of the recirculation systems, and estimated times at minimum flow in various procedures for HPSI, RHR, CS, and AFW pumps. In that regard, the response provided more substantive information than most responses.

With the exception of the RHR pumps, the Plant C response did not discuss current vendor recommendations. The RHR pump discussion was included because the minimum flow provided was less than vendor recommendations. The plant basically relied on lack of historical failure and observed degradation as the basis for system adequacy. This basis has been used in other responses, in the context that utilities have argued that they have not experienced failures or degradation due to low-flow operation.

Thus, the Plant C response, at face value, and without looking at particular pumps, corresponded to an average response to NRC Bulletin 88-04.

B.1.2 On-Site Inspection Activities – General Observations

The site review indicated that the level of scrutiny provided, from an overall context, was minimal. This observation is based on several diverse indicators:

1. A review of the operating procedure for the chemical and volume control system indicated that the procedure allowed continuous operation under certain conditions (alternate letdown) that would result in flow less than the vendor recommendations for continuous operation, even though the utility had asserted that the pumps would be operated at greater than the vendor-recommended flow during normal operation.

2. A review of recent full-flow test data for the RHR and CS pumps indicated that the pumps appear to be operating substantially below the results from the vendor and preoperational testing. While the data may be misleading because of instrumentation

inaccurately depicting pump condition, the plant had not compared test results to the original data. This is an important point because the plant largely depended upon a lack of historical failure/degradation as indication that low-flow degradation has not occurred, and this type of testing provides the best indication about whether the hydraulic performance of the pump has degraded or not.

3. There is a common recirculation line for the RHR and CS miniflow lines downstream of the individual pump's minimum flow orifices. The backpressure from parallel operation had not been considered by the plant. The utility is now in the process of calculating the effect. The impact may turn out to be relatively small (on the order of 10% reduction in individual pump flow rate, compared with the flow rate when operated alone); however, it had not been considered prior to the NRC inspection.

4. Plant personnel were unaware that another plant (Plant D) using the same model pumps as those used in Plant C's AFW system had found substantial damage associated with low-flow operation. The damage was found when the pumps were disassembled for inspection as part of the Plant D response to Bulletin 88-04.

It is important to note that Plant C depended heavily upon successful test results and the lack of calls for corrective maintenance required for the AFW pumps in assessing pump suitability. Plant D noted that performance tests had not identified the damage; rather, it had been discovered only when the pumps were disassembled.

These observations led to the conclusion that a relatively cursory review had been performed.

The plant had taken one notable action to help avoid operation at low flow. Each pump considered had pump motor current indication provided on the main control board. The plant had implemented a program to "band" the motor current indicators to provide operators with an indication of the suitability of the flow regime in which the pumps were being operated. Motor current was selected instead of pump flow because the plant did not have individual flow instruments dedicated to each of the pumps.

As a footnote to these general observations, a concern about the turbine-driven AFW pump was identified. This pump has ~ 20-gal/min minimum flow. About half of the flow goes back to the condensate storage tank, while the other half goes through lube oil and turbine bearing coolers and then back to pump suction. This would result in a continuing increase in suction temperature with time. Operation of this pump for a protracted period in minimum flow would create overheating problems (note that the temperature rise on a single pass through the pump is estimated to be 50° F).

B.2 OBSERVATIONS CONCERNING MAINTENANCE AT PLANT C

Maintenance files for several of the safety-related pumps at Plant C were reviewed during the inspection. Failure reports for the Plant C pumps, as well as failure reports for the same model pumps in service at other plants that have been provided to the Institute of Nuclear Power Operation's NPRDS data base, were also reviewed.

B.2.1 RHR Pumps

RHR pump A was disassembled and inspected for the first time in 1989. The only wear noted was in bushings and sleeves on the intermediate portion of the shaft.

RHR pump B was disassembled just prior to the NRC inspection. Both the lower and upper shaft sections (there are a total of three shaft sections) were noted to be about 37 mils out of true, their bushings were worn, and the first-stage wear ring clearances were found to have increased by about 50 mils, based on verbal communications with maintenance personnel. Based on subsequent discussions with utility personnel, no further damage was noted.

B.2.2 Containment Spray Pumps

No maintenance involving pump disassembly was noted.

B.2.3 AFW Pumps

AFW pump A failed to develop required discharge pressure during periodic testing in late 1983. The pump manufacturer, who was called in to investigate, found excessive thrust clearance. Damage to the seventh- and eighth-stage impellers was found, the balance piston was badly scored, and the thrust bearing had begun to wipe. The utility attributed this to the original shaft positioning (balance drum setting).

It should be noted that Plant D, which uses the same model pump as is used for the motor-driven pumps at Plant C, disassembly and inspection of the AFW pumps found extensive indication of low-flow degradation, including wiped thrust bearings, balance drum grooving, and excessive wear ring clearances, even though the pumps had passed performance tests. The nature of the tests is unknown. Plant D plans to install a full-flow test line for pump testing and extended operation.

B.2.4 HPSI Pumps

HPSI pump C was found with an eroded fifth stage in 1982. During 1985, a mechanic found the B pump shaft to be bound. Internal damage was noted. At the time of the inspection, the C pump rotating element had been removed as a result of some performance degradation noted by in-service testing. Preliminary inspection noted erosion on the suction side of the first stage. This led maintenance personnel to question whether the erosion on the fifth stage noted in the earlier event was really on the first stage, which seems to be a valid observation. Note that this pump has opposed impellers, with the fifth stage at one end and the first stage at the other.

B.2.5 Discussion

Plant C has experienced a relatively low rate of failures with the above-mentioned pumps. While there is some indication of degradation due to operation at low flow for the

HPSI pumps, it is inconclusive. In this context, however, it is important to note that Plant D did not know of degradation in their AFW pumps until they disassembled and inspected them.

The maintenance personnel at Plant C were very forthright and cooperative. The experienced personnel we met with appeared to be extremely competent.

B.3 OBSERVATIONS FOR RHR AND CS PUMP DESIGN AND TESTING AT PLANT C

During the on-site review at Plant C, it was noted that the RHR and CS pump data collected during testing that is conducted on a refueling frequency appeared anomalous. In addition, it was noted that these pumps share a 6-in. common recirculation line. Background information and discussions follow.

B.3.1 Design and Test Results

B.3.1.1 Pump and miniflow design

The RHR pumps are Vendor A, two-stage vertical can pumps, Model Y, with 400-hp, 1760-rpm motors, which were furnished by Vendor A as part of the pump package. The pump BEP is ~ 4100 gal/min at 325 ft head. The miniflow orifices were originally sized to provide 350 gal/min at 325-ft differential pressure. With a single pump operating, measured flow rate for each RHR pump operating under miniflow only has been ~ 400 gal/min (note that the orifice differential pressure under minimum flow is ~ 365 ft).

The CS pumps are Vendor B, two-stage vertical can pumps, Model Z, with 350-hp, 1780-rpm motors. The pump BEP is ~ 4750 gal/min at 265 ft head. With a single CS pump operating, measured flow rate for each pump operating under miniflow only has been ~ 300 gal/min.

A portion of the minimum flow line for the RHR and CS pumps is common to all RHR and CS pumps. Each pump has its own miniflow restriction orifice upstream of the common portion of the line.

B.3.1.2 Current vendor-recommended minimum flow

<u>RHR Pumps</u>

Continuous: 1500 gal/min (~37% BEP); Short term (≤ 2 h in 24 h): 1100 gal/min. Vendor A specifically warned that at 350-gal/min minimum flow, the following could occur:

- Considerable internal vibration and hydraulic instability could occur.
- Pump bushings could be damaged.
- Sustained vibration during an incident could result in significant damage or failure of the bushings, with extensive damage to the pumping element.

<u>CS Pumps</u>

Continuous: 2300 gal/min (~48% BEP); Intermittent: 1600 gal/min (60 to 1500 h/year); Short term (≤ 60 h/year): 200 gal/min.

B.3.1.3 Test Data

Preoperational test data for both RHR pumps were reviewed. In the case of RHR pump A, the data were found to be consistent with the vendor-supplied test curve. The preoperational test curve for RHR pump B was below the vendor curve, particularly at the higher flow end of the curve. Current IST data for the RHR pumps were reviewed and found to be below both curves for both pumps. The IST data are acquired with recirculation flow only, at a measured flow rate of 400 gal/min. It should be noted that the 400 gal/min is in excess of the 350 originally specified; however, it appears to be consistent with the installed orifices.

During each refueling outage, a test (ST1) is conducted in which flow is delivered to the core at flow rates in excess of the pump BEP. This test has recorded flow rate, discharge pressure, and suction pressure for parallel pumps. Using the test data from 1990, it appears that the A and B pumps' performance deviates from vendor/preoperational test data in the range at which the test is conducted (4550 to 4900 gal/min). The noted deviation is estimated to be as follows:

Pump	Pressure deviation at test flow (%)	Flow deviation at test head (%)
A	27/14	12/8
B	21/7	11/4

The above estimates are relative to the preoperational test results. The first entry in each column assumes no head loss from pump discharge to the pressure instrument that is used to measure discharge pressure and no pump suction pressure depression when the pump is running. The second entry is based on measured head plus 15 psi in an effort to approximate head loss from pump discharge to the discharge pressure instrument and suction pressure depression when the pump is running.

The preoperational testing of the CS pumps did not measure flow. During each refueling outage, flow is measured within the same procedure used for RHR flow measurement (ST1). These data indicate that all three of the pumps are performing substantially below the originally supplied vendor curves (indicated head is only about two-thirds that measured at the vendor test facility for the same flow). Even if it is assumed that there is a 15-psi difference between pump actual head and that implied by data from procedure ST1, the indicated operating point for pumps would still be more than 20% less (in either flow or head) than the vendor test curve indicates.

For both the RHR and CS pumps, recent test data appear anomalous. The cause(s) of the anomalous data is unclear and may very well be explainable by instrumentation accuracy, measurement points, etc.* Plant C indicated that further analysis and review would be pursued.

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* It appears that the anomalous data are the result of something other than the pumps, since all the pumps seem to show the same general trend. However, this needs to be borne out by further analysis.

B.3.2 RHR/Containment Spray Common Return Line Review

During the review of system designs and operation, it was noted that the recirculation line for the CS and RHR pumps is a common line downstream of the orifice for each of the pumps. Isometric drawings for a portion of the common return line were reviewed during the visit. A complete trace of the common line through isometric drawings was not made because of time constraints. Based on estimated flow rates for each of the pumps when operated under minimum flow conditions, the backpressure associated with frictional and elevation head losses of just the reviewed portion of the common line when all pumps were operated simultaneously was sufficient to cause a 5% reduction in individual pump flow, assuming clean pipe. If allowances for some fouling and the additional pipe and fittings were made, the flow reduction associated with multiple pump operation in parallel would be more significant, perhaps as high as 25%.

Plant C had not considered common line losses prior to this visit but indicated that they planned to perform a detailed analysis.

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11. ABSTRACT *(200 words or less)*

This report documents the results of a study of the nuclear industry's response to NRC Bulletin 88-04. The work was conducted for the U.S. Nuclear Regulatory Commission (NRC) Nuclear Plant Aging Research Program. All written correspondence between utilities and the NRC was reviewed and classified. Major pump vendors were interviewed to discuss their perspectives on low-flow degradation of pumps. Individual sites were visited to review the details of system design and procedural controls relative to the Bulletin issues.

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