AEOD ENGINEERING EVALUATION REPORT

PUMP DAMAGE DUE TO LOW FLOW CAVITATION

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AEOD ENGINEERING EVALUATION REPORT

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SUBJECT: PUMP DAMAGE DUE TO LOW FLOW CAVITATION

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SUMMARY

Susquehanna 1 Licensee Event Report 86-021 describes an event in which the emergency service water (ESW) system was lost due to severe cavitation damage of the ESW pumps. The plant was at full power when an ESW pump failed. While investigating the cavitation damage, the bottom portion of the pump suction bell separated from the pump body and fell into the pump pit. The pump's impeller vanes were eroded through the wall. Similar but less severe damage was found on the three other ESW pumps. A subsequent inspection of the RHRSW pumps also found similar cavitation damage. The cavitation damage was not the result of an inadequate net positive suction head (NPSH) for the pump. Rather, it was due to impeller suction recirculation which occurs when pump operates at flows significantly less than the design flow. Erosion resulting from recirculation cavitation has also occurred on all four of the RHR pumps at Vermont Yankee. This may be associated with low flow operation during the monthly surveillance testing. The mini-flow bypass lines for the RHR pumps limited flow to about 5 percent of the design flow when the pump operates in the testing mode.

Based on these events an evaluation of pump damage due to low flow cavitation was undertaken. The flow rate at which recirculation occurs is dependent on the design of the impeller. Several pump manufacturers have recently developed guidelines for establishing low flow limits on pump operation. However, the pump mini-flow bypass lines, in most operating plants, were sized solely on fluid temperature rise consideration. Generally, the minimum flows are in the order of 10 percent of design flows. This rate may not be sufficient to avoid the damaging range of internal recirculation. Moreover, for pumps designed for a wide range of flows, the recirculation configuration may not have been fully considered. Major degradation of pump impellers and casings have occurred to centrifugal pumps that have been running continuously within recirculation regimes.

Many of the emergency core cooling systems in most operating plants are designed to operate with a wide range of flows and use a mini-flow bypass line for inservice testing of pumps. These operating conditions and events, therefore, indicate that recirculation cavitation is a potential generic problem.

Operation of pumps at low flow conditions for extended periods of time can cause recirculation cavitation damage to the pumps in spite of available NPSH. Such damage induces slow deterioration of pump internals and, during early stage of cavitation, do not affect the operation of the pump. Hence, this type of damage is not easily detectable. Furthermore, cavitation indication on the pump internals cannot be observed without disassembly of the pump and the plant

routine surveillance tests for pumps may not be capable of detecting early impeller degradation. There is the potential that recirculation cavitation on a pump impeller could go undetected until total failure of the pump occurs. Such failure could prevent the system from performing its safety functions when needed.

This report presents our findings and conclusions based on our evaluation. NRC bulletin (NRCB 88-04, "Potential Safety-Related Pump Loss," May 5, 1988) has been issued notifying licensees of certain aspects of the potential problem. The findings of the AEOD investigation into the low flow problems provided in this study are based on a wide scope of plant operating experiences and provide background information in establishing future guideline for evaluation of licensee response to the bulletin and as backup information for plant inspection regarding the problem.

INTRODUCTION

This engineering evaluation was initiated based on a report of an event at Susquehanna 1 described in LER 86-021, involving severe erosion damage of pump internals. The erosion of pump internals was caused by recirculation cavitation. Recirculation within centrifugal pumps is flow reversal at the inlet or discharge tips of the impeller when pumps are running in off-design regimes. Flow reversal causes vortex action near the impeller vanes, inducing pressure surge and pulsation which cause rapid deterioration by cavitation of impeller metal in the inlet or outlet region even when adequate net positive suction head (NPSH) is provided (Ref. 1).

Recirculation has been one of the most persistent and puzzling problems encountered in the operation of centrifugal pumps in recent years. Although serious failures had not been reported previously, direct evidence of low flow induced failure of pumps in nuclear plants and experience gained in both the laboratory and the field during the past decade, had shown that hydraulic instabilities and imbalance can occur in a pump running significantly below the design flow. Furthermore, it has been proven through analysis and tests that the effects of recirculation can be very damaging not only to the pump's operation, but also to the life of the impeller and casing.

DISCUSSION

Licensee Event Report (LER) 86-021-00, dated May 24, 1986, for Susquehanna 1 describes an event involving pump damage due to erosion caused by recirculation cavitation. The pump damage were discovered in the emergency service water (ESW) and residual heat removal service water (RHRSW) systems. The event began on May 22, 1986, while the plant was operating at full power when an overcurrent alarm for the C ESW pump was received in the control room. Investigation revealed the pump motor to be running at a low amperage, and the pump discharge check valve to be closed. The pump was declared inoperable and the plant entered a limiting condition for operation (LCO). Subsequent disassembly of the pump revealed that the bottom portion of the pump suction bell had separated from the pump body and had fallen into the pump pit. Inspection of the damaged parts revealed that the suction bell had been penetrated around its entire circumference by cavitation.

On May 24, an inspection of the "A" pump by a dive [illegible] severe damage to the pump suction bell. The "A" [illegible] declared inoperable.

Since the condition of the [illegible]ing B [illegible] known, they were also declared inoperable a[illegible]lled [illegible]. [illegible] the A, B and D pumps were [illegible] continued to perform at [illegible] their [illegible] and following the unit shutdowns.

A subsequent inspection of [illegible] and D [illegible] damage similar to the A and C pumps. The suction bel[illegible] [illegible]siderably but had not been penetrated. The impellers showed sign[illegible] [illegible]e high pressure side of their vanes at the suction end. Ho[illegible] [illegible]nes had not been penetrated and had retained their original shap[illegible] [illegible] D pumps were declared operable on May 28. Due to a lack of spare [illegible] [illegible]porary repair were made to the C pump and the A ESW loop was resto[illegible] [illegible]unctional status on the same day.

The ESW pumps normally operate at about [illegible]rcent or less of their design flow of approximately 6000 gpm per one pum[illegible] When the loop supplying cooling water to the diesels is run with two operating pumps, each pump delivers approximately 3500-3900 gpm. The other loop that does not serve the diesels (usually the B loop) is normally run with only one pump at approximately 1000-1500 gpm. Based on the inspection, the licensee concluded that impeller suction recirculation cavitation was the major contributing factor to the ESW pump failure. The type of cavitation occurred when the pumps ran at flow significantly lower than it design flow -- flow less than 60 percent.

Following receipt of the required spare parts, the A and C ESW pumps were repaired, retested and declared operable on June 6, 1986. The B and D ESW pump were also repaired and retested on June 10. Repair of all four ESW pumps was accomplished by the replacement of all suction bells and impellers. The replacement impeller is NiAl-Bronze which has a higher resistance to cavitation damage than the original impellers of carbon steel. The replacement suction bells are made of the original carbon steel material. Stainless steel (nitronics 60) liners were installed on the suction bells of the A and C pumps. Some liners will also be installed in the B and D pumps.

Due to their similar design, the Residual Heat Removal Ser ice Water (RHRSW) pumps were also inspected. These pumps are two stage vertical circulator pumps, Bryron Jackson type 28KXL. Cavitation damage was found on the impeller liners on the Unit 1 pumps A and B, and the liners were replaced. Cavitation damage to the Unit 2 pump A was minimal and impeller liner replacement was not warranted at that time. The Unit 2 pump B was not inspected until the next refueling outage.

Although degraded, the RHRSW pumps were capable of performing their design functions. The A and B pumps of Unit 1 have been able to pump 9000 gpm per pump to their respective heat exchangers (design flow) during subsequent tests. Subsequent inspections found that the impeller liner degrades before any significant damage can be seen on the impeller and the liner damage did not seem to cause a noticable drop-off in pump performance as evidenced by the flow data. There were no indications that the cavitation was attributed to flow vortexing or inadequate NPSH. The cavitation was a result of flow recicrulation which was caused by operating the pumps at low flow rates. These RHRSW pumps had operated at less than 50 percent of design flow most of the time. The licensee indicated that the cavitation damage can be avoided by operating the pump above 50 percent of design flow; specifically 75-100 percent of design flow is desirable. The RHRSW system design and method of operation would be reviewed to determine what changes could be possible to avoid recirculation cavitation.

The damage to the ESW and RHRSW pumps was determined to have been caused by impeller suction recirculation cavitation. The cavitation is caused by operating the pumps at flows which are significantly below the design flow. The cavitation erodes the suction bell wall. The impeller was also eroded but at a slower rate. Once the suction bell wall is penetrated, erosion of both the suction bell wall and the impeller is accelerated as water is drawn through the suction bell penetrations.

This event suggests a common cause failure mode for the pumps with low flow operation modes. The cited damage, which caused the pumps to be inoperable, included eroded impellers and suction bells. The pump damage is due to suction recirculation cavitation which resulted from running the pumps at a low flow rate. (Approximately 60 percent of its design flow of 6000 gpm).

Operation at lower flow creates mismatches of flow angles within the pump and causes water to recirculate back towards the suction. The recirculating currents cause local pressure zones which are below the vapor pressure of the water. This causes vapor bubbles to form which collapse when a high pressure zone is reached, eroding the local material. The erosion begins on the high pressure side of each impeller range at its suction end. Prolonged operation of a pump at its low flow can result in cavitation damage on impellers.

When running a pump at a low flow, flow recirculation can occur at the discharge regions as well. This is called discharge recirculation. Discharge recirculation also creates surges and local deterioration by cavitation at the impeller tips. Recirculation in the suction and discharge regions does not necessarily occur at the same flow rate. The recirculation cavitation is not related to inadequate pump NPSH. Since inadequate NPSH would also cause pump cavitation, the similarity between patterns of cavitation damage from recirculation and from inadequate NPSH may often lead to an erroneous conclusion as to the cause of the damage. However, the mechanisms that cause the damage are entirely different. The cavitation damage from recirculation proceeds from the high pressure side of the inlet edge of the vane through the metal towards the low pressure side, while the damage from inadequate NPSH starts in the opposite direction, from the low pressure side of the vane and proceeding through the metal toward the high pressure side.

Recirculation characteristics are dependent on the design of the impeller. It is inherent in the dynamics of the pressure field that every impeller design must begin to recirculate at some point of flow. Recirculation becomes progressively pronounced as a pump is operated further away from the design flow. The percentage of design flow rate at which recirculation will begin is dependent on many factors. The most critical factors which have influences on low flow pump performance and minimum continuous flow are: power intensity (pump size), suction specific speed, and specific speed. Although pump manufacturers (Ref. 3 and 4) have recently developed guidelines for establishing low flow limits on pump operation, studies on low flow aspects are still continuing. Most of the guidelines which have been published (Ref. 5) stipulating recommended minimum flow for pumps, present minimum flow rates as a function of suction specific speed; the lower the suction specific speed a pump is designed for, the lower the flow rate the pump can operate without recirculation. Low flow operations are generally required for the standby systems when performing inservice surveillance testing of pumps through the miniflow bypass line, and for systems with a wide range of flows when operating pumps in low flow modes. These low flow operations are general design configurations for emergency core cooling system testing in nuclear power plants. In most plants, the pump bypass lines were sized only on the basis of limiting the temperature rise of the pump when operated in the testing or minimum flow mode. Typically, this temperature rise based minimum flow is in the order of 10 percent of the best efficiency point (BEP) flow. In response to the concern by pump manufacturers that testing pumps at low flow on the order of 10 percent of BEP flow, may lead to premature failure of pump components as a result of higher vibration during low flow testing, EPRI (Ref. 2) conducted a study on surveillance testing of standby pumps in operating nuclear power plants in 1985 to determine whether test-related failures were caused by some aspects of the tests. Although this study neither provides conclusive evidence against nor vindicates the use of low flow testing practices, it does support the expectation that low flow test operation will lead to degradation and premature failure of pump internals and concludes that prolonged operation of pumps at very low flow (in the range of 10 percent BEP flow) can cause high vibration which is a hydraulic instability manifested by flow recirculation in the pumps.

Lately, it is increasingly recognized by pump designers and manufacturers that factors other than temperature rise, such as energy level, suction specific speed, developed head per pump stage, and impeller design details, should play a role in establishing the reference value for flow rates during inservice tests. Several pump manufacturers are now recommending that standby pumps be tested at a flow no less than 25 percent of BEP flow(s).

Five additional events involving either pump failure or potential for pump degradation resulting from low flow operations were found in a search of operational experience data base files. The data search included the Sequence Coding and Search System (SCSS), the Nuclear Plant Reliability Data System (NPRDS), and the foreign event files. These five events occurred at Vermont Yankee, H. B. Robinson 2, Turkey Point 3, a foreign reactor and at Haddam Neck. The pump damage at Vermont Yankee was attributable to insufficient miniflow recirculation line capacity. The potential for pump degradation identified at H.B. Robinson and Turkey Point are also associated with the inadequacy in the original design of miniflow recirculation line and that of the last two plants was caused by prolonged operation of pumps in low flow modes.

The effects of recirculation resulting from low flow operation manifest themselves not only in material degradation -- cavitation, but also in the form of pressure pulsations and vibrations. Hydraulic pressure pulsation and pump vibration are also significant contributors to deterioration of pump components because of the high amptitude dynamic forces that they produce. The pump damage at Vermont Yankee was a result of cavitation, while that at the foreign reactor and at Haddam Neck were attributed to pressure pulsation and pump vibration. H. B. Robinson and Turkey Point identified the existence of the potential for pump degradation and failure due to the insufficient flow rate designed for the recirculation lines.

Low flow testing can be a possible source of impeller cavitation damage. The resulting hydraulic recirculation present inside the pump at low flow can create cavitation damage. Vermont Yankee was notified by the pump vendor, Bingham/Willamette, on November 13, 1986 that the minimum flow rates for the RHR pumps should be made higher than previously indicated to Vermont Yankee. Similar notifications for increase of mini-flow rates have also been sent to four other plants: Cooper, Pilgrim, Browns Ferry and Peach Bottom.

The pump vendor indicated that the minimum flow requirements established for the RHR pumps at Vermont Yankee since plant startup may not be adequate for all pump operating modes. Specifically, the pump vender recommended that the value for continuous minimum flow for the pumps should be 2700 gpm, or about 38 percent of the pump design flow of 7200 gpm, and the value for intermittent operation (less than two hours of operation within a 24-hour period) should be 2075 gpm. The RHR pump has a flow orifice in the recirculation line designed to limit flow to about 350 gpm. This orifice sizing was based solely on the pump flow required to limit the temperature rise of pump when operated in the minimum flow mode. The pump vendor apparently has since determined that additional factors must be considered in determining the minimum flow requirements, including pump inlet and outlet circulation flow patterns that will occur at lower flow modes. Recirculation flow patterns can occur and result in component damage even if there is sufficient available NPSH. In a similar letter dated November 21, 1986, the vender also recommended a continuous minimum flow of 1500 gpm (versus about 350 gpm) for the Bingham 12 x 16 x 4 1/2 CVDS core spray pumps. A minimum flow of 1350 gpm was recommended for intermittent operation.

As a result of this advice, Vermont Yankee initiated a Potential Reportable Occurrence and its subsequent review. This review determined that this matter does not pose a substantial safety hazard for the plant because of plant specific application of the pumps. The length of time that the RHR and core spray pumps would be required to operate in the minimum flow mode over the 40-year design life would be far less than the maximum times at minimun flow recommended by the pump vendor. Bingham/Willamette defines "intermittent operation" as less than two hours of operation in a 24-hour period over the 40-year design life. This translates to a value of up to a total 29,200 hours of operation. Vermont Yankee has no significant accumulated time in the minimum flow operating mode to date (other than successful pre-operational testing). Monthly surveillance testing does not utilize the minimum flow path for more than 15 to 30 seconds per month and therefore is considered to be negligible with respect to the 2075 hours allowable. In the event of a small break LOCA, RHR and Core Spray would be required to operate in the minimum flow mode for a maximum of 4 or 5 hours. Vermont Yankee's evaluation estimated a total of 5 to 10 hours of operation in the minimum flow mode for the life of the plant. As can be seen, these operating durations are far below the 29,200 hours of operation that Bingham/Willamette considers to be in the "intermittent" operating range, and that sufficient operating times available in the minimum flow mode for either the RHR or the Core Spray pumps would not be attained for recirculation cavitation failures to develop.

However, this matter could create a substantial safety hazard at another nuclear facility, depending on the application of this manufacturer's pumps and the length of time that a pump would be required to operate in the minimum flow mode. The licensee determined the matter was potentially reportable under 10 CFR 21 and notified the NRC of the potential design defect on March 20, 1987. As an added precaution, the licensee would incorporate a caution statement into the appropriate procedure to alert the operators of the need to minimize time in the minimum flow mode.

NRC Information Notice 86-39, "Failure of RHR Pump Motors and Pump Internal," discussed the failure of a RHR pump at Peach Bottom Unit 3 due to impeller wear ring failure as a result of intergranular stress corrosion cracking (IGSCC). After receiving this notification, the Vermont Yankee licensee performed an inspection of pump internals on the RHR pumps during the period from April to May 1987, since they are the same model and of the same manufacturer (Bingham - Willamette single-stage vertical mounted, model CIVIC, centrifugal pumps). In addition to the findings of through wall impeller cracks on two of the RHR pumps and wear ring cracks on one RHR pump, the inspection coincidently found evidence of erosion resulting from suction recirculation on all four of the RHR pumps. The licensee also indicated that the wear ring with cracks in the "A" RHR pump was a stationary ring, cast from a material not susceptible to IGSCC cracking. However, the cause of impeller and wear ring cracks was not determined, pending the completion of the licensee's destruction examination being performed at Brookhaven National Laboratories. Based on the recirculation flow erosion effect observed on the suction side of several impellers, the licensee would re-evaluate the previous engineering conclusions regarding the adequacy of the RHR minimum flow lines in light of the results of the pump internal inspection.

The impeller and wear ring cracks may also appear related to excessive flow turbulence as a result of suction recirculation. The flow reversal at the impeller eye under the condition of suction recirculation creates a vortex action which induces pressure surges and pulsations, causing rapid deterioration by erosion of impeller metal. The pressure surge and pulsation can produce dynamic forces which may rise high enough to cause vibration and add undue stress on the wear ring, resulting in the cracking failure.

The event at H.B. Robinson was reported in LER 87-026. On October 30, 1987, the potential for degraded recirculation flow for the RHR pumps was identified by the licensee during a review in response to the Westinghouse (NSSS Vendor) concerns of inadequate miniflow design for the RHR pumps. The NSSS designer had identified two concerns recently involving the potential for dead heading of one of two RHR pumps in systems that have a common miniflow recirculation line serving both pumps, and, the potential for insufficient miniflow recirculation line capacity even for single pump operation. Based on the licensee evaluation, the potential for insufficient miniflow recirculation for the RHR pump is due to inadequacies in the original design based on today's criteria. The miniflow recirculation line was designed on the assumption that the two pumps have equal flow/head curves and that each would achieve a flow of about 250 gpm while both were operated simultaneously. Recently, however, the pump vendor recommended a minimum flow of 500 gpm for each pump to prevent excessive vibration and pump binding caused by heat up of the recirculated fluid.

A similar case at Turkey Point 3 was described in LER 88-030. On October 27, 1987, during the design basis reconstitution of the RHR system, it was discovered that the existing minimum recurculation design configuration was potentially inadequate. The miniflow recirculation line, which was shared by the two RHR pumps, was insufficient and had potential for dead heading one of the two pumps in the RHR system. The licensee's corrective action was to install independent minimum recirculation lines for each pump. The modified recirculation system would allow operation of both pumps for at least 30 minutes without affecting pump operability.

In response to the concerns of inadequate miniflow design for RHR pumps, NRR issued an Information Notice on November 17, 1987 (NRC IN 87-059, Potential RHR Pump Loss) which indicates that the problem may be generic 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 percent to 15 percent of pump design flow, while some pump manufacturers are advising that their pumps should have minimum flow capacities of 25 percent to over 50 percent of best efficiency flow for extended operation.

Another event occurred at a foreign reactor. During a periodic inspection, maintenance personnel heard a loud noise from an RHR pump. The pump was immediately stopped. Upon disassembly, the shaft was founded broken, and slight contact marks were found on the wear rings. The markings on the broken area of the shaft indicate that failure was due to a low cycle fatigue fracture. Subsequent evaluations concluded that the pressure distribution around the impeller becomes uneven during low flow operation increasing the radial thrust, and the bending stress becomes approximately three times that at rated flow operation. The RHR pumps perform low flow operations during monthly surveillance testing and cleanup during plant shutdown. The pumps had run approximately 5963 accumulated operating hours in low flow operation when the failure occurred. In addition to the main shaft replacement, the licensee modified its long term operation management of low flow operation. Previously, both modes of operation of the RHR pump, the clean-up and the cooling modes, were performed by one pump for each purpose. Modified operation is to operate one pump for both purposes to minimize accumulated low flow operations of one pump.

The event reported in LER 88-003 at Haddam Neck occurred on February 4, 1988. With the plant in mode 6 and the reactor core off loaded, the electric driven fire pump was declared inoperable due to a high amperage condition noted after a manual start during a routine surveillance. The normal indication of 200 amps increase to 340 - 360 amps. The indication increased to 1000 amps during the following manual restart. The cause of the inoperability was physical damage to the stuffing box brass bushing located in the upper shaft area of the electric driven fire pump. This caused the bushing to shear, resulting in a locked rotor condition. Based on the licensee's evaluation and their discussion with the manufacturer, it was concluded that prolonged low flow operation of the pump may have caused the problem. Operation of the pump at or near shut off head had occurred during the Containment Integrated Leak Rate Test (CILRT) in which the fire pump operates at low flow mode only to provide cooling water to the air compressors.

These events illustrate that recirculation cavitations were caused by operating pumps at flow significantly below the design flow rates, either at low flow modes or at miniflow testing through a bypass line. The damage was a result of slow deterioration accumulated over a long period of time during which the pumps were still functional and remained operable at early degradation. Cavitation indication on the pumps' internals can only be observed by disassembly of the pumps. The routine surveillance tests of pumps provided in the plant inservice test programs may not be capable of detecting early impeller degradation. In addition, since the pumps operated in the specified operating range, the plants were not aware of the problem until the occurrences of pump failure. There is the potential that recirculation cavitation on a pump impeller could go undetected until total failure of the pump occurs. Such failure could prevent the associated system from performing its safety function.

In the ongoing RES effort on aging and service wear of the auxiliary feedwater (AFW) pumps for PWR nuclear plants, testing of AFW pumps at flow less than 25 percent of BEP has been identified as a source of hydraulic instability and unbalance which will accelerate component wear and lead to premature failure of pump internals. The RES study found that the miniflow line for AFW pumps was typically established only to prevent pump overheating and thus is normally 10-15 percent of BEP flow. Although it is suggested that the surveillance testing of AFW pumps be completed at increased flow, in most cases it is not practical to test the pump at higher flows without either modifying the existing miniflow circuit to increase its flow capacity or to perform testing while the plant is shutdown (In response to these concerns, one of the contractors of the RES study has developed improved auxiliary feedwater pump testing guidelines). The preliminary findings and conclusions of the RES studies correlate well with the operating experience evaluated in this report.

FINDINGS AND CONCLUSIONS

Based on the preceding discussion and related follow-up activities conducted for the study, the following findings and conclusions are provided:

1. Operation of centrifugal pumps at low flow conditions for extended periods of time can cause cavitation damage in spite of available NPSH. A centrifugal pump is designed for best performance at a specific combination of capacity, head, and speed, that is, the best efficiency point (BEP). At the design or BEP flow rate, the fluid motion is compatible with the physical contours of the hydraulic passage and is therefore well behaved. Once deviating from design flow, the operation starts to create mismatches of flow angles within the passage and diverts part of flow to recirculate within the pump at certain low flow rates. The circulating currents cause local pressure zones which are below the vapor pressure of the water. This causes vapor bubbles to form which collapse when a high pressure zone is reached, leading to the erosion of the local material. Such flow recirculations can occur at the impeller eye and exit as well as outside the impeller shroud and hub.

2. Low flow operations are generally required for the standby systems when performing inservice surveillance tests of pumps by restricting discharge flow through the mini-flow bypass line, and for systems designed for wide range of flows when operating the pumps in the low flow regime. Many of

the emergency core cooling systems in most operating plants are designed to operate with wide range of flows and use a mini-flow bypass line for inservice testing of pumps during the standby mode.

3. Recirculation cavitation has caused damage to the pumps of the ESW and RHRSW systems at Susquehanna 1 and the pumps of the RHR system at Vermont Yankee. The recirculation cavitations were caused by operating pumps at flows significantly less than their design flow rates, and the damages were the result of prolonged operations of these pumps at the low flows. The cavitation damage of the ESW pumps at the Susquehanna plant was very severe. The impeller vanes were eroded through the wall, and suction bells were penetrated around most of the circumference. One of the suction bells had separated from the pump body and fell into the pump pit. The damages to the RHRSW pumps were less severe. The ESW pumps normally operate at about 60 percent or less of the design flow and had run approximately 18,000 hours when the failure occurred. The 18,000 hours of operation is only a small fraction of the design life. The RHRSW pumps had operated at less than 50 percent of design flow for most of the time and had run approximately 9,000 hrs. The recirculation cavitation of the RHR pumps at Vermont Yankee could be associated with low flow operation during the monthly surveillance tests. The RHR pump miniflow bypass line is a single line sized to bypass about 5 percent of the design flow. The accumulated time in operation at this low flow is not known.

4. The effects of recirculation manifest themselves not only in material degradation--cavitation, but also in the form of pressure pulsations and vibrations. Hydraulic pressure pulsations and pump vibrations are also significant contributors to deterioration of pump components because of the high amplitude dynamic forces that they produce. Excessive forces on the impeller and pump vibration have caused damage to the RHR pump at a foreign reactor and the fire pump at Haddam Neck. The licensees for H. B. Robinson 2 and Turkey Point 3 have identified the existence of the potential for pump failure due to insufficient flow rate designed for the recirculation lines of their RHR pumps.

5. It is inherent in the dynamics of the pressure field that every impeller design must recirculate at some point of flow -- it cannot be avoided. The flow rate at which recirculation occurs is dependent of the design of impeller. Although pump manufacturers have recently developed guidelines for establishing low flow limits on pump operation, the pump bypass lines, in most operating plants, were sized solely on the basis of limiting the temperature rise of the pump when operated in the testing mode or minimum flow mode. Generally, the flows are in the order of 10 percent of design flow.

6. In response to a concern by pump manufacturers that testing pumps at low flows on the order of 10 percent BEP flow, may lead to premature failure of pump components, EPRI conducted a study in 1985 on surveillance testing of standby pumps in operating nuclear power plants. The result of this study does support the expectation that low flow test operation will lead to degradation and premature failure of pump internals and concludes that prolonged operation of pumps at very low flow (in the range of 10 percent to BEP flow) can cause high vibration which is an hydraulic instability.

7. Several pump manufacturers have recently recommended the standby pump be tested at a flow no less than 25 percent of BEP flow(s). One pump vendor, Bingham/Willamette, has informed Vermont Yankee of inadequacy in the minimum flows designed for the RHR pumps and the core spray pumps. The minimum flow requirements were established for the pumps at plant startup. The value for minimum flows for the pumps, according to the vendor, should be increased to about 38 percent of the pump design flows. Similar notifications for increase of minimum flow rate for the RHR pumps also have been sent to four other plants: Cooper, Pilgrim, Browns Ferry and Peach Bottom.

8. In the ongoing RES program on aging and service wear of the auxiliary feedwater (AFW) pumps for PWR plants, surveillance testing of AFW pumps at flows below 25 percent of BEP has been identified as a source of hydraulic instability and unbalance which will accelerate component wear and lead to premature failure of pumps.

9. It appears that degradation caused by recirculation cavitation due to low-flow operation will require a great length of time to cause catastrophic failure of a pump. Such damage induces slow deterioration of pump internals and during early stages of cavitation do not affect the operation of the pump. Hence these types of damage are not easily detectable. In addition, the degradation will also be difficult to detect in the basis of measurements taken during inservice surveillance testing. This follows from the fact that, in most plants, the bypass flow test provides neither the proper operating range of flow nor sufficient running time to comprehensively trend and predict degrading condition. Recirculation cavitation damage of the pump impeller could go undetected until total failure of the pump occurs.

10. Although the mechanism that causes cavitation damage from recirculation is entirely different from that of inadequate NPSH, the similarity between patterns of the cavitation damage from both may often lead to an erroneous conclusion as to the cause of the damage. This may be one of the reasons that the concern of recirculation cavitation has not been widely recognized.

SUGGESTIONS

1. The effects of pump recirculation can cause not only operational problem, such as vibration, but also lead to damage and loss of life of the impeller and casing. Major degradation of pump impellers and casings have occurred to centrifugal pumps running continuously at low flows. Many of these problems can be avoided by specifying and designing pumps for lower suction specific speeds and limiting the range of operation to capacities above the point of recirculation. For example, low flow operation of centrifugal pumps could be avoided in a system in which multiple pumps operate continuously at low flows by reducing the number of pumps running and thus increasing the flow through each pump, or by realigning the system to increase flow through the pumps. It is suggested that pumps specified for operation in a wide range of flows should be checked to determine whether any point in the operating range fall in the recirculation zone of the pumps.

2. The bypass flow rates for the pumps with bypass line should be reconsidered and acceptable values established to avoid operating pump in the recirculation zone. If the condition of running a pump in a recirculating zone cannot be avoided, a procedural control should be established to limit the length of operation in the bypass mode such that premature failure of the pump can be prevented.

3. For pumps having the potential for recirculation cavitation, (i.e., pumps not meeting items 1 & 2 above) appropriate inspection intervals should be established to facilitate early detection of recirculation damage of the pumps.

Near the completion of this study, NRR issued Bulletin 88-04, "Potential Safety-Related Pump Loss," as a result of the staff's evaluation of the miniflow design problems which were initially identified by Westinghouse and subsequently confirmed by several licensees. The bulletin requests all licensees to investigate and correct, as applicable, the pump miniflow design problems in all safety-related systems. The actions addressed in the bulletin appear to be limited to the miniflow problem. However, this study had found that pump damage induced by internal recirculation can be caused not only by insufficient miniflow capacity but also by operating pumps at low flow modes. In view of this concern, we suggest that NRR review the operating experience to determine whether further actions are warranted.

REFERENCES

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3. C. C. Heald and R. Palgrave, "Backflow Control Improves Pump Performance," Oil and Gas Journal, February 25, 1985, pp. 96-105.

4. Bingham - Willamette Company, "Guide for minimum Flow Operation of Pumps," Technical Bulletin No. 68, Rev. 0, November 18, 1982.

5. W. Stanly Tinney, "How to obtain Trouble Free-Performance from Centrifugal Pumps," <u>Chemical Engineering</u>, June 5, 1978, pp. 178-181.

SSINS NO.
IN 88-XX

UNITED STATES
NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REACTOR REGULATION
WASHINGTON, D.C. 20555
August , 1988

NRC INFORMATION NOTICE NO. 88-XX: Pump Damage Due to Low Flow Operation

Addressees:

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

Purpose:

This information notice is provided to alert addressees to potential problems resulting from operation of contrifugal pumps at low flows which may cause severe component damage to the pumps. It is expected that recipients will review the information for applicability to their facilities and consider actions, as appropriate, to avoid similar problems. However, suggestions contained in this information notice do not constitute NRC requirements; therefore, no specific action or written response is required.

Description of Circumstances:

Described herein are three events involving pump damage resulting from low flow operations. The low flow operations created hydraulic instability which resulted in pump damage from cavitation, pressure pulsation and/or vibration following extended periods of operation. These events occurred at Haddam Neck, Susquehanna 1, and a foreign reactor. The pump damage at Susquehanna 1 was a result of cavitation, while that at the foreign reactor and at Haddam Neck were attributed to pressure pulsation and pump vibration.

Haddam Neck Event:

On February 4, 1988 with the plant in Mode 6 and the reactor core off loaded, the electric driven fire pump was declared inoperable due to a high amperage condition noted after a manual start during a routine surveillance. The normal indication of 200 amps increase to 340 - 360 amps. The indication increased to 1000 amps during the following manual restart. The cause of the inoperability was physical damage to the stuffing box brass bushing located in the upper shaft area of the electric driven fire pump. This caused the bushing to shear, resulting in a locked rotor condition. Based on the licensee's evaluation and their discussion with the manufacturer, it was concluded that prolonged low flow operation of the pump may have caused the problem. Operation of the pump at or near shut off head had occurred during the Containment Integrated Leak Rate Test (CILRT) in which the fire pump operates at low flow mode only to provide cooling water to the air compressors.

Susquehanna 1 Event:

The plant was at full power when an emergency service water (ESW) pump failed on May 22, 1986. The pump failure was discovered when an overcurrent alarm for the pump was received in the control room. The pump was declared inoperable and the plant entered a limiting condition for operation. Subsequent disassembly of the pump revealed that the bottom portion of the pump suction bell had separated from the pump body and had fallen into the pump pit, and the pump's impeller vanes were eroded through the wall. Similar, but less severe damage was also found on the three other ESW pumps. A subsequent inspection of the RHRSW pumps also found similar damage. The damage to the ESW and RHRSW pumps was determined to have been caused by recirculation cavitation. The recirculation cavitation was caused by operating the pumps significantly below their design flow rates.

The ESW pumps normally operate at about 60 percent or less of their design flow of approximately 6000 gpm per pump. When the loop supplying cooling water to the diesels is run with two operating pumps, each pump delivers approximately 3500 - 3900 gpm. Pump operation in this range is likely to cause recirculation cavitation. The other loop that does not serve the diesels is normally run with only one pump at approximately 1000 - 1500 gpm. This operation causes recirculation cavitation. The RHRSW pumps had operated at less than 50 percent of design flow most of the time. The licensee indicated that the cavitation damage can be avoided by operating the pumps above 50 percent of design flow; specifically 75 - 100 percent of design flow is desirable.

Foreign Event:

Another event occurred at a foreign reactor in October 1986. During a periodic inspection, maintenance personnel heard a loud noise from an RHR pump. The pump was immediately stopped. Upon disassembly, the shaft was founded broken, and slight contact marks were found on the wear rings. The markings on the broken area of the shaft indicate that failure was due to a low cycle fatigue fracture. Subsequent evaluations concluded that the pressure distribution around the impeller becomes uneven during low flow operation increasing the radial thrust, and the bending stress becomes approximately three times that at rated flow operation. The RHR pumps perform low flow operations during monthly surveillance testing and cleanup during plant shutdown. The pumps had run approximately 5963 accumulated operating hours in low flow operation when the failure occurred. In addition to the main shaft replacement, the licensee modified its long term operation management of low flow operation. Previously, both modes of operation of the RHR pump, the cleanup and the cooling modes, were performed by one pump for each purpose. Modified operation is to operate one pump for both purposes to minimize accumulated low flow operations of one pump.

Discussion:

These events illustrate that pump damages were caused by operating pumps at flows significantly below the design flow rates. The damage was a result of slow deterioration of pump internals accumulated over a long period of time during which the pumps were still functional and remained operable at early degradation. Damage indication on the pumps' internals can only be observed by disassembly of the pumps. The routine surveillance tests of pumps provided in the plant inservice test programs may not be capable of detecting early component degradation. In addition, since the pumps operated in the specified operating ranges, the plants were not aware of the problem until the occurrences of pump failure. There is the potential that pump degradation due to low flow operation could go undetected until total failure of the pump occurs. Such failures could prevent the associated system from performing its safety function.

No specific action or written response is required by this information notice. If you have any questions about this matter, please contact the technical contact listed below, the Regional Administrator of the appropriate regional office, or this office.

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Office of Nuclear Reactor Regulation

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