BWROG-TP-12-018
Revision 0
October 2012

Task 3 – Pump Operation at Reduced NPSHa conditions (CVDS Pump)

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Executive Summary:

This BWROG Technical Product provides a technical evaluation of operation of the Sulzer CVDS pump model at reduced Available Net Positive Suction Head (NPSHa) conditions, including short periods of operation with the NPSHa less than the required NPSH (NPSHr). The CVDS pump model is used at the Monticello station and other BWR stations. This evaluation addresses the effect on pump flow rate as well as the mechanical impact of low suction head on essential pump components.

Implementation Recommendations:

This product is intended for use to address (in part) issues raised in the NRC Guidance Document for the Use of Containment Accident Pressure in Reactor Safety Analysis (ADAMS Accession No. ML102110167). Implementation will be part of the BWROG guidelines on the use of Containment Accident Pressure credit for ECCS pump NPSH analyses.

Benefits to Site:

This product provides a technical response to the NRC concerns raised in the reference above regarding the potential adverse consequences of short term pump operation with NPSHa<NPSHr.

SULZER

QUALITY LEVEL

- ☐ Direct
- ☐ Indirect

SULZER PUMPS (US) INC. DOCUMENT

DOC. NO: E12.5.1911

ORDER NO:

TITLE: Task 3 – Pump Operation at Reduced NPSHa
Sulzer Pumps (US) Inc.
Monticello - 12x14x14.5 CVDS RHR Pump

ASME CODE SECTION	
CLASS NO.	
CODE EDITION (YEAR)	
SEASON YEAR	

CUSTOMER: GE-HITACHI Nuclear Energy Americas LLC

PROJECT: Monticello Nuclear Power Station, Monticello, MN

CUSTOMER P.O. NO.: 437054820

CONTRACT NUMBER:

SPECIFICATION NO.:

ITEM / TAG NUMBER:

CUSTOMER APPROVAL NUMBER:

SPACE FOR CUSTOMER APPROVAL STAMP
(when applicable/available)

CUSTOMER APPROVAL REQUIREMENT

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Date:	11/7/2011

APPLICABLE S.O. NUMBERS:
0

DOCUMENT IDENTIFICATION	Rev.
E12.5.1911	0

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1.0 PURPOSE

This report evaluates the effects of operating a Sulzer CVDS pump used in the Residual Heat Removal (RHR) system at Monticello Nuclear Plant at reduced available Net Positive Suction Head (NPSHa). This includes a short period of operation with NPSHa below the 3% head breakdown required NPSH (NPSHr). For this report, NPSH3 is synonymous with the 3% head breakdown NPSHr of the pump. RHR pump operation is required to assist in mitigation of a Design Basis Accident – Loss of Coolant Accident (DBA-LOCA). For a DBA-LOCA, RHR is assumed to have a mission time of [[ ]]. It is important that during the time period when NPSHa < NPSH3 the pump maintains the required flow rate and does not experience any damage that would result in the pump being unable to perform its safety function for the required mission time. This evaluation addresses low suction head effects on pump flow rate as well as hydraulic and mechanical impacts on essential pump components and attached piping.

2.0 BACKGROUND

NPSH3 is the suction head at which pump discharge head performance degrades 3% compared to the non-cavitating head. Cavitation occurs when the pressure inside the pump drops below the vapor pressure of the pumpage and cavities (vapor bubbles) are formed. In addition to impairing hydraulic performance, the bubbles can implode at the impeller surfaces, which in the long term can cause impeller erosion.

Three primary factors that influence cavitation erosion are: 1) the hydrodynamic cavitation intensity, 2) the cavitation resistance of the material, and 3) the time duration over which the cavitation is acting. The hydrodynamic cavitation intensity is related to the volume of cavitation vapor (related to bubble length) in the flow and the differential pressure (p-pv) driving the bubble implosions. The cavitation resistance is purely a function of the material mechanical properties. A detailed study of impeller service life in the maximum cavitation erosion zone has been conducted [1]. The impeller service life study shows that impeller failure due to erosion is extremely unlikely in the [[ ]] of operation following a DBA-LOCA.

Depending on the relative operating point of the pump and the combined fluid system dynamic characteristics, operation with very low pump suction pressure can cause system pressure pulsations and increase system noise and vibration. According to Gulich, *"During cavitation, low frequency* *pulsations of large amplitudes are created through large fluctuations of the cavitation zones. The compressibility of the cavities may result in cavitation surges*[2]". Cavitation induced pressure pulsations are observed in a broadband frequency range and are unrelated to the rotational frequency of the pump. The amplitude of these cavitation induced pressure pulsations tends to increase when the pump is operated at very low flows where heavy inlet recirculation is present. Operation with reduced NPSHa will also result in a decrease in pump performance in terms of discharge head and flow.

Based on centrifugal pump testing of different sizes and types, it has been observed that cavitation noise increases with decreasing NPSHa up to a maximum value at a point between NPSH0 and NPSH3. As NPSHa is decreased below NPSH3, the cavitation noise reduces substantially. These observed characteristics are portrayed in Figure 1 and have been described in detail by Gulich [2, Chapter 6.5.2]. The phenomenon is likely due to two concurrent causes: 1) absorption or dampening of the bubble implosion energy, which is the source of the noise and vibration by increasing the vapor present at the impeller cavitation zones within the pump, and 2) attenuation of the cavitation induced pressure waves in the pumpage due to dissolved air, if present, coming out of solution resulting in formation/growth of air bubbles in the suction line (i.e., in the region between the cavitation source on the blade surfaces and the location of the hydrophones or pressure transducers in the inlet piping). However, it can not always be assumed that the risk of cavitation damage diminishes as the measured cavitation induced noise decreases. This is because the risk of cavitation damage is dependent on hydrodynamic cavitation intensity which increases with bubble volume and increasing differential pressure.

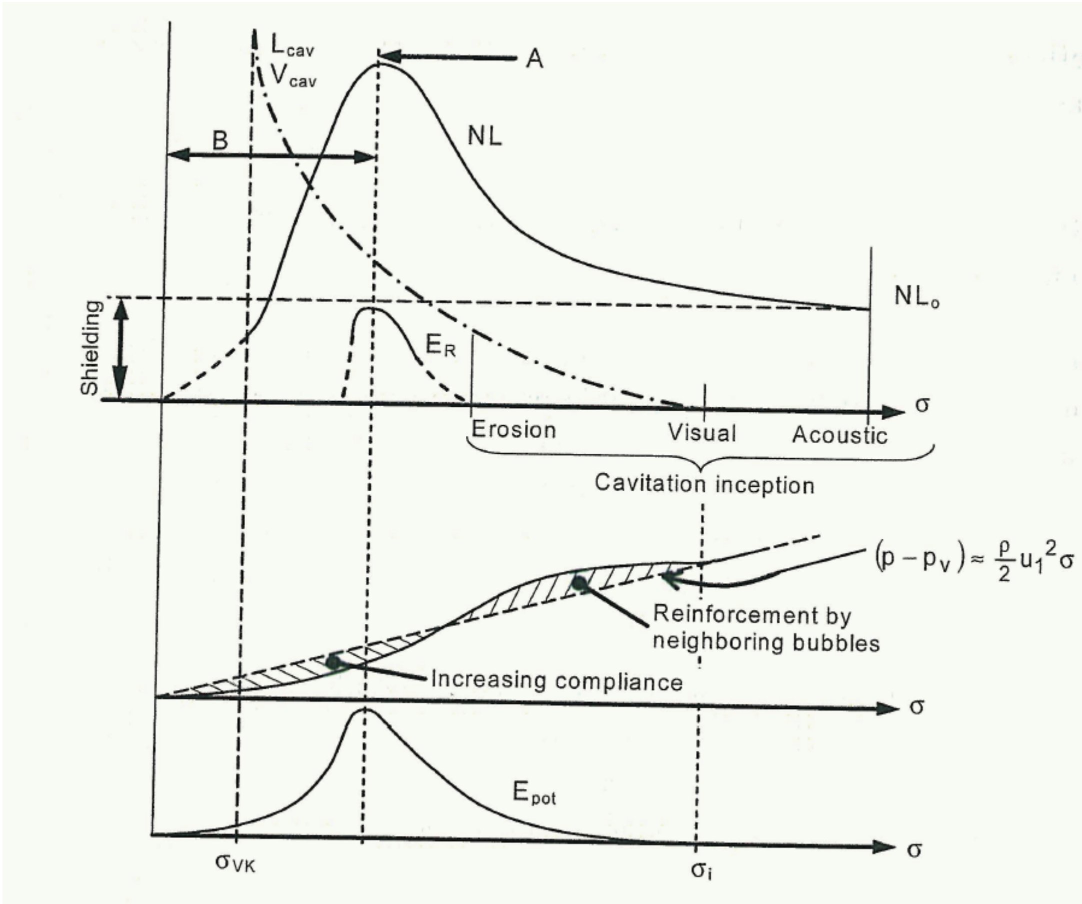

Figure 1: Influence of Cavitation Coefficient (s) on Cavity Volume (L_{cav}), Cavitation Noise (NL), and Erosion (E_R), (Gulich)

A pump performance characteristic observed when NPSHa drops below NPSH0 is the interaction between the new head performance resulting from cavitation and the system characteristics. Namely, the cavitation vapor bubble blockage will limit the pump flow at the point where the pump head drops to the system head curve. Hence, the new operating point is the intersection of the reduced head curve (cavitation characteristic curve) and the system curve. Figure 2 illustrates a general head performance curve and the cavitation characteristic curves (97% and 95%) interacting with the system curve. Appendix A of this report provides a detailed discussion on this performance characteristics and a methodology to determine pump flow at reduced NPSHa.

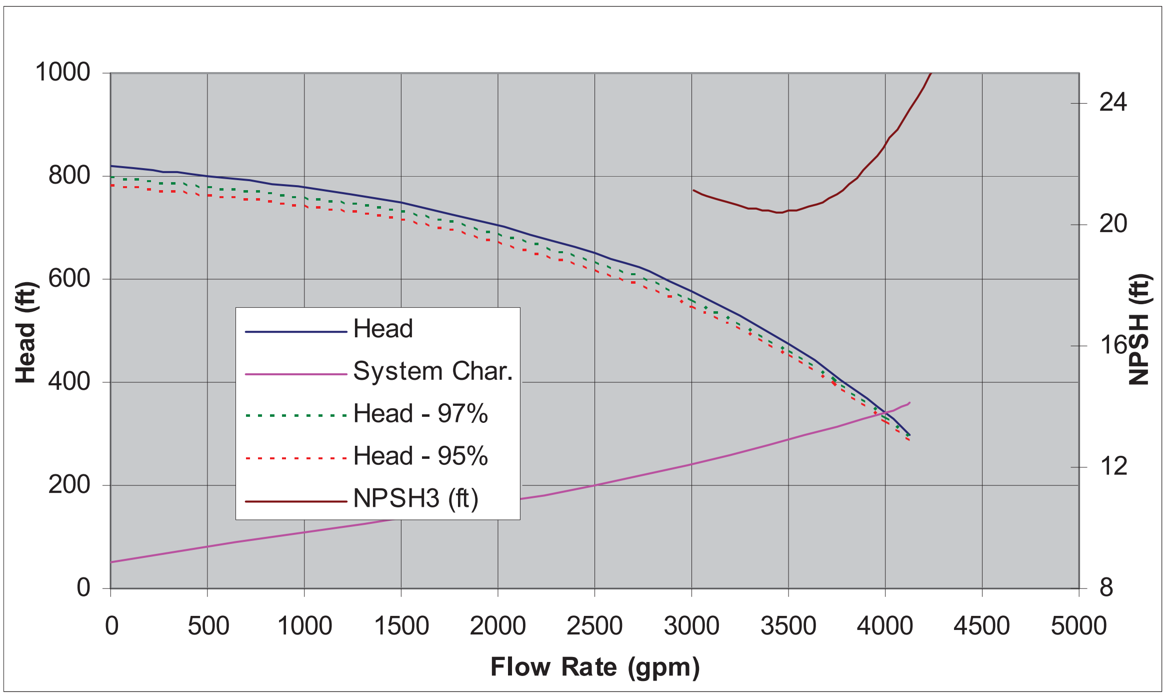

Figure 2: Pump Cavitation Characteristics

3.0 SCOPE

As discussed in the previous section, pump cavitation can result in increased impeller erosion, system noise and vibration, and reductions in pump performance. Experience gained through experimental testing, testing of similar pumps, and operation of the pump in the field are used to assess pump cavitation behavior.

Typically, new pumps undergo performance acceptance tests (flow, head, efficiency, and NPSHr determination) at the manufacturer's test facility to ensure that the pump operating characteristics are acceptable. The standard NPSHr characterization test establishes a 3% NPSHr curve by incrementally reducing NPSHa until a 3% reduction in pump discharge head is measured. Accordingly, the analysis scope of this report includes an evaluation of an in-situ cavitation test performed on a CVDS pump at the Gentilly 2 Nuclear Station, vendor testing of a Quad Cities Nuclear Plant CVDS pump, vendor testing on the Monticello RHR pumps, and Monticello RHR pump operating data. This data and pump operating experience data are used to evaluate the CVDS pumps mechanical design features to assess in-situ operation of the Monticello RHR pumps under short-term conditions when NPSHa < NPSH3 and for long-term operation where NPSHa $\geq$ NPSH3.

Specifically, the following test data and information was used:

a) A cavitation test [3] was performed on a CVDS pump at the Gentilly 2 Nuclear Station in Montreal, Canada. The results from this test correlated noise and vibration values with NPSH. These results were then applied to the Monticello RHR pump to evaluate pump operating conditions expected during a DBA-LOCA event.

b) Cavitation test results for a Quad Cities Nuclear Plant CVDS pump that is similar to the Monticello RHR pump. The tested pump was the same frame size, 12x14x14.5, (different impeller pattern) and exhibits hydraulics similar to the Monticello RHR pumps. The tested pump was disassembled after each test and visually inspected for any damage caused by the cavitation.

c) During typical NPSHr characterization on a test bed, the suction head at the pump inlet is reduced until approximately 10-15% head degradation is recorded at each tested flow rate. By virtue of this testing process, all pumps that underwent such testing have been operated with NPSHa equal to or less than NPSH3. The Monticello RHR pumps underwent such testing at the Sulzer facility prior to shipment for installation at the site. Hence, a comparison of the

NPSH test set-up and the current pump field set-up is relevant to understand the vibration impact of reduced NPSH operating conditions on the mechanical integrity of the pumps.

d) Excessive system vibrations caused by various hydraulic excitations can lead to damage which ultimately could result in failure of pump components including bearings, impellers, mechanical seals, etc. An evaluation of the failure of these components due to cavitation induced vibration is performed.

4.0 ANALYSIS

The following input assumptions, including NPSHa information, were provided by BWROG for use in evaluating short-term pump operation with NPSHa < NPSH3 and during the long-term mission time of a typical DBA-LOCA event.

a) The duration when NPSHa could be less than NPSH3 is in the first [[ ]] following DBA-LOCA event initiation. For this analysis, it is assumed that NPSHa stays within [[ ]] of NPSH3. Figure 3 shows a representative graph of NPSHa and NPSHr with Containment Accident Pressure (CAP) for this time duration.

b) From [[ ]] after a DBA-LOCA, NPSHa is assumed to be equal to NPSH3. This may require taking a portion of CAP credit into account. Figure 4 shows a typical plot of NPSHa with/without CAP credit versus time from [[ ]].

c) After [[ ]], NPSHa > NPSH3 for the remainder of [[ ]]. As shown in Figure 4, NPSHa steadily increases after [[ ]] and exceeds NPSH3 by [[ ]]. Further improvement in NPSHa would be realized as duration extends.

d) The pump is required to operate at the rated flow ([[ ]]) without experiencing a mechanical or a hydraulic failure for the [[ ]] following a DBA-LOCA.

e) A large volume suppression pool maintains a continuous flooded RHR pump suction (water supply elevation is positive with respect to the pump suction).

[[

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Figure 3: Short-Term LOCA NPSHa Timeline

[[

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Figure 4: Long-Term LOCA NPSHa Timeline

4.1 Results of Gentilly 2 In-Situ Cavitation CVDS Pump Testing at Low NPSHa

A Sulzer CVDS pump installed at the Gentilly 2 Nuclear Station in Montreal, Canada, underwent NPSH testing [3] for the purpose of determining the onset of cavitation. The Gentilly 2 test focused on the impact of NPSH variations on pump noise and vibration readings. This report is applicable because the test was conducted at NPSHa values considerably lower than NPSH3 and because the Gentilly 2 CVDS pump and the Monticello RHR CVDS pumps are similar. The Monticello and Gentilly 2 CVDS pumps are vertically mounted, single stage, double suction, radial split pumps with similar volute casings, inlet casings, and impeller hydraulic designs. These pumps also share design principles for bearing design, shaft design, axial thrust, and rotor dynamics. Pumps with such similarities typically exhibit similar vibration characteristics.
Following is a brief outline of the Gentilly 2 test and the test results.

Gentilly 2 Pump specification (Monticello specification):

Type: CVDS	(CVDS)
Size: 14x16x23	(12x14x14.5)
Speed: 1200 rpm	[[ ]]
Flow: 12,400 gpm	[[ ]]
NPSH3: 24 feet	[[ ]]

Test Instrumentation:

Microphones: For measuring the noise emitted through air by the structure.
Accelerometers: For measuring structural vibrations.
Instrumentation was installed at critical points in the system loop, including suction and discharge ends of the pump. Other instruments included; amplifiers, audiometers, frequency analyzer, X-Y plotting table, pressure transmitters, and oscillograph.

Test Procedure:

Water at 70 ^{o}F was the pumping medium. Several tests were run and the test conditions were systematically changed by varying NPSH through positioning of loop valves. Pressures at the pump inlet and outlet were measured during each test, and noise and vibration signals were analyzed at each location using a frequency analyzer. Generally, the pump was operated for 5-10 minutes at each test condition to allow loop stabilization and provide sufficient time for data acquisition.

Data Analysis, Results, and Conclusions:

Noise and vibration levels at different NPSH values were plotted at various frequencies.

a) Figure 5 presents sample results of an NPSHa test. Test results show that the noise and vibration levels remain constant for NPSHa greater than 17 feet and then climb quickly to reach a peak between 12 and 15 feet of NPSHa. This indicates the presence of increasing cavitation in the NPSH3 to NPSH5 range.
b) With NPSHa less than 10 feet, noise and vibration levels decreased rapidly and fell below the normal pump vibration levels. These changes occur because air bubbles grow larger at lower NPSH values and thus absorb more of the implosion energy, which leads to the reduced noise and vibration readings.
c) Similar trends as (a) and (b) were observed at both the suction and the discharge ends. However, the discharge end exhibited less variation in noise and vibration levels.
d) The change in noise levels corresponds with the change in vibration levels. This provides evidence that the onset of cavitation can be predicted based on the change in pump noise or vibration levels only.
e) Peak vibration readings at low NPSHa are about 50-60% higher than the vibration measurements during normal pump operation (NPSHa > 17 feet).

The above Gentilly pump tests included severe cavitation operating conditions and even with NPSHa values as low as 7.5 feet (less than half of NPSH3), the pump operated without any reported deleterious effects.

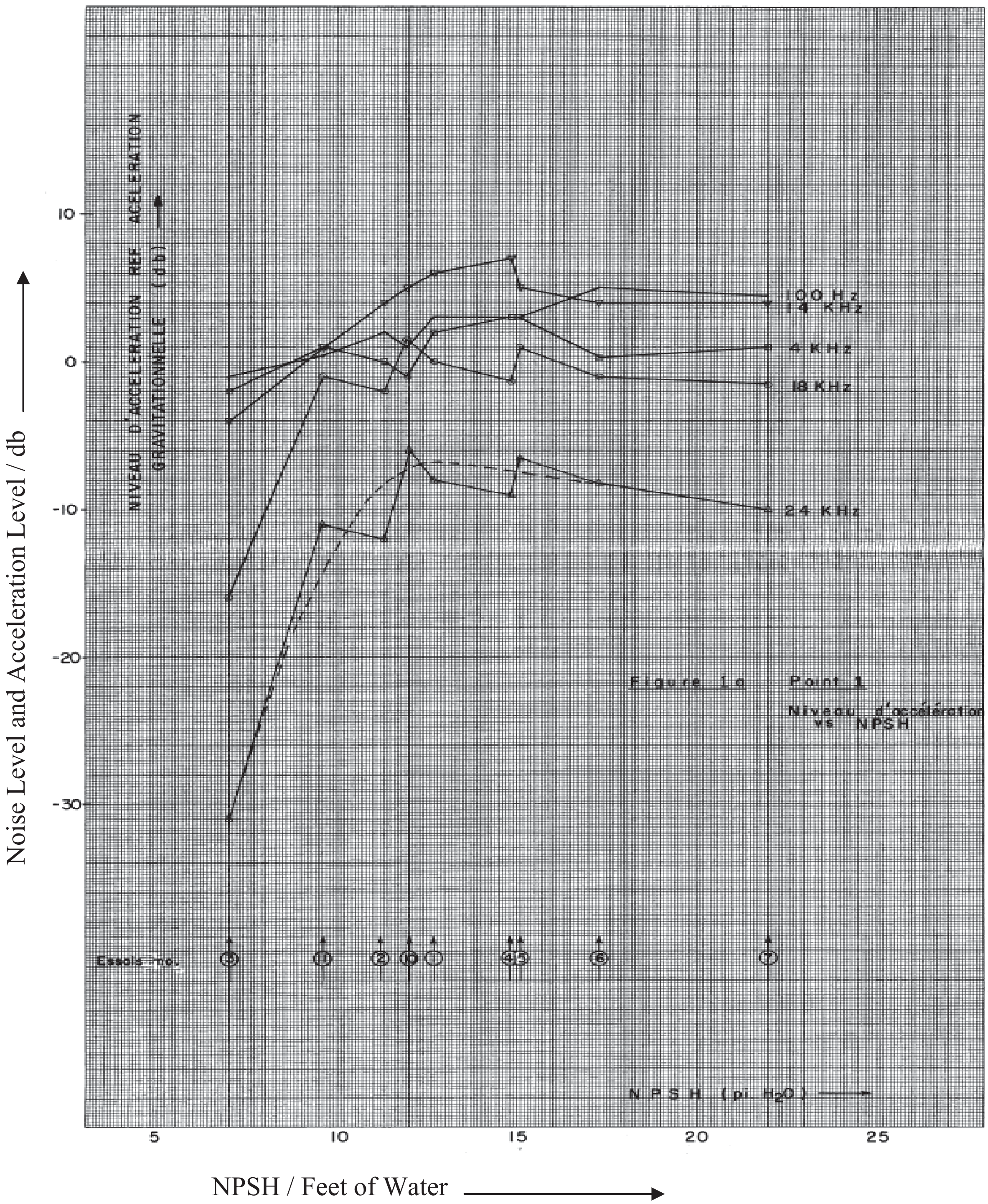

Figure 5: Sample Curve of Noise and Vibration, Gentilly Nuclear Station Report

Experience gained from the Gentilly 2 low NPSHa testing can be extended to the Monticello CVDS pumps, which are similar type pumps, but with a smaller frame size. The Monticello pumps experience low NPSHa during the short-term DBA-LOCA analysis for a brief period of time (see Figure 3). The vibration levels observed during the Gentilly 2 NPSH tests peaked at approximately 1.5 times the normal vibration levels. Vibration readings recorded at the site during normal operation of the Monticello RHR CVDS pumps exhibit an average value of 0.18 in/sec (pump inboard average vertical readings for 4 pumps from 2003-2011). If the same scaling factor is used to estimate the cavitation induced vibration of the Monticello pumps, a value of 0.27 in/sec is obtained. This value is well within the alert vibration limit of 0.325 in/sec [4] and is below the required action limit of 0.700 in/sec [4]. Therefore, cavitation induced vibration of the Monticello RHR pumps with NPSHa < NPSH3 is expected to be well within the allowable vibration limits. These are estimated vibration values and actual values may differ due to differences in pump hydraulics, frame size, speed, and set-up.

For Monticello a very conservative DBA-LOCA analysis shows that RHR short-term pump operation (see Figure 3) with NPSHa less than NPSH3 occurs for a period [[ ]]. The Gentilly tests showed a similar CVDS pump operated with no deleterious effects at very low NPSHa values for a longer time period. This supports that a brief period of RHR operation with NPSHa less than NPSH3 will not have an adverse effect on pump components.

4.2 Quad Cities Cavitation Testing Results

A Quad Cities 12x14x14.5 CVDS RHR pump, which has the same frame size and similar hydraulics (different impeller pattern) as the Monticello RHR pump, underwent extensive cavitation testing at the Sulzer Portland facility. A report outlining the test procedure and the results is available as Reference 5 and a brief summary is provided here.

Test Procedure:

a) The pump was set-up in a closed loop with a large suppression tank.
b) The test set-up, instrumentation, and the testing procedure were in strict accordance with Hydraulic Institute and ASME PTC 8.2 standards.

c) Each test consisted of setting the desired flow and then reducing the pump suction pressure to various NPSH values until the impeller was cavitating (usually a 3% reduction in the head performance).
d) Test 1 was a general performance and NPSH test.
e) Test 2 was a cavitation test at flow rates of [[ ]].
f) Test 3 was a run-out cavitation test at [[ ]]. The pump was operated in this cavitating condition for a period of one hour. At [[ ]] the NPSH3 is approximately [[ ]]. For the duration of the test [[ ]] the NPSHa ranged from [[ ]].
g) Additional tests at lower NPSH values (5-10% head reduction) were performed with the initial pump flow set at [[ ]]. The pump discharge throttle valve was maintained in a fixed position while the NPSHa was incrementally decreased until the pump flow rate was reduced to [[ ]]. The NPSHa ranged from [[ ]]. These cavitating conditions were maintained for one hour. The NPSHa was then further decreased until the pump flow rate reduced to [[ ]]. This cavitating condition was maintained for [[ ]]. At this condition NPSHa ranged from [[ ]].

Test Results:

a) All critical pump components including the impeller, bearings, mechanical seals, wear rings, and shaft were physically inspected by the General Electric and Sulzer personnel for any visible signs of damage.
b) Post Test 1, visual inspection showed no damage to any of the components.
c) Post Test 2, a slight rubbing on the bottom impeller wear ring surface was noticed. (Slight rubbing is an indication that component contact did not lead to galling. This demonstrates that heavy cavitation is unlikely to result in seizure of pump components)
d) Post Test 3, no cavitation damage was observed on the impeller. Indication of slight wear was noticed at the bottom of the wear ring.
e) After all the tests were completed; no recordable cavitation damage was evident on any of the components. The shaft sleeves and the bearings exhibited some minor scratches.

The Quad Cities pump test report demonstrates that the CVDS pump can operate with NPSHa < NPSH3 for durations well in excess of [[ ]] without sustaining any visible cavitation damage to the pump components and thus can operate at low NPSHa during short-term DBA-LOCA without adversely impacting the long-term pump performance.

4.3 Vendor Testing of Monticello and Other CVDS Pumps

Reduced NPSHa conditions, similar to the DBA-LOCA analysis conditions, are created during NPSHr characterization tests performed in the pump test facility. During these tests, pumps are held at NPSHa conditions corresponding to a full range of inlet conditions from no cavitation present to NPSHa < NPSH3. These conditions are maintained for a few minutes at each test point for the purpose of loop stabilization and data collection. The Monticello RHR pumps underwent similar NPSH testing and no failures or unreasonable levels of vibrations were reported. Hence, the Monticello CVDS pumps should be able to withstand cavitation induced noise (pressure pulsations under low NPSHa) and vibrations arising during brief periods of low NPSHa operation (including periods where NPSHa < NPSH3) that might be encountered during the short-term DBA-LOCA.

Moreover, similarly designed CVDS pumps of various frame sizes used for Browns Ferry, Monticello, and other customers (see Table 1) also went through NPSH tests in Sulzer facilities without any reported failures or unacceptable levels of vibrations.

Table 1: Pump Test List

[[			
			]]

Differences between the vendor test and field configuration set-up can impact the pump system vibration levels for the same excitation frequency. For instance, pump/piping rigidity determines how the system responds to a given force amplitude at a particular excitation frequency. Table 2 below shows a comparison between the test and field set-up of some of the factors that can impact system vibrations.

Table 2: Sulzer Test Facility Set-up versus Monticello RHR Field Set-up

Elements	Test	Field	Note
[[			
			]]

This comparison shows that the test facility set-up and field configuration of the Monticello RHR pumps are similar in several important aspects. Therefore, it is reasonable to expect that the magnitude of cavitation induced vibrations observed during tests and field will be similar.

4.4 Excitation Frequency and Failure Modes Analysis for Long-Term Pump Operation

Typical vibration spectra applicable to a wide range of pumps under various flow and speed conditions have been provided by Gülich [1, Chapter 10]. Vibrations observed during the normal operation of a pump include rotational frequency and vane passing frequency. Both of these frequency components are speed dependent.

In the case of cavitation induced vibrations, the excitation frequencies are not speed dependent and tend to be broadband above 500Hz. The amount of cavitation and corresponding vibration will depend on NPSHa, speed (related to energy level) and relative operating flow rate. At very low flows with inlet recirculation present, fluctuating cavities entrained in the recirculation flow will typically be present as low frequency excitation in the range of 0.5 Hz to 0.2 times rotational frequency [[ ]] [1, Chapter 10, Table 10.9/Spectrum 6]. For the Monticello RHR pump speed this frequency is:

[[ ]]

These frequencies are dependent on the flow rate (degree of inlet recirculation and NPSHa). For long-term DBA-LOCA service, the Monticello RHR pumps are operated at [[ ]]; so low flow inlet recirculation is not a consideration.

Cavitation induced pressure pulsations typically impact the impeller blades causing both axial and radial excitation forces. Hence, primary pump components that could be affected by cavitation induced vibrations are the impeller blades, wear rings, radial and axial bearings, mechanical seal faces, and suction and discharge piping. Table 3 below lists the possible failure modes for these components.

Table 3: Potential Pump Failure Modes

Component	Function	Failure Mode	Cause of Failure
a) Mechanical Seal	Controls leakage from the pump	Excessive leakage	Axial vibration damages seal faces
b) Motor Bearing	Provides rotor support & stability. Controls deflection at the mechanical seal.	Severe wear or rupture of bearing	Excessive loading due to axial vibrations
c) Suction & Discharge Piping	Transport pumpage	Bending, crack, or rupture	Axial vibrations
d) Impeller	Impart kinetic energy to fluid	Crack/Break	High vibration
e) Wear Ring	Limit leakage flow between high pressure impeller discharge and impeller eye	Increased leakage flow due to increased clearances from contact/wear	Contact between rotating and stationary parts due to high vibration
f) Pump Bearing	Support cantilevered rotor	Loss of bearing support due to increased clearances from contact/wear	Contact between rotating and stationary parts due to high vibration

Although the vibration amplitudes are not expected to reach damaging levels for extended pump operation at NPSH3, the CVDS type RHR pumps have additional features that improve the reliability of these components:

a) Mechanical Seals – Increased seal leakage will not adversely affect pump operation.

b) Motor Bearing – The hydraulic damping forces in the pump axial direction are very significant. The pumpage that is present between the impeller shroud and the case sidewall clearance absorbs the impact of vertical vibrations and the axial motor bearings have a high capacity to withstand axial loads due to cavitation induced vibration. Below is a calculation that compares the motor bearing thrust load capacity with the pressure pulsation load acting on the bearings.

The suction pressure pulsation amplitude under normal operating conditions (based on tests conducted on similar pumps) is ≤ 1 pounds per square inch (psi). Based on numerous pump tests and EPRI GS-6398 [6], the maximum pressure pulsation amplitude under the worst cavitation condition is 4 to 5 times the value at normal conditions. Therefore, the maximum amplitude of pressure pulsations under the worst cavitation condition is :

$$= 5 \text{ x } 1 \text{ psi} = 5 \text{ psi}$$

The increase in axial thrust load in terms of pounds force (lbf) in the pump under the worst cavitation condition is:

Axial Thrust = Pulsation Pressure x Impeller Wear Ring Frontal Area

$= (5 – 1) \text{ x } \pi \text{ x } d^2 / 4$ lbf [1, Chapter 9, Eq 9.2.10]

Where d = impeller wear ring OD (Sulzer Impeller machining drawing)

$= 4 \text{ x } \pi \text{ x } 8.607^2 / 4$ lbf

$= 234$ lbf

From the SKF Catalog, the L10h bearing life is given by the following equation:

$$L10h = 1{,}000{,}000 / 60 / n \text{ x } (C/P)^3 \text{ hours}$$

Where,

L10h = life at which 10% of the bearings can be expected to have failed due to fatigue.

C = basic dynamic loading, lbf

P = equivalent dynamic bearing load, lbf

n = rotational speed, rpm

The L10h bearing life under a normal maximum axial thrust load of [[

]] (Per Monticello Dwg: NX-7905-76, Motor Bearing Information [7])

Therefore;

[[ ]] ………... (1)

Similarly, the bearing life under an increased thrust load condition:

[[ ]]….(2)

Eq. (2) divided by Eq. (1) yields:

[[ ]]…….………..(3)

[[ ]]

[[ ]]

The calculated L10h bearing life under conservative axial thrust conditions due to cavitation is [[ ]], which is significantly greater than the required operation time of [[ ]]. Therefore, the motor bearings will not fail due to increased dynamic loading in the worst cavitation conditions.

c) Pump Suction and Discharge Piping – Piping in the field is Seismic Category I, which is designed to withstand forces of greater magnitude than cavitation pressure pulsations.

d) The CVDS pump impellers are of a robust double suction shrouded design. Thousands of pumps using similar impeller design have accumulated millions of hours of field operation.

e) Wear rings used in the Monticello CVDS type RHR pumps provide squeeze film damping that absorbs small radial vibrations. Radial bearing clearances are smaller than wear ring clearances further reducing the possibility of wear ring contact and failure. Also, these components are made of non-galling materials so that even if accidental contact was to occur, they will not sustain any damage.

f) The long length over diameter (L/D) of the lubricated radial bearing located between the impeller and the mechanical seal in the Monticello CVDS type RHR pump acts like a squeeze film dampener to significantly reduce the transmission of dynamic forces from the rotor to the pump case. Moreover, the carbon bushing used in the construction of these bearings has self-lubrication properties that minimize damage potential due to galling should contact occur.

5.0 CONCLUSION

Operating experience gained through experimental testing, testing of similar pumps, and operation of the pump in the field are reliable methods for evaluating the expected performance of CVDS pumps, including the Monticello RHR pump assembly under different operating modes and cavitation regimes.

During NPSH testing at the Gentilly 2, a CVDS pump similar to the Monticello RHR CVDS pump was operated under severe cavitation at low NPSHa values without any reported failures or unreasonable level of vibrations. Based on the vibration magnitudes observed during these tests, when applied to the Monticello RHR pumps, the vibration levels that will be reached by the RHR pumps during operation with NPSHa < NPSH3 are expected to be well within the acceptable limits. Cavitation tests followed by visual inspection of the Quad Cities CVDS RHR pumps also demonstrate that the cavitation induced pressure pulsations will not result in pump component failure during short-term operation under reduced NPSHa conditions.

As discussed previously, the time period during which NPSHa could be less than NPSH3 is short [[ ]] at the beginning of a DBA-LOCA. These Monticello RHR pumps were subjected to operation under severe cavitation (NPSHa < NPSH3) conditions in the vendor test facility during NPSHr characterization tests. Since these pumps and their components survived the NPSH shop tests without sustaining damage or experiencing any unreasonable level of vibrations under a test facility set-up similar to the field set-up, it is reasonable to expect that CVDS pumps, of similar frame size, hydraulics and mechanical configuration operating under similar conditions as the Monticello RHR CVDS pumps, will be able to survive a postulated DBA-LOCA event for a period of [[ ]]. It is important to note that the BWR pumps have a flooded suction that is continually fed by the suppression pool; therefore, the pumps will normally have a positive suction head available.

The information presented in this report provides ample evidence that cavitation induced vibration in the CVDS pumps of similar frame size, hydraulics and mechanical configuration, operating under conditions similar to those evaluated for the Monticello RHR pumps, is not expected to lead to pump component failure during the [[ ]] of operation under DBA-LOCA conditions. Further testing of similar CVDS pumps is not expected to yield results different from those reported herein or change the basic conclusion with respect to survivability of the Monticello CVDS pumps during the proposed DBA-LOCA event.

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7.0 APPENDIX A

This appendix provides a methodology for predicting pump steady state flow rate under reduced NPSHa for Monticello RHR pumps. For pumps operating in parallel, such as the Monticello RHR system, pump-system interactions can result in unsteady pump operating modes. Also, when NPSHa is reduced to where a pump's NPSH3 breakdown knee approaches a vertical asymptote, the pump operating flow rate can become unstable since small perturbations in NPSHa can cause large changes in discharge head. The net result is that the system flow rate must vary since the pump can only operate at the intersection of the system characteristic and a pump characteristic. Nonetheless, this methodology provides a conservative estimate of the minimum steady state pump flow rate based on the parameters used in the analysis.

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Figure A1: Pump and System Curve Overlay

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Figure A2: Steady State Flow Rate Reduction due to operation with NPSHa = NPSH5

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Figure A3: Estimated (worst case) Steady-State Flow Reduction due to Operation with [[ ]]. (Based on a stable, steady-state operating condition)

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Figure A4: Estimated (worst case) Steady State Flow Reduction due to Operation with [[ ]]. (Based on a stable, steady-state operating condition)