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Containment Accident Pressure Committee

Task 4 – Operation in the Maximum Erosion Rate Zone (CVDS Pump)

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Executive Summary

This BWROG Technical Product provides an evaluation of the impact of cavitation on the service life of the Sulzer CVDS pump model used at the Monticello station and other BWR stations. The evaluation considers the potential effects of operating in the range of $NPSH_A$ that result in the maximum erosion rate.

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 about the potential for cavitation wear during long term pump operation in a post-accident environment.

SULZER

QUALITY LEVEL

☐ Direct
☐ Indirect

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Monticello - 12x14x14.5 CVDS RHR Pump

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1.0 PURPOSE

To evaluate the impact of cavitation on the service life of a Monticello RHR pump impeller. Cavitation in a pump can result in pump vibration, noise and component erosion. This report addresses the material erosion aspects of an impeller under cavitation. The material erosion of an impeller under cavitation is predicted using formulae from Gülich's Book; Centrifugal Pumps [Ref 1]. These formulae were developed in an EPRI study [6] from empirical data collected for various pump types for predicting the number of hours an impeller will survive under reduced Net Positive Suction Head (NPSH). The purpose of this evaluation is to show that the impeller service life is at least 30 days (720 hours) of operation when operating at reduced NPSH margin.

2.0 BACKGROUND

The service life of an impeller can be predicted based on a defined percentage of material loss due to cavitation erosion and on a known or predicted cavitation bubble length. The three primary factors influencing cavitation erosion are : 1) The hydrodynamic cavitation intensity. 2) The cavitation resilience of the material. 3) Time duration over which the cavitation is acting. The hydrodynamic cavitation intensity is related to the volume of the cavitation vapor (related to bubble length) in the flow and the differential pressure ($p-p_v$) driving the implosion of the bubbles. The cavitation resilience is purely a function of the mechanical properties of the material. The rate of cavitation erosion will then depend on the hydrodynamic cavitation intensity, the material cavitation resilience and the time duration during which the cavitation is occurring. The service life of an impeller undergoing cavitation depends strongly on absolute pressure of the fluid (suction pressure minus vapor pressure) which drives the gas-bubble implosion, the impeller material properties (strength and modulus of elasticity), and on the flow characteristics and liquid properties. Gülich [Ref 1] explains that cavitation erosion occurs only when the hydrodynamic cavitation intensity (dependent on flow and fluid properties) exceeds the cavitation resistance (dependent on material properties; fixed for a given material and temperature) of the impeller material and that "hydrodynamic cavitation intensity increases with the total volume of all vapor bubbles created in the flow".

The length of the cavitation bubble is related to the bubble volume, which in turn is an indicator of the damage producing potential. The optimal way to determine the true bubble length for a given impeller geometry while operating under a given set of inlet conditions (flow rate and NPSHa) is by flow visualization from model testing. Recently, with the advent of advanced CFD techniques it is possible to simulate the bubble length as a function of inlet conditions. [[

]] Relationships between cavitation bubble length and the rate of material erosion have been derived empirically.

3.0 SCOPE

For evaluating impeller damage due to cavitation erosion; impeller material properties, flow properties, and available NPSH are considered for this analysis.

a) Impeller life due to cavitation damage is predicted using Gülich's empirical formulae and CFD analysis results [8].
b) Validity of the impeller life prediction formulae conducted during experimental and field operation analysis work is briefly discussed.
c) Impeller life prediction method is presented in a step-by-step format. Calculation steps include methods for bubble length, material resilience, erosion power, erosion rate and impeller life calculation. Several conservatisms, which are listed in section 5, are incorporated in the calculation.

4.0 ANALYSIS

A CFD study of the Monticello RHR impellers using a commercial CFD package was conducted to predict NPSH 3%, bubble lengths, and bubble location under varying flow rates and NPSH margins [8]. Figure 1 shows bubble lengths versus NPSH margin predicted by the CFD analysis for four different pump flow rates. As would be expected, Figure 1 shows the bubble length grows as the NPSH margin decreases.

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Figure 1: Bubble Growth versus NPSH margin

The bubble lengths and the corresponding NPSHa values obtained from the CFD results are then used in the Gulich formulae to predict maximum erosion rate at different pump flow rates and NPSH margins. Figure 2 shows impeller erosion rate (μm/hr) versus NPSH margins at different flow rates. It is observed that the maximum erosion occurs at [[ ]] for an NPSHa margin of [[ ]]. A sample maximum erosion rate calculation for the [[ ]] flow is provided in the following sections of the report along with the corresponding impeller service life calculation.

[[

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Figure 2: Erosion Rate versus NPSH Margin

NPSH values corresponding to the full diameter impeller (14.5") are used for this analysis. The current Monticello trim diameter is [[ ]] (approximately [[ ]] trim). [[

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Given:

Impeller Material: [[ ]]

	SI units	Imperial units
Tensile strength, R_m	[[ ]]	[[ ]] [Ref 3]
Young's modulus, E	2.01 x 10^{11} N/m^2	29,200 kpsi [Ref 4]
Impeller blade thickness at cavitation length[2], e	[[ ]]	[[ ]]
Density of water, ρ (at 95ºF)	994 kg/m^3	0.994 S.G.
Gravitational constant, g	9.81 m/s^2	32.2 ft/sec^2
Impeller outer diameter, D_2	[[	
Impeller eye diameter, D_1		
Circumferential velocity[3] at impeller eye, u_1		
Eye Area (each side)		]]
	[[ ]]	
Meridional velocity[4], c_1	[[ ]]	
NPSH 3%	[[ ]] (as predicted by CFD)	

The formulae used in this report for predicting impeller erosion rate and impeller service life have been empirically derived from a large pool of cavitation test results obtained from several pump manufacturers for different pump types [6]. These test results were used to develop a correlation between NPSH, cavitation resistance, vapor density, speed of sound, gas content, and the erosion rate.

These formulae have been verified through experimentation using visual inspection techniques. Bruno Schiavello in paper, "Pump Cavitation – Various NPSHR Criteria, NPSHA Margins, and Impeller Life Expectancy" [Ref 5] validates Gülich's erosion rate formulae by comparing the cavitation damage depth on impellers in the field with the predicted values. Several other field tests and research papers have verified the use of these formulae for accurately predicting impeller service life.

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[2] [[ ]]

[3] Calculated as π x (impeller eye diameter) x (revolutions per second)

[4] Meridional velocity is calculated as flow rate, Q, divided by eye area

Following steps outline the impeller life prediction method in a step-by-step approach.

Step 1: Calculate resistance to cavitation damage (U_R) for the impeller material

This quantity depends only on the impeller material properties. For [[ ]] at 35°C (95°F):

[[ ]]

Step 2: Estimate cavity length

Cavity length data is generally obtained experimentally using flow visualization techniques or analytically from CFD simulation results. In the case of the Monticello RHR pumps, cavity lengths were determined via CFD, see Figure 1. A bubble length of 0.05 m, obtained from the CFD analysis for 3900 gpm at the NPSH margin of 2.0 (predicted maximum erosion zone), is used for this sample calculation.

When the cavity length data is absent and there is an NPSH margin (additional NPSH available above the $NPSH_{3\%}$ required), the following formula can be used to estimate cavity length based on impeller geometry and coefficients derived from the NPSH values.

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Depending upon flow conditions and the impeller inlet geometry the bubble formation can occur at the suction side, the pressure side or both sides of the impeller blade inlet (Figure 3 shows the general effect of incidence angle on cavitation bubble formation). Generally, zero incidence angle (i = 0) occurs at the BEP flow rate. However, 1-D Excel based flow calculation tools, and the CFD analysis results provide evidence that for the Monticello impeller design the positive flow incidence angle is observed at the blade inlet (suction side cavitation) even at the highest flow rate considered for the analysis ([[ ]]). Therefore, only suction side erosion calculation methods are used for the impeller life analysis. In the case of Monticello RHR impeller, the vertical red line (Figure 3), zero incidence occurs at approximately [[ ]] of BEP flow. Further, Figure 3 below also shows a general trend for $NPSH_i$ (inception cavitation), $NPSH_{3\%}$, Noise and Erosion as a function of inlet flow incidence.

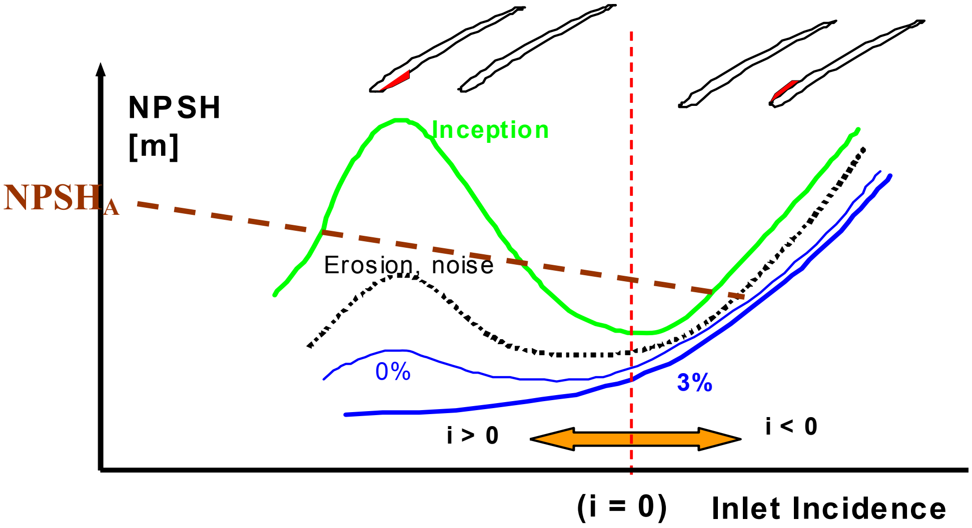

Figure 3: NPSH, Noise and Erosion versus Inlet Incidence

The erosion formulae and the CFD results have been used to develop the relationship between erosion rate and the flow incidence angle (Figure 4) for the different flow rates. As shown in Figure 4, the lowest erosion rate zones are found at BEP ([[ ]]) and at low incidence angles ([[ ]]).

[[

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Figure 4: Maximum Erosion Rate versus Incidence angle

Step 3: Determine absolute pressure Δp at the impeller inlet

This is the differential pressure that drives bubble implosion. It is dependent upon $NPSH_{A.}$ For this calculation, NPSHa is equal to [[ ]] times the $NPSH_{3\%}$ (See Figure 2 - maximum erosion zone at [[ ]]).

$$\Delta p = p_1 - p_V$$

$$= \rho g(NPSH_A) - \frac{\rho}{2} c_1^{\,2}$$

$$= (994kg/m^3)(9.81m/s^2)(13.2) - \left(\frac{994kg/m^3}{2}\right)(6.47)^2$$

= [[ ]]

p_1 = suction pressure at impeller inlet

p_v = vapor pressure at impeller inlet

Step 4: Determine erosion power P_{ER}

[[

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Erosion power is calculated as follows (Gülich, equation 6.1.2):

$$P_{ER} = C_1 \left(\frac{\Delta p}{p_{ref}}\right)^3 \frac{F_{cor}}{F_{mat}} \left(\frac{L_{cav}}{L_{ref}}\right)^{x_2} \frac{a}{a_{ref}} \left(\frac{\alpha_{ref}}{\alpha}\right)^{0.36} \left(\frac{\rho''_{ref}}{\rho''}\right)^{0.44}$$

Where:

C_1 = 5.4 x 10^{-24} W/m² for suction side erosion (constant from empirical data)
Δp = [[ ]] (for [[ ]] flow rate)
p_{ref} = 1 N/m² (used by Gülich in empirical calculations)
F_{cor} = corrosion factor
= 1 for fresh water (Sulzer Handbook 1.008.004 Table 3)
F_{mat} = material factor
= 1 for ferritic steel (Sulzer Handbook 1.008.004 Table 3)
L_{cav} = [[ ]] (From CFD analysis for [[ ]] flow rate)
L_{ref} = 0.010m (used by Gülich in empirical calculations)
x_2 = 2.83 for suction side erosion (constant from empirical data)

a = speed of sound in the fluid
= [[ ]] (water at [[ ]]) (Using Lubber and Graff's eqs)
a_{ref} = 1497 m/s (water at 20°C) (Using Lubber and Graff's eqs)
α = gas content of fluid
= [[ ]] ([[ ]])
α_{ref} = 24ppm (reference: ordinary, untreated water)
ρ" = density of saturated vapor
= [[ ]] (water at [[ ]])
ρ''_{ref} = 0.02 kg/m³ (water at 20°C)

<u>For [[ ]]:</u>

[[

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<u>Step 5: Calculate erosion rate E_R</u>

[[ ]]

E_R = [[ ]] for [[ ]] flow

Step 6: Calculate expected impeller life $L_{I,\,exp}$

$$L_{I,\exp} = \frac{(n)(e)}{3600\sum((\tau)(E_R))}$$

$L_{I,\,exp}$ = expected impeller life in hours
n = defined proportion of impeller material lost at end of service life
e = original thickness of impeller blade at site of cavitation
= [[ ]]
τ = duration of service at particular load considered

The function τ would be used in situations where the impeller was subject to different cavitation conditions over the course of its service life. In this study only one cavitation situation is being considered for the estimation of impeller service life, so τ = 1.

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[[ ]]

5.0 CONCLUSION

The cavitation erosion and the impeller service life calculations for the maximum erosion zone show that the Monticello RHR impeller would operate for at least [[ ]] while operating at the flow rate and NPSH margin corresponding to the maximum erosion rate, [[ ]] and [[ ]] respectively. This service life is [[ ]] times the minimum required service life of [[

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Based on the above analysis, the impeller life at the maximum erosion rate greatly exceeds the [[ ]] mission time. Hence, it can be concluded that the impeller integrity is assured.

6.0 BIBLIOGRAPHY

[1] J. Gülich Centrifugal Pumps (2008), Springer-Verlag publishers
Section 6.6 "Cavitation erosion"

[2] Speed of Sound in water -
http://resource.npl.co.uk/acoustics/techguides/soundpurewater/content.html#LUBBERS

[3] ASTM Standards A487A/487M-93 (Reapproved 2007)

[4] ASME B31.1-1995

[5] Bruno Schiavello, "Pump Cavitation – Various NPSHR Criteria, NPSHA Margins, and Impeller Life Expectancy".

[6] Gülich JF: Guidelines for prevention of cavitation in centrifugal feedpumps. EPRI Report GS-6398, Nov 1989.

[7] Philippe Dupont and Gary Fitch, "Impeller Life Prediction in Pumps", 10th European Fluid Machinery Congress, April 2008.

[8] Philippe Dupont, Bruno Maroccia – Investigation Report 2012, Numerical prediction of $NPSH_{3\%}$ by means of an impeller only CFD calculation for Monticello 12x14x14.5CVDS.