BWROG-TP-13-021
Revision 0
December 2013

Containment Accident Pressure Committee (344)

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

Authors:	Ankur Kalra (Sulzer Pump)
Project Manager:	Kenneth Welch (GEH)
Committee Chair:	John Freeman (Exelon)

INFORMATION NOTICE

Recipients of this document have no authority or rights to release these products to anyone or organization outside their utility. The recipient shall not publish or otherwise disclose this document or the information therein to others without the prior written consent of the BWROG, and shall return the document at the request of BWROG. These products can, however, be shared with contractors performing related work directly for the participating utility, conditional upon appropriate proprietary agreements being in place with the contractor protecting these BWROG products.

With regard to any unauthorized use, the BWROG participating Utility Members make no warranty, either express or implied, as to the accuracy, completeness, or usefulness of this guideline or the information, and assumes no liability with respect to its use.

BWROG Utility Members	
CENG – Nine Mile Point	Chubu Electric Power Company
DTE – Fermi	Chugoku Electric Power Company
Duke Energy – Brunswick	Comisión Federal de Electricidad
Energy Northwest – Columbia	Hokuriku Electric Power Company
Entergy – FitzPatrick	Iberdrola Generacion, S.A.
Entergy – Pilgrim	Japan Atomic Power Company
Entergy – River Bend/Grand Gulf	J-Power (Electric Power Development Co.)
Entergy – Vermont Yankee	Kernkraftwerk Leibstadt
Exelon (Clinton)	South Texas Project
Exelon (D/QC/L)	Taiwan Power Company
Exelon (Oyster Creek)	Tohoku Electric Power Company
Exelon (PB/Limerick)	Tokyo Electric Power Company
FirstEnergy – Perry	
NPPD – Cooper	
NextEra – Duane Arnold	
PPL – Susquehanna	
PSEG – Hope Creek	
SNC – Hatch	
TVA – Browns Ferry	
Xcel – Monticello	

Executive Summary

This BWROG Technical Product provides an evaluation of the impact of cavitation on the service life of the Sulzer CVIC pump model used at the Browns Ferry, Peach Bottom, and other BWR stations. The evaluation considers the potential effects of operating in the range of $NPSH_A$ that results 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

SULZER PUMPS (US) INC. DOCUMENT

DOC. NO: E12.5.1948

ORDER NO:

TITLE: Task 4 – Operation in Maximum Erosion Rate Zone
Sulzer Pumps (US) Inc.
Browns Ferry/Peach Bottom - 18x24x28 CVIC RHR Pump

ASME CODE SECTION

CLASS NO.

CODE EDITION (YEAR)

SEASON YEAR

CUSTOMER: GE-HITACHI Nuclear Energy Americas LLC

PROJECT: Browns Ferry/Peach Bottom Nuclear Power Station

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

☐ Yes ☐ No ☑ Information Only

CERTIFIED AS A VALID SULZER PUMPS (US) INC. DOCUMENT

☐ For Outside Vendor

☒ For Manufacture at Sulzer Pumps (US) Inc.

☐ Risk Release Inspection Report # ____________

☐ Other (specify) ____________

APPROVALS (SIGNATURE)		Date
Engineering	[signature]	10/04/13
Quality Assurance		

CERTIFICATION (when applicable)

This Document is certified to be in compliance with THE APPLICABLE PURCHASE ORDER, SPECIFICATIONS, PROCEDURES, AND ADDITIONAL REQUIREMENTS LISTED IN THE APPENDICES.

Professional Engineer

State ____________ Registration No. ____________

Date ____________

Originating Dept: Advance Engineering

By: Ankur Kalra

Title: Hydraulic Design Engineer

Date: 10/03/2013

APPLICABLE S.O. NUMBERS:
270671/82
270683/90

DOCUMENT IDENTIFICATION	Rev.
E12.5.1948	0

TABLE OF CONTENTS

1.0 PURPOSE

To evaluate the impact of cavitation on the service life of a Browns Ferry and Peach Bottom (henceforth referred as Browns Ferry) Residual Heat Removal (RHR) CVIC 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 [1]. These formulae were developed in an EPRI funded study [2] from empirical data collected for various pump types and are used for predicting impeller erosion rate based on materials of construction, fluid properties, and pump operating conditions. The purpose of this evaluation is to show that the impeller service life under severe cavitation is at least 30 days (720 hours) of operation when operating at reduced net positive suction head (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) hydrodynamic cavitation intensity, 2) cavitation resistance of the impeller material, and 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 ($p-p_v$)[1] driving the implosion of the bubbles. The cavitation resistance is purely a function of the mechanical properties of the material. The service life of an impeller undergoing cavitation depends strongly on the absolute pressure of the fluid at the impeller inlet that drives the vapor-bubble implosion, the impeller material properties (strength and modulus of elasticity), and on the flow characteristics and liquid properties. Gülich [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 available NPSH (NPSHa)) is by flow visualization from model testing. Recently, with the advent of advanced

[1] p - Static pressure of impeller inlet
p_v - Vapor pressure of liquid

computational fluid dynamics (CFD) techniques it is possible to simulate the bubble length as a function of pump 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, the impeller material properties, flow properties, and NPSHa are considered for this analysis.

a) Impeller life due to cavitation damage is predicted using Gülich's empirical formulae [1, 2] and bubble lengths obtained from an impeller alone CFD analysis [3].
The Impeller alone CFD analysis uses ANSYS CFX 13.0 software. The method and the justification for this analysis has been detailed in Reference [4].

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 Browns Ferry RHR impellers using a commercial CFD package was conducted to predict NPSH3, bubble lengths, and bubble location under varying flow rates and NPSH margins [3]. Depending on flow rate the bubble formation is predicted on the suction side, the pressure side, or on both sides of the impeller blade inlet. Significant pressure side bubbles were observed only above [[ ]] flow rate. Figure 1 shows suction side and pressure side bubble lengths versus NPSH margin as predicted by the CFD analysis for six different flow rates. As would be expected, Figure 1 shows that bubble length grows as the NPSH margin decreases.

[[

]]

Figure 1: Bubble Length versus NPSH Margin

The suction side and pressure side bubble lengths, and the corresponding NPSHa values obtained from the CFD results are then used in the Gülich's formulae [2] to predict erosion rate in micrometers per hour (μm/hr) at different flow rates and NPSH margins. The Gülich's formulae [2] use different factors for calculating pressure side and suction side cavitation erosion rates. For this study, the erosion rates for both sides of the impeller blade were calculated and then added together at a given NPSH margin to obtain a combined erosion rate at that flow rate. Table 1 shows the combination of pressure side and suction side erosion rates at the specific NPSH margin which produced the maximum erosion rate for that flow rate.

Table 1: Maximum Erosion Rate at Given Flow Rate and NPSH Margin

[[				
]]				

Figure 2 shows the combined (suction and pressure side) impeller erosion rate versus NPSH margins at different flow rates. The maximum erosion rate of [[ ]] (considering both pressure and suction side cavitation) occurs at [[ ]] for an NPSHa margin of approximately [[ ]]. Maximum erosion rate calculation for the [[ ]] flow condition is provided in the following sections of the report along with the corresponding impeller service life calculation.

[[

]]

Figure 2: Erosion Rate versus NPSH Margin

NPSH values corresponding to the full diameter impeller (27.5") are used for this analysis. The current Browns Ferry and Peach Bottom trim diameter is [[
[[ ]]

In Figure 2, the shape of the [[ ]] curve is different from the other curves because of the negative flow incidence angle (shown later in this report in Figure 4) and its associated pressure side cavitation at this high flow rate. For the same bubble length, pressure side cavitation has a higher erosive power than the suction side cavitation due to the higher "x2" constant value used for pressure side erosion in Gulich's formulae ("x2" described later in step 4 - erosion power section of this report). For the low flow rates with positive flow incidence angles i.e. suction side cavitation, when NPSH margins are being reduced, a peak is observed when the erosive power, contributed by NPSH margin, decreases more than the erosive power, resulting from the bubble length, increases. In the case of significant pressure side cavitation, as observed with [[ ]] case, erosive power contribution of the NPSH margin decreases, but the erosive power contribution of the bubble length

continues to increase at a high rate (due to the high x2 constant). Therefore, an erosion rate peak is not observed at this high flow rate case.

Given:

Impeller Material: [[ ]]

	SI units	Imperial units
Tensile strength, R_m	[[	]]
Young's modulus, E	2.01×10^{11} N/m^2	29,200 kpsi [6]
Impeller blade thickness at cavitation length[3], e	[[	]]
Density of water, ρ (at 95 ºF)	994 kg/m³	0.994 S.G.
Gravitational constant, g	9.81 m/s²	32.2 ft/sec²
Impeller outer diameter, D_2	[[	
Impeller eye diameter, D_1		
Circumferential velocity[4] at impeller eye, u_1		
Eye Area		
Meridional velocity[5], c_1		
NPSH3		]]

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 [2]. 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. In his paper, "Pump Cavitation – Various NPSHR Criteria, NPSHA Margins, and Impeller Life Expectancy" [7] Bruno Schiavello validates Gülich's erosion rate formulae by comparing the cavitation damage

---

2 [[

]]

3 Impeller life prediction requires a value for the thickness of metal at the site where cavitation occurs. The exact cavitation behavior is unknown; conservative assumptions are being used. [[

]]

4 Calculated as π x (impeller eye diameter) x (revolutions per second)

5 Meridional velocity is calculated as flow rate, Q, divided by eye area

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 [8,9].

Following is a step-by-step outline of the impeller life prediction method.

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

This quantity depends only on the impeller material properties.

[[ ]]

Step 2: Estimate bubble (cavity) length

Cavity length data is generally obtained experimentally using flow visualization techniques or analytically from CFD simulation results. When the cavity length data is absent and there is an NPSH margin (NPSHa above the NPSH3), the following formula can be used to estimate cavity length based on impeller geometry and coefficients derived from the NPSH values.

[[ ]]

[[

]]

In the case of the Browns Ferry RHR pumps, cavity lengths were determined via CFD (see Figure 1). A suction side bubble length of [[ ]] (obtained from the CFD analysis for [[ ]] flow rate at the NPSH margin of [[ ]], the predicted maximum erosion zone) is used in this calculation. For the same NPSH margin of [[ ]]; the pressure side bubble length is [[ ]]. Therefore, a combination of the suction side and pressure side cavitation calculation gives the maximum erosion rate at this flow rate.

Figure 3 below shows a general trend for $NPSH_i$ (inception cavitation), NPSH3, and Noise and Erosion as a function of inlet flow incidence. In the case of the Browns Ferry RHR impeller, zero incidence (i = 0; the vertical red line in Figure 3) occurs at approximately [[ ]] of the Best Efficiency Point (BEP) flow rate of [[ ]].

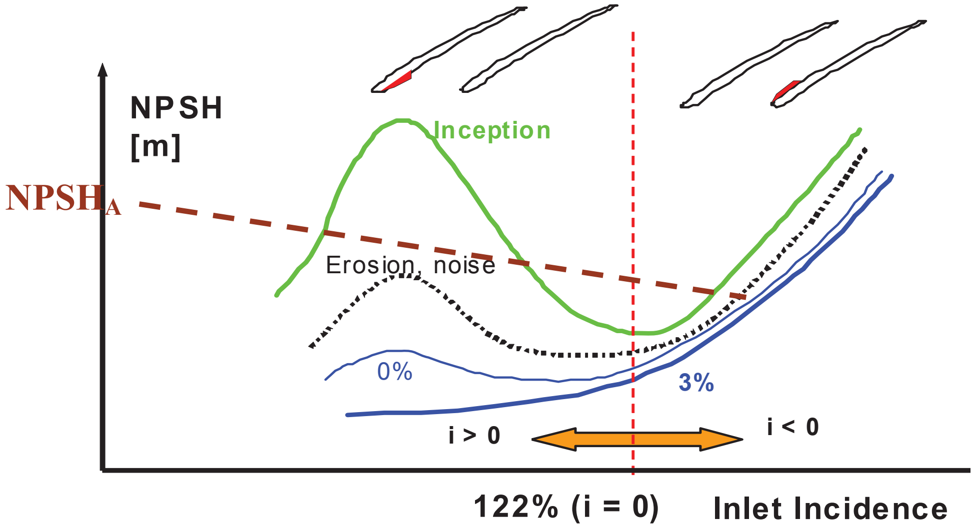

Figure 3: NPSH, Noise and Erosion versus Inlet Incidence

The erosion formulae and the CFD results have been used to develop the relationship between erosion rate and the flow incidence angle for the Browns Ferry CVIC pump at each of the simulated flow rates. The result is illustrated in Figure 4 and show a similar erosion trend as seen in Figure 3, where the erosion rate versus impeller inlet flow incidence angle is shown. Lowest erosion rate zones are found at [[ ]] and at low incidence angles corresponding to the flow band between [[ ]]. As the incidence angles become negative, erosion rates tend to increase.

[[

]]

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 NPSHa. For this calculation, NPSHa is equal to [[ ]] times the NPSH3 (maximum erosion zone at [[ ]]).

$$\Delta p = p_1 - p_V$$

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

$$= (994kg/m^3)(9.81m/s^2)(13.33) - \left(\frac{994kg/m^3}{2}\right)(6.87)^2$$

= [[ ]]

p_1 = suction pressure at impeller inlet

p_v = vapor pressure at impeller inlet

Step 4: Determine erosion power P_{ER}

[[

]]

Erosion power is calculated as follows (Gülich [1], 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)
= 2.5 x 10^{-22} W/m² for pressure side erosion (constant from empirical data)

Δp = [[ ]] (for [[ ]] flow rate)

[6] Consultation with Dr. Philippe Dupont, Head of the Hydraulic Department, Sulzer Pumps, Winterthur, Switzerland

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)
$L_{cav - Suction\ Side}$	= [[ ]]	(for [[ ]] flow rate)
$L_{cav - Pressure\ Side}$	= [[ ]]	(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)
	= 2.6 for pressure side erosion	(constant from empirical data)
a	= speed of sound in the fluid	
	= [[ ]]	(water at [[ ]]) (Using Lubber and Graff's eqs)[10]
a_{ref}	= 1497 m/s	(water at 20° C) (Using Lubber and Graff's eqs)
α	= gas content of fluid	
	= [[ ]]	[[ ]]
α_{ref}	= 24 ppm	(reference: ordinary, untreated water)
ρ"	= density of saturated vapor	
	= [[ ]]	(water at [[ ]])
ρ''_{ref}	= 0.02 kg/m³	(water at 20° C)

For [[ ]]:

[[

]]

Step 5: Calculate erosion rate E_R

[[

]]

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.

[[

]]

5.0 CONCLUSION

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

]]

Based on the above analysis the impeller service life while operating in the maximum erosion rate zone greatly exceeds the [[ ]] mission time. Hence, it can be concluded that the impeller integrity is assured for the [[ ]] mission time if operated at any flow rate within the range [[ ]] gpm. Since RHR flow rate for long-term operation would fall within the [[ ]] curves on Figure 2, by inspection the maximum erosion rate is less than about [[ ]]. This would extend the estimated impeller life by several times.

6.0 BIBLIOGRAPHY

[1] Johann Gülich, Centrifugal Pumps, 2nd Edition, Section 6.6 "Cavitation erosion".

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

[3] Philippe Dupont, Bruno Maroccia – Investigation Report 2012, Numerical prediction of $NPSH_{3\%}$ by means of an impeller only CFD calculation for Browns Ferry 18x24x28 CVIC.

[4] Philippe Dupont, Ernesto Casartelli –Numerical prediction of the cavitation in pumps, Proceedings of ASME FEDSM, July 2002

[5] ASTM Standards A487A/487M-93 (Reapproved 2007), Standard Specification for Steel Castings Suitable for Pressure Service.

[6] ASME B31.1-1995, Power Piping.

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

[8] Paul Cooper, Rehan Farooqim, Bruno Schiavello, Ron Ungewitter, James McKenzie, Wayne Robinson. Reduction of Cavitation Damage in a High-Energy Water Injection Pump. Proceedings of the ASME-JSME-KSME 2011 Joint Fluids Engineering Conference, 2011.

[9] Ravi Balasubramanian, Eugene Sabini, Simon Bradshaw. Influence of Impeller Leading Edge Profiles on Cavitation and Suction Performance,. Proceedings of the Twenty-Seventh International Pump Users Symposium, Houston, TX, 2011.

[10] Speed of Sound in Pure Water – Technical Guide - http://resource.npl.co.uk/acoustics/techguides/soundpurewater/content.html#LUBBERS

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