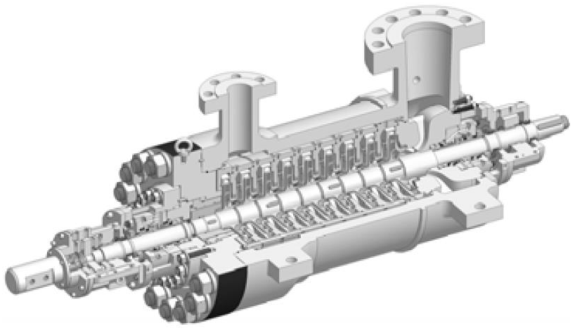
Applied Predictive Analytics to Evaluate Centrifugal Pumps Reliability, based on Hydraulic Operation Regions



Prepared by:

Ernesto Primera, B.S., M.S.
Machinery Reliability Engineer
PhD Candidate – University of Delaware

Phone: 713 410 9538
Email: eprimera@udel.edu

Applied Predictive Analytics to Evaluate Centrifugal Pumps Reliability

Ernesto Primera

Mechanical/Maintenance Engineer with 20 years of experience in Rotating Machinery, Condition Monitoring, Performance Analysis, and Reliability Evaluations. Experience in the Oil and Gas Industry, Power Plants and OEMs. A passionate about Data Analysis using technology platforms such as: R Studio, SAS, Minitab, SPSS Statistic & Modeler, Risk Simulator, @Risk, MS Power BI, and Tableau. Proven experience as employed for Chevron, Phillips-66, Williams, Flowserve and SKF. During the last 10 years Ernesto have worked in the Rotating Machinery Reliability Group at the Pascagoula Refinery in Mississippi (CHEVRON) and Lake Charles Refinery and Alliance Refinery in Louisiana (PHILLIPS-66). Global Instructor for the American Society of Mechanical Engineers (ASME), Industry Partner and Instructor for the Hydraulic Institute, certified Maintenance & Reliability Professional CMRP, Certified Vibration Analyst Category III by the Technical Associate of Charlotte. Bachelor's Degree in Maintenance Engineering (University Complex AJS - Venezuela), Master's degree in Predictive Maintenance & Diagnostics Technique (Sevilla University - Spain), Master's degree in business Analytics (Grand Canyon University) and currently studying PhD in Applied Statistics in the University of Delaware. Ernesto is currently a SRE Lifetime National Member.

Content

1. Background.
2. Pumps Applications
3. Pumps Industry Standards.
4. Centrifugal Pump Typical Hydraulic Curve.
5. Problem Statement.
6. Previous Research
7. Pumps Life Cycle Cost
8. Centrifugal Pumps Reliability.
9. New Research Purpose
10. Development of the Research Project.
11. Research Project Conclusion

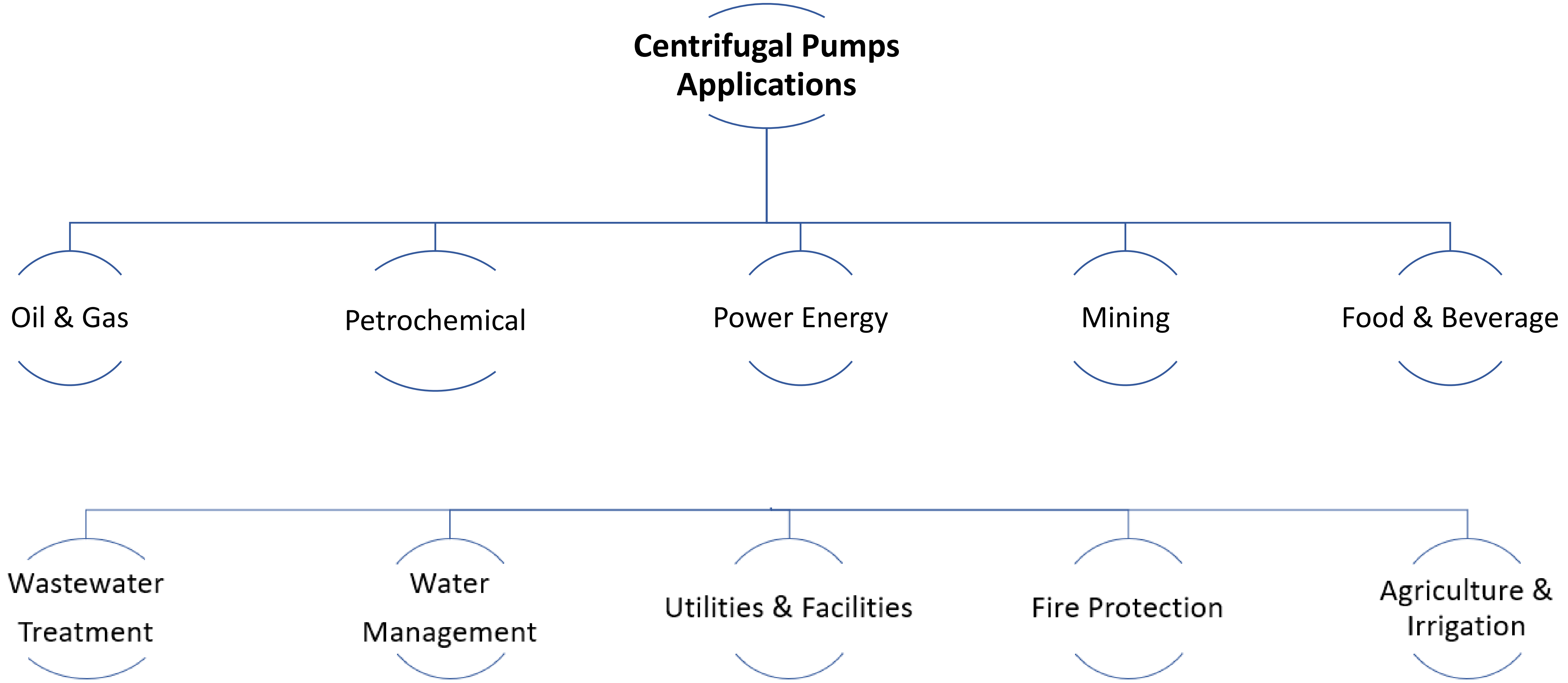
Applied Predictive Analytics to Evaluate Centrifugal Pumps Reliability

Background

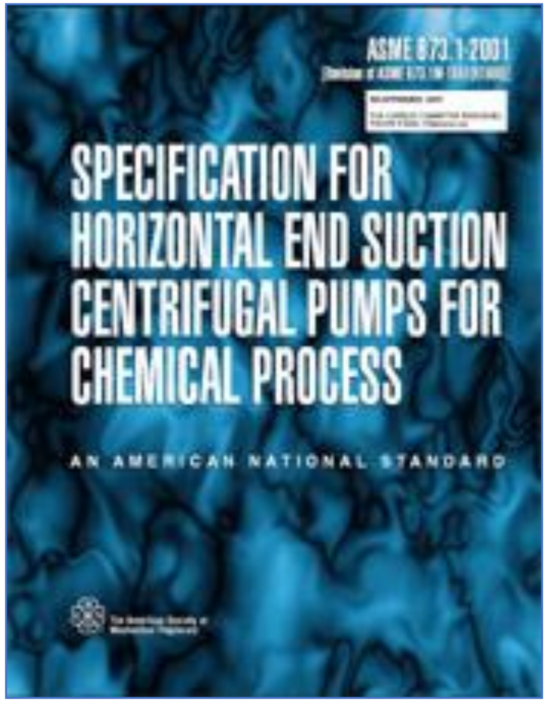
- Pumping systems are undoubtedly one of the main equipment that is part of the global industry, with an emphasis on the water industry, the global sales revenue from the deployment of pumps represented US $ 34.39 Billion at the end of 2016 and is projected to reach a market value of US $ 49.40 Billion by 2024 [Persistence, 2021]. Therefore, it the importance of aligning scientific research, technological advances, resources, and efforts of science towards improving the reliability of the equipment with the greatest global presence in productive industrial systems and in the management of our waters.

Prepared by: Ernesto Primera

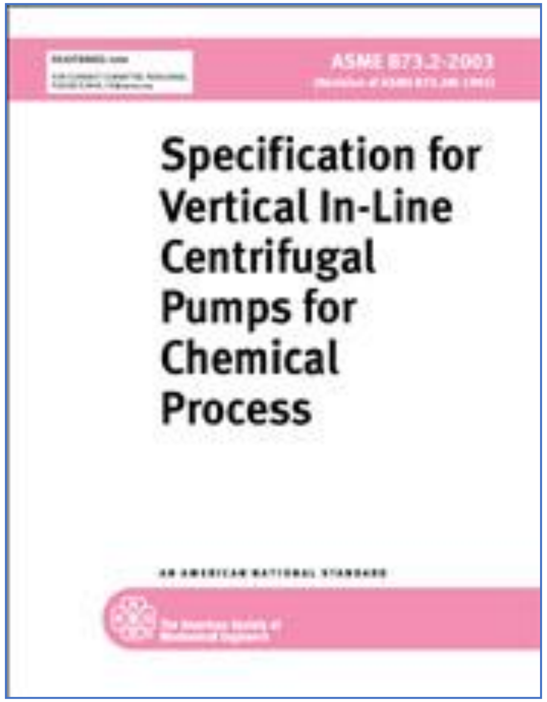
Pumps Applications



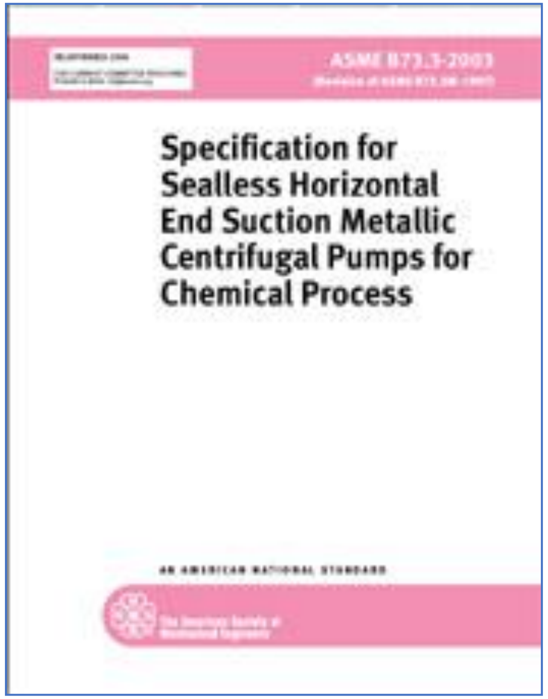
Pumps Industry Standards



ASME B73.1 - 2001
Specification for Horizontal End Suction Centrifugal Pumps for Chemical Process



ASME B73.2 - 2003
Specifications for Vertical In-Line Centrifugal Pumps for Chemical Process



ASME B73.3 - 2003
Specification for Sealless Horizontal End Suction Metallic Centrifugal Pumps for Chemical Process

Source: American Society of Mechanical Engineers

SOCIETY OF RELIABILITY ENGINEERS Huntsville

Applied Predictive Analytics to Evaluate Centrifugal Pumps Reliability

RAM XIV

Pumps Industry Standards

Centrifugal Pumps for Petroleum, Petrochemical and Natural Gas Industries

ANSI/API STANDARD 610
ELEVENTH EDITION, SEPTEMBER 2010

ERRATA, JULY 2011

ISO 13709:2009 (Identical), Centrifugal pumps for petroleum, petrochemical and natural gas industries

AMERICAN PETROLEUM INSTITUTE

Sealless Centrifugal Pumps for Petroleum, Petrochemical, and Gas Industry Process Service

API STANDARD 685
SECOND EDITION, FEBRUARY 2011

AMERICAN PETROLEUM INSTITUTE

NFPA 20

Standard for the Installation of Stationary Pumps for Fire Protection

2007 Edition

NFPA, 1 Batterymarch Park, Quincy, MA 02169-7471
An International Codes and Standards Organization

ANSI/HI 12.1-12.6-2005

American National Standard for

Rotodynamic (Centrifugal) Slurry Pumps

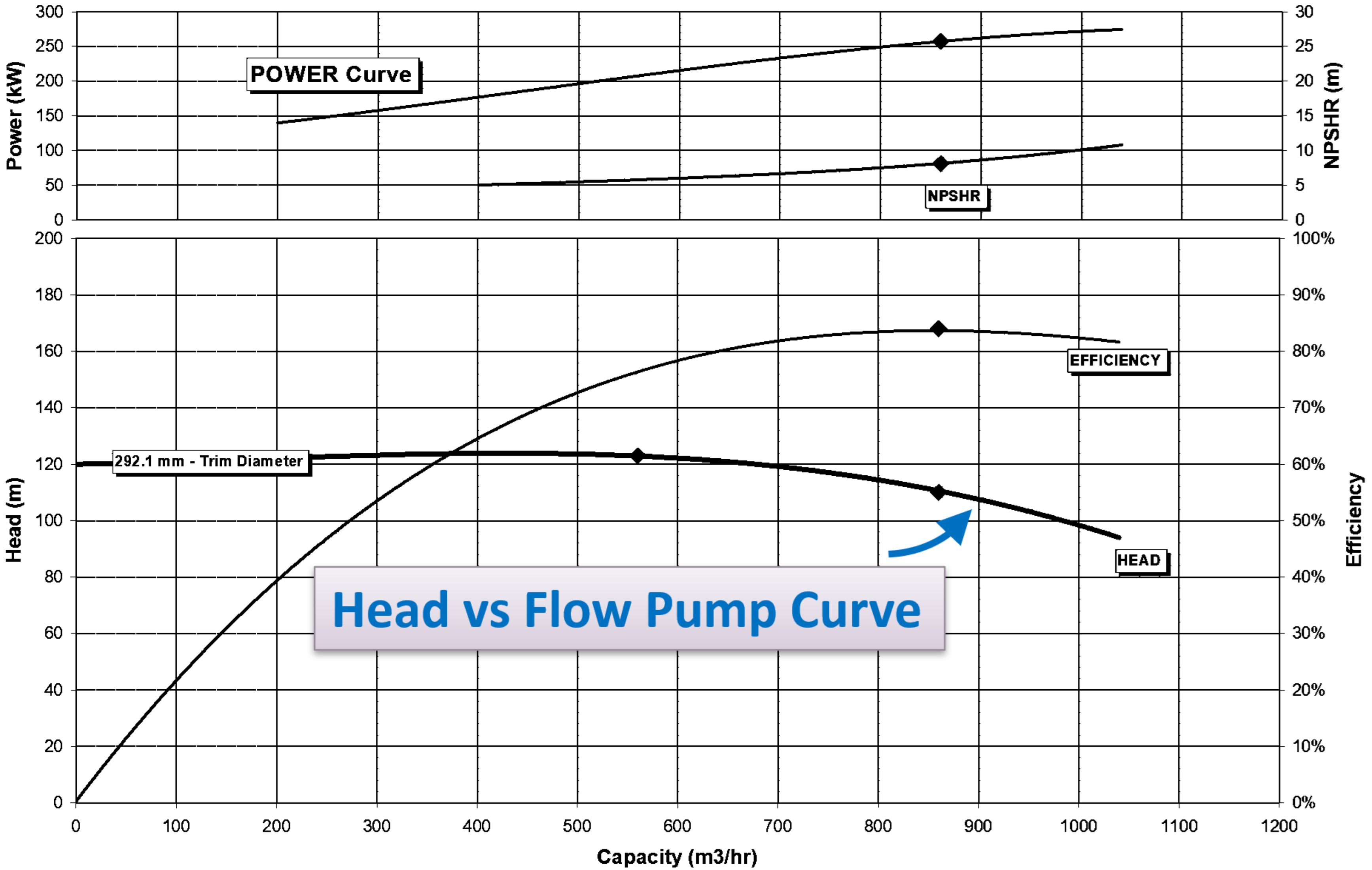
for Nomenclature, Definitions, Applications, and Operation

Hydraulic Institute

6 Campus Drive
First Floor North
Parsippany, New Jersey
07054-4406
www.Pumps.org

Applied Predictive Analytics to Evaluate Centrifugal Pumps Reliability

Centrifugal Pump Typical Hydraulic Curve

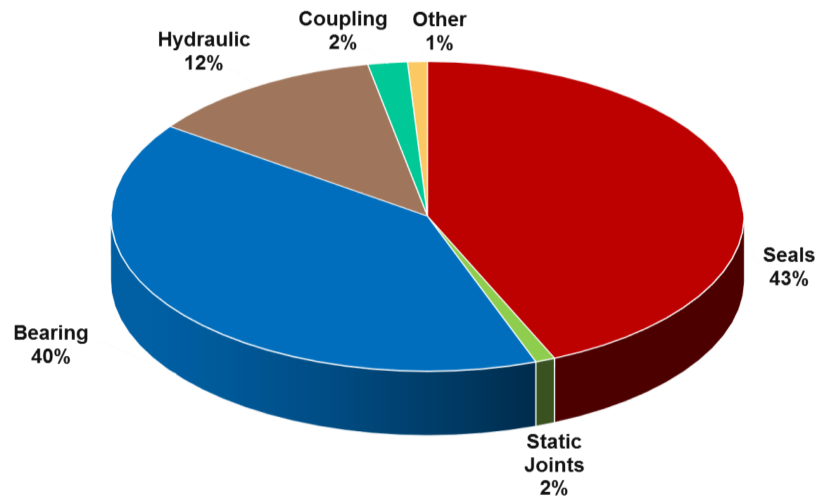


Applied Predictive Analytics to Evaluate Centrifugal Pumps Reliability

Problem Statement

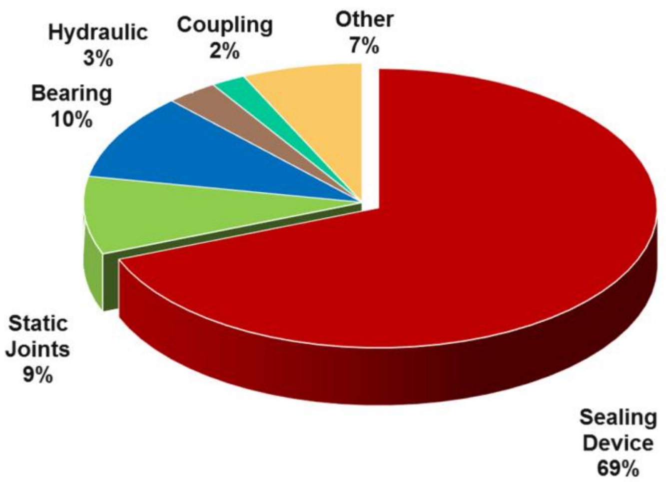
- The unexpected pumping systems failures in the fluid handling circuits in their different global services are the cause of the quality and efficiency of services decrease, it also impacts of the business profitability, due to rework, overtime, and high costs for repairs. We can also add a high amount of waste of fluids such as water, and spills of industrial fluids that directly impact our environment.

HYDROCARBON PROCESSING



10 Years of Reliability Data on Centrifugal Pumps in the U.S.A. Industry and its Typical Causes of Failures

FLUID SEALING ASSOCIATION FSA



Previous Research

- Over the years, the industry and pump manufacturers have implemented preferred operating windows to operate their pumping systems, with the aim of reducing the probability of failures and reducing unnecessary energy consumption.
- Researchers and SMEs like H. Paul Barringer and Heinz P. Bloch have concluded that operating the pumps close to their Best Efficiency Point (BEP) is the key to maintaining desired reliability, as shown in the next slide.

Previous Research

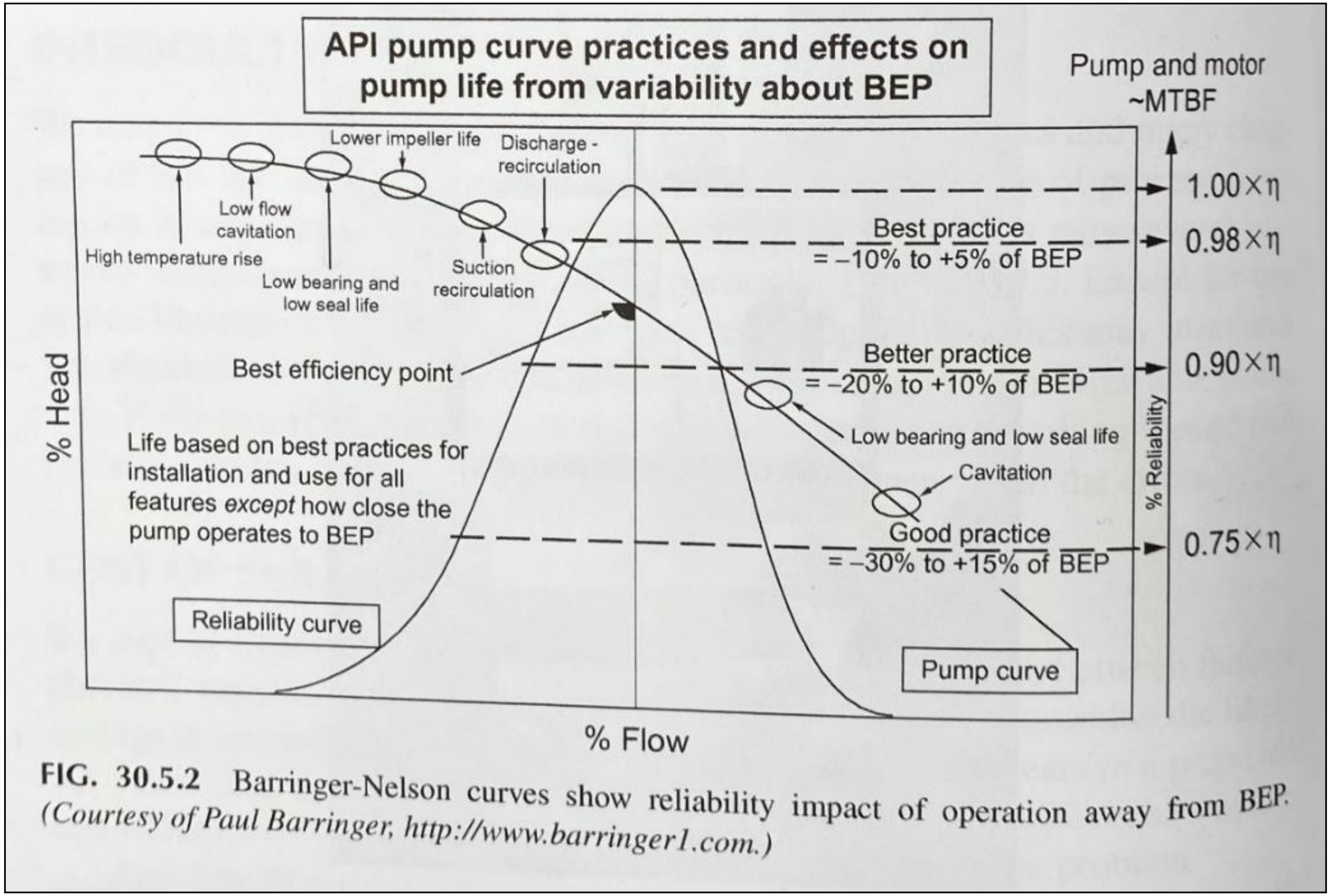


FIG. 30.5.2 Barringer-Nelson curves show reliability impact of operation away from BEP. (*Courtesy of Paul Barringer, http://www.barringer1.com.*)

Pump Curve – Reliability Impact of Operation away from BEP

Source: Hydraulic Institute "Reliability of Pumping Equipment" p.64, and Heinz P. Bloch "Petrochemical Machinery Insights" p. 454

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$ Reliability Function

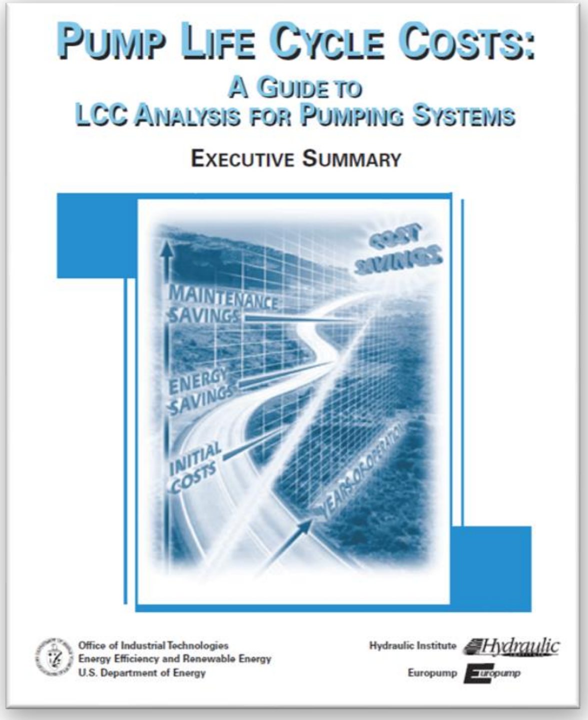
1. Shape parameter (β):
2. Characteristic life (η):
3. Time period of interest (t):
4. Units associated with inputs #2 and #3 above: hours
5. Decimal places: 2

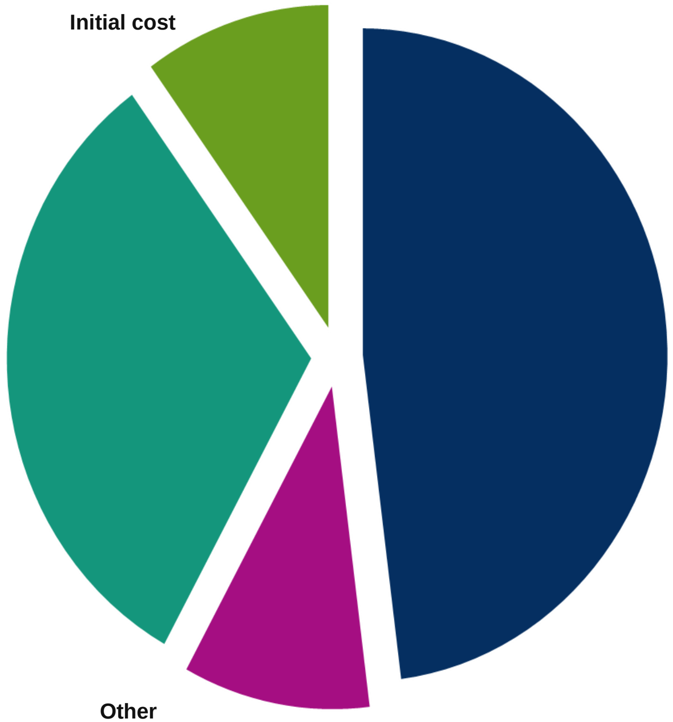
Pumps Efficiency

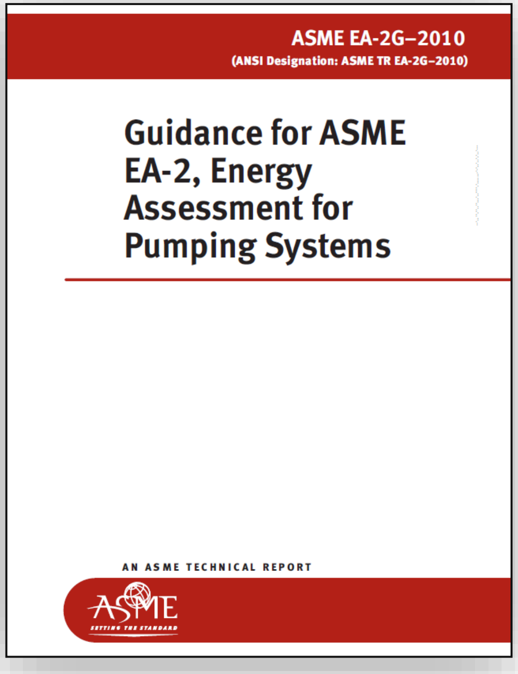
Means

Reliability

Pumps Life Cycle Cost







Source: Hydraulic Institute

Centrifugal Pumps Reliability

Machinery info	MTTF					MTTF (yrs)
Description	OREDA 2009	PERD	Paul Barringer	OREDA 2002	Heinz Bloch	
Multistage Centrifugal Pump	2,78	3,76	3,99	1,58	2,00	**2,82**

Eta(η)

OREDA: The Offshore and Onshore Reliability Data project

ESReDA: European Safety, Reliability & Data Association

PERD: Process Equipment Reliability Database. CCPS (Center for Chemical Process Safety)

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$ Reliability Function

Centrifugal Pumps Reliability

Inputs:

Shape parameter (β): **1.30** ← For Bearings, based on H. Paul Barringer Failures Database

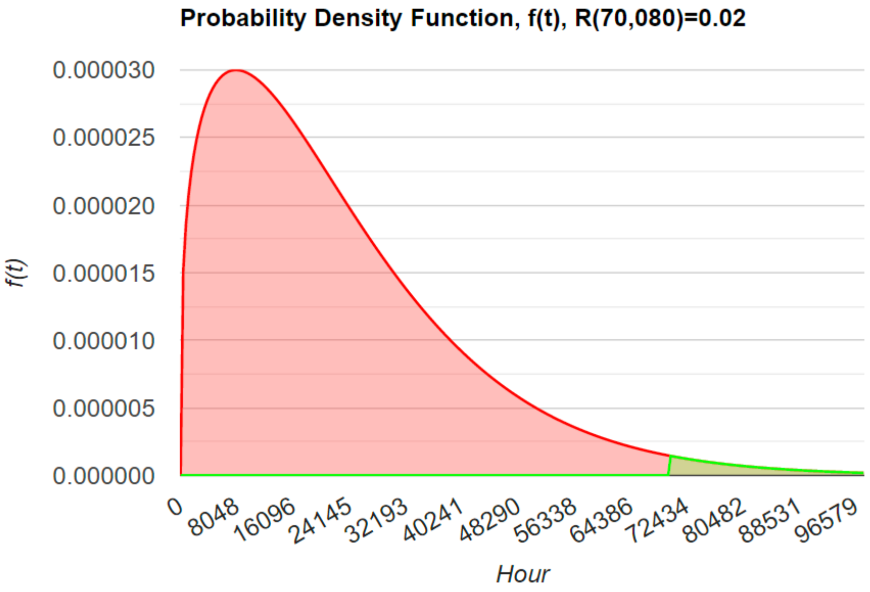
Characteristic life (η, hours): **24,528**

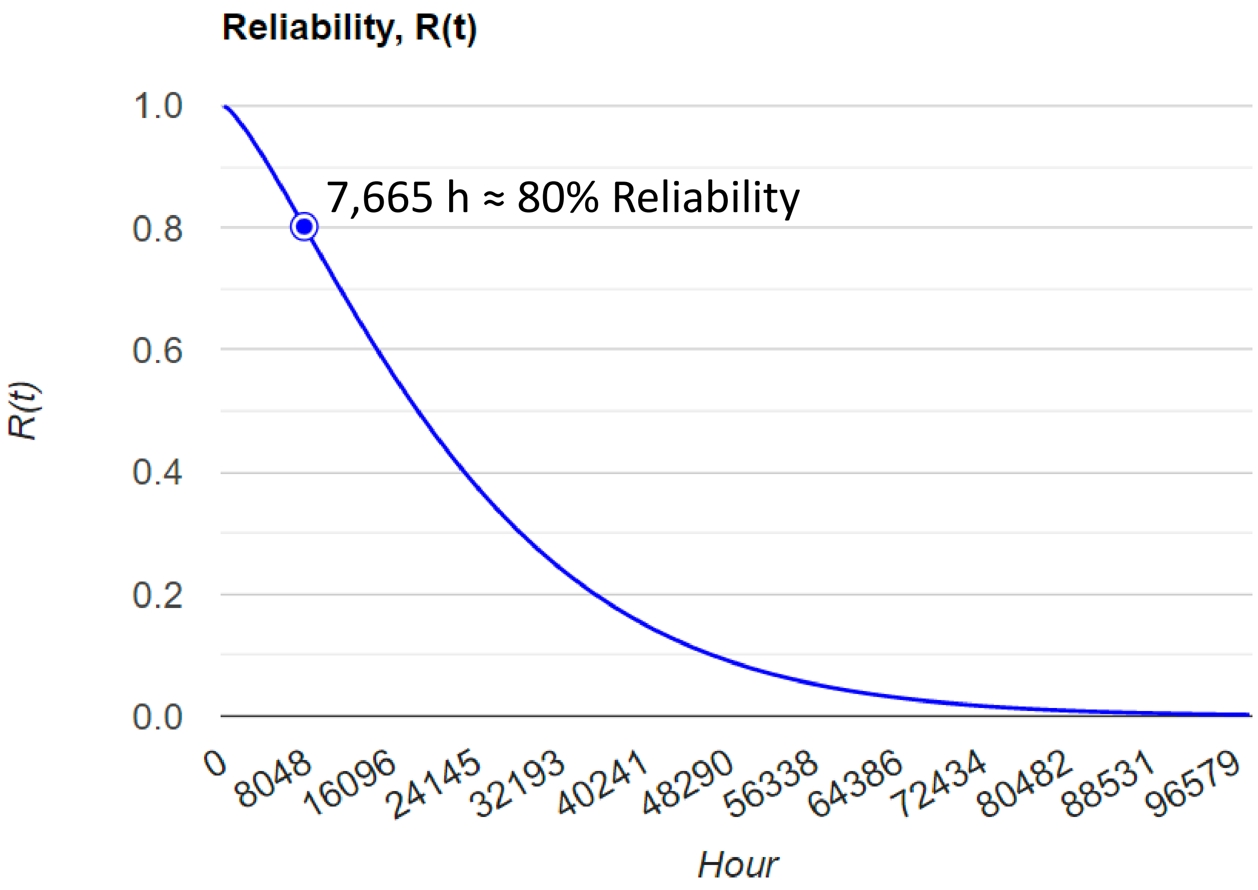
Time period of interest (t, hours): **70,080**

Solution:

Mean life = η x Γ(1 + 1/β)

Mean life = 24,528 x Γ(1.77) = **22,658** hours





Source: Reliability Analytics Corporation

Applied Predictive Analytics to Evaluate Centrifugal Pumps Reliability

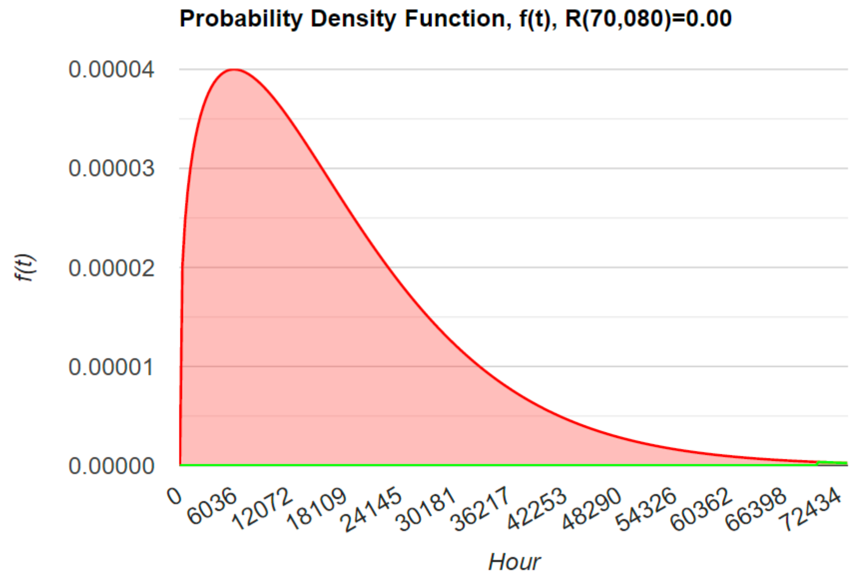
Centrifugal Pumps Reliability

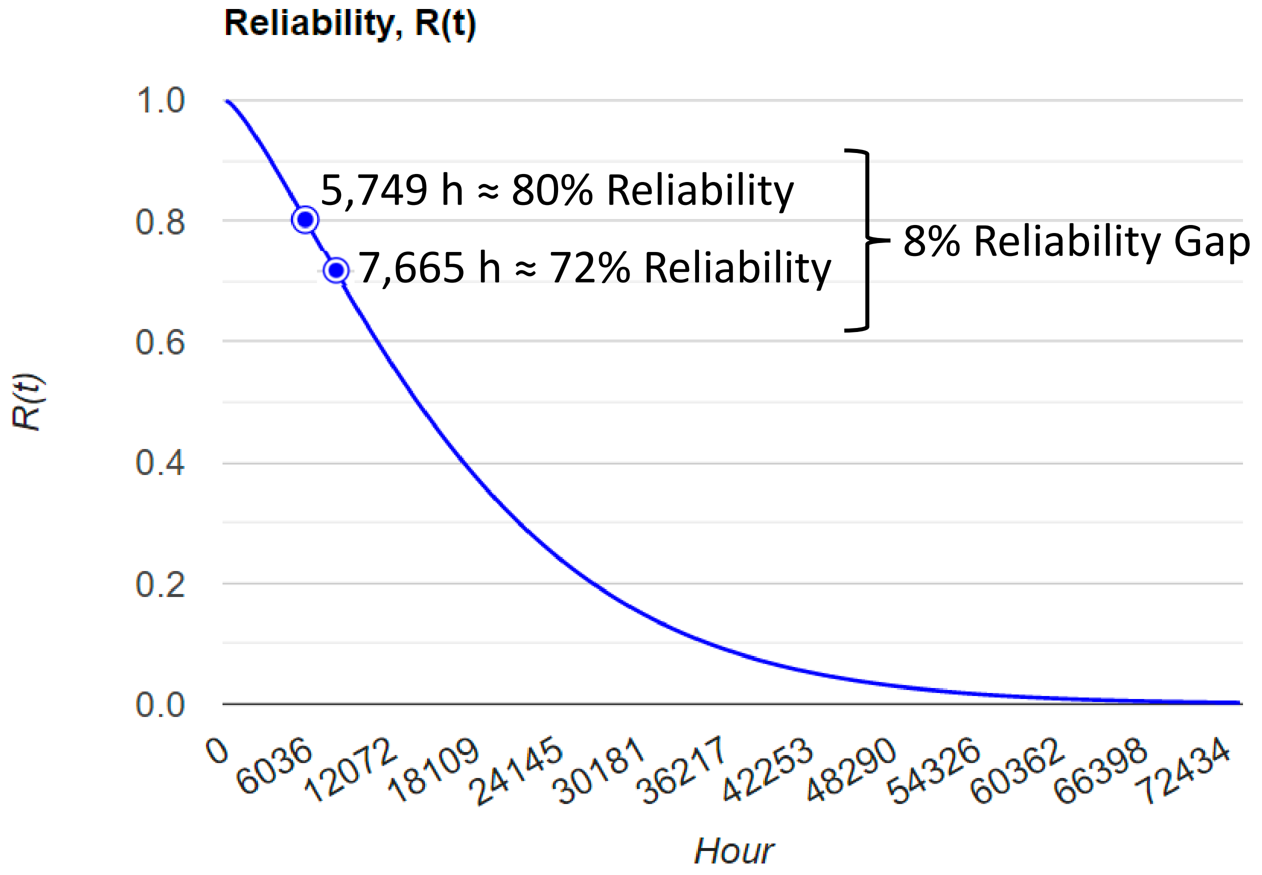
Inputs:

Shape parameter (β): **1.30**
Characteristic life (η, hours): **18,396** ← 75% of Eta(η)
Time period of interest (t, hours): **70,080**

Solution:

Mean life = η x Γ(1 + 1/β)
Mean life = 18,396 x Γ(1.77) = **16,994** hours





7,665 - 5,749 = 1916 h (≈80 days)

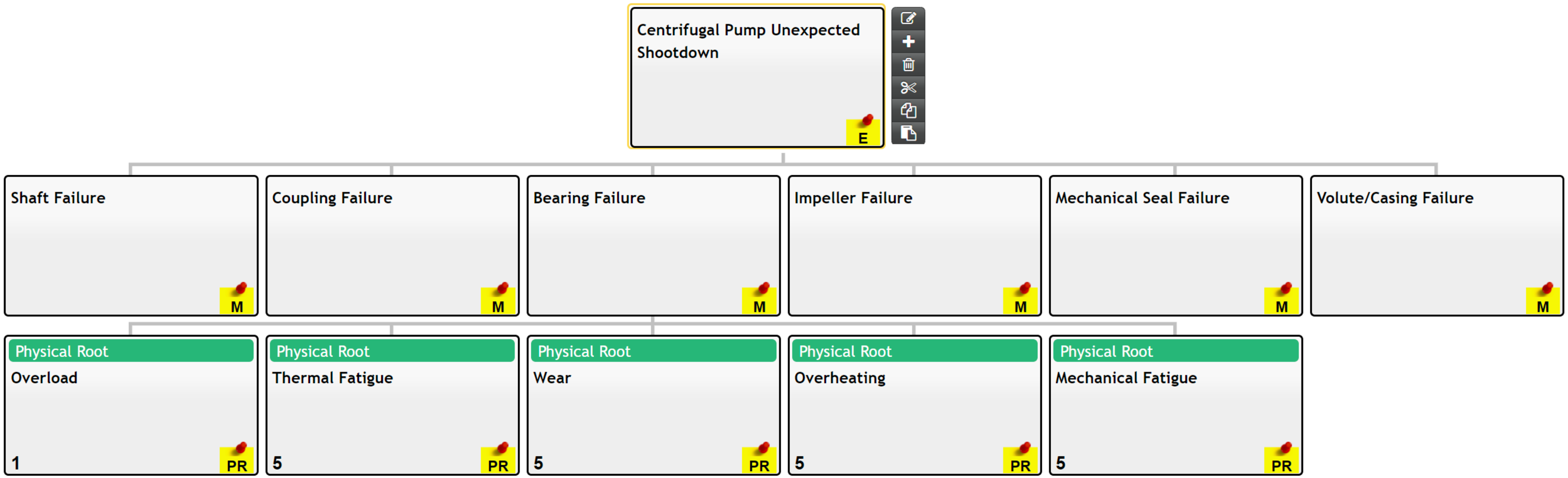
Source: Reliability Analytics Corporation

Prepared by: Ernesto Primera

Applied Predictive Analytics to Evaluate Centrifugal Pumps Reliability

Centrifugal Pumps Reliability

We can say that the unexpected shootdown of a centrifugal pump is attributable to the failure of its main components (Maintainable Items), as described in the fault logic tree. Exploring one of the failure modes (bearing failure); We can observe that the physical causes or degradation mechanisms can originate from subjecting the pump to high mechanical vibrations, for this reason, we will use mechanical vibrations as a condition that generates potential failures of the main components.



Source: Reliability Center Inc. PROACT® RCA Methodology and Software

Research Purpose

- The objective of this project was to identify which operating variables had the greatest effect on pump reliability in terms of mechanical condition (Vibration), and thus validate the hypotheses of the previous research by Barringer and Block, and directly identify the operating variable that most affects pump vibration.
- We developed the case of a 10-stage high-energy pump.
- For the project, 19,755 data are available for each variable, collected over one year in 2021.
- Overall, we wanted to identify the most important factors that influence pump reliability and find the levels of these that maximize pump reliability.

Development of the Research Project

For this project, we used four variables that are considered relevant to pump performance in terms of influence mechanical condition (Vibration):

- Discharge Pressure in PSIG.
- Discharge Flow in gallons/min (gpm)
- Discharge Temperature in ◦F.
- Driver (Electric Motor) current consumption in Amps.

For the validation of the results obtained in the previous research, we used 3 steps:

1st Step: Dataset review

2nd Step: Correlation Analysis

3rd Step: Multiple Linear Regression Analysis

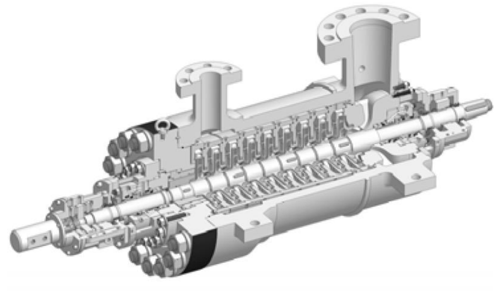
Applied Predictive Analytics to Evaluate Centrifugal Pumps Reliability

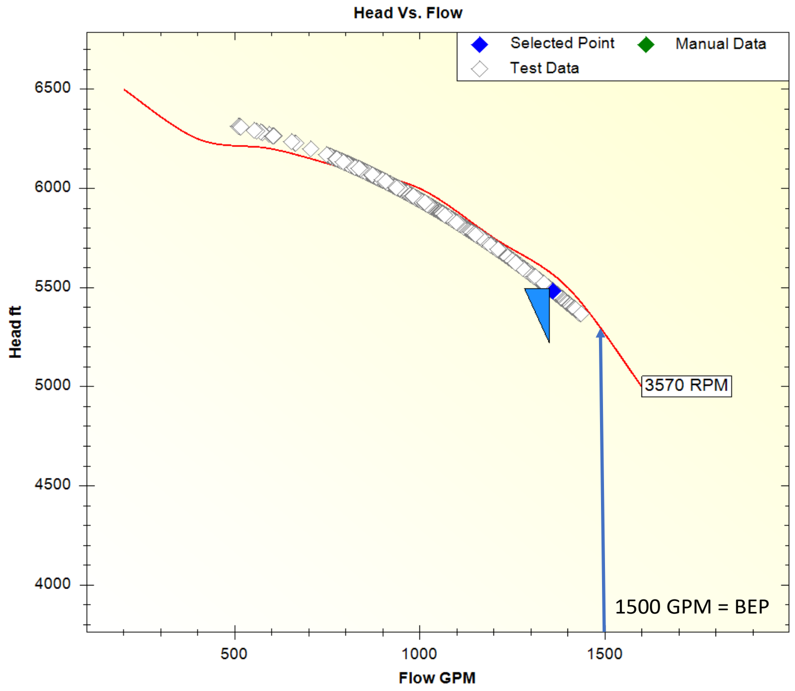
Huntsville SOCIETY OF RELIABILITY ENGINEERS

RAM XIV

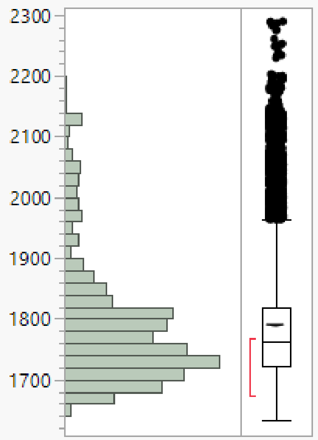
Development of the Research Project

1st Step: Dataset review





Disch Press



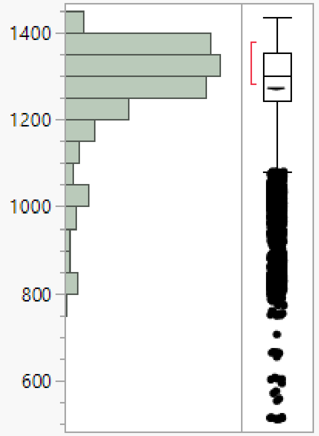
Quantiles

100.0%	maximum	2289.471
99.5%		2139.2159
97.5%		2090.2143
90.0%		1952.8206
75.0%	quartile	1818.107
50.0%	median	1761.745
25.0%	quartile	1721.259
10.0%		1690.6964
2.5%		1674.2018
0.5%		1657.8788
0.0%	minimum	1632.119

Summary Statistics

Mean	1790.3381
Std Dev	103.99294
Std Err Mean	0.7398869
Upper 95% Mean	1791.7884
Lower 95% Mean	1788.8879
N	19755

Disch Flow



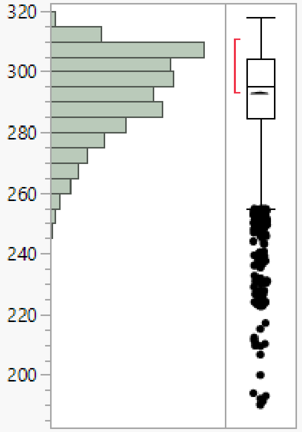
Quantiles

100.0%	maximum	1435.903
99.5%		1422.7538
97.5%		1401.9763
90.0%		1383.4182
75.0%	quartile	1351.706
50.0%	median	1300.663
25.0%	quartile	1243.245
10.0%		1082.8504
2.5%		861.8526
0.5%		811.06125
0.0%	minimum	510.6045

Summary Statistics

Mean	1270.0117
Std Dev	127.29591
Std Err Mean	0.9056824
Upper 95% Mean	1271.7869
Lower 95% Mean	1268.2365
N	19755

Disch Temp



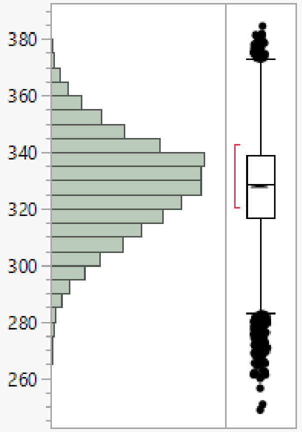
Quantiles

100.0%	maximum	318.0246
99.5%		314.74821
97.5%		311.81847
90.0%		308.75854
75.0%	quartile	304.3716
50.0%	median	295.083
25.0%	quartile	284.5545
10.0%		273.30998
2.5%		261.29368
0.5%		249.8576
0.0%	minimum	190.1906

Summary Statistics

Mean	292.80722
Std Dev	14.130399
Std Err Mean	0.1005347
Upper 95% Mean	293.00427
Lower 95% Mean	292.61016
N	19755

Motor Current



Quantiles

100.0%	maximum	384.5304
99.5%		369.18885
97.5%		359.77039
90.0%		348.8423
75.0%	quartile	339.1513
50.0%	median	328.664
25.0%	quartile	316.597
10.0%		305.48118
2.5%		293.33461
0.5%		279.95205
0.0%	minimum	248.7921

Summary Statistics

Mean	327.75747
Std Dev	16.99686
Std Err Mean	0.1209289
Upper 95% Mean	327.9945
Lower 95% Mean	327.52044
N	19755

Prepared by: Ernesto Primera

Applied Predictive Analytics to Evaluate Centrifugal Pumps Reliability

Development of the Research Project

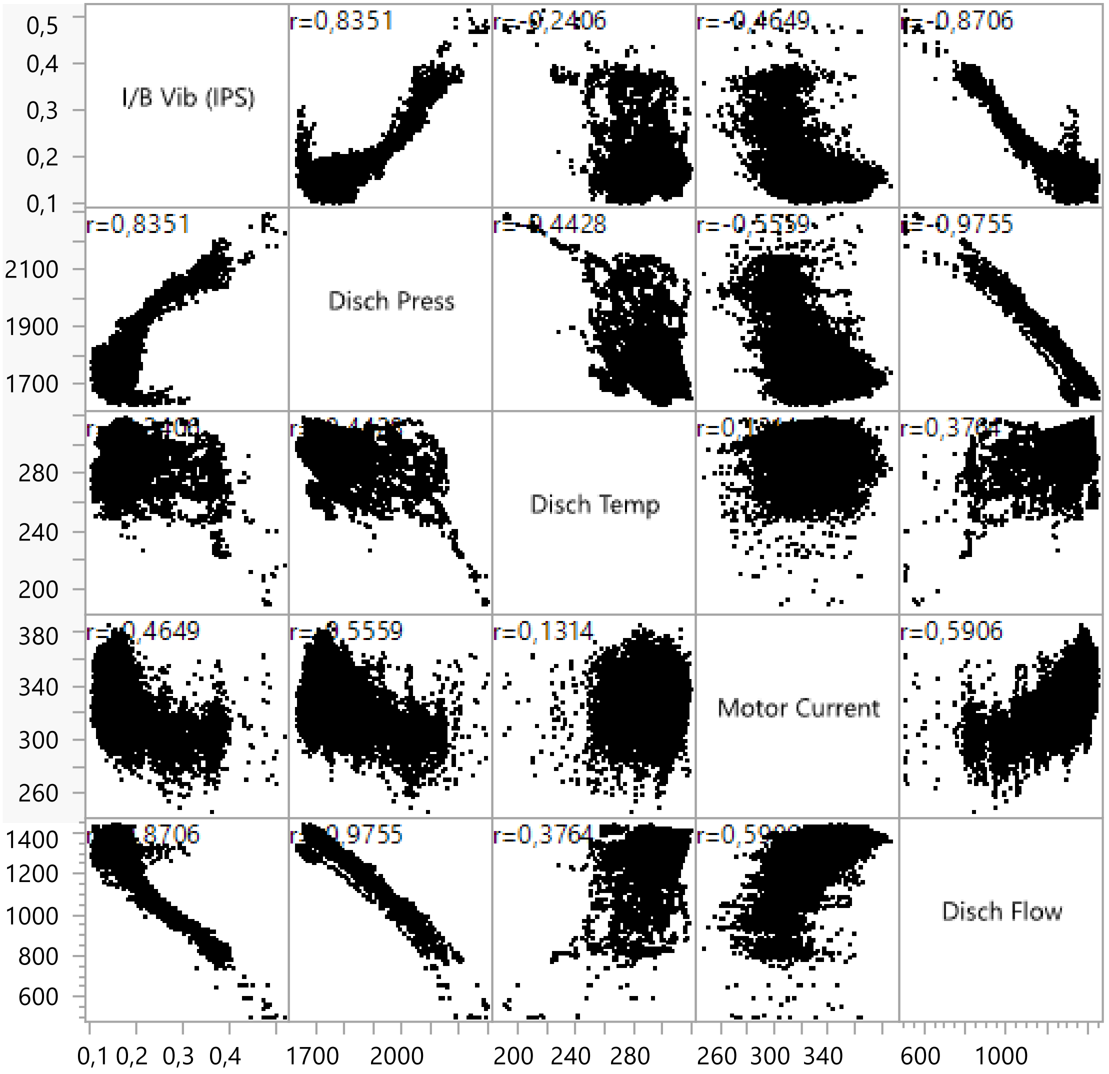
2nd Step: Correlation Analysis

We calculated the partial correlations of the model and their respective scatter plots.

We can see that there is a significant correlation between the variables "Disch Press" and " Disch Flow" with the response variable " I/B Vib (IPS)".

It is important to mention that the correlation between the variables " Disch Press " and " I/B Vib (IPS)" is positive and high (p-value= 0.8351), while the correlation between the variables " Disch Flow " and " I/B Vib (IPS)"." is inverse and high (p-value = -0.8706).

Scatterplot Matrix



Applied Predictive Analytics to Evaluate Centrifugal Pumps Reliability

Development of the Research Project

2nd Step: Correlation Analysis

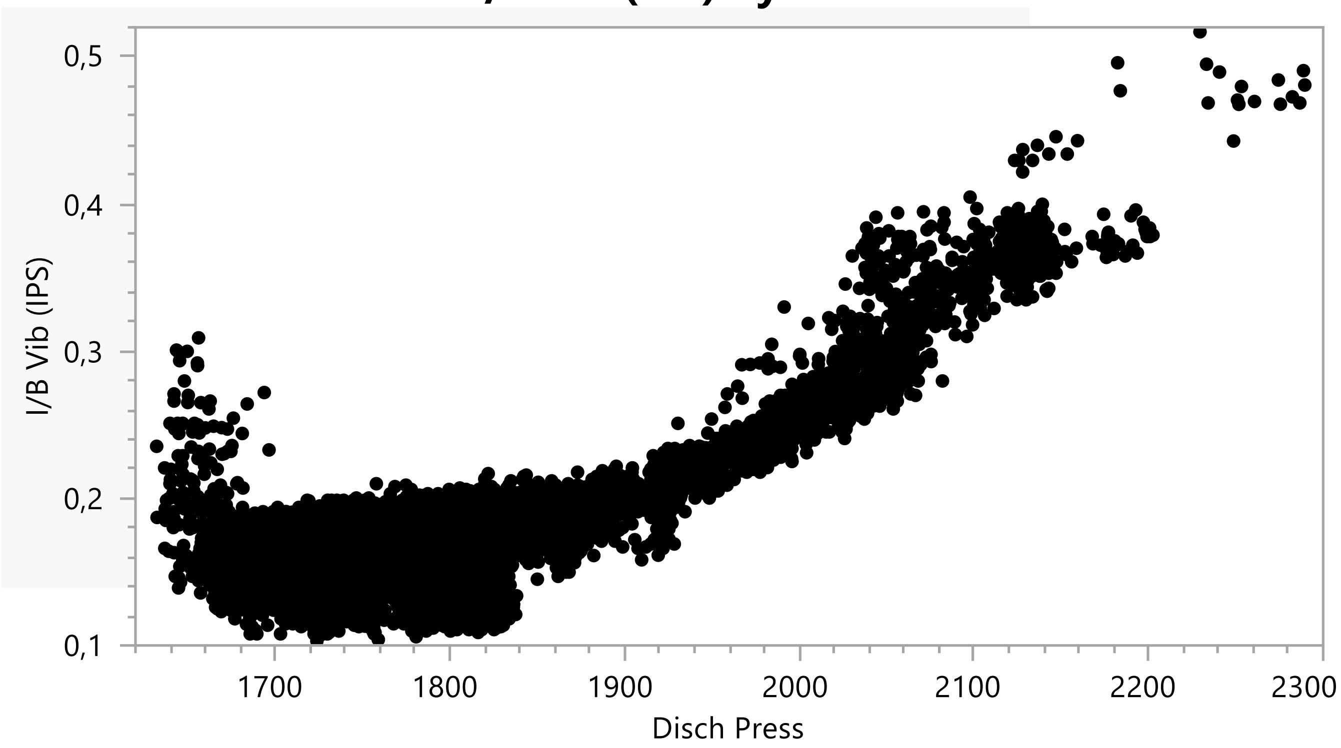
On the other hand, analyzing the scatter plots, we can say that for the first case, an increasing relationship between discharge pressure and the vibration is shown, that is, when discharge pressure increases, vibration also increases. radial.

Summary Statistics

	Value	Lower 95%	Upper 95%	Signif. Prob
Correlation	0,835088	0,830818	0,839259	<,0001*
Covariance	3,986567			
Count	19755			

Variable	Mean	Std Dev
Disch Press	1790,338	103,9929
I/B Vib (IPS)	0,180908	0,045905

Bivariate Fit of I/B Vib (IPS) By Disch Press



Prepared by: Ernesto Primera

Applied Predictive Analytics to Evaluate Centrifugal Pumps Reliability

Development of the Research Project

2nd Step: Correlation Analysis

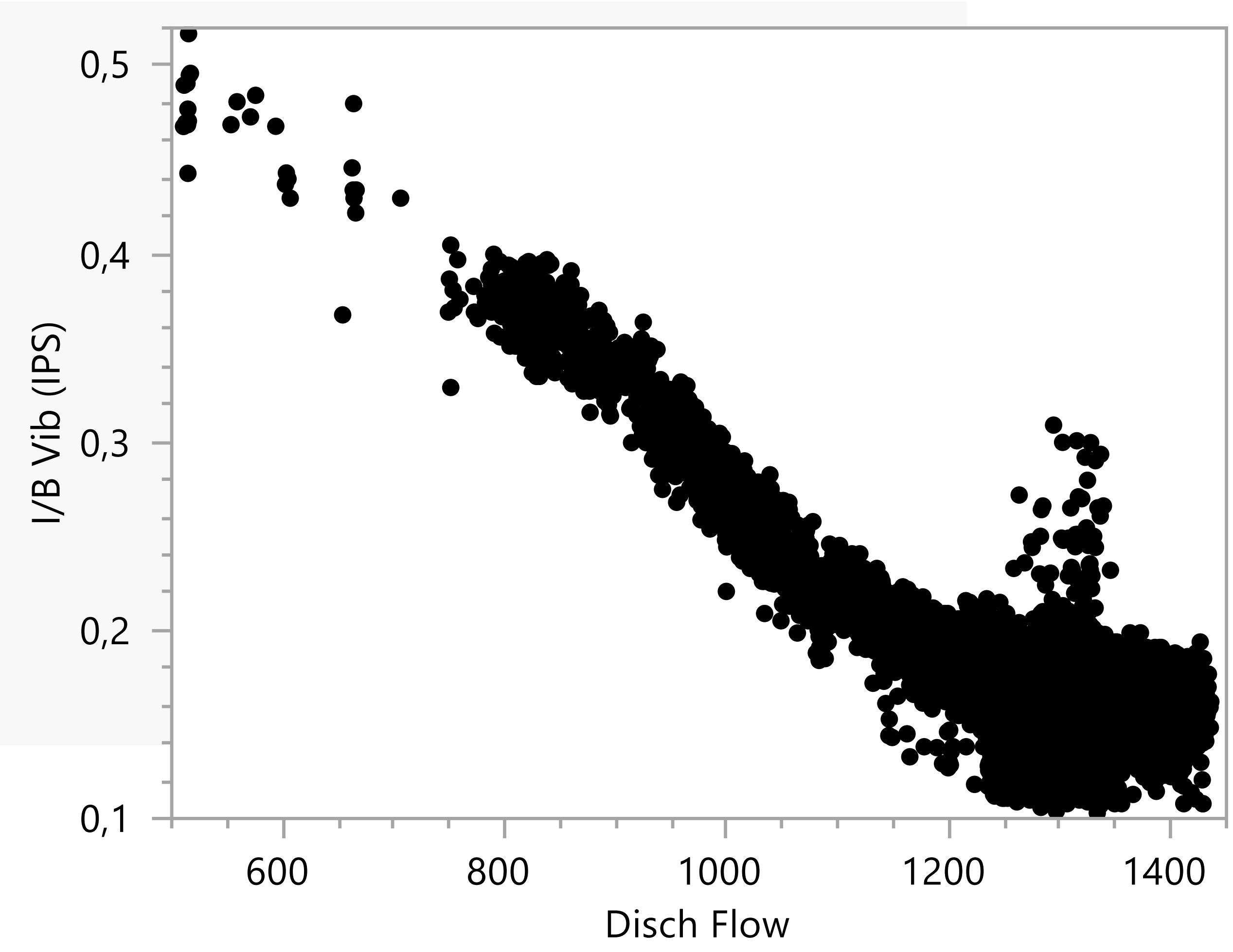
Likewise, we can notice that there is a decreasing relationship, in other words, when the discharge flow increases, the radial vibration decreases or vice versa.

Summary Statistics

	Value	Lower 95%	Upper 95%	Signif. Prob
Correlation	-0,87057	-0,87391	-0,86715	<,0001*
Covariance	-5,08724			
Count	19755			

Variable	Mean	Std Dev
Disch Flow	1270,012	127,2959
I/B Vib (IPS)	0,180908	0,045905

Bivariate Fit of I/B Vib (IPS) By Disch Flow



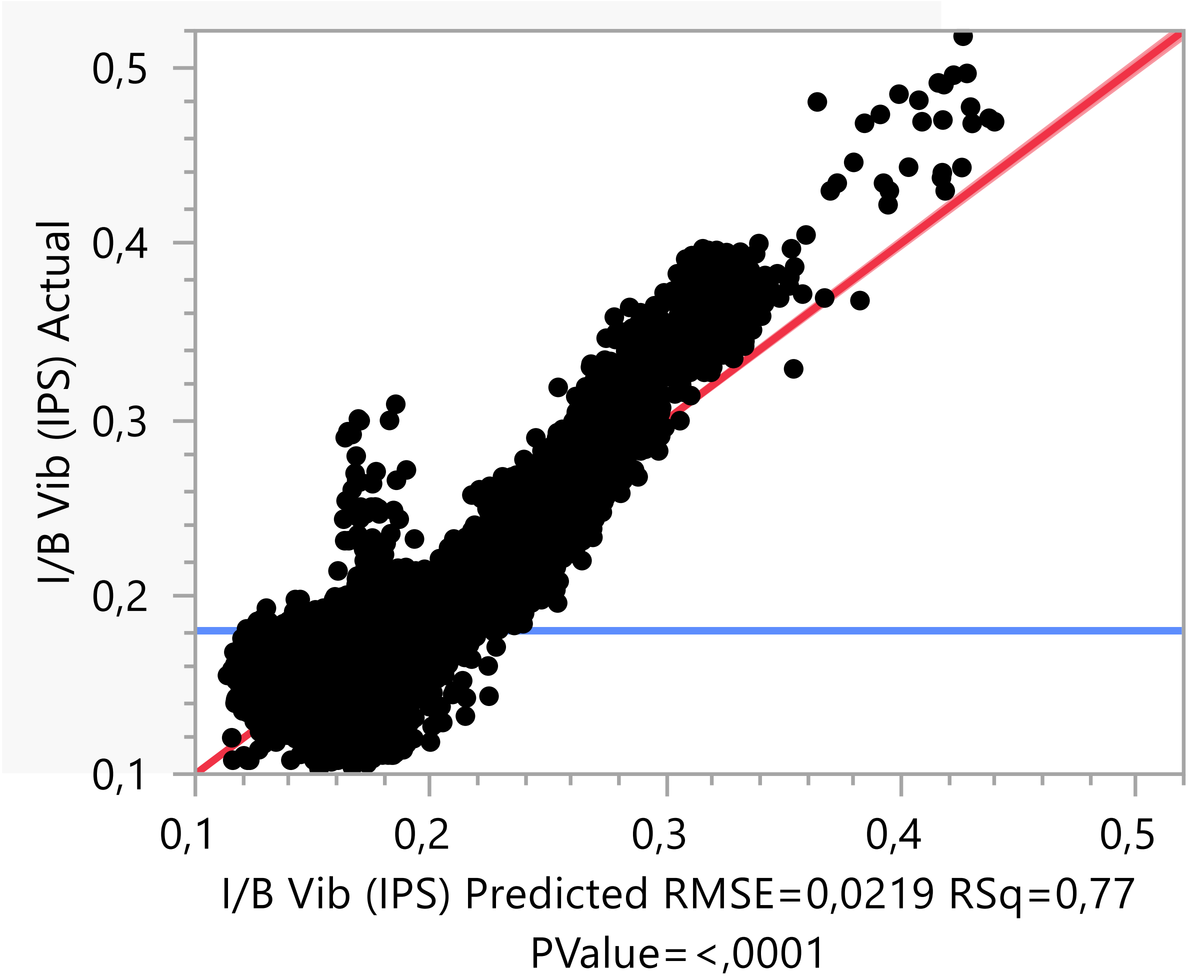
Prepared by: Ernesto Primera

Development of the Research Project

3rd Step: Multiple Linear Regression Analysis

The regression model is significant. The R-squared is **0.77**, which indicates that the model explains 77% of the variance of the dependent variable. The variables are significant for the response variable, with a p-value < 0.05. The studentized residual plot does not show any violation of the model assumptions. No unusual or outlier values.

Response I/B Vib (IPS) Actual by Predicted Plot



Applied Predictive Analytics to Evaluate Centrifugal Pumps Reliability

Research Project Conclusion

Through the results of the application of Predictive Analytics (multiple linear regression) to the time series data of our pump, we can conclude that the results of the previous research carried out by H. Paul Barringer and Heinz P. Bloch were correct.

Considering that the Pump's Best Efficiency Point (BEP) is 1,500 GPM, we can see that as the flow moves away from the BEP, the vibrations increase exceeding the limits allowed according to ISO standards (≥ 0.16 IPS-RMS), when projecting the flow at 1,050 GPM, just 30% less than the BEP, the mechanical vibration reaching values of up to 0.5 IPS-RMS, to adjust to the prediction of the previous research that concludes an effect in 0.75xEta.The results also validate the inverse relationship between the effects of the flow versus the effects of the discharge pressure, according to the negative slope shown in the Pump curve.

"In Memory of H. Paul Barringer and Heinz P. Bloch"

H. Paul Barringer, PE
Reliability Consultant at Barringer & Associates, Inc.
Humble, Texas, United States
1936 – 2016

Heinz Bloch
Consulting Engineer at Process Machinery Consulting
Westminster, Colorado, United States
1933 – 2022