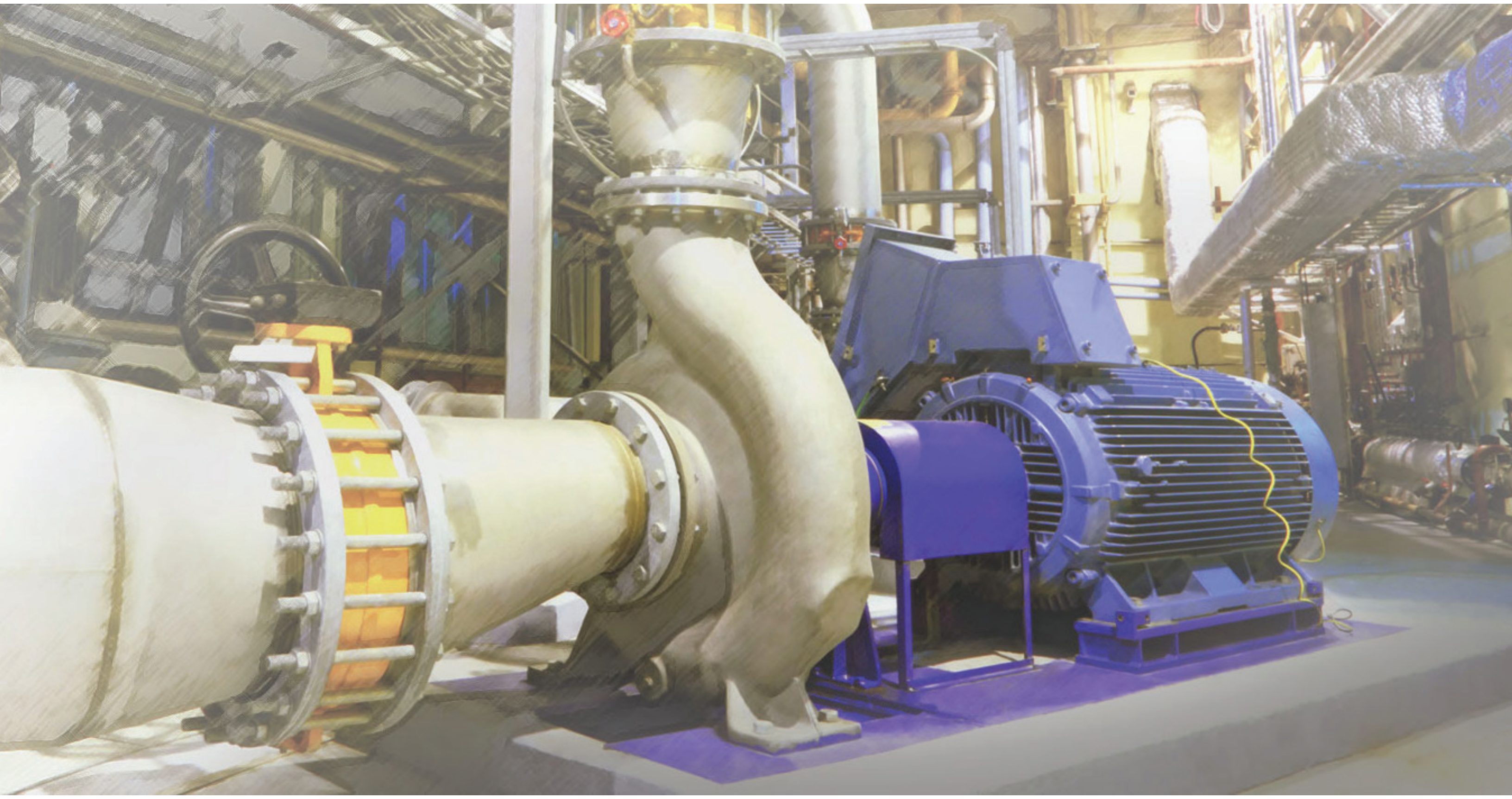
PSAP

Pump Systems Assessment Professional

Certification Study Guide



This Study Guide Includes:

- 100% coverage of the required knowledge areas
- Practice exam questions that match the format on the exam
- Work exercises with detailed explanations
- Test taking tips and strategies

Book

Online

PUMP SYSTEMS MATTER
Energy | Efficiency | Economics

PUMP SYSTEMS MATTER

Energy | Efficiency | Economics

Pump Systems Assessment Professional (PSAP) Certification Study Guide

Developed by Pump Systems Matter®

- *Includes practice exam with answers and explanations*
- *Covers all three domains of the PSAP Job Task Analysis*
- *Includes work exercises with detailed explanations for extra preparation*

📖 Book 🖱 Online

Published January 2018

1st Edition

Pump Systems Assessment Professional (PSAP) Certification Study Guide

Printed in the United States of America.

Published by:
PUMPS SYSTEMS MATTER
6 Campus Drive, First Floor North
Parsippany, New Jersey 07054-4406
USA
www.Pumps.org

Publication Data

Pump Systems Assessment Professional (PSAP) Certification Study Guide – 1st ed.

Includes bibliographical references and index.
ISBN 978-1-935762-70-6

It is not possible, nor is it the intent of this study guide, to cover all information and experience required for an individual to be able to successfully pass the pump system assessment certification exam. Therefore, this study guide does not contain a complete description of all information required to pass the pump system assessment certification exam, but covers knowledge areas that should be mastered by an individual through research and industry experience that are required to successfully pass the pump system assessment certification exam.

NOTICE

This publication was prepared by Pump Systems Matter. Neither Pump Systems Matter, its committees, nor any person acting on behalf of Pump Systems Matter a.) makes any warranty, expressed or implied, with respect to the use of any information, apparatus, method, or process disclosed in the publication or guarantees that such may not infringe privately owned rights; b.) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this publication. Pump Systems Matter is in no way responsible for any consequences to a user or anyone else resulting from reference to this guideline.

Current printing (last digit):
10 9 8 7 6 5 4 3 2 1

Printed on recycled paper

PUMP SYSTEMS MATTER

Energy | Efficiency | Economics

About Pump Systems Matter

Pump Systems Matter (PSM) is a nonprofit 501(c)3 educational affiliate of the Hydraulic Institute with the vision of being the leading training authority on pumps and pumping systems. PSM's mission is to provide product-neutral training on energy efficiency, reliability, economics, and effective application of pump systems. PSM currently offers over 20 courses relating to energy efficiency, pump technology, and systems in various formats, including classroom instruction, online webinars, and e-learning opportunities.

PSM partners with key groups, such as the energy efficiency community, utilities, engineering consulting firms, pump system users, the Hydraulic Institute, and other associations and government agencies. PSM strategically supports educating, encouraging, and creating incentives for end users and trade partners to adopt systems optimization products, services, and practices by building awareness that energy efficiency and reliability go hand in hand.

Pump Systems Matter
6 Campus Drive
1st Floor, North
Parsippany, NJ 07054
Phone: (973) 267-9700
Fax: (973) 267-9055
www.Pumps.org

Table of Contents

Introduction to pump systems assessment

Foreword

For more than 20 years the Northwest Energy Efficiency Alliance (NEEA) has worked to accelerate the adoption of more energy efficient products, services, and practices in Idaho, Montana, Oregon, and Washington. During this time NEEA has supported The Hydraulic Institute's efforts to improve the efficiency and reliability of the pumping systems market.

As part of transforming this market, NEEA is sponsoring the new Pump Systems Assessment Professional (PSAP) Certification, which will bring a new benchmark of knowledge to understanding and managing pump systems assessments. These assessments can be used to identify more opportunities to increase performance and reduce energy consumption of pump systems. PSAP certified professionals will be able to improve assessments for Level I, Level II and even Level III audits of pump systems.

Pump Systems Matter and the Hydraulic Institute created the following study guide to help its members prepare for the PSAP Certificate examination. NEEA is proud to support the Hydraulic Institute's efforts to reduce the energy consumption of the pumping systems market.

Geoff Wickes

Product Manager, Emerging Technology

Northwest Energy Efficiency Alliance

Introduction

The Hydraulic Institute™ serves member companies, engineering consulting firms, and pump users worldwide by developing and delivering comprehensive industry standards and technical resources. The Institute strives to continually expand industry's pump system knowledge base through education and tools for the effective application, testing, installation, operation, maintenance and performance optimization of pumps and pumping systems. For more information on the Hydraulic Institute, its member companies and partners, visit www.pumps.org.

Pump Systems Matter is a nonprofit educational organization established by the Hydraulic Institute along with leading utilities and energy efficiency organizations. Its mission is educate the industry on the benefits of pump systems optimization and energy efficiency to improve bottom-line savings of end-user companies.

Pump Systems Matter has created a study guide to support individuals preparing for **Pump System Assessment Professional (PSAP)** certification. The ***Pump Systems Assessment Professional (PSAP) Certification Study Guide*** synthesizes and summarizes the information required to prepare for the PSAP examination. From the practical to the underlying theories, this study guide covers the jobs and tasks required to perform formal pump system assessments including:

- Hydraulic System behavior and its effect on energy and reliability
- Pump performance characteristics and their relationship to overall system optimization
- Methods to identify, qualify and quantify potential energy and cost savings
- Techniques required to collect and analyze system data and recommend system improvements

The ***PSAP Certification Study Guide*** through the sample multi-choice test questions, concise explanations, study checklist, reference materials and test strategies can serve as a stand-alone, self-study resource or can be integrated into formal training program.

Ultimately, this guide will

- Highlight knowledge and skills required to become PSAP certified
- Identify individual strengths and weaknesses
- Establish a study plan to prepare for the PSAP Exam
- Provide a list of resources to expand the knowledge base
- Support and supplement the PSAP Body of Knowledge and continuous learning
- Build knowledge, confidence for a successful exam experience

About the Pump Systems Assessment Professional (PSAP) Exam

Eligibility for Certification

The PSAP Certification Program offered by the Hydraulic Institute (HI) outlines that applicants must meet the following eligibility requirements to take the Certification Examination:

- Applicants are required to possess an undergraduate degree from a regionally accredited university or college in a technical/business field. Acceptable degrees include physics, engineering, chemistry, science, mathematics, accounting, finance, and management. Other degrees will be considered, but require preapproval by the PSAP-CB.

Note: In lieu of an undergraduate degree, applicants must possess direct industrial or commercial fluid transfer and pumping systems professional experience with five or more years in a field/management positions and must have completed a minimum of seven pump systems assessments. Reports of seven of the completed pump systems assessments, including the name of the company/organization and completion date, must be submitted to HI.

- A minimum of three (3) years of professional pump/pumping systems experience.

Note: Applicants for the Certification Examination are NOT required to be a member of any organization for purposes of determining eligibility or pass any prerequisite course or workshop. However, knowledge of the ISO 14414 Standard is beneficial.

Certification Process

1. The applicant decides to apply for certification and determines whether he/she meets the eligibility requirements from their own perspective.
2. The applicant consults www.pumps.org, the certification website, for a digital copy of the application and the *Candidate Handbook*.
3. The applicant completes and submits an application. The certification management staff determines eligibility or contacts HI to resolve any questions. Staff reviews all applications to determine compliance with application requirements.
4. Once the eligibility notice is received, approved candidates are allowed to take the examination. Candidates may choose to take the exam on the dates offered by HI at an HI-sponsored test site, or make arrangements with an HI-qualified proctor at a mutually agreeable date and location. Candidates have one (1) year to successfully complete the examination upon receipt of the notice of eligibility from HI.
5. Candidates will be notified of their exam results within thirty (30) calendar days of their examination date. Candidates who successfully pass the exam will earn the PSAP certification.
6. Certified individuals are required to recertify every three (3) years in order to maintain certified status.

Certification Renewal Process

One of the hallmarks of a strong professional certification program is the implementation of a process to help assure the continuing competence of certificants in the discipline. HI has decided to use a Professional Development Hour (PDH) system similar to those used in other similar professional certifications (see table below).

HI also determined that a three (3) year recertification period is appropriate for this discipline taking into consideration various factors such as the following:

- Regulatory requirements and changes in codes/standards
- The nature and maturity of the pump assessment field
- Ongoing changes in technology and requirements for certificants
- Requirements of various interested parties

Professional development hours are measures used to quantify acceptable learning and professional service activities. Essentially, one PDH is the equivalent of one hour spent engaged in approved learning or other professional development work.

All certificants are required to achieve a total of 30 PDHs in the three (3)-year renewal period. The following chart describes various options for achieving the required PDHs along with any required minimum or maximum PDHs specified in each category.

All claimed PDHs must be submitted to HI prior to the conclusion of the certificants three-year renewal cycle. Certificants are reminded that they will not be able to claim more than the maximum PDHs allowed in any specific category.

Certificants are required to keep accurate records of all professional development activities including all certificates/letters confirming attendance/participation in approved education/training programs. HI will periodically audit a sample of certificants to verify the PDHs claimed in their renewal application.

PDH category	Description of policy	PDH points allowed
Participation in formal education/training programs provided on PSA topics	This option includes courses, seminars, and workshops on PSA-related issues (as defined in the Pump Systems Assessment Body of Knowledge).	1 PDH per each hour of instruction. Certificants must achieve a minimum of eight PDHs in this category during a 3-year renewal period.
Self-directed learning	This category includes reading articles and books or watching instructional videos on PSA issues.	1 PDH per each hour of self-directed learning. Note: Certificants cannot earn more than 10 hours in this category in a 3-year period.
Creating new PSA knowledge or content	Examples include authoring articles, books, newsletters, etc. PDHs are also awarded for serving as faculty at various learning events.	1 PDH is awarded for each hour spent in these activities.

PDH category	Description of policy	PDH points allowed
Volunteer service	Examples in this category including serving as a volunteer in HI or a related PSA organization, working on PSA meetings, or assisting the certification process.	1 PDH is awarded for each hour of volunteer service. Certificants cannot earn more than 10 hours in this category in a 3-year period.
PSA professional work experience	Full-time employment as a PSA practitioner[a] for a minimum of 1 year.	5 PDHs are awarded for each full year of employment as a PSA practitioner.

[a] To be considered a PSA practitioner, the certificant must have responsibility – either as a team leader or as a member of a team – for pump system assessments, or for key tasks of a pump system assessment.

The renewal process consists of the following steps:

1. Certificants are encouraged to maintain written or digital records of all recertification and professional development activities.
2. A reminder notice is sent to all certificants at least one year before the end of each recertification cycle.
3. All certificants are required to submit a recertification form along with a listing of all professional development activities and payment of required recertification fees. Recertification also requires reaffirmation of compliance with the code of ethics and all other certification policies.
4. HI certification staff review all documentation to determine compliance with recertification requirements and the achievement of required PDH activity.
5. A more detailed audit is conducted on a sample of all recertification applications. This audit requires that certificants provide some written documentation of all claimed PDH activity during the recertification cycle.
6. Staff sends a written notice to certificants successfully meeting recertification requirements informing them of continuing certification status. Certificants who fail to meet recertification requirements are informed of this finding and alternatives to maintain certification in the future.
7. Certification body records are updated to reflect the current certification status of all individuals who are required to demonstrate conformity with recertification requirements.

Special Examination Arrangements

- HI complies with the Americans with Disabilities Act (ADA). HI strives to ensure that no individual with a documented disability is deprived of the opportunity to take the certification examination solely by reason of that disability provided that reasonable special accommodations can be made.

To request special accommodations, candidates must complete the request for Candidate Accommodations as part of the application process. The request includes a statement of the accommodations and a history of previous accommodations in education, training, or assessment circumstances. In the absence of a history of previous accommodations, an appropriate, qualified health-care provider must submit the Health Care Professional Accommodations form along with a copy of their professional evaluation. The professional evaluation must include a description of the assessment of disability along with positive findings. These forms are available on the certification website. Candidates must provide all of this documentation with their application and fees at least

45 days prior to a desired examination date. HI also requires that applicants notify HI of any requests for special accommodations when calling to schedule examinations.

Examination Administration

1. Positive identification is required of all candidates prior to admission to a test site. Government issued photo IDs are the preferred method of identification.
2. Candidates MUST have a reviewed application on file in order to sit for the examination.
3. Candidates taking examinations shall be monitored at all times by proctors according to procedures stated in the Proctor Manual. Candidates are prohibited from using any unauthorized test aids in their examination process. Use of unauthorized aids can result in disciplinary action that can include permanent exclusion from certification eligibility.
4. Rules of conduct for examinees are reviewed by proctors prior to each examination.
5. All examination materials are sent to and returned from test sites using traceable means and following strict security procedures. Staff and volunteer access to examination materials is limited to the Certification Manager, designated HI volunteers, and officially designated proctors for a specific examination administration.
6. Formal reports are to be filed regarding all testing irregularities and security breaches.
7. All examination materials are the sole property of HI. Examination materials are not available for review by candidates before or after the examination.
8. The sharing or reporting of the substance of any HI examination content, orally or in writing, with anyone, including other candidates, employers or course instructors is prohibited.
9. No visitors are allowed at examination sites other than officially designated HI observers.
10. Failing candidates are only permitted to retake the examination two (2) additional times during the first year following the approval of the application.
11. Passing candidates are not allowed to take the exam again.
12. All candidates must agree in writing not to release confidential examination materials or participate in fraudulent test-taking practices.

Results Notification

1. Candidates will receive results via email within 30 calendar days of the exam date.
2. No examination scores will be given to passing candidates. PASS/FAIL status only will be provided.
3. Candidates who are unsuccessful will receive a report indicating performance in the major content areas assessed by the examination.
4. Certification status shall not be granted to applicants/candidates until all certification requirements are fulfilled.

Nondiscrimination

HI does not discriminate among candidates on the basis of race, color, creed, gender, age, religion, national origin, ancestry, disability, military discharge status, sexual orientation, or marital status. HI strives to adhere to all federal, state, and local regulations pertaining to nondiscrimination practices.

HI implements its policies and procedures in a fair and impartial manner among all applicants, candidates, and certificants.

Test-taking Skills and Strategies

Before the Exam

This study guide is an excellent way to review core concepts related to the Pump Systems Assessment Professional exam. Another resource for exam preparation is the Pump Systems Assessment: Body of Knowledge (BOK).

The BOK outlines and describes the specific tasks and knowledge applied by professionals when conducting a Pump Systems Assessment to identify high-value pump systems opportunities and achieve greater energy efficiency and improved pump system reliability. It is intended to serve as an overview of the knowledge areas in which the professional should be proficient to appropriately and successfully conduct a Pump Systems Assessment. The BOK also provides the Pump Systems Assessment professional with a guideline, or starting point, for determining his or her readiness to take the Pump Systems Assessment Professional Master Certification exam.

In preparation for the PSAP exam, remember to

- Review concepts that you need to understand better
- Make a study timeline covering several weeks or months, and stick to it
- Test your knowledge by taking the practice exam
- Get plenty of rest the night before the exam
- Be confident in your knowledge and abilities

On Exam Day

- Arrive at the testing center 15 minutes prior to the scheduled exam time in order to check in
- Bring a government-issued form of identification
- No personal items, such as purses, wallets, or cell phones are allowed in the testing area
- You will be provided with materials to perform calculations or take notes
- You will be provided with a physical calculator. You may also use your own nonprogrammable calculator
- All materials must be returned to the proctor at the end of the examination
- The maximum time allowed for the examination is three and half (3½) hours

After the Exam

After completing the exam, candidates will receive results via written letter within 20 business days of receipt of the answer sheets by the psychometrician consultant. The score report will indicate “pass” or “fail.” A certificate will be sent to passing candidates within six to eight weeks. Failing candidates will be provided with additional information indicating performance in the major content domains assessed by the examination. Failing candidates will also be notified of retake options and procedures.

Candidates who received failing scores may request a hand scoring of their answer sheet. A $75 fee will be charged for this service. Information about hand scoring will be included with the candidate’s score report and in the candidate handbook. Requests for hand scoring of answer sheets must be received no later than 30 days following the release of examination results.

Certificants must renew their certification within a three-year time period from the date of the written letter confirming certification status.

PSAP Exam Sample Test – Answer Sheet

1. Ⓐ Ⓑ Ⓒ Ⓓ
2. Ⓐ Ⓑ Ⓒ Ⓓ
3. Ⓐ Ⓑ Ⓒ Ⓓ
4. Ⓐ Ⓑ Ⓒ Ⓓ
5. Ⓐ Ⓑ Ⓒ Ⓓ
6. Ⓐ Ⓑ Ⓒ Ⓓ
7. Ⓐ Ⓑ Ⓒ Ⓓ
8. Ⓐ Ⓑ Ⓒ Ⓓ
9. Ⓐ Ⓑ Ⓒ Ⓓ
10. Ⓐ Ⓑ Ⓒ Ⓓ
11. Ⓐ Ⓑ Ⓒ Ⓓ
12. Ⓐ Ⓑ Ⓒ Ⓓ
13. Ⓐ Ⓑ Ⓒ Ⓓ
14. Ⓐ Ⓑ Ⓒ Ⓓ
15. Ⓐ Ⓑ Ⓒ Ⓓ
16. Ⓐ Ⓑ Ⓒ Ⓓ
17. Ⓐ Ⓑ Ⓒ Ⓓ
18. Ⓐ Ⓑ Ⓒ Ⓓ
19. Ⓐ Ⓑ Ⓒ Ⓓ
20. Ⓐ Ⓑ Ⓒ Ⓓ
21. Ⓐ Ⓑ Ⓒ Ⓓ
22. Ⓐ Ⓑ Ⓒ Ⓓ
23. Ⓐ Ⓑ Ⓒ Ⓓ
24. Ⓐ Ⓑ Ⓒ Ⓓ
25. Ⓐ Ⓑ Ⓒ Ⓓ

PSAP Exam Sample Test

Sample Test Directions

You will have 50 minutes to complete the following 25 questions. For each question, select the choice that BEST answers the question.

Remember, this sample test should be used to help you determine which areas require additional review. Each question represents a particular Domain of the Pump Systems Assessment Job Task Analysis (JTA).

You should be able to correctly answer all 25 questions on this sample test. Questions with incorrect answers should be reviewed further to ensure comprehension of the underlying topics.

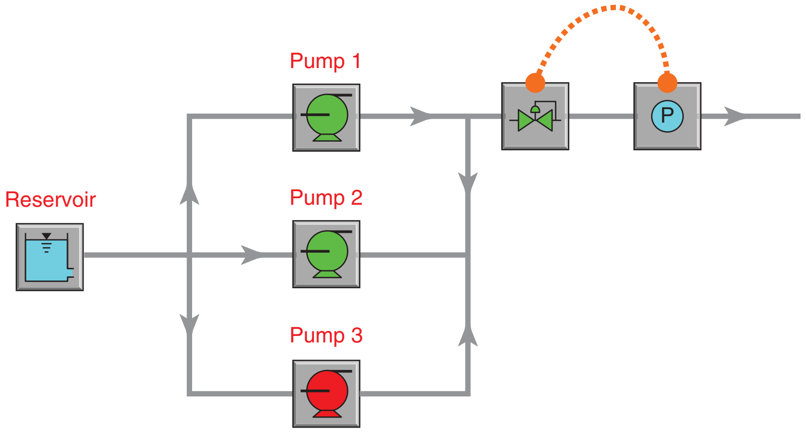
1. The control valve in the system below is normally operating only 20% open. What is the opportunity to save energy by optimizing this system?

a) Reduce the pump head, allowing the control valve to operate more closed

b) Increase the pump head, allowing the control valve to operate more closed

c) Reduce the pump head, allowing the control valve to operate more open

d) Increase the pump head, allowing the control valve to operate more open



2. The power required to drive a centrifugal pump is directly proportional to

a) The cube of its impeller diameter.

b) Its impeller diameter.

c) The square of its impeller diameter.

d) The square root of its impeller diameter.

3. Which of the following is the BEST method of direct, nonintrusive flow measurement in a pump system with clean water?

a) Doppler ultrasonic flowmeter

b) Transit-time ultrasonic flowmeter

c) Orifice plate

d) Coriolis flowmeter

4. Per the ISO/ASME 14414 standard, a Level 3 pump system assessment should involve Level 2 capabilities and knowledge, plus

a) The ability to analyze how flow rate, pressure, and power consumption vary with time using histograms and duration diagrams.

b) The skills to assess the plant pump population to determine which pump systems are the best targets for further study.

c) The ability to analyze which systems have a variable flow rate and/or a head that does not operate in a steady state under normal conditions.

d) The skills to identify the static head and decide which pump systems are the best candidates for applying variable speed drives to achieve energy reduction.

5. A pump supplies a 65% slurry of organic solids through a 4-in. pipeline to the furnace. In order to improve measurement accuracy and, thereby, combustion efficiency, the facility plans to remove the installed refractometer and install a new flowmeter. Which of the following flow technologies would be the best fit for this application?

a) Differential pressure

b) Magnetic

c) Vortex

d) Coriolis

6. A centrifugal pump in a closed loop is controlled by a flow control valve that is downstream of a filter. If the control valve continually opens wider over a period of a year, what is most likely the cause?

a) The control valve is wearing

b) The filter is becoming fouled

c) The pump is losing efficiency

d) The motor is losing efficiency

7. A 75 hp electric motor has a nameplate full-load efficiency of 89.5%. Assuming full-load conditions and annual run-time of 6000 hours, what would be the simple payback of replacing the motor with 94.1% premium efficiency motor? Use energy cost of \$0.10 per kW·h and motor acquisition cost of \$10,000.

a) 5.4 years

b) 9.8 years

c) 6.5 years

d) 12.5 years

8. The hydraulic efficiency of a variable speed pump can be improved by

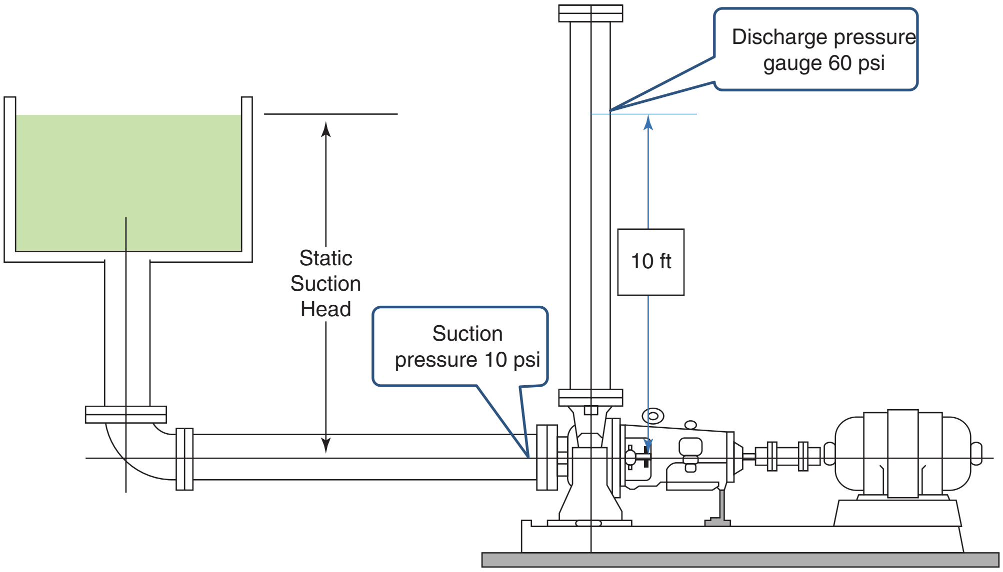
a) Increasing the ramp rate to reach full speed.

b) Using a voltage regulator.

c) Resetting the impeller clearances.

d) Using dead-band control to regulate motor amperage within a ±10% range.

9. Ignoring piping frictional losses, what is the total head (*H*) of the pump below with fluid SG = 1, flow rate of 1000 gpm, suction piping 6-in. ID and discharge piping 4 in. ID?



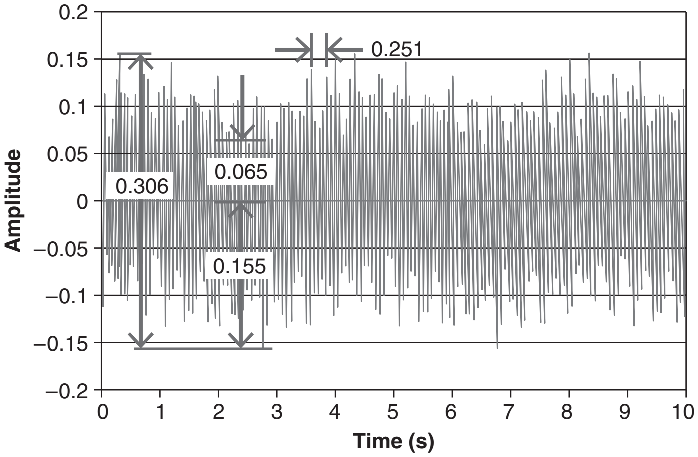
a) 115.5 ft

b) 125.5 ft

c) 133.6 ft

d) 148.6 ft

10. In the time waveform signature below, what value represents the RMS vibration?



a) 0.065

b) 0.155

c) 0.251

d) 0.306

11. Increased temperature in a pumped fluid across a centrifugal pump at constant speed is an indication of what condition?

a) High flow runout condition

b) Low flow condition outside AOR

c) Operating at maximum motor load

d) Pump is cavitating

12. A centrifugal pump is pumping 70 °F water and operating at 3000 gpm at 120 ft, 80% efficiency, and 1200 rpm. Due to process demand increases, the pump is to have a speed increase to 1400 rpm. Assuming the efficiency is unchanged, what size motor will be needed to drive the pump at the new speed?

a) 125 hp

b) 150 hp

c) 200 hp

d) 250 hp

13. Without any direct method for measuring capacity, what is the best method for estimating the pump capacity for a low specific speed pump?

a) Speed and fluid temperature rise

b) Power and suction pressure

c) Motor slip and pump differential pressure

d) Power and total head

14. What is the most important section to include in an assessment report when presenting to management?

a) System(s) studied and significant issues

b) Executive summary

c) Detailed calculations

d) Performance improvement opportunities and prioritization

15. Pumps operating in parallel should have approximately matching

a) Shut-off heads

b) Best efficiency points

c) Maximum flow rate characteristics

d) Allowable operating regions

16. Hydraulic efficiency and operational reliability are NOT substantially reduced when operating a pump at its

a) Runout condition

b) Allowable operating region (AOR)

c) Minimum continuous stable flow (MCSF)

d) Preferred operating region (POR)

17. Excessive pump nozzle loads will most likely lead to

a) Pump casing failure

b) Pump cavitation

c) Reduced pump efficiency

d) Mechanical seal and bearing failures

18. When unscheduled repairs, including shaft failures, occur on a regular basis, what course of action should be implemented?

a) Shaft failure analysis

b) Bearing failure analysis

c) Root cause failure analysis

d) Field pump performance test and energy analysis

19. During what operating condition does a pump mechanical seal face the greatest chance of damage?

a) Process flow change

b) Uncontrolled pump start-up and shut-down

c) Operation outside of the preferred operating region (POR)

d) Operation with the minimum required NPSH margin

20. A new constant speed positive displacement pump system unloading viscous oil from a rail car is drawing more power than expected, while a constant discharge pressure of 100 psig is controlled with a bypass line. What is the likely cause of the increased power?

a) The bypass valve is allowing more flow to recirculate than expected.

b) The oil is less viscous than expected.

c) There is more friction head loss in the suction piping than expected.

d) The pump differential pressure is lower than expected.

21. For reciprocating pumps, what term needs to be considered when evaluating the net positive inlet pressure available to the pump, which is not considered with rotary pumps?

a) Atmospheric pressure

b) Acceleration pressure

c) System discharge pressure

d) System suction pressure

22. The amount of slip in a rotary positive displacement pump is primarily affected by

a) Fluid properties and differential pressure

b) System discharge pressure and fluid viscosity

c) System discharge pressure and speed

d) Fluid viscosity and speed

23. A rotodynamic pump is operating in a closed system with the following related conditions:

- Liquid level above pump centerline: 15 ft
- Suction vessel pressure at top of liquid level: 10 psia
- Suction friction losses: 2.0 ft
- Liquid vapor pressure: 5.4 psia
- Atmospheric pressure: 14.7 psia
- Liquid specific gravity: 0.8
- Suction velocity head: negligible
- Suction nozzle: 8-in. ID

What is the system NPSHA?

a) 21.3 ft
b) 23.5 ft
c) 26.3 ft
d) 57.5 ft

24. Calculate the hydraulic efficiency of a flooded suction pump, pumping 70 °F water, using the following field measured conditions:

- Current: 71.1 A
- Voltage: 482 V
- Power factor: 0.9
- Flow: 2500 gpm
- Suction pressure: 2.8 psig (12 inch ID at measurement)
- discharge pressure: 29.9 psig (12 inch ID at measurement)
- Motor efficiency: 93%
- VFD efficiency: 97%

a) 56%
b) 61%
c) 72%
d) 74%

25. What type of throttling valve is LEAST likely to result in a water hammer system condition when opening or closing?

a) Ball valve
b) Butterfly valve
c) Gate valve
d) Globe valve

PSAP Exam Sample Test – Answer Key

1. C
2. A
3. B
4. A
5. D
6. B
7. A
8. C
9. C
10. A
11. B
12. C
13. D
14. B
15. A
16. D
17. D
18. C
19. B
20. C
21. B
22. A
23. C
24. B
25. D

PSAP Exam Sample Test Correct Answer Explanations

1. The system shown represents centrifugal pumps with a valve controlling a pressure set point. If the control valve is only 20% open normally, the head of the pumps are higher than that needed to meet the normal system demand. The head loss across the control valve could be reduced if the pump head is reduced resulting in a more open normal valve position (less head loss across valve) to meet the pressure set point. The system is optimized by reducing energy consumption across the valve and reducing potential valve maintenance. Therefore, “c” is the correct answer.

2. Per the affinity rules, flow (Q) is directly proportional to impeller diameter (D), and head (H) is proportional to the square of diameter. The resulting power (P) draw is the combination of flow and head, or cube of diameter; therefore, “A” is the correct answer.

$$Q_2 = Q_1 \frac{D_2}{D_1} \quad H_2 = H_1 \frac{D_2^2}{D_1^2} \quad P_2 = P_1 \frac{D_2^3}{D_1^3}.$$

3. Answers “a” and “b” are both ultrasonic nonintrusive flowmeters that can be strapped onto the outside of a pipe. The Doppler ultrasonic flowmeter requires particles or bubbles to reflect the ultrasonic signals and is best suited for dirty or aerated liquids such as wastewater and slurries. A significant amount of solids or bubbles in the liquid will weaken the signal emitted by the transit-time ultrasonic flowmeter; therefore, it is best used with clean liquids such as water or oil. Additionally, transit-time meters typically can achieve better accuracy than Doppler meters; therefore, since the application is for “clean water” with no mention of aeration or solids, the transit-time flowmeter is preferred, and answer “b” is correct.

4. ISO/ASME outlines the requirements for pumps system energy audits. Three levels of assessment are defined as follows:

   - A Level 1 assessment is a qualitative review with possible quantitative elements intended to determine the potential for significant energy savings based on further assessments and to identify specific systems that merit a greater level of attention.

   - A Level 2 assessment is a quantitative review intended to determine energy consumption and potential savings based on measurement of a single steady state operating condition requiring a single set of measurements.

   - A Level 3 assessment is a quantitative review that takes varying system demands into account by monitoring the system over a time span long enough to capture the various operating conditions which require their own set of measurements.

   Since a Level 3 assessment requires documenting a variable system over a period of time, answer “a” is correct.

5. For a furnace or boiler combustion fuel, mass flow is preferred. Of the flowmeters listed, the Coriolis type is the only one that is a direct mass flowmeter and can achieve the best accuracy of the meters listed. Therefore, “d” is the correct answer.

6. In a closed system, the system head is made up of primarily the friction head. A control valve gradually opening wider is an indication that there is additional friction head in the system that is not related to the control valve. Since the filter is a component designed to capture particles, it is prone to clogging and is the most likely source of the additional friction. Therefore, “b” is the correct answer.

7. Simple payback is calculated by dividing the investment upgrade cost by annual savings that result from the investment. Using the pump nameplate power given, you can calculate motor input power by dividing it by the motor efficiency. Energy cost is billed in kW·h so you also need to convert input power to kW by multiplying it by the conversion constant 0.746 kW per hp. Once you know the motor power input in kW, you can subtract the two values to determine the power savings of the motor in kW. You then multiply the power savings by operating hours per year and the cost of electricity to determine the cost savings per year of the more efficient motor. Simple payback is then determined by dividing the investment cost by the annual cost of electricity savings. The calculation steps are detailed below, showing that “a” is the correct answer.

- 75 hp × 0.746 kW/hp ÷ 0.895 = 62.5 kW
- 75 hp × 0.746 kW/hp ÷ 0.941 = 59.4 kW
- 62.5 kW – 59.4 kW = 3.1 kW
- 3.1 kW × 6000 hours/year × $0.10/kW·h = $1860/year
- $10,000 ÷ $1860/year = 5.4 years

8. The hydraulic efficiency of a pump independent of the operating flow is dependent on volumetric losses, such as leakage flow across wear rings or, for open impellers, the axial gap between the impeller and the casing. Resetting the wear-ring clearance or resetting the axial gap between the impeller and pump casing will reduce the volumetric losses and improve pump hydraulic efficiency. For these reasons, “c” is the correct answer.

9. If friction loss in the pipe up to the pressure measurement is being neglected, the total head developed by the pump is calculated by three terms as follows: (1) differential static pressure rise across the pump, converted to feet, (2) velocity head difference between the measurement points, and (3) the elevation gauge correction to the pump centerline datum. The equation provided below details the summation of each term (1, 2, and 3).

Note:

- The 1 and 2 subscripts represent the suction and discharge measurement points, respectively.
- Velocity head (h_v) is calculated at each measurement point by calculating the velocity in the pipe in feet per second and dividing the square of velocity by two times the acceleration of gravity in feet per square second.

- The constant 2.31 is to convert psi to feet of liquid with a specific gravity of 1.0
- The constant 0.4085 is used to convert flow in gpm to feet per second when the ID of the pipe is in inches.

As detailed in the calculation, "c" is the correct answer.

- H (ft) = $((P_2 - P_1) * 2.31 \div SG) + (h_{v2} - h_{v1}) + (Z_2 - Z_1)$
- $P_2 = 60$ psig
- $P_1 = 10$ psig
- $Z_2 = 10$ ft
- $Z_1 = 0$ ft
- $h_v = v^2 \div (2 * g)$
- v = gpm x 0.4085 ÷ pipe inside diameter^2
- $g = 32.2$ ft/s^2
- $h_{v2} = (1000 * 0.4085 \div 4^2)^2 \div 2 * 32.2 = 10.1$ ft
- $h_{v1} = (1000 * 0.4085 \div 6^2)^2 \div 2 * 32.2 = 2$ ft
- $H = ((60 - 10) * 2.31 \div 1.0) + (10.1 - 2) + (10 - 0) = 133.6$ ft

10. For a pure sine wave, RMS amplitude equals 0.707 times peak amplitude. In more complex waveforms, as is shown in the figure, it is a measure of the "average" amplitude. Average is in quotes because the RMS takes each point in the waveform, squares it, adds them all together, takes the arithmetic mean, and then takes the square root of that number. If you want to think of it another way, it is the average energy in the waveform over time. For complex time wave forms, the calculation of RMS amplitude is done by the analyzer used to measure it and is not done by hand. In the figure, 0.306 indicates peak to peak, 0.155 indicates from 0 to peak, 0.065 indicates from 0 to an average of the amplitude, and 0.251 indicates the period of two amplitude peaks. The only measurement that is an average representation of the amplitude is 0.065. Therefore, answer "a" is correct.

11. The fluid temperature rise across the pump depends on the mass flow rate and the amount of power imparted to the fluid (Δtemp = power ÷ [mass flow rate * specific heat]). As flow is reduced below the AOR, the hydraulic efficiency is reduced. The reduced hydraulic efficiency results in additional power being imparted into the fluid. Additionally, when volume flow rate is reduced, the mass flow rate is reduced. Evaluating the formula, if the power is increased and the mass flow rate is reduced, the temperature will increase. Therefore, answer "b" is correct.

12. To determine the power required at the higher speed, the pump input power (P) must be calculated for the original condition as

P_1 = flow × head × SG ÷ 3960 ÷ eff = 3000 gpm × 120 ft ÷ 1.0 ÷ 3960 ÷ 0.8 = 113.6

Note: A specific gravity of 1.0 is used for water at 70 °F and 3960 is a constant that incorporates two conversions, (1) convert flow (gpm) to pounds/minute, and (2) convert the product of mass flow and head (pound-foot/minute) to horsepower.

Once the pump's original input power is known, use affinity rules to determine pump input power required at 1400 rpm

$$P_2 = P_1 \frac{N_2^3}{N_1^3}$$

P_2 = 113.6 × (1400 rpm ÷ 1200 rpm)^3 = 180.4 hp

Motors are rated based on the power delivered to the shaft, sometimes called shaft power or brake horsepower (BHP). This is the power available at the output of the motor and is delivered to the pump shaft. Therefore, the rated motor power must be greater than 180.4 hp. Since answer "c," 200 hp, is the answer that is the lowest rated power greater than 180.4 hp, it is the correct answer.

13. Low specific speed pumps generally have a relatively flat head capacity curve and a continually rising pump input power curve. Using manufacturer curve or certified curve performance data for the pump and motor and comparing the measured pump total head and pump input power is the best method to estimate the flow rate of the pump for a low specific speed pump when a direct measurement cannot be made. Two measurements are required to cross validate one another. Therefore, answer "d" is correct.

14. The executive summary of the assessment report should condense and summarize the report in brief for the management who will need to be informed of the project as a whole with overall opportunities and benefits. Therefore, answer "b" is correct. Answer "d" would be second in importance, as it provides information on the opportunities and savings potential, but may be in more detail than is required for facility management. The executive summary should provide an overview of

a) facility background, products made, and operating cost/avoidance objectives

b) objectives and scope of the assessment

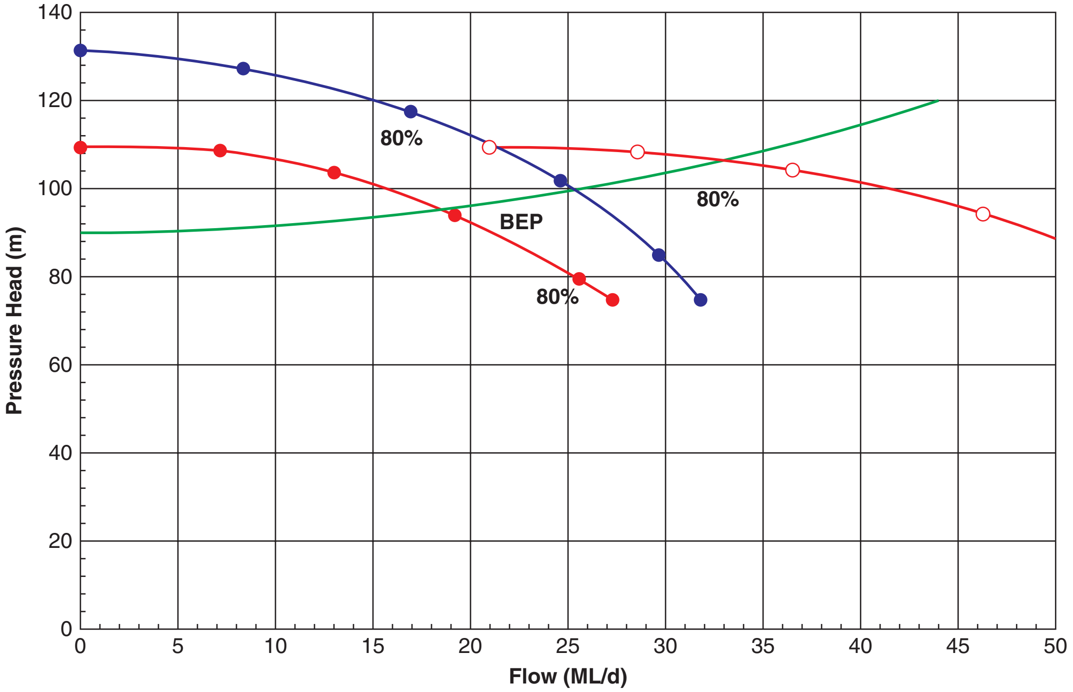
c) system(s) assessed and measurement boundaries used

d) annual operating costs

e) performance opportunities identified, with associated operating cost savings

g) list of recommendations to accomplish the estimated operating cost savings

15. When pumps are added in parallel, the combined pump head capacity curve changes by adding flow at a constant total head. Each individual pump will contribute a portion of the total flow based on where the system head curve intersects the combined parallel pump head capacity curve. As shown in the figure below of two pumps with differing shut-off heads, the combined parallel pump curve does not change shape until the head is below the shut-off head of the lower pump curve. The pump system will operate where the system curve intersects the "combined" parallel pump curve, and if the system head is not controlled below the lower shut-off head pump's total head, the higher shut-off head pump will contribute most or all of the flow to the system and the lower head pump could operate at a low flow or deadhead flow condition. Therefore, "a" is the correct answer. If the pumps have significantly differing shut-off heads and the system head is not controlled below the lower shut-off head pump's total head, the higher shut-off head pump will contribute most or all of the flow to the system and the lower head pump could operate at a low flow or deadhead flow condition.



16. As defined in industry standard ANSI/HI 9.6.3 *Rotodynamic Pumps – Guideline for Operating Regions*, the preferred operating region (POR) is a range of rates of flow to either side of the pump's best efficiency point within which the hydraulic efficiency and the operational reliability of the pump are not substantially degraded. Within this region, the design service life of the pump will not be affected by the internal hydraulic loads or by flow-induced vibration. Operating a pump within the POR ensures higher reliability and lower energy consumption. Therefore, "d" is the best answer.

17. Answer "d" is the best answer because excessive nozzle loads on the pump flanges will cause casing distortion that will preload the pump bearing housing and cause the pump shaft to deflect at the bearing/coupling location. This causes additional loading of the bearings during operation and deflection at the shaft seal, both of which result in premature failure. Additionally, the rotating element could contact the distorted casing and cause additional loading to the bearings and seal. Excessive nozzle loads could also result in answer "a – pump casing failure." However, this occurs in extreme cases and is not as common as the resultant seal and bearing failures.

18. Answer "c" is the best answer because a root cause failure analysis (RCFA) is a multistep, multidisciplinary process that is conducted to drive down and determine the base reason for the failures. The other answers may be conducted as part of a RCFA, but may be incomplete in determining the base cause or multiple contributing factors to the failure.

19. Answer "b" is the best answer because unexpected or uncontrolled starts/stops of the pumping system result in transient conditions where the mechanical seal can be subject to additional uncontrolled loading, deflection, flashing, dry running, etc., which can result in rapid seal failure. Process changes, minimum NPSH margin, and operation outside the POR could also contribute to seal failures, but they are typically done in a controlled manner that considers the mechanical sealing system.

20. Positive displacement pumps deliver a relatively constant flow rate over a range of differential pressures when the speed is held constant. The power consumption of the positive displacement pump is a function of the flow rate and the differential pressure the pump must overcome. Since the flow rate of the constant speed pump will be relatively constant, a higher than expected differential pressure is the most likely cause of the new pump drawing excessive power. The question states that the discharge pressure is controlled to 100 psi, but it does not indicate the suction pressure. Of the answers provided, the most likely cause of higher differential pressure is that the suction piping leading to the pump has high friction head losses, requiring the pump to provide flow against more differential pressure than expected and the resulting power consumed is greater than expected. Therefore, answer “c” is the best choice.

21. Reciprocating pumps are different than rotary pumps because reciprocating pumps start and stop the flow of fluid with every rotation of the shaft. This requires accelerating the fluid with every rotation of the shaft and results in a pressure pulsation, which does not occur with rotary positive displacement pumps. Per ANSI/HI reciprocating pump standards covering power pumps, direct-acting pumps, and controlled volume metering pumps, this acceleration pressure needs to be accounted for in the NPIPA calculation of reciprocating pumps to ensure that the fluid does not flash prior to entering the pump. Therefore, answer “b” is correct.

22. Slip is the quantity of fluid that leaks through internal clearances of a rotary pump per unit of time. It is dependent upon the internal clearances, the differential pressure, the characteristics of the fluid handled, and, in some cases, the speed. Answer “a” is the best answer because differential pressure and the fluid handled are the primary dependent variables. Answer “d” is a good answer as well, but less so than answer “a” because speed is not always a primary variable that impacts slip.

23. To determine the NPSHA for this system, the total suction head needs to be determined. The question indicates that the velocity head can be neglected, so that portion of the total suction head calculation is omitted. The question also indicates that it is a closed system and the pressure at the liquid level of the suction vessel is given as an absolute pressure; therefore, the atmospheric pressure given can be ignored. The NPSHA is determined by the absolute pressure difference between the pressure in suction vessel and the fluid vapor pressure (converted to feet of the liquid pumped), plus the fluid level above the pump centerline, minus the friction losses in the suction line, as follows:

$$\text{NPSHA} = [(10 \text{ psia} - 5.4 \text{ psia}) \times 2.31 \text{ ft/psi} \div 0.8] + 15 \text{ ft} - 2 \text{ ft} = 26.3 \text{ ft}$$

Therefore, answer “c” is correct.

24. To calculate the hydraulic efficiency, the hydraulic power and pump input power need to be determined. To determine the hydraulic power, the following calculation is used:

$$\text{Hydraulic power } (P_u) = 2500 \text{ gpm} \times (29.9 \text{ psi} - 2.8 \text{ psi}) \times 2.31 \text{ ft/psi} \times 1.0 \div 3960 \times 0.746 \text{ kW/hp} = 29.5 \text{ kW}$$

Note: A specific gravity of 1.0 is used for water at 70 °F and 3960 is a constant that incorporates two conversions (1) convert flow (gpm) to pounds/minute, and (2) convert the product of mass flow * head (pound-foot/minute) to horsepower.

To determine pump input power, the electrical input power needs to be calculated, and the pump input power is calculated by factoring the motor and VFD efficiencies, as follows:

Pump input power (P) = 482 Volts × 71.1 Amperes × 0.9 * $\sqrt{3}$ ÷ 1000 (watt/kW) × 0.93 × 0.97 = 48.2 kW

Hydraulic efficiency is determined by taking the ratio of hydraulic power and pump input power, as follows:

Efficiency (η) = 29.5 ÷ 48.2 × 100 = 61%

Therefore, answer "b" is the correct answer.

25. When pumps start or stop, or when the momentum of the fluid in the piping is changed by any other means (like opening or closing a valve rapidly), a pressure wave is formed. The pressure wave can be either above or below the normal pressure in the piping. These pressure waves are called "surge pressures" or "water hammer" (when water is the fluid), and their magnitude can be sufficient to burst or collapse piping, valves, machinery casings, and other devices. Of the valves noted, butterfly and ball valves are one-fourth turn to full open/close and therefore can be closed or opened very quickly, resulting in rapid change in momen-tum of the fluid. Gate valves and globe valves are both continuously rising stem valves that take longer to open and close, resulting in less rapid change of momentum of the fluid. Additionally a globe valve has a higher full open "*K*" value that dissipates energy. Therefore, a globe valve is the least likely valve to result in a water hammer condition, so answer "d" is the best answer.

Domain I

Information/Data Gathering **36%**

- ➢ Task 1: Assess the present situation and determine if it is amenable to a pump system assessment (i.e., jointly determine the value proposition/objectives).
- ➢ Task 2: Obtain and analyze initial information about the pump system (i.e., perform prescreening).
- ➢ Task 3: Assemble a pump system assessment team and define roles and responsibilities.
- ➢ Task 4: Make a visual assessment of the pump system, or have the plant verify the accuracy of the information provided, in order to confirm initial information, obtain additional information, and make a final determination of the project scope.
- ➢ Task 5: Conduct a pump systems operation discussion with personnel in a position to answer questions, verify information previously obtained, and provide additional information.
- ➢ Task 6: Obtain real-time pump system operation data.

Learning Objectives

- ○ Be able to identify the various types of pumps and pump system components.
- ○ Understand pump system component interactions and operating procedures.
- ○ Identify the benefits of pump system optimization.
- ○ Understand factors that affect pump and pump system efficiency and reliability.
- ○ Understand the various elements of lifecycle costing and perform lifecycle cost analysis.
- ○ Understand basic pump maintenance practices.
- ○ Be able to read and understand isometric drawings, process flow diagrams, and blueprints.
- ○ List key plan personnel required on an assessment team and the key roles and responsibilities of the team.
- ○ Understand field measurement parameters and their acceptable ranges.
- ○ Understand and apply hydraulic and electrical formulae.
- ○ Be able to identify measuring devices and understand their requirements for proper applications.
- ○ Identify common operating problems and errors.

Introduction to Pump Systems Assessment

The chapters of this study guide provide information related to the required tasks and knowledge areas to conduct a pump systems assessment. When learning about each knowledge area, it is important to have an understanding of what it takes to implement a pump systems assessment. The tasks outlined in the Job Task Analysis (Appendix A) describe in detail the 13 steps, or tasks, required in conducting a pump systems assessment, as well as the knowledge requirements for each step. This introduction provides a consistent but simplified action plan that the student should be familiar with prior to learning the more detailed requirements. When implementing a pump systems assessment, the tasks can be simplified to a six-step action plan, as follows.

Pump Systems Assessment Action Plan

1. Prescreen and prioritize your pumping systems to identify good performance improvement candidates.
    - Step 1a – Obtain buy-in from management to support assessing and improving the highest priority pumping systems.
2. Work with an appropriate pumping system specialist and/or in-house team to gather and analyze additional data (develop the assessment team).
3. Identify and economically validate improvement opportunities, through level 1, 2, or 3 assessments, as appropriate.
4. Document actions and report results to management with a prioritized implementation strategy.
5. Implement optimization and perform a postimplementation assessment.
6. Repeat the Action Plan process for other good candidate systems.

Step 1 – Pump screening

Before the first step is undertaken, management support should be obtained for screening the pumps to identify the highest priority systems. Screening and prioritizing the pumping systems to identify the best performance improvement candidates is important because plants have many pumps – sometimes thousands – and screening provides a methodical approach to identify the best opportunities to work on.

The pump systems screening process can be broken down into two areas: prescreening and postscreening. During prescreening, use a pump system basic assessment guide form and checklist. Then, conduct the on-site inspection to gather data. From there, conduct a data analysis to prioritize opportunities. Based on the results, choose pumps for further analysis. This leads into the postscreening process. Work with your pumping system specialist or in-house team to gather and analyze system data. Develop economic justification and identify performance opportunities.

The prescreening form should target all the plant systems that are of interest to be optimized, with the following information:

- List of pumps
- Pump description
- Installed motor horsepower
- Yearly operational hours

- Control methods
- Maintenance records

In addition, the following information should be documented:

- Pump operating parameters (including power/current, flow, pressure)
- Cavitation at pump or in system
- Load over the full range of operations
- Equipment information (such as service type, time in service, shared duty, and voltage)
- Overall installation
- Typical flow rates and variations
- Duration diagrams
- Maintenance costs
- Process and instrument diagrams

Prioritize opportunities from the prescreening process by ranking pumps with the best performance opportunities and focusing on their energy use and maintenance problems.

Step 1a – Obtain buy-in to further assess and improve the performance of the highest priority pumping systems.

The first step is to get management support for improving the highest priority pumping systems. Take a business approach by presenting the purpose of the assessment to management. Explain performance opportunities and associated energy and cost savings. The assessment professional should provide an overview of the systems proposed for the assessment as well as the proposed measurement boundaries. Build a business case for the assessment and outline the return on investment.

Step 2 – Assessment team

Work with a pumping system specialist and/or in-house team to gather an analyze data from a collective viewpoint. First, identify how the data will be collected and analyzed. Next, decide on required tools and software. The content of the assessment report and team responsibilities should also be defined at this step.

Step 3 – Assessment and performance improvements

Through assessment of the system, identify, economically validate, and implement performance improvement opportunities. After prescreening, confirm energy costs on the pumping system using the following process:

1. Collect data, including electricity cost per kW·h.
2. Determine the time period during which those costs are valid.
3. Review problems, such as demand charges and trends, to identify situations not clear by average values.
4. Calculate average baseline annual energy costs/kW·h.

Energy usage is only one aspect. Identify and correct pump reliability issues, such as signs of disrepair and incorrect operation. In many cases, the systems selected for the pump systems assessment will be systems lower mean time between failures (MTBF), which signals poor efficiency operation and high maintenance costs. The high maintenance costs and costs of poor reliability will be an important factor to consider in the total cost of ownership.

Step 4 – Documentation

Document pump systems actions and report results to the management team. The following key points should be included in the executive summary:

- Facility review, background, and products
- Goals and scope of pump system assessment
- System(s) assessed and boundaries utilized
- Annual energy usage and cost
- Annual maintenance and other related costs such as downtime and loss of production
- Performance opportunities with associated improvements, focusing on total cost of ownership improvements

Step 5 – Implement optimization and perform postassessment verification

The whole point of implementing pumps systems assessment and optimization is to improve the operation and performance of the plant and reduce the cost of pumping systems. This requires follow through on implementing the opportunities identified in the report. Additionally, once optimization has been implemented, a postassessment should take place to verify that savings have been realized.

Step 6 – Repeat action plan

Repeat this action plan for other system improvements. The assessment report will recommend other systems that need analysis. Focus on the system with the greatest potential improvements and then move to the next system that shows performance improvement opportunities.

Pump Types

1

There are two basic types of pumps: positive displacement and rotodynamic. A positive displacement pump is a constant torque, direct-acting device that moves fluid through pressurization. A rotodynamic pump is a variable torque, kinetic machine in which energy is continuously imparted to the pumped fluid by means of a rotating impeller, propeller, or rotor. Kinetic energy is then converted into pressure energy in the discharge collector. The most common types of rotodynamic pumps are centrifugal (radial), mixed flow, and axial flow (propeller) pumps, including pumps that are historically referred to as vertical turbine.

There are many categories of rotodynamic and positive displacement pumps, with many subcategories of each, as shown in Figure 1.1.

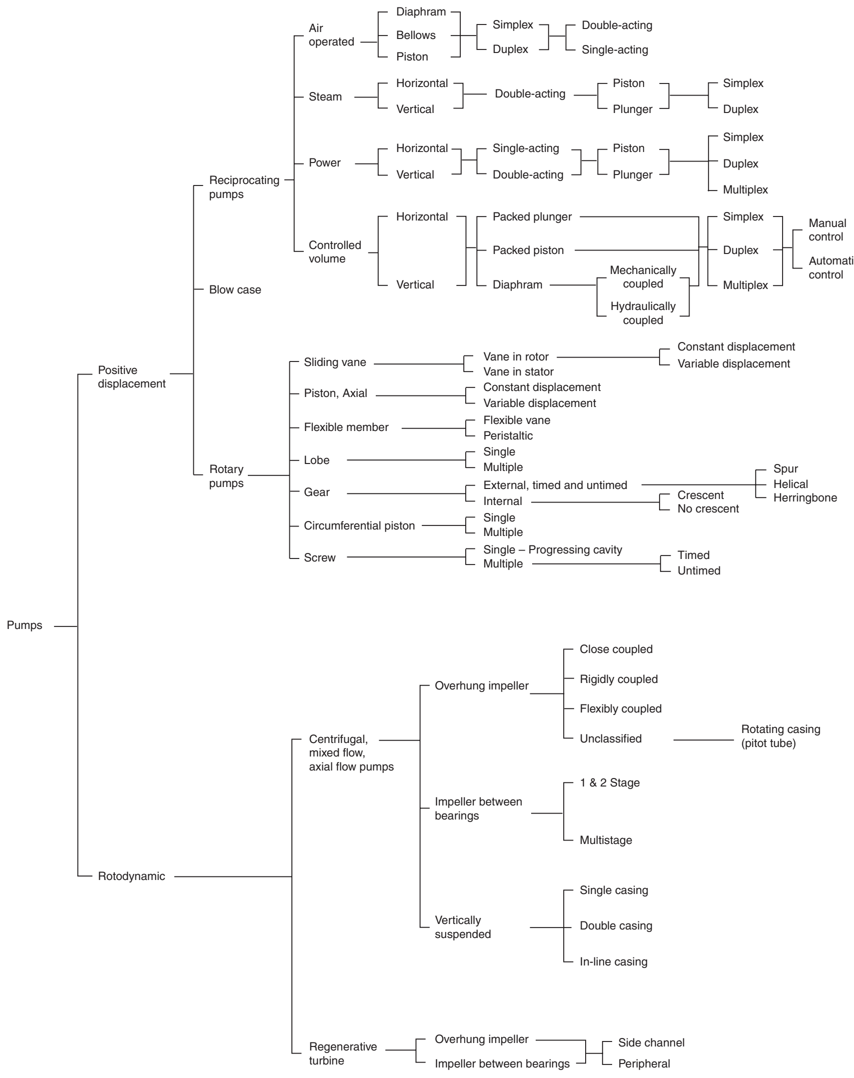


Figure 1.1: Pump Types Matrix: Rotodynamic and Positive Displacement

Rotodynamic

The most common type of rotodynamic pump is one with an essentially radial outlet, which is typically referred to as a centrifugal pump. A centrifugal pump converts kinetic energy to pressure energy in the following manner:

The amount of energy given to the liquid is proportional to the velocity at the edge or vane tip of the impeller. The faster the impeller revolves, or the larger diameter of the impeller, the higher the liquid velocity at the vane tip and the greater the energy imparted to the liquid. This kinetic energy – caused by a liquid coming out of an impeller – is efficiently converted into pressure energy in the discharge collector, which is typically a volute or diffusor.

Rotodynamic pumps have a variable flow/pressure relationship. When acting against a higher system pressure it generates less flow than it does when acting against a lower system pressure. The pump's flow/pressure relationship is described by a performance curve, which plots the pressure in terms of head of the fluid being pumped at various flow rates. Understanding this relationship is essential to properly sizing a pump and designing a system that performs efficiently. A typical close-coupled centrifugal pump is shown in Figure 1.2 with common components called identified. There are many variations of rotodynamic pumps, for a comprehensive review of the types and components, refer to latest editions of ANSI/HI 1.1–1.2 and 2.1–2.2 which will be combined into ANSI/HI 14.1–14.2 *Rotodynamic Pumps for Nomenclature & Definitions*.

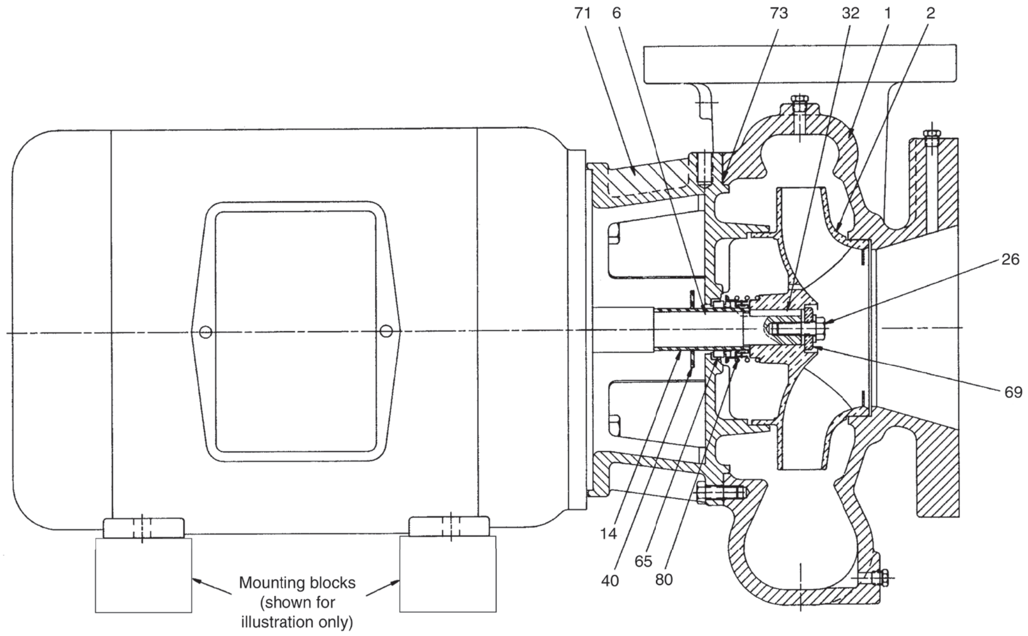


Figure 1.2: Typical Close-Coupled Centrifugal Pump

1	***Casing***	***40***	***Deflector***
2	***Impeller***	***65***	***Seal, mechanical, stationary element***
6	***Shaft, pump***	***69***	***Lock washer***
14	***Sleeve, shaft***	***71***	***Adapter***
26	***Screw, impeller***	***73***	***Gasket***
32	***Key, impeller***	***80***	***Seal, mechanical, rotating element***

Positive Displacement

Positive displacement pumps pressurize fluid with a collapsing volume action, essentially squeezing an amount of fluid equal to the displacement volume of the system with each piston stroke or shaft rotation.

Positive displacement pumps have a fixed displacement volume and, therefore, generate flow rates directly proportional to their speed. The pressures they generate are determined by the system's resistance to this flow. Generally positive displacement pumps can be classified into rotary and reciprocating types. Figure 1.3 provides two examples of common rotary pumps. Many other rotary pumps types are used in industry. Refer to the latest edition of ANSI/HI 3.1–3.5 *Rotary Pumps for Nomenclature, Definitions, Application and Operation* for a comprehensive listing. Figure 1.4 provides an example of a common reciprocating pump.

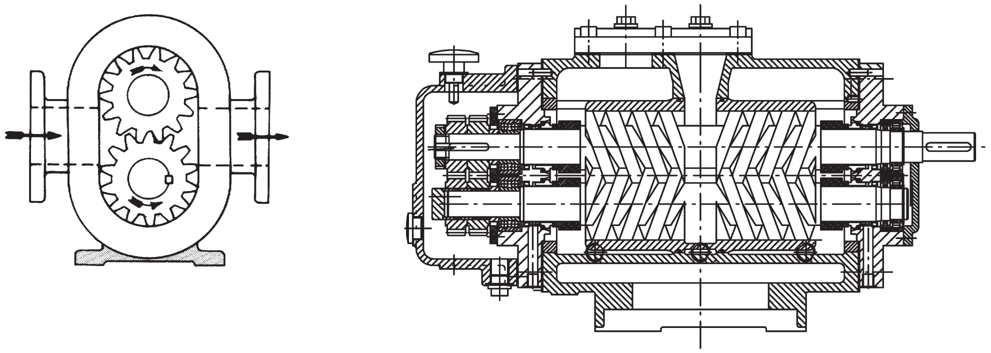


Figure 1.3: External Gear and Twin Screw Rotary Pumps

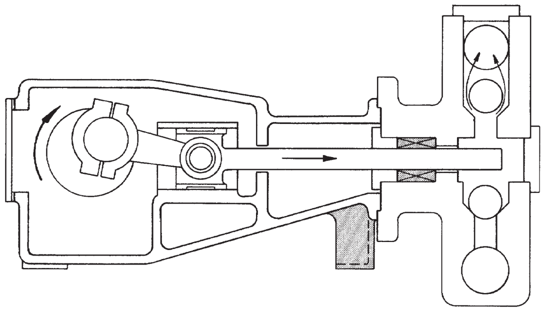


Figure 1.4: Horizontal Double-Acting Piston Power Pump

Positive displacement pumps typically require a system safeguard against overpressure, such as relief valves because they will pump against increasing differential pressure to displace the fixed volume. For example, if the valves downstream of a pump are closed, system pressure will build until a relief valve lifts, a pipe or fitting ruptures, or the driver stalls.

Because there are fewer variables to optimize, these are less frequently considered candidates for energy optimization. Positive displacement pumps have operating advantages that make them more practical for certain applications. Positive displacement pumps are typically more appropriate for situations in which

- The working fluid is highly viscous
- The system requires high pressure, low flow pump performance
- The pump must be self-priming
- The working fluid must not experience high shear forces
- The flow must be metered or precisely controlled
- Pump efficiency is highly valued

Pump System Components and their Interactions

2

Pump system components include the prime mover, drive train, pump, piping, valves, instrumentation, and other end-use equipment.

The vast majority of prime movers are electric motors, but there are many types of pump prime movers available, which are used as applications dictate, such as diesel engines and steam turbines. There are two main types of electric motor, including direct current (DC) and alternating current (AC), with many varieties of each. The most common type of pump prime mover is the AC induction motor, due to its low cost and high reliability. Some prime movers are inherently variable speed such as combustion engines and steam turbines, while others like electric motors require a variable frequency drive (VFD) or other means to create slip between the motor and pump to vary the speed of the pump. The drive train varies and can included mounting of the pump components directly to the motor shaft (close-coupled), rigid coupling, flexible couplings, and gearboxes.

Typically pump systems are dynamic in time, meaning the operation varies in an uncontrolled or preferably a controlled way. Components of the pumping system can be static or dynamic and other components enable dynamic operation. Examples of static components in the system are piping, heat exchangers, and fixed restriction orifices, and examples of dynamic components in the system are control valves and variable speed pump operators. The dynamic components in the system require logic to control them to a desired set point.

System Curve

The system is represented by a system head curve that includes all of the frictional resistance from flow through system components, including the piping, valves, and end-use equipment to the required static lift and pressure head requirements of the system. The development of the pump and system head curves is covered in detail in chapters 14 and 15, respectively.

One way to demonstrate the basic interaction of all the system components is with the use of pump and system curves. The system curve consists of a curve showing the head required to pass a given flow rate through the piping system. Superimposed on the system curve is a pump curve. The point where the system curve and the pump curve intersect is the operating point or flow rate through the pump (Refer to Chapter 15 for specific examples).

The system curve has two components: friction head and static head. Friction head includes the dynamic losses in the system that are proportional to the fluid velocity. Static head is made up of two components: (1) the lift or height between the supply and the destination, and (2) any pressure difference between the supply and destination; for example, pumping from a low pressure tank into a high pressure boiler (or tank) (For specific examples, see Chapter 15).

The system will operate where the pump and system curves intersect. Figure 2.1 shows an example of the pump head capacity curve and system curve with valve open and throttled. (For additional information, see Section 15, *System curves*.)

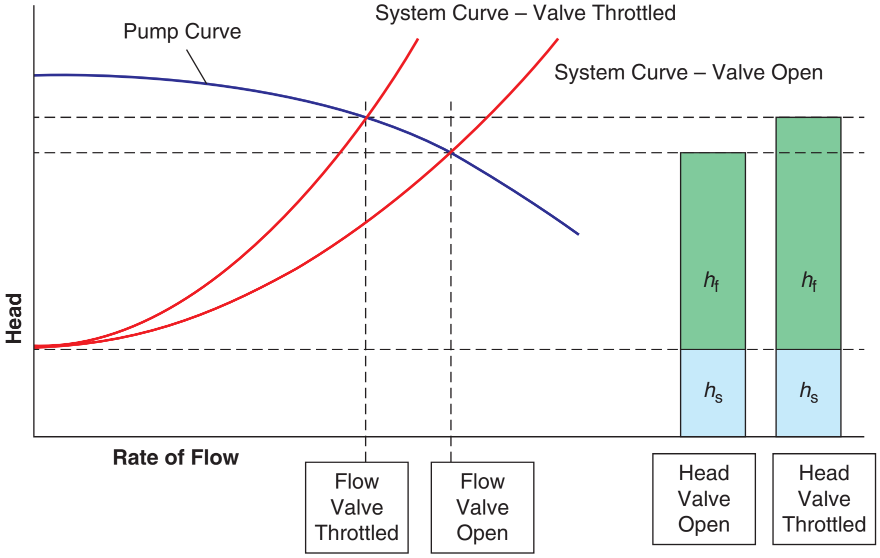


Figure 2.1: Pump and System Curves with Valves Open and Throttled Changing Flow Rate

Piping

The head loss due to the piping system and valves can be described by the Darcy–Weisbach equation as follows:

$$\Delta h_{\text{loss}} = \left(\frac{fl}{d} + \sum K\right) \times \frac{v^2}{2g}$$

Where

f = pipe friction factor

l = pipe length, m (ft)

d = pipe inside diameter, m (ft)

$\sum K$ = sum of the minor losses, which includes losses across valves

v = average liquid velocity in suction line, ft/s (m/s)

g = acceleration due to gravity = 32.2 ft/s^2 (9.81 m/s^2)

Piping is the conduit that contains the pumped fluid and transports it to and from the pump to the point of use. Improper pump piping is a leading source of wasted energy and cause of pump reliability issues.

TIP

As shown in the equation, head loss in the system will change with the square of velocity or flow rate in fixed piping.

The piping size and material as well as associated equipment will heavily influence the system resistance and, hence, the system curve. This will affect the operating point, which is the intersection of the pump and system curves.

Because piping modifications can be very expensive and not justifiable after initial build, optimal piping selection should be evaluated for a new system during the design phase.

The critical aspects of piping are its condition (age/roughness), dimensions, material type, and cost. Since all three aspects are interrelated, optimal pipe sizing is an iterative process. The flow resistance at a specified flow rate of a pipe decreases as the pipe diameter gets larger; however, larger pipes are heavier, take up more floor space, and cost more than smaller pipes. Small diameter pipes will have higher friction head losses for a given flow rate due to the higher velocity. The higher velocity can result in increased erosion and wear. The additional friction head loss due to higher velocity increases the head required of the pump, which directly impacts the energy required. A minimum velocity is required when transporting material (slurries) such as mine tailings, which will settle and clog the piping at reduced velocity.

Valves

Selecting the correct valve for an application depends on a number of factors, such as ease of maintenance, reliability, leakage tendencies, cost, and the frequency with which the valve will be open and shut. Valves can be used to isolate equipment or regulate flow. Isolation valves are designed to seal off a part of a system for operating purposes or maintenance.

Flow-regulating valves either restrict flow through a system branch (throttle valve) or allow flow around it (bypass valve). A throttle valve controls flow by increasing or decreasing the flow resistance across it. In contrast, a bypass valve allows flow to go around a system component by increasing or decreasing the flow resistance in a bypass line.

A check valve allows fluid to move in only one direction, thus protecting equipment from being pressurized from the reverse direction and helping to keep fluids flowing in the forward direction. Check valves are used at the discharge of many pumps to prevent flow reversal when the pump is stopped. If flow reversal occurs, the pump can run in reverse direction at speeds it is not designed for, resulting in damage and failure.

Prime Movers

The selection of the prime mover affects the pump curve, due to its operating speed and the ability to vary its operating speed. The selection of a prime mover for a pumping application is dictated by many factors. The first consideration is whether or not a suitable electrical supply is available for use of an electric motor. The next consideration is whether the pump needs to be run in the event of an emergency power outage, such as fire service pumps. However, when electricity is available, the primary pump driver is the AC electric motor. The electric motor is highly reliable and has varying levels of efficiency, but generally very high motor efficiency can be attained. Additionally, electric motors can have the speed varied directly with VFDs or only the pump speed can be varied through a slip device such as an eddy current drive or fluid coupling between the motor and pump.

In high-run-time applications, improved motor efficiencies can significantly reduce operating costs. However, it is often more effective to take a systems approach that uses proper component sizing, control strategies, and effective maintenance practices to avoid unnecessary energy consumption. A subcomponent of a pump motor or VFD is the motor controller. The motor controller is the switchgear that receives signals from low-power circuits, such as an on–off switch or process input, and connects or disconnects the high-power circuits to the primary power supply from the motor. In DC motors, the motor controller also contains a sequence of switches that gradually builds up the motor current during start-ups.

TIP

If a system curve can be determined, it can help identify the effects of pump and/or system modifications.

3

Standard Pump System Operating Procedures

The assessment professional must be familiar with the operating procedures for the pumping systems being evaluated, including industry standards and the equipment manufacturers' *Installation and Operation* manuals for installing, operating, monitoring, and maintaining the equipment.

The assessment professional should also ensure that the plant has operating procedures in place and that these written procedures are followed.

In review of the operating procedures and the actual operation of the system, there are a few symptoms in pumping system operations that often exist when there is improper sizing, selection, monitoring, operation, or other issues that result in less-than-optimal performance. These symptoms are

- Systems in which valves are throttled to regulate flow rate, level, pressure, etc.
- Systems that employ bypass (recirculation) flow regulation
- Systems that involve a batch-type process, but one or more pumps operate continuously
- Frequent on/off cycling of a pump
- Presence of cavitation noise at the pump or elsewhere in the system
- Equipment procurement based solely on lowest bid price
- A multiple parallel pump system in which the same number of pumps is always in operation
- A pumping system that has undergone a change in function but with no change in pump equipment operation
- A pumping system with no flow, pressure, or power indication

The existence of any one of these symptoms does not guarantee significant savings potential, but it indicates a greater likelihood of achieving savings. The more the symptoms present, the greater the likelihood of potential energy savings.

The following points are important to consider:

- Parallel and Series Operation – Systems that have not been specifically designed for and that do not have established procedures for this type of operation should not be operated in parallel or series.
    - For parallel operation, the pumps should have approximately matching shut-off heads. Otherwise, the system operating head may exceed the shut-off head of one or more pumps, resulting in the pump(s) operating below the minimum flow or with zero output flow.

  - Additionally, curve shape is important to consider when pumps are operated in parallel. For example, if two identical pumps with flat curves are used, a small performance degradation of one pump can cause it to operate back on its curve (low flow) when operated in parallel with the pump that is not as degraded. This is of less concern when pumps with steep curve are used.
  - Pumps are operated in parallel to meet varying flow demands. If the same number of pumps is always operated in a parallel pumping system, it is likely not being controlled to meet the varying flow demands indicating that individual pumps are operating at a low flow condition where efficiency and reliability are minimized.
  - For series operation, the pumps should have approximately the same rate-of-flow characteristics. Because each pump takes suction from the preceding pumps, the stuffing boxes and all pressure-containing components should be designed for the corresponding pressure, and the thrust bearing requirements may also change. The discharge pressure of the first pump must be sufficient to provide adequate net positive suction head available (NPSHA) to the suction of the second pump.
- Frequent cycling – Frequent cycling is a sign that the system is not controlled efficiently. It is also hard on the motor and pump components and will result in reduced reliability. Systems where frequent cycling occurs present an opportunity to evaluate whether the pump or system can be resized or if variable speed pumping can be employed.
- Minimum flow/reduced flow condition – When operating at reduced flow, energy goes into suction and discharge recirculation, resulting in pressure pulsations, noise, and vibration. This inefficient operation may lead to premature failure.
- Condition monitoring program – Properly monitoring hydraulic conditions, temperatures, powers, vibration, etc., allows the user to know the current condition of the equipment and whether it is operating efficiently and to make appropriate repairs and modifications.

4

Benefits of Pump System Optimization

System optimization is the process of identifying, understanding, and cost-effectively eliminating unnecessary losses in order to reduce energy consumption and improve the reliability of pumping systems. While continuing to meet process requirements, system optimization minimizes the cost of ownership over the economic life of the pumping systems.

Component optimization involves segregating components and analyzing them in isolation. System optimization involves looking at how the whole group functions together and how changing one can help improve the value of the entire application solution. At each interface, there are inefficiencies. The primary objective should be to maximize the overall cost-effectiveness of the entire system – in other words, how much output energy is delivered per unit of input energy.

Focusing exclusively on individual components can overlook potential cost savings. Often, component failures are actually caused by system problems. Therefore, it is better to take a lifecycle cost (LCC) approach when designing systems and evaluating repair and maintenance.

The acceptable performance of in-field equipment is complex and there are many factors to consider. The following questions should be evaluated to determine if the operation of the in-field equipment is acceptable.

- Is it serving the system needs?
- Is there a more efficient pump or motor option?
- Is there a more reliable option?
- Is an upgrade to a more efficient or reliable option justified by an LCC analysis?

Lifecycle Costs

Often improved efficiency alone is not enough to drive a pump system improvement. However, when the total cost of ownership is considered through a LCC analysis, the justification is greatly enhanced by showing improved plant profitability inclusive of important factors such as increased productivity, improved reliability, and reduced maintenance costs. When the total cost of ownership is evaluated, approval of capital to implement the improvement is more likely.

Nonenergy Factors to Consider in Total Cost of Ownership

There are benefits of pumping system optimization that typically require more work to quantify than energy savings. These require a thorough understanding of the system, process, maintenance, and environmental impacts to quantify in a cost-benefit or LCC analysis, but are equally important to consider and quantify. These benefits may include

- Increased production
- Reduced production costs
- Improved product quality
- Improved capacity utilization through less downtime
- Improved reliability
- Improved worker safety
- Reduced environmental impact

5

Factors That Impact Pump and Pump System Efficiency and Reliability

Rotodynamic Pump Specific Speed

The specific speed (n_s metric, or N_s US units) of a pump is a normalized index of pump performance (total head) at the pump's best efficiency point (BEP) rate of flow, with the maximum diameter impeller, and at a given rotational speed. Its purpose is to allow comparison of geometrically similar pumps. The normalized resultant is the rotational speed required to deliver one unit of flow producing one unit of head (e.g., in imperial units, the rpm the impeller would turn to deliver 1 gpm producing 1 ft of head, or for metric units, the rpm to deliver 1 m³/s producing 1 m of head). It is calculated using the following formula:

$$n_s(N_s) = \frac{n * Q^{1/2}}{H^{3/4}}$$

Where

n_s = *specific speed (metric)*

N_s = *specific speed (US units)*

n = *rotational speed, rpm*

Q = *flow rate at best efficiency, with max diameter impeller, gpm (m^3/s)*

H = *head at best efficiency, with max diameter impeller, ft (m). For multistage pumps, use H of one stage.*

TIP

The specific speed of a pump relates to the shape of the pump impeller and the performance curve shapes. It also impacts the attainable efficiency of a rotodynamic pump.

The following conversion is applied to convert specific speed in metric units, above, to US units (*n* in rpm, *Q* in gpm, *H* in ft):

$$N_s\ [\text{US units}] = 51.65 * n_s\ [\text{metric}]$$

Rotodynamic pumps have n_s in the range of 4–300 (200–15,500).

For a given n_s value, there is an optimal meridional shape of impeller to obtain maximum possible efficiency, as shown in Figure 5.1.

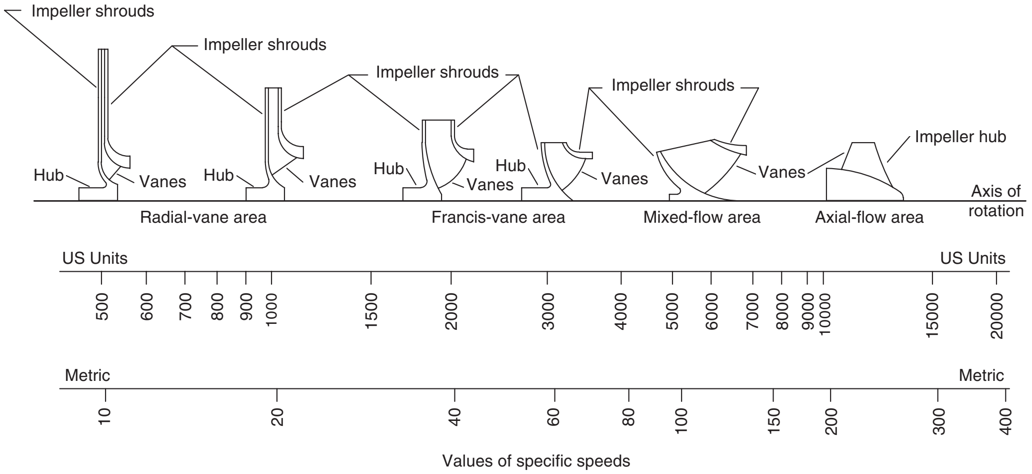


Figure 5.1: Meridional Shape of Impeller for Best Efficiency at Different Specific Speeds

Pumps with low n_s typically have high head and lower flow, and on the other side, pumps having high n_s typically produce lower head and higher flow.

Figure 5.2 shows the relationship that n_s and flow rate have on attainable efficiency. The optimal efficiency is reached when n_s is in the range of 40–60 (2100–3100), and as the design flow rate increases so does the attainable efficiency.

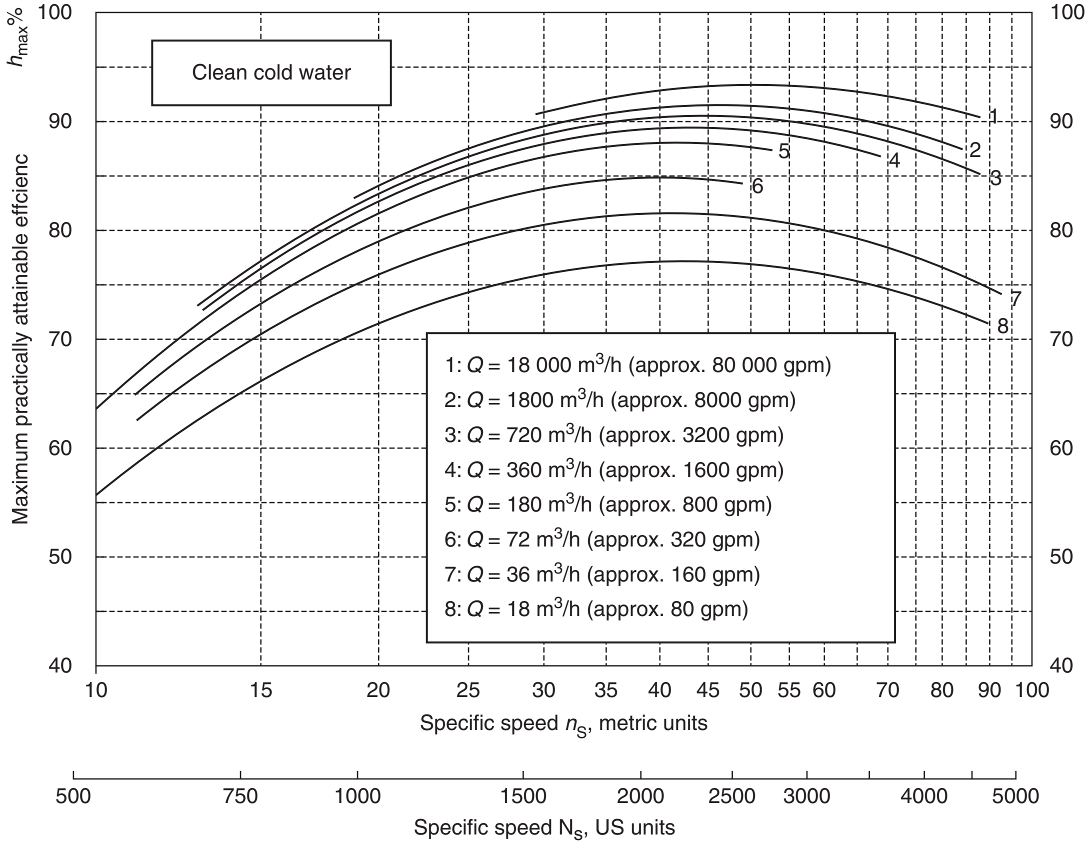


Figure 5.2: Efficiency of Pump as a Function of Specific Speed (n_s) and Pump Size, Represented by Best Efficiency Point Flow (BEP) (Reference 2)

Having an understanding of n_s helps identify what efficiency may be expected for a given normal point (speed, flow, and head normally operated), providing a useful tool in selecting the correct pump. In addition to efficiency predictions, there are typical curve shapes for head and power, based on specific speed, illustrated in Figure 5.3. For example, a low specific speed pump's head curve will be flat or even droopy at low flows before dropping off at higher flows, and the power will increase at higher flows. On the other hand, with high specific speed pumps, the head is typically much steeper at lower flows and continues to drop off at higher flows, and the power is highest at shut-off and decreases with an increase in flow. These factors are important to understand when operating a pump away from the rated or normal points and during transient conditions such as start-up. This is necessary to ensure minimal energy usage and optimal pump life.

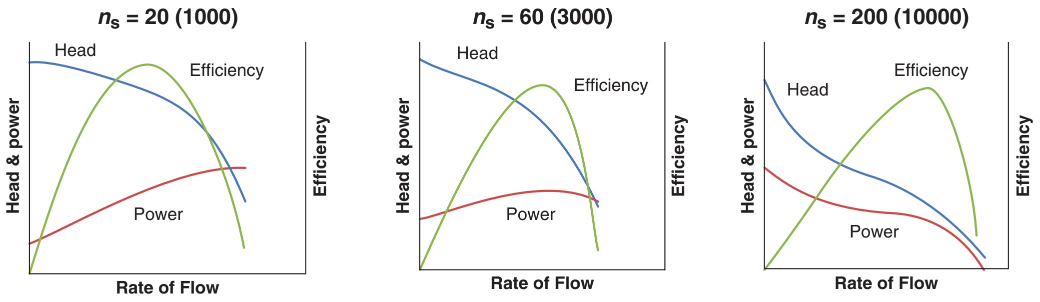


Figure 5.3: Typical Curve Shape Based on Specific Speed

Understanding the pump specific speed allows the individual responsible for selecting the proper pump to

- Select the shape of the pump curve
- Determine the pump efficiency
- Anticipate motor overloading problems
- Select the lowest cost pump for their application

With specific speed, a better understanding is obtained of the shape of the head capacity curve, required power, and pump efficiency. The chart above provides a graphic illustration of how specific speed impacts these various parameters.

The steepness of the head or capacity curve increases as specific speed increases. At low specific speed, power consumption is lowest at shutoff and rises as flow increases. This means that the motor could be overloaded at the higher flow rates, unless considered at the time of purchase.

At medium specific speed, the power curve peaks at approximately the BEP. This is a nonoverloading feature, meaning that the pump can work safely over most of the fluid range with a motor speed to meet the BEP requirement.

TIP

As a rule of thumb, lower specific speeds produce flatter curves, while higher specific speeds produce steeper ones.

High specific speed pumps have a falling power curve, with maximum power occurring at minimum flow. These pumps should never be started with the discharge valve shut. If throttling is required, a motor of greater power will be necessary.

Design Review and Operation

To obtain maximum reliability and mean time between repair (MTBR), the pump equipment being used must be properly designed and selected for the intended application and be operated according to the manufacturer's recommendations.

When reviewing the selection of the pump, consider the following:

- Type of pump: What pump type is best suited for the application?
- Materials of construction: Are the materials selected compatible with the fluids being used and the environment in which they will be used?
- Capacity: Does the pump have the proper performance characteristics (flow, head, power, net positive suction head required [NPSHR], efficiency) for all operating conditions? Is the pump sized to operate in the POR for the maximum amount of time?
- Net positive suction head (NPSH) margin: Will the pump be operated with a proper NPSH margin?
- Pressure capability: Can the pump withstand the hydrostatic pressure of all the application conditions?
- Structural capability: Can the pump withstand the external mechanical loading from the piping?
- Thermal capability: Is the pump designed to handle the temperature requirements, i.e., fluid temperature as well as ambient temperature?
- Space: Does the pump fit into the space available and is there access for maintenance?
- Control: Will the pump system be controlled to achieve the intended purpose and to optimize energy and reliability?

Rotodynamic Pump Operating Regions

Effects of operating a rotodynamic pump continuously or for a long duration at rates of flow greater than or less than the pump's BEP rate of flow should be understood. These effects influence the power consumption and life of pump components and, therefore, determining the preferred/allowable operating range of flows is essential to reliable, efficient pump operation.

Design characteristics for both performance and service life are optimized near a rate of flow designated as the BEP. At BEP, the pump operates with maximum hydraulic efficiency because the pumped liquid passes through the impeller vanes, casing diffuser (discharge nozzle), or vaned diffuser with minimal losses. In addition, the flow through the impeller and diffuser vanes (if so equipped) is relatively uniform and matched to the hydraulic geometry.

When the operating rate of flow moves away from BEP, the flow through the pump is no longer uniform. Areas of flow recirculation and separation develop increasing hydraulic losses. Nonuniform flow and uneven pressure distribution in the pump result in increased hydraulic loads and vibration.

When pumps operate at reduced capacity significantly less than BEP, the flow is mismatched to fixed vane angles causing eddy flows within the impeller, casing, and between the wear rings. The radial thrust on the rotor will increase, causing higher shaft stresses, increased shaft deflection as well as potential bearing and mechanical seal problems. Radial vibration and shaft axial movement may also increase. For high specific speed pumps the power requirements are maximum at reduced flow rates.

When pumps operate at excess capacity significantly greater than BEP, the pump can operate with insufficient NPSH margin and excessive vibration that can result in bearing and shaft seal problems. With low specific speed pumps the power requirements are maximum at the end of curve condition.

Equal and stable pressure within the volute casing is a critical component to pump reliability and efficiency. To fully appreciate the importance of operating a pump at its BEP, think of the pump casing as a pressure vessel. When a vessel or chamber is pressurized, the pressure is exerted equally and at 90 degree angles to all surfaces. As long as the forces within the volute casing are equal and stable, the impeller, which is a rotating component, will remain stable and centered within the stationary component.

When the pressure in the casing is unequal, the radial loads on the impeller increase, which results in greater shaft deflections, potential seal wear, and wear-ring contact.

Figure 5.4 shows the impact on pump reliability when the pump operates away from BEP.

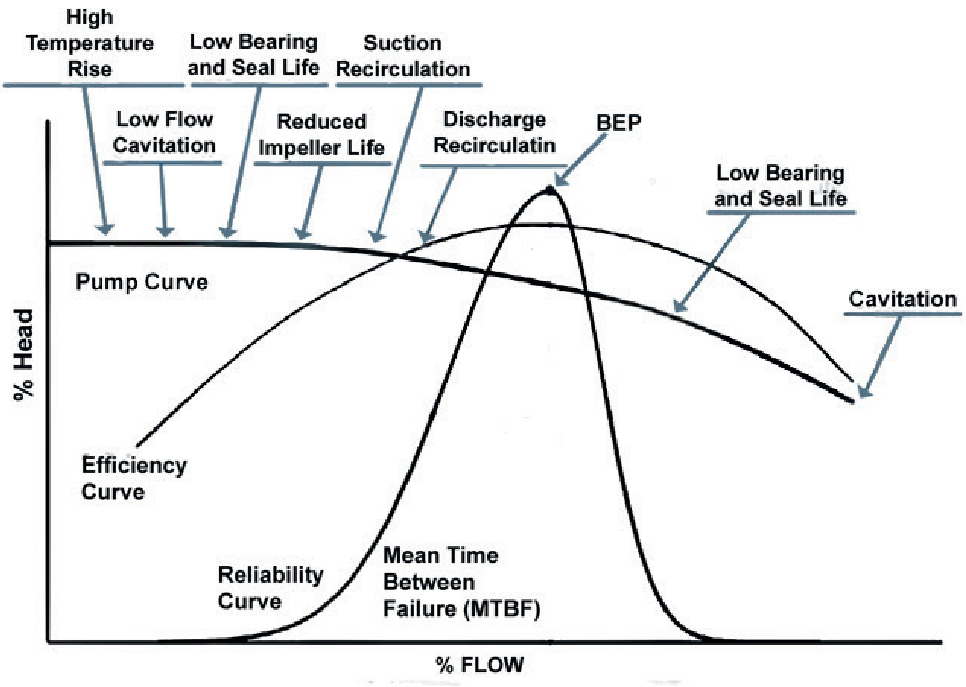


Figure 5.4: The Reliability Curve is Maximum at BEP and Reduces as Flow Moves Away from BEP

Preferred Operating Region

As noted in Figure 5.4, it is desirable to operate a rotodynamic pump in a range around the BEP to maximize the pumps reliability. This region of operation is termed the preferred operating region (POR). The POR is defined as a range of flow rates to either side of predicted BEP within which the hydraulic efficiency and the operational reliability of the pump are not substantially degraded. Within this region, the design service life of the pump will not be affected by the internal hydraulic loads or flow-induced vibration.

Operating a pump within the POR ensures higher reliability and lower energy consumption. Depending on the specific pump design, the appropriate POR can be as small as 90%–110% of BEP for axial flow pumps, or as wide as 70%–120% of BEP for centrifugal pumps. The POR is set by industry standards such as ANSI/HI *9.6.3 Rotodynamic Pumps Guideline for Operating Regions*.

Allowable Operating Region

A wider range of rates of flow, outside the POR, over which the service life of a pump is acceptable, is designated the allowable operating region (AOR). The limits of AOR are determined by requirements other than energy consumption, and should be defined with the help of the pump manufacturer. Operation in regions that are not fully defined by the pump curve (head, efficiency, and NPSH) should not be undertaken without consultation with the manufacturer.

Bearing life will be reduced and noise, vibration, and component stresses will be increased when a pump is operated outside its POR. As a result, service life of a pump operated within the AOR may be lower than the service life of this pump operating within the POR. While the predicted bearing life will vary significantly over the AOR, it is recommended that the calculated bearing life be a minimum of two years of operation in this range (basic rating life L10 equal to or greater than 17,500 hours, refer to ANSI/HI 1.3 *Rotodynamic Pumps for Design & Application*.

AOR depends on a large number of factors, some of which are application-specific. This discussion is limited to those factors related to operating rates of flow and pump design.

Following is a list of the factors that a pump manufacturer considers when establishing the AOR. Within the AOR, the manufacturer has determined that none of the factors exceeds limits that will severely impact the service life of the pump. The factor that determines the upper or lower limits of the AOR will normally vary with pump type and specific design, and may not be evident from the manufacturer's literature. This list, and the following discussion of each, is provided as an aid in understanding the acceptable operating limits.

- Hydraulic loads – dynamic effects on
  - Bearing life
  - Shaft seal life
  - Internal mechanical contact
  - Fatigue life of components
  - Thrust reversal
- Temperature rise
- Vibration
- Noise
- Power limit
- Liquid velocity
- Pumpage and potential for clogging
- NPSHA margin
- Head versus rate-of-flow curve
- Suction recirculation
- Pump size

Rotodynamic Pump Net Positive Suction Head

It is important to note that the NPSHR curves historically provided by pump manufacturers may not show sufficient NPSH values to provide zero head loss or to eliminate cavitation.

By HI definition, the required NPSH of a pump is the NPSH available that will cause the total head (first stage head of multistage pumps) to be reduced by 3%. The required NPSH qualified by this criterion is referred to as NPSH3. The full published pump head will not, however, be achieved (by definition) when the NPSHA equals the NPSH3 of the pump. The value of 3% head drop for NPSH3 is based on accepted industry practice for defining a condition of head breakdown due to cavitation. The choice of 3% measured head drop is based on the fact that this was the smallest head drop practically measurable and the 3% measured head drop value continues to be the industry-accepted norm for characterizing pump suction performance.

Figure 5.5 shows a plot of how NPSH3 is determined at a constant flow rate. In the plot, flow rate is held constant and total head is measured while the NPSHA is reduced until the total head breaks down. The NPSHA where the 3% head breakdown occurs is the NPSH3 for that flow rate.

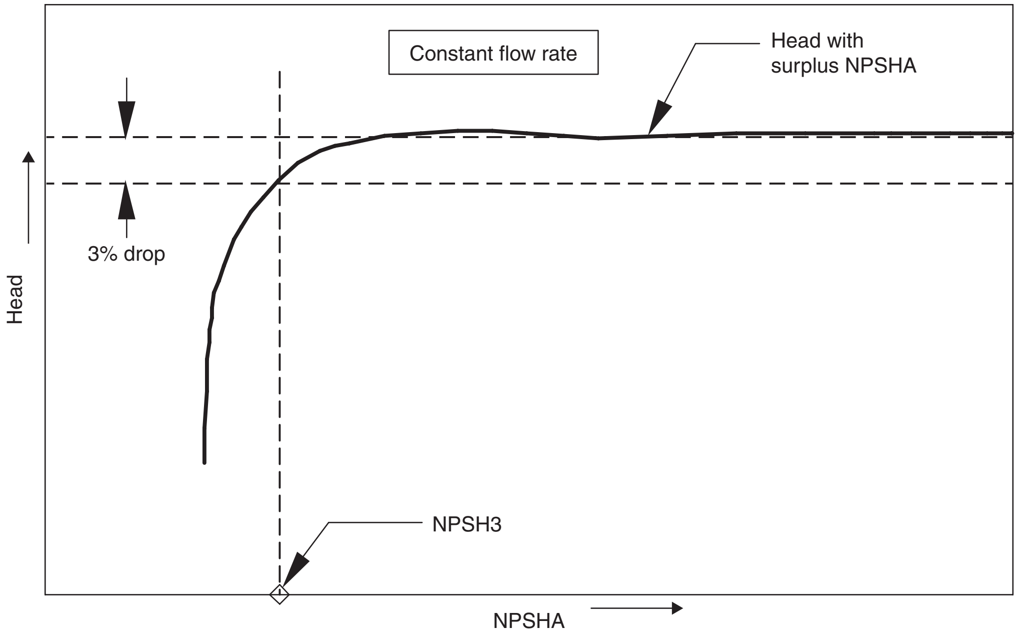


Figure 5.5: NPSH3 Determination for Constant Flow Rate

When the 3% head loss criteria was implemented, pumps operating under conditions of 3% head drop would achieve generally acceptable service lives. This was probably true at the time when pumps for a given application were typically larger and slower than pumps for the same application today. Today's higher speed, higher energy density pumps might not achieve acceptable service life under suction conditions without an adequate NPSH margin.

HI defines NPSH margin as NPSHA minus NPSH3 and NPSH margin ratio of NPSHA and NPSH3. The amount of NPSH margin required depends on the pump design and application. For example, condensate pumps in power generation have special demands or operating conditions that affect NPSH margin requirements. Since they are typically required to operate with very low NPSHA, they are designed to function with some cavitation present. The vertical canned arrangement is preferred for this application because it provides NPSHA by virtue of water elevation above the first-stage impeller. For such an application, there often is minimal NPSH margin at the maximum flow rate, and the pump must be designed to withstand cavitation. Cavitation-resistant materials should be supplied for the first-stage impeller.

The manufacturer's NPSHR curve, typically produced using NPSH3 values, will require the system to have an NPSHA with margin above the NPSH3 value for the pump to achieve its full, published performance. Figure 5.6 illustrates that additional NPSHA is required to achieve 0% head loss, and this NPSHA requirement generally increases when the pump is operated away from BEP to maintain a certain head loss criteria.

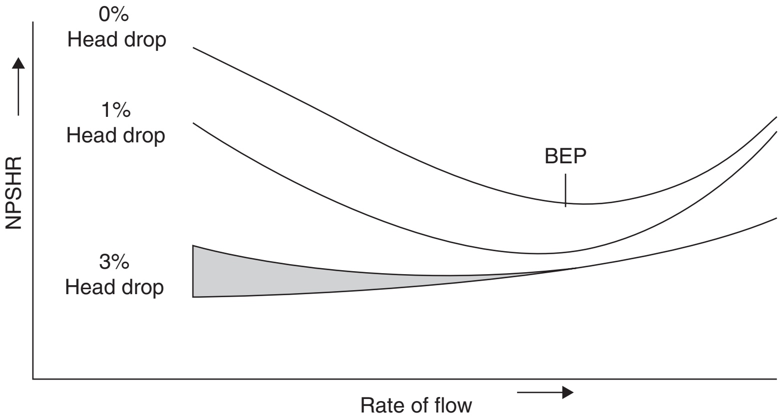


Figure 5.6: NPSHR to Meet Various Head Drop Criteria as a Function of BEP

Cavitation

Cavitation is a phenomenon commonly found in rotodynamic pumps in which the system pressure is less than the vapor pressure of the liquid, causing the formation and violent collapse of tiny vapor bubbles.

Classic cavitation occurs at the suction side of the pump where the liquid enters the impeller eye. When the liquid enters the impeller eye the pressure is minimized causing several things to happen simultaneously.

- The cavities or bubbles form and collapse when they pass into the higher regions of pressure, causing noise, vibration, and damage to many of the components
- The vapor cavities block the flow area, resulting in reduced pump performance

In addition to classic suction, cavitation occurs for other reasons, such as

- Suction or discharge recirculation, which occurs when the pump is operated away from BEP
- Distorted nonuniform flow entering the eye of the impeller
- Vane passing syndrome, where the outer diameter of the impeller passes too close to the pump cutwater (the velocity of the liquid increases as it flows through this small passage, lowering the fluid pressure and causing local vaporization)

Cavitation results in damage to various components within a pump, erosion wear of the impeller, volute/casing, and cutwater. It also impacts rotor stability, which can cause

- Shaft fatigue
- Fretting or coupling wear

- Premature bearing failure
- Premature seal failure
- Wear-ring degradation

Improper Pump Installation and/or Maintenance

Poor equipment condition can be the result of improper installation and/or poor maintenance during operation. Some common installation and maintenance conditions that impact pump reliability are

- Pump alignment (hot and cold)
- Nozzle loads (hot and cold)
- Foundation integrity and base/sole plate level
- Installation of base plate and proper grouting of base plate when required
- Soft foot (irregular contact between the machine feet and the baseplate) resulting in distortion when the machine is secured to the baseplate
- Coupling alignment and spacing
- Pump seal installation, setting, adjustment, and piping plan
- Shaft runout or bent shafts
- Balance and mechanical vibration
- Gasket seating and correct gasket thickness
- Lubrication systems
- Wear-ring or axial gap clearances
- Maintenance of wear parts

Allowable Nozzle Loads

Nozzle loads are forces and moments applied to the pump nozzle from attached piping. The piping should be designed with proper anchors and aligned with the pump nozzles to prevent excessive nozzle loads. Additionally, excessive nozzle loads can be caused by thermal expansion of the pipe, unsupported piping and equipment weight, axially unrestricted expansion joints, and misaligned piping. Excessive pump nozzle loads lead to misalignment of the pump shaft with the driver shaft, mechanical seal failures, bearing failures, binding or rubbing of the pump rotor, and in extreme cases, failure of pump nozzles or mounting feet.

Suction and discharge piping should be anchored, supported, and restrained near the pump to avoid application of forces and moments to the pump in excess of those permitted by the pump manufacturer. In calculating forces and moments, the weights of the pipe, internal thrust, contained fluid and insulation, as well as thermal expansion and contraction, should be considered.

Expansion joints or flexible connections provided at the pump suction and discharge may need to be restrained to prevent transmitting excessive loads to the pump. When reducers or increasers are used, the flexible connection should be placed in the smaller diameter pipe. The allowable thrust values that various compliant pump types can withstand are typically detailed by the manufacturer and are outlined in ANSI/HI 9.6.2 for certain pump types.

API design standards dictate that the pump must be able to withstand a certain nozzle load. Typically this is specified as two (2) times the specified nozzle loads. This results in custom designed pumps for many of these applications.

Three of the more common detrimental mechanical effects from poor pump piping are

- Excessive loads that the piping can place on a pump because of pipe misalignment with the pump connections
- Failure to properly transfer the unbalanced force generated by the pump to the piping
- Transferring the weight of unsupported or poorly supported valves and fittings to the pump

Excessive pump nozzle loads lead to misalignment of the pump shaft with the driver shaft, mechanical seal failures, bearing failures, binding or rubbing of the pump rotor, and in extreme cases, failure of pump nozzles or feet.

Excessive nozzle loads can also be caused by

- Thermal expansion of the pipe
- Unsupported piping and equipment weight
- Axially unrestricted couplings
- Misaligned piping

Pump Suction Piping and Intake Design

Specific hydraulic phenomena have been identified that can adversely affect the performance and mechanical reliability of pumps. Figure 5.7 shows examples of free and submerged vortices that increase in severity. Generally, phenomena that should be avoided or reduced in pumping systems are

- Submerged vortices
- Free-surface vortices
- Preswirl magnitude and variation with time
- Nonuniform flow profile into pump inlet
- Entrained air or gas bubbles

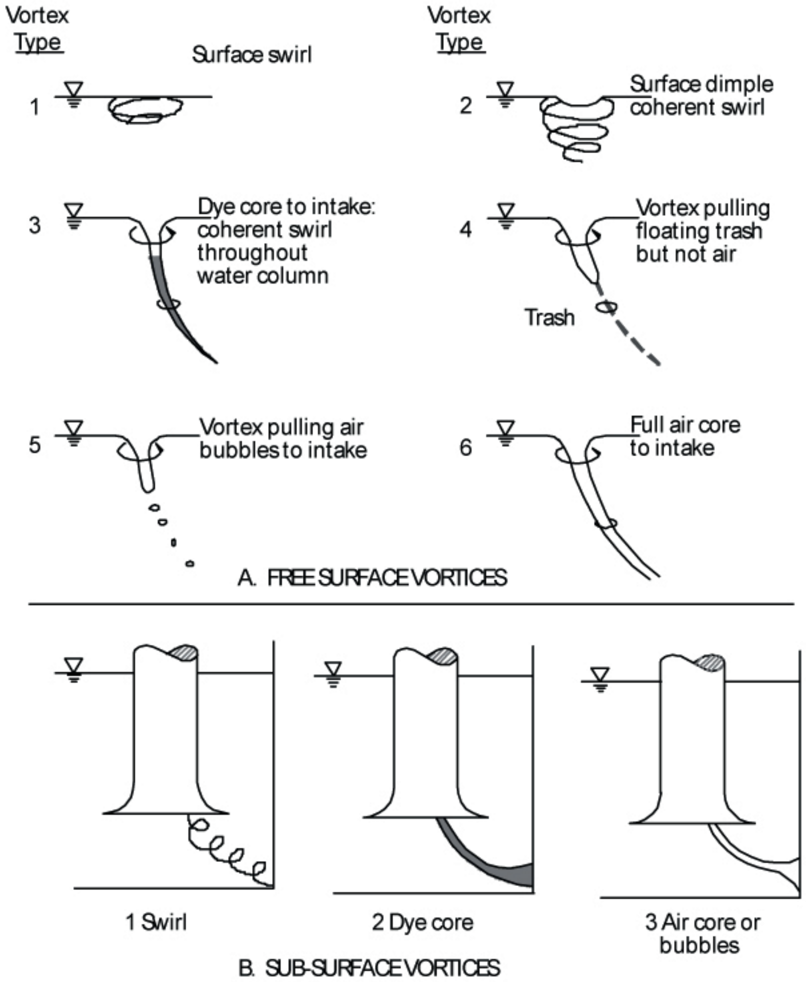


Figure 5.7: Classification of Free-Surface and Subsurface Vortices

Ideally, the flow of liquid into any pump should be uniform, steady, and free from swirl and entrained air. Lack of uniformity can cause the pump to operate away from the optimum design condition, and at a lower hydraulic efficiency. Unsteady flow causes the load on the impeller to fluctuate, which can lead to noise, vibration, bearing problems, and fatigue failures of pump shafts.

The negative impact of each of these phenomena on pump performance depends on pump specific speed and size, as well as other design features of the pump that are specific to a given pump manufacturer. In general, larger pumps and axial flow pumps (high specific speed) are more sensitive to adverse flow phenomena than smaller pumps or radial flow pumps (low specific speed).

To ensure that these negative impacts do not occur, it is imperative that free-surface pump intakes are designed per ANSI/HI 9.8 *Rotodynamic Pump Intake Design*, and all suction piping that connects to the pump is configured per the requirements of ANSI/HI 9.6.6 *Rotodynamic Pump Piping*.

The function of suction piping is to provide a uniform velocity profile approaching the pump suction connection with sufficient pressure to avoid cavitation in the pump. An uneven distribution of flow is characterized by strong local currents and swirls. The ideal approach is a straight pipe (L2 in Figure 5.8) directly to the pump, with no turns or flow-disturbing fittings close to the pump. Failure of the inlet (suction) piping to deliver the liquid to the pump in a suitable condition can lead to noisy operation, random axial load oscillations, premature bearing or seal failure, cavitation damage to the impeller and inlet portions of the casing, and occasionally damage due to liquid separation on the discharge side. Proper mounting of piping elements at the pump suction and L2 straight length is important. The required L2 length depends on the direction of flow, pump type, and disturbing fittings prior to the pump. Refer to ANSI/HI 9.6.6 for specific L2 dimensions for various flow-disturbing fitting configurations.

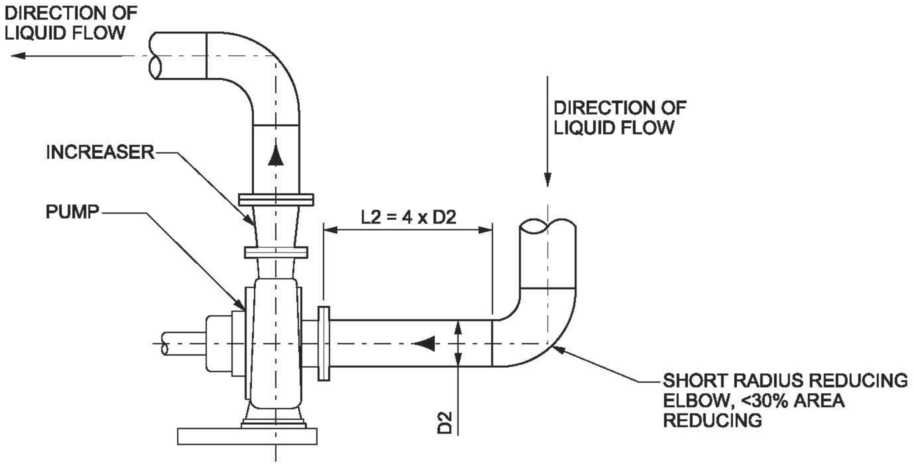


Figure 5.8: General Example of Pump Suction with a Required L2 Length from a Flow-disturbing Fitting

Figure 5.9 illustrates the undesirable effect of mounting a horizontal elbow directly to the suction flange where it directs more flow to one side of the impeller than the other. This configuration is an example of improper suction piping that could result in reduced performance and reliability of the pump.

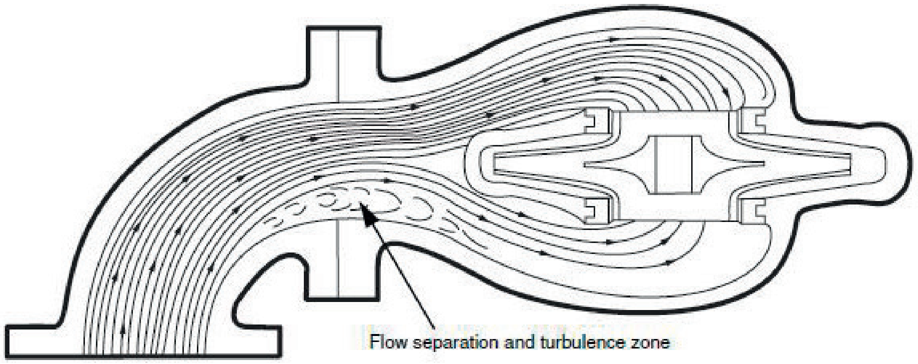


Figure 5.9: Undesirable Effect of a Horizontal Elbow Mounted Directly on Suction Flange

TIP

To ensure that negative hydraulic impacts do not occur, it is imperative that free-surface pump intakes are designed per ANSI/HI 9.8 *Rotodynamic Pump Intake Design*, and all suction piping that connects to the pump is configured per the requirements of ANSI/HI 9.6.6 *Rotodynamic Pump Piping*.

Outlet (discharge) piping flow characteristics will not normally affect the performance and reliability of a rotodynamic pump, with a few exceptions.Sudden valve closures can cause excessively high water-hammer-generated pressure spikes to be reflected back to the pump, possibly causing damage to the pump. Where there may be a sudden closure of a check valve or sudden stopping of the pump, a transient flow analysis may be required.

Materials of Construction

Material designations for rotodynamic and positive displacement pump types are outlined in ANSI/HI 9.1–9.5 *Pumps – General Guidelines*. In this standard, common designations are given and explained. Additional content on what different materials may be most suitable for is provided.

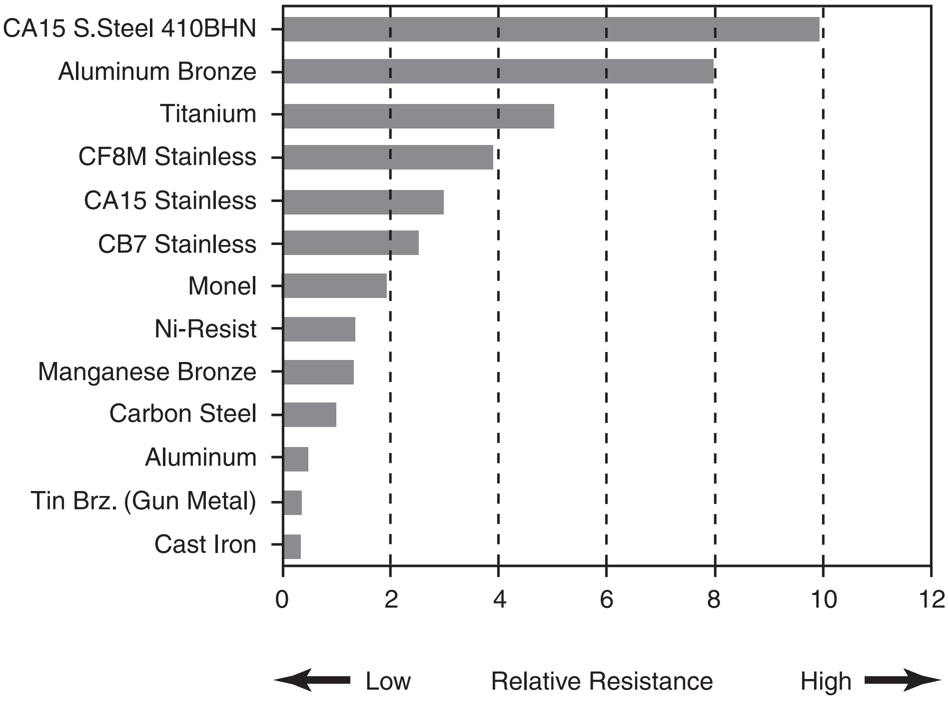
Industry standards provide material of construction guidance by industry.

- Slurry pumps: ANSI/HI 12.1–12.6
- Clear water: ANSI/AWWA E103
- Chemical process: ASME B73
- Oil & gas services:
  - API 610 – centrifugal pumps
  - API 674 – reciprocating positive displacement pumps
  - API 675 – controlled volume positive displacement pumps
  - API 676 – rotary positive displacement pumps

Material selection is of utmost importance to ensure chemical compatibility and resistance to erosion when applicable. An example of requiring hard material due to erosion is when pumps are forced to operate in a state of cavitation due to system requirements. In these cases selecting erosion resistant materials will result in extended life of the equipment.

The wear mechanism associated with cavitation damage is very complex and not fully understood and there is no single identifiable property in a material that clearly quantifies its resistance to cavitation erosion. It is known, however, that materials should have high resilience, hardness, tensile strength, and impact and fatigue resistance. Brittle materials should be avoided.

A general ranking of the relative cavitation erosion resistance for metal castings commonly used in the construction of rotodynamic pumps, when pumping clear water at ambient temperature, is illustrated by Figure 5.10 as a general guide for impeller material selection. Note that the provided guide is for general reference only; the relative cavitation erosion resistance and therefore the sorting of material in this figure may change depending on the specific material form, heat treatment, and pumped liquid properties.



Note: Rate of wear due to cavitation erosion increases with increased temperature.

Figure 5.10: General Ranking of Cavitation Erosion Resistance of Common Cast Metals

Pump Antifriction Bearings

A bearing arrangement consists of suitable bearings along with an adequately sized shaft and housing designed to carry the operating loads. The methods of determining the different hydraulic radial and axial loads are provided in the latest edition of ANSI/HI 1.3. The pump bearings and bearing housings must include provision for suitable lubrication and seals to provide adequate protection from corrosion and the ingress into the assembly of foreign matter.

There are many parameters that have a significant influence on the life of rolling bearings, including

- Contamination level
- Particle size
- Particle shape
- Particle hardness
- Operational lubrication condition
- Bearing load
- Material fatigue stress limit
- Bearing type

From these variables, three factors are derived: contamination index, fatigue load limit, and equivalent bearing load.

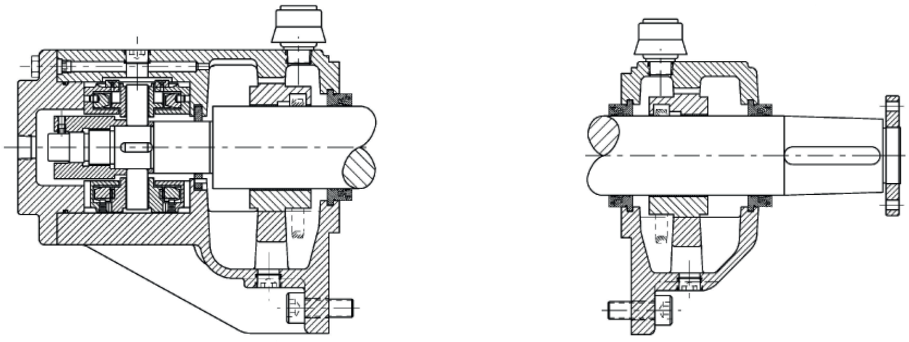
Pump Sleeve Bearings

Some applications dictate that sleeve (journal) bearings are used. Typically these are used on high-speed and high-horsepower equipment. They are also used in vertical pumps as line shaft bushings. Sleeve bearings operate on a hydrodynamic principle. The proper application of this principle depends on the maintenance of a lubricating film between wear surfaces. This film is dependent on lubricant viscosity, shaft speed, bearing running clearance, length, and radial pressure on the bearing. Heat buildup and wear can be appreciable if there is insufficient lubrication. Subsynchronous shaft whirling (orbiting) in the bearing occurs when the lubrication film viscosity and thickness are not adequate to dampen the dynamic action of the shaft. Material contact can occur when the lubrication film viscosity and thickness are not adequate to dampen the dynamic action of the shaft. Shaft and bearing materials must be carefully chosen to minimize the coefficient of friction and optimize wear properties.

In some cases, sleeve bearings are used both on the inboard and outboard for the radial thrust with an antifriction bearing outboard of the outboard sleeve bearing to absorb the axial thrust. See Figure 5.11 for examples of sleeve bearings.

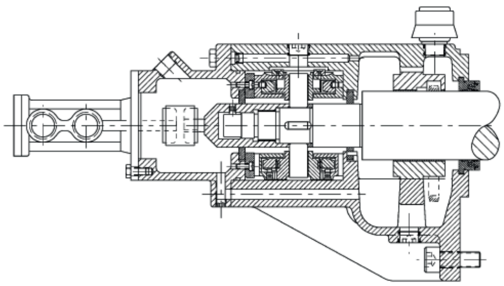
Sleeve with Pivot-shoe-type Thrust Bearing

The sleeve bearing is comprised of a journal, usually the shaft itself, and a bearing bushing that is horizontally split and lined with a suitable material with the proven tribological properties of low friction, high lubricity, and acceptable wear resistance (such as Babbitt). Outboard of the outboard sleeve bearing is a pivot-shoe-type thrust bearing. Pumps with this bearing arrangement usually have a separate lubrication system with its own reservoir, oil pump, and cooler.



Pivot-shoe-type thrust bearing

Cylindrical-type radial journal
(sleeve) bearing



Pivot-shoe-type bearing — complete with shaft-driven oil pump
arranged for force feed lubrication

Figure 5.11: Sleeve Bearings

Bearing Housings, Seals, and Lubricants

Bearing lubrication and protection of the lubricant are essential factors affecting pump reliability. The primary function of the lubricant is to minimize or eliminate friction by separating the moving parts, controlling wear, protecting surfaces from corrosive substances, controlling temperature, and/or preventing dirt and wear debris from contaminating the bearing elements. Key factors to consider are the method of lubrication, correct fill levels, and lubrication protection.

The quantity and quality of the lubrication are critical considerations to achieve reliability. If the lubrication level is too low, then the bearing will not receive enough lubricant necessary for proper film strength. This is a precursor to surface contact, skidding, and possible catastrophic failure. As temperature increases, the ball and race both expand causing an even tighter fit leading to “thermal runaway.”

If the oil sump level is filled too high, then churning of the lubricant will occur, accelerating the oxidation rate due to excessive air and elevated temperatures. It is a common mistake to believe more is better, especially when it comes to oil sump lubrication. Too much oil can also limit the effective operation of oil/flinger rings.

Mechanical Seals

Mechanical seals have been identified as one of the most prevalent causes for removing a pump from service for repair. While other components may be damaged or have failed, it is the seal that provides evidence of a problem through visible leakage. In some cases pressure, temperature, or level gauges, or alarms on auxiliary equipment can be an indication of an impending seal failure.

Sealing devices can be classified as static seals, such as gaskets, and dynamic seals, such as rotating interfacial axial seals, also known as *end face mechanical seals*. Mechanical seals are used in many types of pumps of various sizes and pressure ratings, and are used to transport a great diversity of fluids in many industries. Therefore, mechanical seals are available in a variety of configurations. Their selection depends on the application conditions. However, regardless of the service conditions, all mechanical face seals operate on the same basic principle. A simple mechanical seal is shown in Figure 5.12.

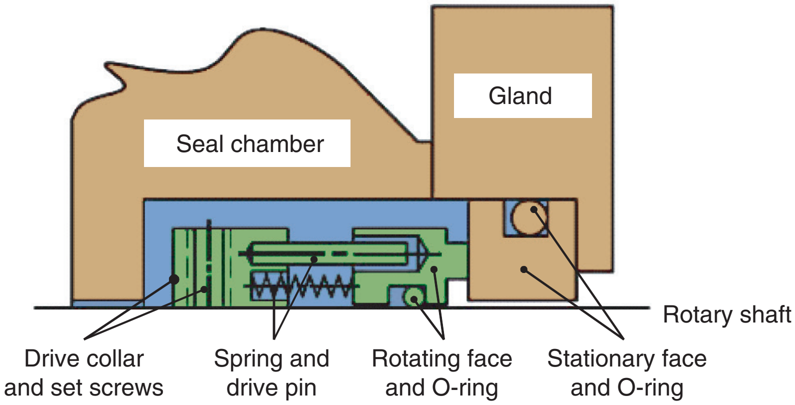


Figure 5.12: Essential Components of a Mechanical Seal

A seal consists of two sealing rings, either of which rotates relative to the other. One of the rings is mounted rigidly and the other is arranged so that it can move freely and align radially, axially, and angularly with the rigidly mounted ring. A dynamic seal is achieved where the two rings contact perpendicularly to the pump shaft. These rings are called *seal faces*, one the rotating face and the other the stationary face. The faces are lapped flat, which results in very low levels of leakage, while at the same time providing long life on the basis of normal wear.

Besides the two faces, the mechanical seal contains a set of secondary sealing elements and several metal parts. These serve the function of sealing dynamically and statically, loading the faces, and transmitting rotation. The secondary seals provide sealing between the seal faces and the metal parts, such as mating ring housing, sleeve, and gland. The metal parts transmit the torque and provide an axial mechanical force by means of a spring element to load the lapped faces.

A single mechanical seal may leak along one of five paths shown in Figure 5.13. Dual mechanical seals have similar static and dynamic leak paths, which include the following:

1. Seal face leakage is visible at the point where the shaft exits the gland or at the drain connections.
2. Dynamic secondary seal leakage is also visible at the point where the shaft exits the gland or at the drain connections.
3. Static secondary seal leakage is visible at the point where the shaft exits the gland or at the drain connections.
4. Gland gasket leakage is visible at the gland–seal chamber interface.
5. Hook sleeve gasket leakage or cartridge sleeve secondary seal leakage is visible at the point where the sleeve ends outside of the seal chamber.

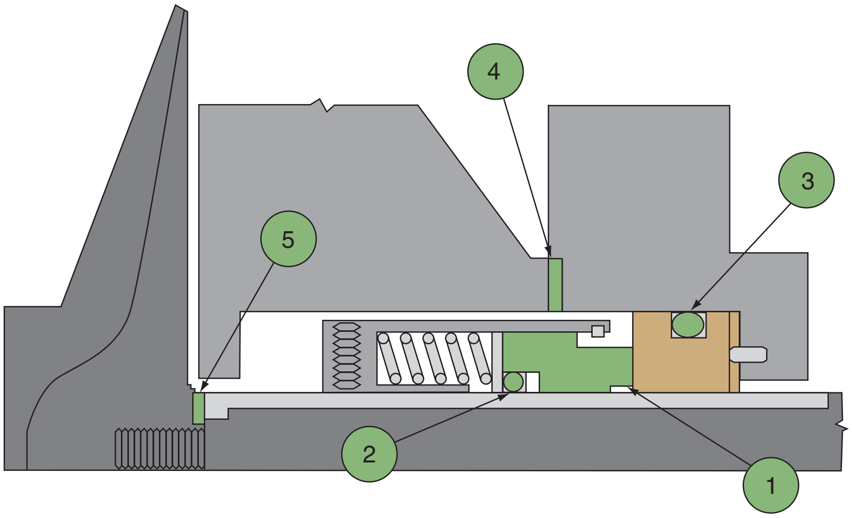


Figure 5.13: Possible Seal Leakage Points

One study of seal failure causes found that 42% were related to improper equipment operation, 26% were related to equipment condition, 24% were related to system design, and the remaining 8% were due to incorrect seal selection. To effectively improve performance, the user should conduct an initial seal failure analysis when the seal is removed from service to look for probable causes of failure. Breaking down the major causes of seal failures noted above can assist in finding the root cause of the problem. In some cases, it may be a combination of problems. Once the issues are known, corrective action needs to be taken to eliminate the issue(s), as simply replacing a seal will result in the same short life.

Critical to the reliable operation of a mechanical seal is selecting and implementing the proper piping flush plan. At the time of publication, the most complete set of plans is covered by the American Petroleum Institute Standard 682 but are also covered by ASME standards for chemical process pumps. The various piping plans can be grouped by a variety of categories. One method to group the plans is as follows:

API Plan	ANSI/ASME Plan	Description
01, 02	7301, 7302	Internal systems
11, 13, 14	7311, 7313	Simple recirculation systems
12, 21, 22, 23, 31, 41	7312, 7321, 7322, 7323, 7331, 7341	Recirculation systems with ancillary equipment designed to modify the product pumped
32, 62	7332, 7362	External system used to modify the sealing environment
52, 53, 54, 74	7352, 7353, 7353	External systems for dual seals
72, 75, 76	No corresponding plans	External control for containment seals used on dual seals

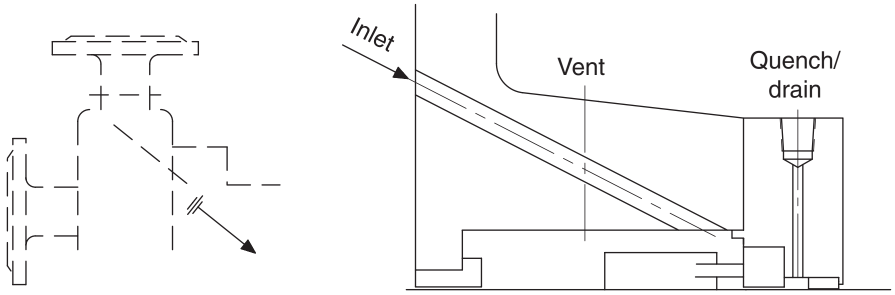
The point of the seal piping flush plans is to provide suitable fluid to the seal face(s) to lubricate and cool the seal, which is critical for reliable operation. There are many seal piping flush plans available to meet the needs of various applications such as

- Nonvolatile clean liquids with NPSH margin
- Dirty liquids
- Volatile liquids
- Corrosive liquids
- Dangerous or unsafe to the environment liquids

Covering the proper seal plans for all applications is beyond the scope of this study guide. One common seal arrangement (Plan 01) is covered below for information on some typical considerations.

Figure 5.14 shows the Plan 01, which is an integral (internal) recirculation from the pump discharge to the seal chamber, which is typically at a pressure slightly above pump suction pressure. It is similar to Plan 11 in that it uses the pressure differential between pump discharge and pump suction to develop flow, but is different in that there are no external lines (piping or tubing) on the pump. It is recommended for clean products only.

This flush system can perform its function well when used properly. Changes in pump impellers, or changing seal designs that can move the seal faces away from the flush hole, can cause problems that result in seal failures. This system is not recommended on vertical pumps.



Plan 01

Seal chamber for Plan 01

Figure 5.14: Plan 01

Advantages

- No product contamination. The flush source is coming from the pump and going back to the pump.
- No reprocessing of product.
- Simplified piping. There is no external piping on the pump.
- Useful arrangement for fluids that are high viscosity at normal ambient temperatures to minimize the risk of freezing if exposed to low temperatures in external piping plans, such as a Plan 11.

Disadvantages

- Must be used for clean products only because dirty products could easily clog the passageway and would require pump disassembly to repair.
- Flush has to be repumped.
- The flush is not usually directed right at the faces, but may come in over the seal head.

Improper Mechanical Seal Support System Design

Many seal system failures relate to the support system design of the seal plan. Such factors include

- Improper flow to the seal – excessive or inadequate flow rates
- Multiphase operation (liquid and vapor) – resulting in a portion of the face running dry
- Heat exchanger or cooling jacket sizing or fouling – excessive seal chamber temperature
- Incorrect size and number of orifice(s) in flush system to the seal chamber – low or excessive flow rates
- Seal quench flow, temperature, and pressure controls – inadequate environmental conditions in seal chamber or on atmospheric side of seal
- Corrosion and/or erosion
- Improper or inadequate seal flush plan(s) – incorrect piping plan or setup for the application

- Pipe size and design for the equipment and seal support system(s) – e.g., use of small-diameter pipe/tubing resulting in high pressure drops and low flow rates
- Inadequate piping system and pump supports – vibration and/or misalignment
- Air ingestion – results in dry running

Three primary resources are available to learn more about the reliable application of mechanical seals.

- Reliability of Pumping Equipment: *Guidelines for Maximizing Uptime, Availability and Reliability* (HI 2015)
- Mechanical Seals for Pumps: Application Guidelines (HI 2008)
- Fluid Sealing Association knowledge base – www.fsaknowledgebase.org

Drivers (Electric Motors)

Variations in piping system resistance can cause significant changes in flow, head, and power draw. There can be other causes, but a need for increased power beyond that originally specified can result in higher current draw from the motor leading to overheating that affects the life of the motor. If motor protection is used and sized correctly, it should shut down the motor when a detrimental amount of current is being drawn or when the motor gets too hot. Excessive heat will accelerate motor insulation deterioration and cause premature insulation failure.

Since the total temperature of a motor is greater than the surrounding environment, heat generated during motor operation will be transferred to the ambient air. The rate of heat transfer affects the maximum load and/or the duty cycle of a specific motor design. Factors affecting this rate of transfer are

- Motor enclosure: Different enclosures result in different airflow patterns that alter the amount of ambient air in contact with the motor.
- Frame surface area: Increasing the area of a motor enclosure in contact with the ambient air will increase the rate of heat transfer. Most motor enclosures are cast with many ribs (or fins) to increase their surface area for cooler operation.
- Airflow over motor: The velocity of air moving over the enclosure affects the rate of heat transfer. Fans are provided on most totally enclosed motors and some open motors to increase the velocity of air over the external parts.
- Ambient air density: A reduction in the ambient air density will result in a reduction of the rate of heat transfer from the motor. Therefore, total operating temperature increases with altitude. Standard motors are suitable for operation up to 3300 ft; motors with service factor may be used at altitudes up to 9900 ft at 1.0 service factor.
- For liquid cooled motors, such as canned motors, that are cooled by the process fluid or separate flush: Similar to traditional motors, which depend on ambient air temperature, canned motor winding temperature is dependent on the motor load and temperature of the fluid cooling the motor. In addition to monitoring the power draw, for canned motors, it is wise to monitor the temperature of the fluid cooling the motor.

TIP

It is important to monitor gear drives on a periodic basis to assess their condition. Vibration analysis and oil particle analysis are two common methods used to monitor the condition of a gear drive.

Gearboxes and Gearing

The gear drive contains rotating geared elements that increase or decrease the speed of the output shaft. In addition the geared elements there are supporting shafting, bearings and housing are necessary to position rotating gear elements in their optimum operating positions. Like any other piece of rotating equipment, the gear drive exterior is also a heat sink that must be kept clear to allow airflow around and over the gear drive to aid in rejected heat dissipation from the gear drive. Keeping lubrication and cooling oil, which is going to the gear drive clean, keeping lubrication and cooling oil continuously supplied to the gear drive, and operating the gear drive within its design powers and speeds are the major considerations in achieving long life.

Elements of Lifecycle Costing

6

The lifecycle cost (LCC) describes the total cost of providing, running, maintaining, and disposing of plant and associated equipment.

When applying the evaluation process or selecting pumps and other equipment, the plant manager must establish the best information concerning the output and operation of the plant. The process itself may be mathematically sound, but if incorrect or imprecise information is used, an incorrect or imprecise assessment will result. The LCC process is a way to predict the most cost-effective solution; it does not guarantee a particular result but allows the plant designer or manager to compare alternate solutions within the limits of the available data.

The elements that make up the LCC are

$$\mathbf{LCC = (C_{ic} + C_{in} + C_e + C_o + C_m + C_s + C_{env} + C_d)}$$

Where

LCC = lifecycle cost

C_{ic} = initial cost, purchase price (pump, system, pipe, auxiliary services)

C_{in} = installation and commissioning cost (including training)

C_e = energy costs (predicted cost for system operation, including pump driver, controls, and any auxiliary services)

C_o = operating cost (labor cost of normal system supervision)

C_m = maintenance and repair cost (routine and predicted repairs)

C_s = downtime and loss of production cost

C_{env} = environmental cost (contamination from pumped liquid and auxiliary equipment)

C_d = decommissioning and disposal cost (including restoration of the local environment and disposal of auxiliary services)

Initial Cost (C_{ic})

The pump plant designer or manager must decide the outline design of the pumping system. The smaller the pipe and fitting diameters, the lower the cost of acquiring and installing them, however, the smaller diameter installation requires a more powerful pump leading to higher operating costs and possibly a larger and more expensive pump and driver. In addition, smaller pipe sizes on the inlet side of a pump will reduce the NPSHA, often resulting in a larger, slower speed, more expensive pump being needed. Provisions must be made for the acceleration head needed for a positive displacement pump or the depth of submergence needed for a wet pit pump.

Other choices made during the design stage can affect initial investment cost. One important choice is the quality of the equipment selected. There may be options for materials with differing wear rates, heavier duty bearings or seals, or more extensive control packages, all of which would increase the working life of the pump. These and other choices may incur higher initial costs but reduce LCC.

The initial cost also typically includes the following items:

- Engineering (e.g., design and drawings, regulatory issues)
- Bid process
- Purchase order administration
- Testing and inspection
- Inventory of spare parts
- Auxiliary equipment for cooling and sealing liquid

Installation and Commissioning (Start-up) Cost (C_{in})

Installation and commissioning costs include the following:

- Foundations (i.e., design, preparation, concrete, and reinforcing)
- Setting and grouting of equipment on foundation
- Connection of process piping
- Connection of electrical wiring and instrumentation
- Connection of auxiliary systems and other utilities
- Provision for system flushing or commissioning on water (“water runs”)
- Performance evaluation at start-up
- Training

Energy Cost (C_e)

Energy consumption is often one of the larger cost elements and may dominate the LCC. Energy consumption is calculated first by gathering the data on the pattern of the system output. If output is steady, or essentially so, the calculation is simple (Level 2 assessment). If output varies over time, then a time-based usage pattern needs to be established (Level 3 assessment). This pattern can be accomplished by producing a graph of output against time over the operating cycle, which may be hourly, daily, weekly, monthly, or annually (see Figure 6.1a). The usage is then analyzed to determine the time spent delivering the output rates (see Figure 6.1b).

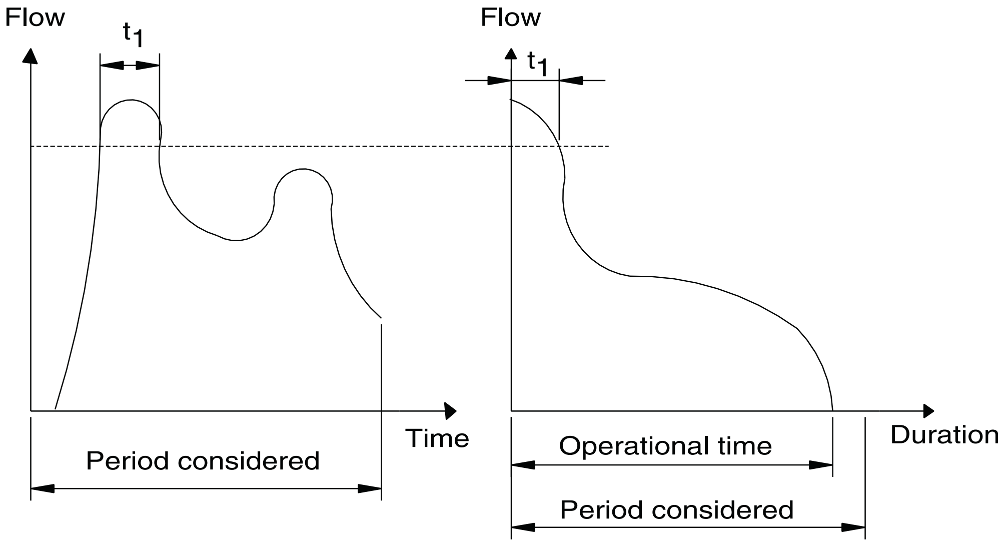


Figure 6.1a and 6.1b: Flow Versus Time and Duration Curve

To properly design or assess the energy consumption, the engineer needs to obtain separate data showing the performance of each pump system being considered or installed over the output range. Performance can be measured in terms of the overall efficiencies of the pump unit or of the energies used by the system at the different output levels. Driver selection and application will affect energy consumption. For example, much more energy is required to drive a pump with a pneumatic motor than with an electric motor. In addition, some energy use may not be output dependent. For example, a control system sensing output changes may itself generate a constant energy load, whereas a variable speed electric motor drive may consume different levels of energy at different operating settings. Control by throttling valve, pressure relief, or flow bypass will reduce the operating efficiency and increase the energy consumed.

TIP

Energy cost calculations for Level 2 assessments are simple because the output is steady. But for Level 3 assessments, the energy cost calculation is more complex, requiring a duration curve.

The plant total levels of power used should be plotted on the same time base as the pump system power usage values. The area under the curve for the pump system usage then represents the total energy absorbed by the system being reviewed over the selected operating cycle. The result will be in kW·h (kilowatt-hours). If there are differential power costs at different levels of load, then the areas must be totaled within these levels.

Once the charge rates are determined for the energy supplied, they can be applied to the total kW·h for each charge band (rate period). The total cost of the energy absorbed can then be found for each system under review and calculated for a common period.

Finally, the energy and material consumption costs of auxiliary services need to be included. These costs may come from cooling or heating circuits, required air conditioning, from liquid flush lines, or fluid barrier arrangements. They often do not differ for different system designs but can be affected by selection of variable speed drives, materials, or seal designs. For example, the cost of running a cooling circuit using water should include the following items: cost of the water, booster pump service, filtration, circulation, and heat dissipation. Disposal costs are considered elsewhere.

Operating Cost (C_o)

Operating costs are labor costs related to the operation of a pumping system. These vary widely depending on the complexity and duty of the system. For example, a hazardous duty pump may require daily checks for hazardous emissions, operational reliability, and performance within accepted parameters. On the other hand, a fully automated nonhazardous system may require very limited supervision. Regular observation of the functioning of a pumping system can alert operators to potential losses in system performance. Performance indicators include changes in vibration, shock pulse signature, temperature, noise, power consumption, rate-of-flow, and pressure.

Maintenance and Repair Cost (C_m)

Obtaining optimum working life from a pump requires regular and efficient servicing. The manufacturer will advise the user about the frequency and the extent of this routine maintenance. Its cost depends on the time and frequency of service and the cost of materials. The design can influence these costs through the materials of construction and components chosen and the ease of access to the parts to be serviced.

The maintenance program can comprise less frequent but substantial repair as well as the more frequent but simpler servicing. Major service can be described as "pump unit not repairable in place," while routine work is described as "pump unit repairable in place."

The cost per event is calculated as follows:

$$\text{Cost (repair in place)} = \text{labor} + \text{parts \& inventory} + \text{consumables} + \text{loss production (if applicable)}$$

$$\text{Cost (unit not repairable in place)} = \text{labor} + \text{cleaning} + \text{transportation} + \text{inspection} + \text{reinstallation}$$

The total cost of routine maintenance is found by multiplying the costs per event by the number of events expected during the life cycle of the pump.

Although unexpected failures cannot be predicted precisely, they can be estimated and accounted for statistically by calculating MTBF. MTBF can be estimated for components and then combined to give a value for the complete machine.

The cost of each event and the total costs of these unexpected failures can be estimated in the same way that routine maintenance costs are calculated.

Downtime and Loss of Production Cost (C_s)

The cost of unexpected downtime and lost production could be a very significant item in the total LCC and can rival the energy costs and replacement parts costs in its impact. Despite the design or target life of a pump and its components, there will be occasions when an unexpected failure occurs. In those cases where the cost of lost production is unacceptably high, a spare pump may be installed to reduce the risk. If a spare pump is used, the initial cost will be greater but the cost of unscheduled maintenance will include only the cost of the repair.

Environmental Cost, Including Disposal of Parts and Contamination from Pumped Liquid (C_{env})

The cost of contaminant disposal during the lifetime of the pumping system varies significantly depending on the nature of the pumped product. Certain choices can significantly reduce the amount of contamination, but usually at an increased investment cost.

Examples of environmental contamination can include cooling water and packing box leakage disposal, hazardous pumped product flare-off, used lubricant disposal, contaminated used parts, such as seals. Costs for environmental inspection should also be included.

Decommissioning and Disposal Cost, Including Restoration of the Local Environment (C_d)

In the vast majority of cases, the cost of disposing of a pumping system will vary little with different designs. This is certainly true for nonhazardous liquids and, in most cases, for hazardous liquids also. Toxic, radioactive, or other hazardous liquids will have legally imposed protection requirements, which will be largely the same for all system designs. A difference may occur when one system has the disposal arrangements as part of its operating arrangements (e.g., a hygienic pump designed for cleaning in place) while another does not (e.g., a hygienic pump designed for removal before cleaning). Similar arguments can be applied to the costs of restoring the local environment.

When disposal is very expensive, the LCC becomes much more sensitive to the useful life of the equipment.

7

Basic Pump Maintenance Practices

Pumping systems require maintenance to keep them operating well and to detect problems in time to schedule repairs. Delayed pump maintenance can result in progressive efficiency and capacity loss as well as premature failure. Additionally, mission critical pumping systems can cause downtime and inordinate cost.

Maintenance actions are often classified as preventive or predictive. Preventive maintenance addresses routine system needs like lubrication, alignment, and component replacement. Predictive maintenance focuses on tests and inspection to detect deteriorating conditions.

Preventive Actions

Preventive maintenance of pumps involves coupling alignment, lubrication, and seal maintenance and replacement.

Mechanical seals should be periodically inspected to ensure that leakage is nonexistent or within specifications. Seals that are leaking excessively should be replaced. For packing seals, a certain amount of leakage is required for lubrication and cooling of the seal. When this leakage is outside pump manufacturer specification, the packing gland must be adjusted. Packing needs to be replaced when gland tightening no longer affects the leakage rate. Over-tightening will cause excessive wear on the shaft or its wear sleeve and increase electric power usage.

Lubrication of bearings and gearboxes should be maintained on a periodic basis to ensure that it is not contaminated or degraded and it is able to suit its purpose.

Predictive Actions

Predictive maintenance techniques are vital to minimizing unexpected equipment outages. Sometimes called “condition assessment” or “condition monitoring,” predictive maintenance is made easier by modern testing methods and equipment.

Once baseline values have been established, machinery condition may be assessed by monitoring the following indicators:

- Power consumption
- Temperature change
- Corrosion/erosion
- Leakage
- Pressure (suction, discharge, differential)
- Vibration
- Noise (sound) characteristics

- Lubricant condition
- Shaft position
- Rate of flow
- Speed (rpm)
- Bearing wear

Periodic Efficiency Testing

When preventative or predictive maintenance results in repairs on a regular basis, they may be taken as the norm and hide operational problems that cause energy and maintenance expenditures including downtime and loss of production. It is important to review the root cause of the required maintenance and remove the cause to optimize the system effectively.

One of the best forms of condition monitoring is to periodically test the wire-to-water efficiency and keep records for trending, so that underlying issues are detected. Conduct the efficiency test at the same flow rate each time if there is an available throttling valve downstream of the pump discharge. Begin the trending series with throttling to at least 10% below the wide-open throttle flow rate. This will allow the assessment professional to test at the same flow rate as the pump begins to degrade. Degrading pump condition will be revealed by a trend of declining discharge pressure and system efficiency.

If it is not possible to control the flow rate for testing, track both flow rate and head. If both flow rate and head drop over time, this is indicative of pumping system degradation. If flow rate and head change in opposite directions over time, this is indicative of changes in the piping system restriction and is inconclusive about pump efficiency.

Test data can be plotted and compared to the manufacturer's pump curve for the impeller, if available. The measured flow rate and pressure point should lie somewhere near the pump curve for the installed impeller diameter. If it lies closer to a smaller diameter impeller curve, the pump has degraded. If it lies near the correct impeller curve, but far from the best efficiency point, the pump is not degraded but it may be misapplied or mismatched to the system requirements.

TIP

Of all the ways that pumps can degrade, wear ring and rotor erosion are the most costly in operation. They can reduce wire-to-water efficiency by 10% or more.

8

System Drawings, Schematics, and Diagrams

Process Flow Diagrams

TIP

The process flow diagram is a great first step to understand the major components of the system.

Process flow diagrams, sometimes referred to as “flow sheets,” indicate the general flow of processes and equipment and display the relationships between major equipment in the plant.

Process flow diagrams of a single process will typically include the following:

- Major equipment
- Process piping
- Control valves and other major valves
- Connections with other systems
- Major bypass and recirculation streams
- Operational data, such as temperature, pressure, mass flow rate, density, etc.
- Process stream names

TIP

When a process flow diagram represents multiple process units within a large industrial plant, it will generally contain less detail. In these cases, the process flow diagram may be referred to as a “block flow diagram” or a “schematic flow diagram.”

Process flow diagrams typically *do not include*

- Pipe classes or piping line numbers
- Process control instrumentation (sensors and final elements)
- Minor bypass lines
- Isolation and shut-off valves
- Relief and safety valves
- Maintenance vents and drains
- Flanges

Piping and Instrumentation Diagrams

The piping and instrumentation diagram (P&ID) shows how the process piping and equipment are connected and what instrumentation and controls are available.

This diagram is important to the assessment professional because it is a simplified depiction of the system and provides reference of important system instrumentation and controls that are important to safely operate and assess the system.

The P&ID depicted in Figure 8.1 is an example of a pump system with continuous level control. Some important things to note from P&ID for the assessment engineer are

- The pump is operated with and speed is controlled with variable frequency drive
- The VFD is provided feedback from a level indicating controller (LIC) with set point (sp) logic
- Level indication is available
- Pressure indication is available on the suction and discharge of the pump

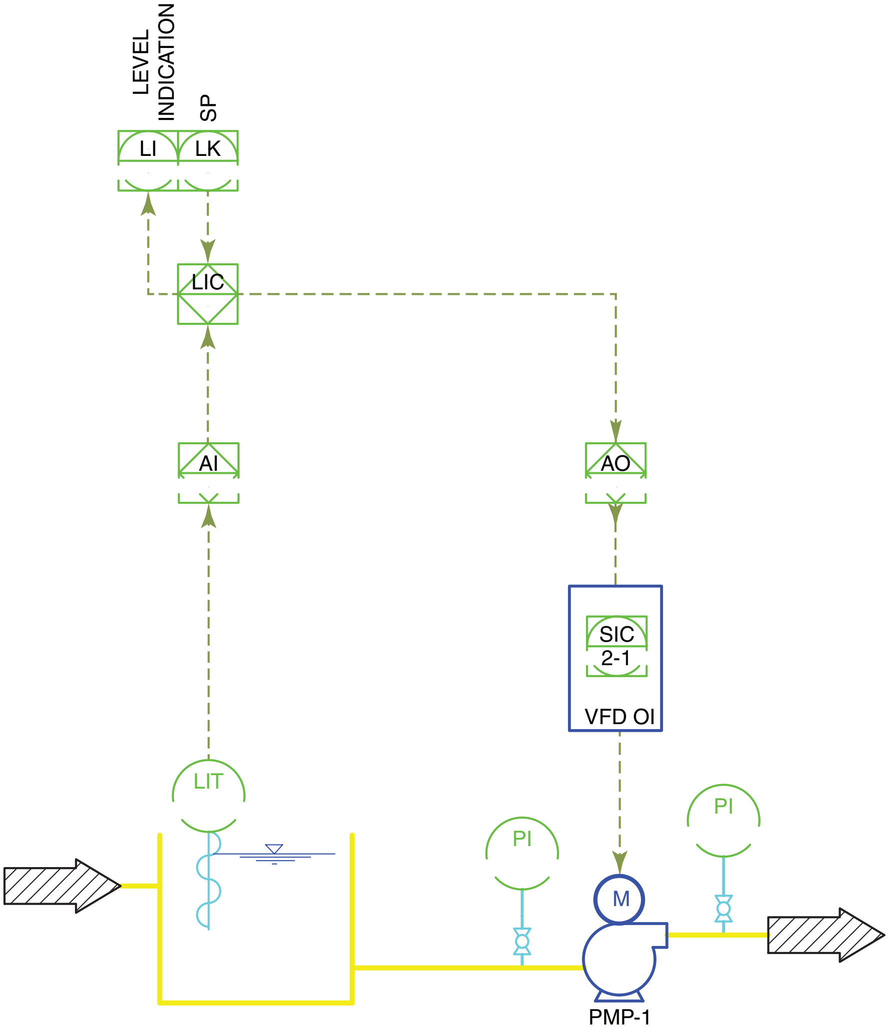


Figure 8.1: Piping and Instrumentation Diagram

TIP

When making detailed system calculations or software aided-hydraulic models of a pumping system, the piping system isometric drawings are required in order to accurately depict the components of the system and their relative locations and elevations. There will likely be a series of isometric drawings that accurately depict the system.

Isometric Drawings

Piping isometric drawings, such as Figure 8.2, provide a realistic view of the piping from three sides. Location and direction are provided on the drawing to properly orient equipment and piping in the process. By reviewing the isometric drawing, the assessment professional can determine the actual length of process piping, size of the piping, fittings and elevation of the piping, and the process components. This is very important when developing piping system models to accurately determine process values, such as pressure at specific locations, or flow through specific sections of the system. Additionally, it is important to review isometric drawings when identifying where to take measurement such as flow rates to ensure flow meters can be installed properly and that the desired process flow is being measured.

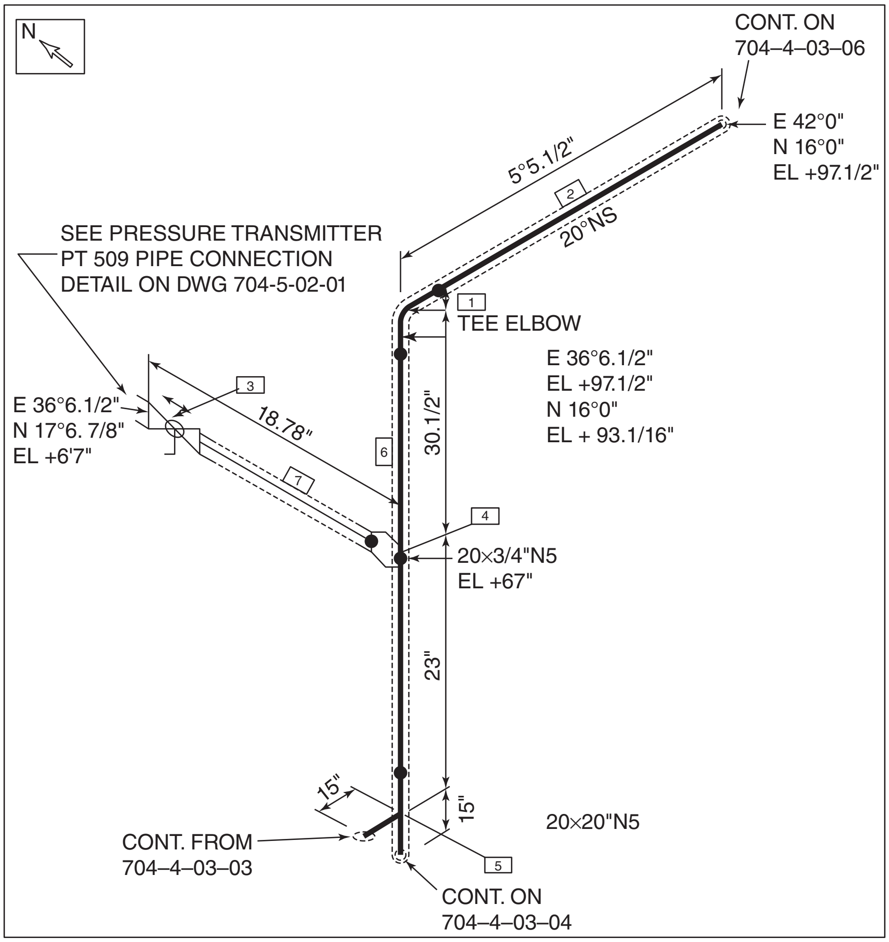


Figure 8.2: Isometric Drawing

Engineering Drawings

Reading and understanding engineering drawings, or blueprints, is an essential part of a pump system assessment. Therefore, it's important to be familiar with the standard symbols, rules, and conventions used for various types of engineering drawings.

While the format and information contained on a drawing will vary widely among vendors and manufacturers, all drawings will consist of the basic anatomy described below.

A basic engineering drawing includes the following five primary areas or parts:

1. Title block
2. Grid system
3. Revision block
4. Notes and legends
5. Engineering drawing (graphic portion)

Key Personnel (Positions) Needed on an Assessment Team

9

- **Team leader:** Multiple positions including, for example, the engineering manager, energy manager, maintenance manager, reliability manager, process control manager, plant pump champion, or other titles that have a good overview of the pump population and overall pump engineering, maintenance, reliability, and process control aspects of pumps (see personality traits below) – to be selected by the plant.
- **Maintenance and/or reliability engineer:** Understands pump population and reliability issues; i.e., helps identify pump systems that are bad actors.
- **Process control engineer:** Knowledgeable of the process and pump controls, including instruments, control valves, and DCS/PLC systems.
- **Process engineer:** Understands the plant information (PI) system, P&ID drawings, and how the process operates
- **Electrical engineer:** Understands the motor control center (MCC), motors and power supply systems. When power measurements are required, the electrical engineer or electrician will coordinate the locating of existing meters or the installation of meters for the assessment.
- **Purchasing or capital projects manager or buyer:** Understands equipment and parts purchases along with capital purchasing requirements to implement pump optimization projects.
- **Millwright:** At some sites, it is required that a millwright or other plant personnel does the physical work of installing instrumentation such as pressure gauges/transducers, temperature devices, and flow meters.
- **Permitting personnel:** In some industries (for example, oil & gas, chemical process, power, and pharmaceutical), there will need to be interaction with the permitting office to go into the process area and do work.

Personality Traits

There are certain personality traits or characteristics that are critical to successful assessments. Some of these are inherent with the individual, not easily learned, and even more difficult to teach.

Successful assessments involve both big picture perspectives (business and management perspectives) and technical details (engineering analysis orientation). Operators, as a group, tend to be much better adapted to holistic viewpoints, while engineers are more likely to focus on technical details. The successful assessment leader must be able to transition between the two roles with ease. It is important to emphasize that this is a very uncommon skill combination to find in a single individual. Those who are very experienced in assessment leadership roles will recognize the challenge of the dual role, particularly of the tendency to lose the larger picture perspective when in the midst of measurement details, and constantly challenging themselves and the other team members to think about the entire system.

The assessment leader should understand that although their technical expertise may be a necessary ingredient, it is normally not sufficient. While system engineers will hopefully have at least a fundamental understanding of the design and functional requirements of the system, it is system operators who are often the owners of key knowledge. Maintenance staff can also provide essential insights. Assessment leaders must be able to relate well to all of these individuals. A wise assessment leader will recognize that a successful assessment should be as much a learning experience for him/her as for the plant staff.

Establishing the assessment as a plant/consultant team effort, rather than as an audit conducted by an outsider, is a critical distinction to make. It is highly recommended that this distinction be made before the assessment begins and repeated often. Use of the pronoun “we” rather than “I” or “you” when discussing both existing and potential operations is strongly encouraged.

An important work ethic that the team leader should be prepared to demonstrate is a willingness to take the lead on the “dirty work” activities. Being actively involved in test equipment installation is a good practice not only from the technical standpoint (verifying that the location and configuration are proper), but is perhaps more important in the attitudinal message that it delivers.

Standard Roles and Expectations

Implementation is a team effort – no one person at a plant should take on implementation by himself or herself. As such, following are typical roles and responsibilities for each team member throughout the implementation process.

Senior management: A company’s senior management must be involved at all stages of implementation. This demonstrates a top-down approach to total cost of ownership through reliability and energy management, sending the message to plant employees that management supports implementation. Senior management must

- Agree to allow the plant to participate in the assessment
- Dedicate staff to the assessment process
- Set aside budget and allocate resources for implementation – set hurdle rates for the project
- Share expectations regarding postassessment activities, such as achieving measurable results
- Participate in the assessment kick-off meeting covering the assessment’s purpose, goals, and process
- Participate in the closeout meeting to hear first-hand about the assessment results and key lessons learned from the process
- Receive ongoing updates from either the assessment lead to gauge progress of projects
- Recognize both individual and group achievements relating to implementation progress and attained results

Project lead/Energy manager: This individual will lead implementation efforts. As such, the lead is ultimately responsible for assigning accountability to the implementation team, in addition to ensuring that the implementation process runs smoothly from start to finish. This includes activities, such as the following:

- Make sure all assessment principles are applied throughout the process
- Achieve corporate buy-in
- Ensure all parties involved understand their roles and carry out their responsibilities
- Coordinate staff involvement with supervisors
- Lead kick-off and closeout meetings
- Ensure the team understands and works to fulfill senior management's expectations related to implementation
- Verify the credibility of the assessment company prior to participating in the assessment
- Work with the assessors to ensure that there are no surprises during the assessment
- Share "need-to-know" information with the assessor
- Assign staff to implementation projects or activities
- Ensure measurement and verification efforts are performed throughout the assessment and implementation process
- Sign off on all pursuable opportunities
- Track project status and keep management informed of progress

Communications: The communications team can announce the plant's commitment to implementation as another means of accountability. This group can help with public relations efforts, including disseminating information about implementation progress and results to company stakeholders. This will let stakeholders know how implementation efforts are positively impacting them. Additionally, this group can help with recognition efforts by sharing this information internally and setting up and executing some sort of recognition event. The communications team can also help increase employee awareness of implementation efforts, as well as plant-floor recognition (level of involvement: approximately 1 hour per week).

Financial staff: Financial staff should help the plant energy manager make the business case for implementation by identifying available funding within the organization. The financial team can also help by identifying potential external funding sources to assist with implementation (level of involvement: approximately 1 hour per week).

Procurement staff: Procurement staff must understand that they are part of the implementation team. By doing so, they can be supportive of implementation efforts through the purchasing process. As such, procurement staff should be present at the closeout meeting (level of involvement: approximately 1 hour per week).

Operators: Operators participate in installation of equipment and manipulations of the process for the purpose of the assessment.

Engineers: Engineers are in charge of the process or equipment and will be involved in verification of energy efficiency and process benefits gained from the proposed modifications.

Assessment Team

Knowing how to organize a pump system assessment goes beyond just data collection and analysis. The assessment professional needs to start by establishing internal team functions in selecting the best assessment group. Members of this group will have responsibility and management control for funding the assessment, allocating resources, choosing required resources, and managing the personnel who will handle scheduling, contracts, and agreements for the assessment process.

In forming the assessment team, ensure diversity in different competencies. Select an assessor that has the right skills and expertise to conduct a pump system assessment. Establish a project leader that can handle all assigned responsibilities based on both skills and their availability. Ensure there are engineers on the team who understand the processes and function of the pump system under evaluation. Involve maintenance and operations, as well as finance and business operations, as all parties play a role in the ongoing pump system operation.

All participants: Though the project lead is responsible for assigning specific roles to each member of the implementation team, every participant should expect to do the following as part of their commitment:

- Participate in the kick-off and closeout meetings
- Ask clarifying questions of the assessor or project lead
- Complete projects and activities on time
- Participate in next-step discussions
- Seek funding for implementation
- Review implementation efforts
- Identify and address lessons learned
- Be accountable for their role in the process

Field Measurement Parameters and Their Acceptable Ranges

10

Electrical Input Power

Individual motor input power is not always monitored by permanently installed instruments. Individual motor current is sometimes monitored and displayed at the MCC or remotely, but typically only for larger motors. Motor input power and/or current can be measured on “low” voltage buses (e.g., 480V) with portable test equipment.

Fluid Properties

Generally speaking, the fluid viscosity and specific gravity are either essentially constant or can be readily determined by either direct measurement or from relationship to some other easily measured parameter (such as temperature).

Pump and System Head

Most pump applications include suction and discharge connections for pressure measurement, which are the parameters of primary importance in pump head calculation. Static head can be readily determined from system drawings, linear measurements, and/or pressure/level gauges. If pressure is not able to be measured at the pump suction and discharge location but can be measured elsewhere in the system, the pressures at the suction and discharge can be estimated based on the elevation difference and friction loss calculations between the measurement point and the suction or discharge of the pump. Additionally, pressure may need to be measured at different locations in the system to verify friction head loss in piping, fittings, valves, or other end-use equipment.

Pump and System Flow

Flow rate is measured via permanent instrumentation in some applications, but is less commonly available than pressures. When permanently installed flow rate instrumentation is not available, temporary test devices can be employed.

Alternatively, flow rate can be estimated using the measured differential pressure and pump performance curves. Estimating flow rate from measured differential pressure and the pump performance curve is obviously not the preferred approach; but in some cases, it is the only available means. When the wear condition of the pump (impeller and wear rings) is not known, estimating flow based on differential pressure and power can be misleading due to degraded performance.

There are other sources of data that can help corroborate or refine flow rate estimates. When using pump performance curves, be sure to measure actual speed. If it is significantly different than the speed at which the curve was developed, adjust the curve using pump affinity rules.

11

Hydraulic and Electrical Formulae

Rotodynamic Pump NPSHA

NPSH is the total suction head in feet of the liquid being pumped at the centerline of the impeller eye, less the absolute vapor pressure of the liquid being pumped.

NPSHR is checked to ensure that the liquid inside the pump will not vaporize as it accelerates into the eye of the impeller. This factor is determined by the pump Original Equipment Manufacturer (OEM) on a test stand.

NPSHA is the total suction head absolute, over the vapor pressure of the liquid pumped at its operating conditions in the NPSH datum plane defined as follows:

$$\text{NPSHA} = h_{\text{atm}} + h_{\text{s}} - h_{\text{vp}}$$

Where

h_{atm} = atmospheric pressure head, ft (m)

h_s = total suction head = $h_{gs} + h_{vs} + z_s$, ft (m)

h_{gs} = suction gauge head, ft (m)

h_{vs} = suction velocity head, ft (m)

z_s = elevation from the suction gauge centerline to datum (see Figure 11.1), ft (m)

h_{vp} = liquid vapor pressure head (taken at the highest sustained operating temperature), ft (m)

NPSHA must be greater than NPSHR for the pump to function properly. How much greater the NPSHA must be than the NPSHR is determined by the pump type and pumpage.

NPSH datum plane: The horizontal plane through the center of the circle described by the external points of the entrance edges of the impeller blades; in the first stage in the case of multistage pumps. In the case of double inlet pumps with vertical or inclined axis, it is the plane through the higher center. The manufacturer should indicate the position of this plane with respect to precise reference points on the pump (see Figure 11.1).

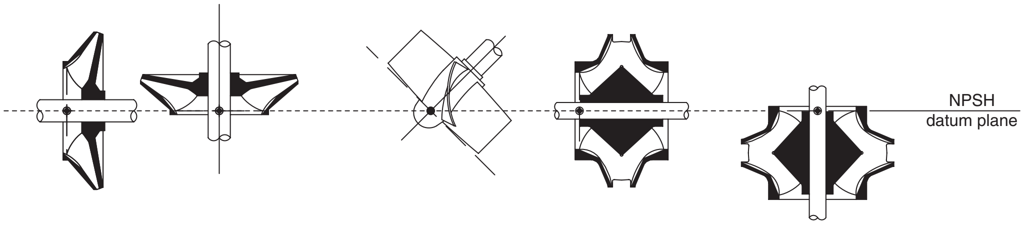


Figure 11.1: Datum Elevation for Various Pump Designs at the Eye of First-stage Impeller

Rotary Pump Net Positive Inlet Pressure

It is customary for positive displacement pumps to express performance in terms of pressure instead of head. Similar to the NPSH for rotodynamic pumps, rotary pumps have the term net positive inlet pressure available (NPIPA), which is the algebraic sum of the inlet pressure and barometric pressure minus the vapor pressure of the liquid at inlet temperature. NPIPA must always exceed NPIPR for satisfactory pump operation.

Note: NPSHA is often used and is normally expressed in feet (meters). It is the nominal equivalent of NPIPA with appropriate unit conversions.

$$\text{NPIPA} = p_s + p_b - p_{vp}$$

Where

- NPIPA = net positive inlet pressure available, bar (psia)
- (metric units, bar) Inlet suction pressure $= p_s = p_{gs} + 9.8 \times 10^{-2} \times s \times \left(Z_s + \frac{v_s^2}{2g} \right)$
- (US Customary Units, psig) Inlet suction pressure $= p_s = p_{gs} + 0.433 \times s \times \left(Z_s + \frac{v_s^2}{2g} \right)$
- p_b = barometric pressure
- p_{vp} = vapor pressure

The inlet pressure (p_s) is the algebraic sum of the gauge pressure (p_{gs}), the velocity pressure, and the elevation pressure as measured at the pump inlet. In the above equations, the elevation head (Z_s) and velocity head terms are converted to pressure with the constants. Specific gravity (s) is included in the equations to account for different densities in the conversion from head to pressure.

The symbol p_s may be positive or negative with reference to atmospheric pressure and may, therefore, have positive or negative values. The symbol is called *inlet pressure* when positive and *inlet vacuum* when negative. The measuring section should be located in the inlet pipe immediately before the pump inlet connection.

Reciprocating Pump Net Positive Inlet Pressure

Because of the characteristic pulsating flow of reciprocating pumps (Figure 11.2), where peak flow rates can reach three times greater than the average flow, careful consideration must be given to suction piping to ensure that it is capable of delivering adequate fluid to the pump inlet.

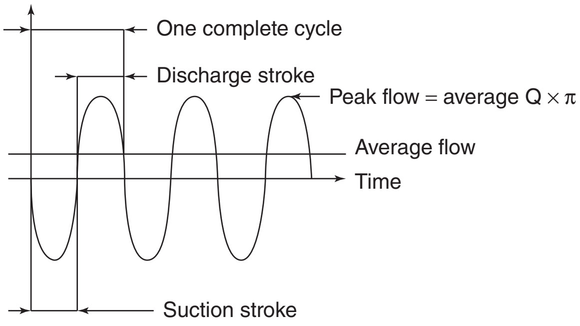


Figure 11.2: Example of Pulsing Flow

Reciprocating pumps are unique in that the liquid in the suction and discharge piping has to be accelerated because flow varies from zero to peak with each stroke. This results in alternate pressure drops and surges. The instantaneous pressure drop required to accelerate the mass of liquid in the suction line, or the instantaneous pressure rise required to accelerate the mass of liquid in the discharge, is referred to as acceleration head (h_{acc}) or acceleration pressure (p_{acc}). The acceleration head (pressure) must be calculated and subtracted in the NPIPA calculation for reciprocating pumps.

The most frequent reason for technical support calls to pump manufacturers regarding problems with reciprocating pump performance is because of suction piping that cannot supply the demands of the pump. To ensure adequate flow to the inlet of the pump, refer to the following NPIPA calculations.

$$\text{NPIPA} = p_s + p_b - p_{vp} - p_{acc}$$

Where

- NPIPA = net positive inlet pressure available, bar (psia)
- (metric units, bar) Inlet suction pressure $= p_s = p_{gs} + 9.8 \times 10^{-2} \times s \times \left(Z_s + \frac{v_s^2}{2g} \right)$
- (US Customary Units, psig) Inlet suction pressure $= p_s = p_{gs} + 0.433 \times s \times \left(Z_s + \frac{v_s^2}{2g} \right)$
- p_b = barometric pressure
- p_{vp} = vapor pressure
- p_{acc} = acceleration pressure

See calculation of acceleration head and conversion to acceleration pressure

$$h_{acc} = \frac{l \times v \times n \times C}{g \times k}$$

Where

h_{acc} = acceleration head, ft (m)
l = actual length (not equivalent length) of suction line, ft (m)
v = average liquid velocity in suction line, ft/s (m/s)
n = speed of pump crankshaft, in rpm
C = constant depending on pump type
= 0.400 for single-acting simplex
= 0.200 for single-acting duplex
= 0.115 for double-acting duplex
= 0.066 for triplex
= 0.040 for quintuplex
= 0.028 for septuplex
= 0.022 for nonuplex
g = acceleration due to gravity = 32.2 ft/s^2 (9.81 m/s^2)

k = constant depending on fluid compressibility
= 1.4 for noncompressible liquids such as deaerated water
= 1.5 for most liquids
= 2.5 for compressible liquids (such as ethane)

To convert acceleration head to acceleration pressure (p_a), the following conversions apply:

p_{acc} (bar) = h_{acc} (m head) × (9.8 x 10^{-2} bar/1 m head)

p_{acc} (psi) = h_{acc} (ft head) × (0.4335 psi/1 ft head)

Affinity Rules

The pump affinity rules describe how changing the impeller diameter and rotational speed affect the pump performance data. The pump curve is derived from a series of test points connected together forming a smooth line. The discrete flow and head test values can be thought of as belonging to a coordinate point. When using the pump affinity rules, it is important to adjust both the head and flow values for the same coordinate point.

Changes in Rotational Speed

When the rotational speed of a pump is changed, the rate of flow (capacity), head, and power for a point on the pump curve vary according to the pump affinity rules. The affinity rule equations with respect to speed are the following:

The equations relating the rotodynamic pump performance parameters of flow rate, head, and shaft power, to speed are known as the affinity rules:

$$Q_2 = Q_1 \frac{n_2}{n_1} \quad H_2 = H_1 \frac{n_2^2}{n_1^2} \quad P_2 = P_1 \frac{n_2^3}{n_1^3} \cdot$$

Where

Q_1 = rate of flow at original speed, gpm (m^3/h)
H_1 = total head at original speed, ft (m)
P_1 = pump shaft power at original speed, hp (kW)[1]
n_1 = original pump speed, rpm
Q_2 = rate of flow at desired speed, gpm (m^3/h)
H_2 = total head at desired speed, ft (m)
P_2 = pump shaft power at desired speed, hp (kW)[1]
n_2 = desired pump speed, rpm

[1] This refers to the pump input power. Other drive train losses will not follow this relationship.

The implication of the squared and cubic relationships of head and power absorbed is that relatively small changes in speed give very significant changes in these values, as shown in an example of a rotodynamic pump in Figure 11.3.

Points of equal efficiency on the curves for the three different speeds are joined to make the ISO efficiency lines, showing that efficiency remains constant over small changes of speed providing the pump continues to operate at the same position relative to its BEP.

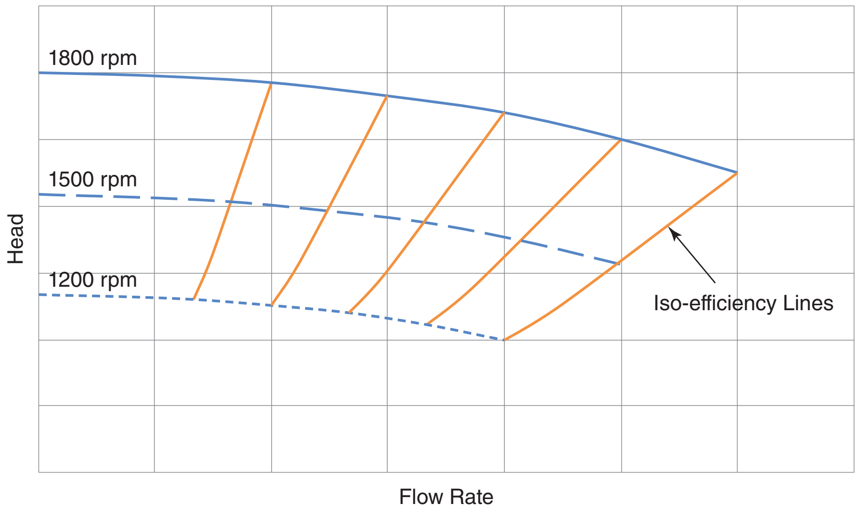


Figure 11.3 – Example of Speed Variation Affecting Rotodynamic Pump Performance

Changes in Impeller Diameter

Within limits, the change in speed affinity rules can be applied to changes in diameter of the pump impeller. For diameter change, substitute in the aforementioned equations D_1 for n_1 and D_2 for n_2:

D_1 = original impeller diameter

D_2 = changed impeller diameter

When changing impeller diameters more than 5%, the aforementioned equations are not recommended without consulting the pump manufacturer.

The manufacturer should be consulted to determine minimum acceptable impeller diameter. As the casing and impeller become mismatched due to trim, efficiency and NPSH are negatively affected.

As noted, aforementioned efficiency varies when the diameter is changed within a particular casing. Note the difference in ISO efficiency lines in Figure 11.3 compared with Figure 11.4. The relationships shown here apply to the case for changing only the diameter of an impeller within a fixed casing geometry, which is a common practice for making small permanent adjustments to the performance of a centrifugal pump.

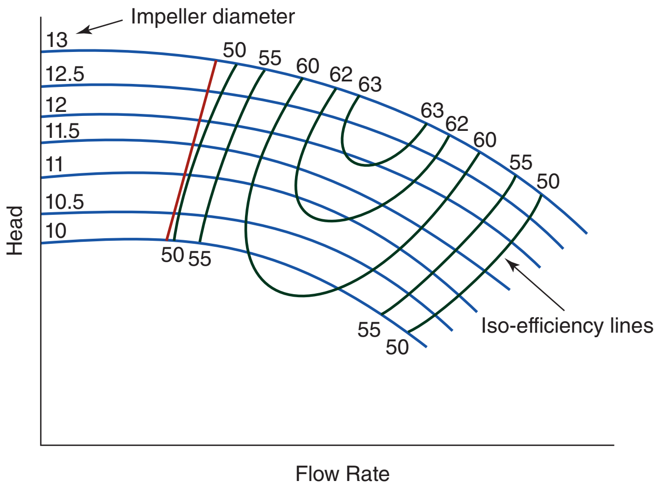


Figure 11.4: Example of Impeller Diameter Reduction Affecting Rotodynamic Pump Performance

NOTE: The system requirements may limit pump performance so that the rate-of-flow change in the system will not follow the above calculation (see Chapter 15).

Motor Load and Efficiency

An induction motor is a highly efficient electrical machine when operating close to its rated efficiency and load. It is important to understand motor efficiency as it relates to load. As motor load is reduced, efficiency begins to drop off, impacting the wire-to-water efficiency.

There are many important reasons to determine motor loading efficiency relating to pumping systems. Figure 11.5 highlights how motor efficiency drops dramatically when it operates below 50% load, but it varies, depending on motor horsepower size. Notice how the top curve, which represents larger 75–100 hp motors, drops off slowly. Yet, the 0–1 hp motor range, shown in the bottom curve, drops off steeply after 50% load.

TIP

It is important to understand the motor efficiency as it relates to load. As motor load is reduced, efficiency begins to drop off, impacting the total pump system efficiency.

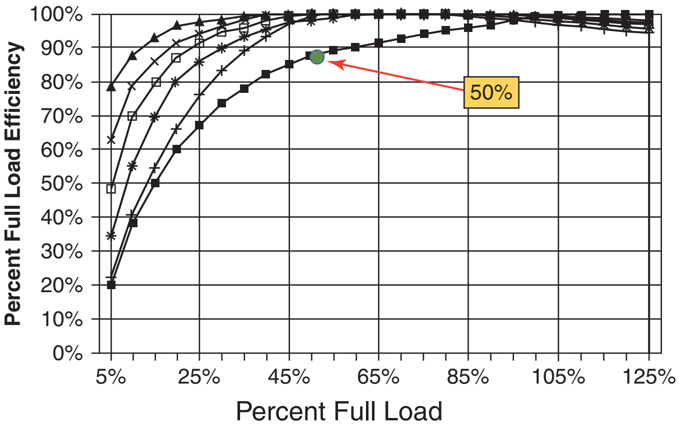


Figure 11.5 Efficiency versus Percent Full Load

To estimate motor part-load, "direct-read" power measurements must be used. Using parameters measured with hand-held instruments, Equation 1 can be used to calculate the three-phase input power to the loaded motor.

TIP

Power factor (PF) can be obtained from the motor performance data sheet.

Equation 1

$$\text{Motor Input power (kW)} = \frac{I \times V \times PF \times C}{1000}$$

Where

I = RMS current in amperes (A) (meter reading)

V = RMS volts (meter reading)

PF = power factor (motor curve or measured)

C = 1 for single-phase current

= 2 for two-phase four-wire control

= 1.73 for three-phase current

Equation 2 can be used to calculate the full load input power (kW) based on the nameplate rated motor output power (hp). Note that this shows the typical output rating in the United States being horsepower and converting to kilowatts.

Equation 2

$$\text{Rated Full Load Motor Input power (kW)} = \frac{P_r \times 0.746}{\eta_r}$$

Where

P_r = rated motor output power (hp)

0.746 = conversion factor (hp to kW)

η_r = rated motor efficiency (%)

Using the relationship shown in Equation 3, the motor's percent load can be quantified by comparing the measured input power under load (Equation 1) to the power required when the motor operates at rated load (Equation 2).

Equation 3

$$\text{Motor Load (\%)} = \frac{\text{Motor Input power (kW)}}{\text{Rated Full Load Motor Input power (kW)}} \times 100$$

Nameplate full-load current value applies only at the rated motor voltage. Thus, RMS current measurements should always be corrected for voltage. If supply voltage is below what is indicated on the motor nameplate, the measured amperage value is correspondingly higher than expected under rated conditions and must be adjusted downwards. The converse holds true if the supply voltage at the motor terminals is above the motor rating. The equation that relates motor load to measured current values is shown in Equation 4.

Equation 4

$$\text{Motor Load (\%)} = \frac{I}{I_r} \times \frac{V}{V_r} \times 100$$

Where

I = RMS current in amperes (A) (meter reading)
I_r = nameplate rated current
V = RMS voltage, mean of three phases (meter reading)
V_r = nameplate rated voltage

Once the motor input power is known from measurements, the annual electricity cost can be calculated as follows:

Annual Electricity Cost = motor input power (kW) × hours × rate

Where

Hours = annual operating hours
Rate = electricity cost in $/kW·h

Note: If the load varies in time, you will need to determine a load profile and calculate an average motor input power to use in the calculation.

12

Measuring Devices and Their Requirements and Proper Application

Definitions

Calibration: Calibration is the process of adjusting an instrument's output signal (or indication) to accurately represent the physical quantity that is being measured. The output signal is typically linear throughout the entire measuring range, although this is not always achievable.

Calibration can be called for when

- An instrument is new
- A specified time period has elapsed
- A specified usage (operating hours) has elapsed
- An instrument has had a shock or vibration that potentially may have put it out of calibration
- A sudden change in weather occurs
- Observations appear questionable

Some instruments are factory-calibrated and are ready for use "out of the box," while others may require field calibration. A certificate of calibration can be obtained from the instrumentation manufacturer.

Drift: Long-term exposure to heat, humidity, and other taxing environments in an industrial process can cause the instrument's calibration to drift. The output signal may read higher or lower than calibrated values. The instrument needs to be recalibrated, repaired, or replaced.

Environmental considerations: When selecting an instrument, it is important to consider the environment where the instrument will be mounted. Environmental considerations can dictate the instrument's temperature rating, ingress protection, rating against water and dust, vibration rating, pressure rating, and hazardous location rating.

Hazardous location: Some instrumentation is suitable for installation in hazardous locations. There are tight regulations for the selection and installation into these environments. Always consult the manufacturer for best selection and installation guidelines, and follow local and national codes. Only qualified personnel should install and service instrumentation.

Indicator: An indicator is a meter or gauge used to monitor the operation or condition of a process, or to show the presence of a physical quantity, such as pressure, temperature, flow, current, voltage, and vibration for force.

Instrumentation: A collection of instruments for the purpose of observation, measurement, protection, or control.

Percent full-scale accuracy (% FSA): The accuracy based on the full scale of the instrument.

For example, if a pressure transmitter has a measuring range of 0–100 psi (0–690 kPa), and was specified to have a ± 1% FSA, then the allowable error range would be ±1 psi (±7 kPa). If this pressure transmitter was tested with a pressure of 10 psi (69 kPa), then the acceptable output signal would correspond to a reading of 9–11 psi (62–76 kPa).

Range and span: The range of an instrument is the measurement for which it is capable. The span is the measurement for which it is calibrated. The span can equal the range or be less than the range. Whatever span has been calibrated for, the transmitter will be represented by the output signal.

As an example, if the instrument has a measurement range of 200 psi (1400 kPa), the span could be adjusted to 200 psi (1400 kPa), but it would correspond with the maximum range of 200 psi (1400 kPa), possibly introducing inaccuracies when operating near the end of the range. It would be preferable to select a device with a range of 250 psi (1700 kPa) and then adjust the span so that 200 psi (1400 kPa) causes a full-scale output of 20 mA. This is a span of 80% of the range (200/250 [1400/1700]). Standard instrument design procedures will normally try to select an input range that will cause the majority of the normal operation measurements to fall within 20%–80% of the range.

Sensor: A sensor is a device that measures a physical quantity, such as pressure, temperature, flow, current, voltage, vibration, or force, and converts it into an analog or digital signal that can be read by an observer or an instrument.

Signal types: Signal types include the following:

- Analog voltage or current signal proportional to the physical quantity measured
- Pulse trains, whose frequency or duty cycle convey the information
- Wired serial communications
- Wireless communications

Switch: A switch is a device that, after the deviation of a physical quantity such as pressure, temperature, flow, current, voltage, vibration, or force from its set point, opens or closes a set of contacts.

Transmitter: A transmitter is an electronic device used in combination with a sensor and voltage-to-current signal conditioner to generate a proportional 4–20 mA (or other type) output signal.

Selection Considerations

- Accuracy
- Range
- Repeatability
- Product compatibility
- Operating conditions
- Mounting method

- Installation environment
- Cost
- Approval rating
- Calibration and maintenance requirements
- Connectivity

Pressure

Type	Pros	Cons	Relative Cost
Pressure gauge	Simple, local read out	No transmission	$
Pressure switch	Simple operation, adjustable	On/off operation only	$
Pressure transducer/ transmitter	Continuous monitoring	Cost	$$

Temperature

Type	Pros	Cons	Relative Cost
On/off			
Thermostat	Simple	On/off only, mechanical device	$
Thermistor	Simple	On/off only, requires controller	$
Direct measure			
Thermocouple	Available in higher temperature ranges, fast response time, many sizes	Requires special wires for connection, medium accuracy, linearity only fair	$$
RTD	More accurate measurement, more stable, greater repeatability and linearity, most common	Narrower range, requires external power source, slower response time	$$$
Thermistors	Highest sensitivity, robust signal	Narrowest range, lowest stability and linearity	$

Level

Type	Pros	Cons	Relative Cost
Invasive			
Float switch	Low cost	Maintenance, moving parts, on/off only	$
Conductive	No moving parts	Maintenance may be issue depending on conductivity	$$
Capacitance	No moving parts, can be designed for high- temperature and high- pressure conditions	Limited application	$$
Submersible hydrostatic pressure	Accurate, easy installation, low cost	Suspended in the liquid	$$
Noninvasive			
Ultrasonic	Can be used with bulk solids, lower cost noninvasive option	Cost increases with accuracy, not for excessive turbulence and foaming applications	$$$
Microwave	Can be used in high- temperature and pressure applications, and vaporous and dusty environments	Higher cost non-invasive option	$$$

Flow

Type	Pros	Cons	Relative Cost
Through pipe			
Magnetic flow meter	No moving parts	Liquid must be conductive, low accuracy at low flow, high cost for large diameters	$$
Vortex flow meter	Accuracy	Cost	$$$
Mass flow	Accuracy	Cost	$$$
Turbine	Simple, low cost	Moving parts, low flow	$
Venturi	Simple and stable	Bulky	$$
Orifice plate	Simple and stable	Can clog, limited to clean liquids, creates pressure drop	$
Insertion type			
Turbine	Low cost, easy to install	Moving parts, reliability	$
Pitot tube	Low cost	Point measurement, may not represent the average flow	$
Paddle wheel	Low cost, easy to install, accuracy at low flow	Moving parts, reliability	$
Noncontact			
Ultrasonic	Noncontact, mounts on the outside of the pipe	Accuracy or functionality may be affected by fluid characteristics	$$
Other			
Differential pressure across a calibrated valve/pump	Simple	Low accuracy, need the valve/pump curve to calculate flow	$
Pump motor power and rpm	Sensorless	Low accuracy, need the pump and curve to calculate flow, must factor in the liquid properties	$
Volume change over time	Accurate	Does not work for continuous pumping operation	$
Weir or flume level	Effective for large flows and contaminated liquids	Elaborate set up and installation	$$

Pressure

Collecting pressure measurement data is a critical parameter in a pump system assessment. For accurate results, use calibrated and reliable pressure instruments and position them close to the suction and discharge side of the pump. Additional pressure measurements throughout the system may be required.

When taking pressure measurements, it is important to determine the service history of the instruments.

Here are some practical considerations:

- Service environment, history
- Calibration
- Instrument range
- Accuracy
- Overpressure capability
- Physical location, setup
- Process connection point
- Accounting for sensing element elevation
- Proper instrument line fill and vent

Flow

Measuring flow rates will determine pump system efficiency. Use accurate flow meters to measure all conditions. When installed flow meters do not exist, use portable flow meters. Remember that flow meter data should always be cross-checked with pressure and power measurements to determine if there are anomalies in the data, or if the published pump performance has degraded over time; i.e., the pump does deliver the same head or flow as when it was originally installed.

There are a variety of flow meter types including

- Differential pressure
- Velocity (i.e., vortex, magnetic, ultrasonic, etc.)
- Open flow
- Positive displacement
- Coriolis mass flow meters

When selecting flow meters for an application, it is important to consider the flow profile and required installation and application characteristics, such as

- Proper flow profile and installation
- Range
- Calibration
- Wear
- Corrosion, scale, or foreign material
- Sensing line issues (similar to pressure)

Portable nonintrusive flow meters are based on ultrasound, either transit-time or Doppler technology. They are advantageous because they can strap on the outside of the pipe without intrusion in the process. Transit-time technology typically works only in low solid and nonaerated solutions, since the particles or air bubbles deflect or attenuate the transit-time sound waves. In contrast, Doppler technology works in applications where there are solids or aerated fluids. Portable flow meters are required when there are not installed flow meter(s) to measure the desired system flow(s), and are also used to cross-validate the installed (in-situ) flow meter.

TIP

In electrical engineering terms, a wattmeter is a device used to measure the amount of electric power, in watts, within a given circuit. There are three methods for measuring wattage, the one-, two- and three-wattmeter methods. The two-wattmeter method is commonly used on three-phase loads, or circuits such as induction motors.

Input Power

Input power is another critical measurement. A power meter will provide the most accurate data. When required, an electrician may connect power monitors in the MCC so that the motor input power can be determined accurately. If power can't be measured directly, measure voltage and current to the motor and determine the power factor from the motor performance curve and calculate motor input power per Equation 1 (Chapter 11).

Common Operating Problems and Errors

13

After the review process has been completed and it is confirmed an appropriate type and size of pump has been installed correctly then attention needs to shift to how the pump equipment is being operated. The operator is responsible to see that the pump is always operated within the manufacturer's limits and maintained according to the manufacturer's requirements.

Improper Equipment Operation

Improper equipment operation can be related to a number of factors, such as

- Start-up and shut-down
  - Improper and uncontrolled start-up and shut-downs can lead to premature failure of the pump and its components. When starting and stopping a pump, the mechanical seal faces the greatest chance of damage. The following areas should be reviewed and checked to be proper during the starting and stopping procedures:
    - Check for proper direction of rotation
    - Pump priming, venting, and system valve positioning
    - Proper seal quench and flush when required
    - Suction pressure (NPSHA) and the possibility of dry running
    - Maintain flow above minimum
    - Proper valve settings
    - Lubrication systems
- Operational process conditions/changes
  - Stability of pressure. Pressures could exceed mechanical seal limits and cause distortion of the seal faces (face rotations), or pressure could be insufficient to prevent vaporization between the seal face set.
  - Stability of temperature. Some fluids solidify at low temperatures, at high temperatures, or in a narrow range of temperatures.
  - Changes in process fluid viscosity, especially in winter climates at start-up. The high viscosity on a cold start-up in a low-temperature environment can result in grain pullout on the seal faces.
  - Runout flow, where the pump is developing practically no head but at a high flow rate can have negative impacts to both the mechanical seal as well as the pump.
  - Variable process fluids being pumped. Different fluids having different viscosities as well as other thermal properties can result in significantly different net faces distortions from pressure and temperature. Pressure distortions typically result in seal face outside diameter (OD) contact and thermal distortions result in inside

  diameter (ID) contact. This can result in unstable seal operation or high leakage when process fluids change.
  - Load swings can create a condition where the net face distortion changes. If the seal faces wear at one condition, a load swing will change the distortion (divergent or convergent), which can result in higher leakage during a transition period.
  - Water hammer can create extreme mechanical forces. This can cause the faces to separate and slam back together resulting in chipping of the faces or can fracture the seal faces. In addition other damage to the seal drive mechanism as well as components with close clearance, such as bushings, can be destroyed.
  - Contaminants or foreign objects in the pump system can cause abrasive wear, erosion, and/or hang-up of dynamic secondary seals.
  - Process chemistry transients – may cause unexpected or accelerated corrosion.
- Operation relative to the pump curve
  - Operating with a closed discharge valve – dead head operation.
  - Operation outside the preferred operating range (POR) or, particularly, the allowable operating range (AOR).
  - Hydraulic-related vibration due to internal pump recirculation when the pump is operated outside the POR.
- Other
  - Allowance for thermal expansion/contraction. If the seal assembly is not designed for transient differences in growth between the pump casing and the pump shaft, then it may run at solid height resulting in excessive face loads or at free height where the faces are not in contact, and leak.
  - Erosion in the pump seal chamber – creating excessive wear of pressure-retaining components and introducing additional abrasives that can damage the seal components and especially the seal faces.

- ○ A positive displacement pump has a fixed displacement volume and, therefore, generates a flow rate directly proportional to its speed. The pressure it generates is determined by the system's resistance to this flow.
- ○ A rotodynamic pump is a variable torque device that uses an impeller and volute to create a partial vacuum and discharge pressure to move water through a casing. A rotodynamic pump has a variable flow/pressure relationship.
- ○ Pump system components include prime movers (typically electric motors), piping, and valves.
- ○ A pump curve describes the pump and prime mover. A system curve represents all the system components, including piping, valves, and end-use equipment. The system will operate where the pump and system curves intersect.
- ○ The assessment professional should be familiar with the operating procedures for the pumping systems being evaluated, including industry standards and the manufacturers' installation and operating procedures.
- ○ The purpose of system optimization is to reduce energy consumption and improve the reliability of pumping systems, ultimately minimizing the cost of ownership over the economic life of the pumping system.
- ○ The best efficiency point (BEP) describes the rate of flow at which both performance and service life of the pump are optimized.
- ○ Nozzle loads and hydraulic phenomena caused by improper suction piping and intake design can have an adverse effect on the performance and reliability of pumps.
- ○ Pump system performance depends on the design of mechanical seals and the prevention of excessive heat from the motor or gearbox.
- ○ The lifecycle cost (LCC) analysis describes the total cost of providing, running, maintaining, and disposing of the pump or pumping system. It allows the plant designer or manger to compare alternative solutions.
- ○ Understand and apply hydraulic and electrical formulae
- ○ Preventive and predictive maintenance activities are undertaken to keep pumps operating well and to detect problems. Periodic efficiency testing – specifically, wire-to-water efficiency – is a form of condition monitoring.
- ○ Process flow diagrams indicate the general flow of processes and equipment and display the relationships between major equipment and the plant.
- ○ The key personnel needed on an assessment team span nearly all areas of the plant.
- ○ In-field equipment should be evaluated to determine if its operation is acceptable.
- ○ Be familiar with the formula for calculating Net Positive Suction Head available (NPSHA), Net Positive Inlet Pressure available (NPIPA) and with the affinity rules.
- ○ Be familiar with the types of measuring devices for pressure and flow, and understand the methods for determining input power.
- ○ Improper equipment operation can be related to many factors, including start-up and shut-down, operational process conditions or changes, and operation relative to the pump curve.

Domain I – Knowledge Check

1. **Task:** Assess the present situation and determine if it is amenable to a pump system assessment (i.e., jointly determine the value proposition/objectives).

   Exercise: Using the Current Situation/History develop a list of questions to identify/develop the Value Proposition Objectives and Customer Expectations/ Deliverables.

   Plant Configuration: 400 MW oil-/gas-fired combined cycle plant

   Current Situation/History: The plant has three 600 hp fuel oil transfer pumps used to transport # 5 fuel oil from “day tanks” (located on plant site) through a filtration system and heater to the fuel oil burner pumps. The pumps are driven by 600 hp, 1200 rpm fixed speed induction motors and coupled to a twin screw positive displacement pump with a limited end float gear-type coupling.

   Issue: High vibration and frequent motor/pump bearing failures as well as frequent mechanical seal failures.

Answer:

Qualifying Questions:

- How long have these units been in service?
- Historically, what is the MTBR of the subject equipment and was it ever acceptable?
- How is the system controlled, and what is the primary variable that is controlled ?
- What is the current MTBR of the motor/coupling/pump?
- When did the premature failures begin to occur or become more frequent?
- Are maintenance costs available for the pump system?
- Has the operation, design, or equipment changed?
- Have you changed or modified the pump design from original OEM configuration?
- What component(s) typically fails first?
- Have you performed a Root Cause Failure Analysis and are findings available?
- Do you have a failed component to inspect?
- What is the impact on your operation if a single transfer pump fails or multiple transfer pumps fails and have multiple transfer pumps failed simultaneously?
- What is the normal, low and peak demand for the system?
- How many pumps are typically run at any given time to meet demand?
- What regular maintenance is performed on the motor/coupling/pump?
- What type of alignment procedure/equipment are used and tolerances?
- What is the typical start-up procedure for the pumps and sequence for operating multiple pumps?

- Do you start and stop frequently, how many times a day, year?
- Do you conduct condition monitor on the pumps such as vibration, performance measurements, power draw, temperature, etc.?
- What hydraulic and motor data is available for the pumping system and is trend data available?

2. **Task:** Distinguish between various levels of a pump system assessment.

   Exercise: What constitutes level 1, 2, and 3 assessments and which level would be appropriate for the situation presented in task 1?

Answer:

A Level 1 assessment is a qualitative investigation to identify optimization potential without physical data acquisition and monitoring the equipment. It includes gathering of system information for pumping systems that impact cost of ownership of the equipment, much of which is included in a prescreening process.

A Level 2 assessment is a quantitative (data acquisition/measurement-based) investigation to determine the cost of ownership saving potential for a system that does not vary operation. Data is acquired for the pumping system at one operating condition within a limited time frame that represents the typical performance of the system.

Level 2 assessments are performed when it is clear that the observed operating conditions are representative of the operation of the system and the changes in operating condition are small or nonexistent.

A Level 3 assessment is a quantitative investigation over an extended period of time sufficient to develop and understand a system load profile and the pumps operation within it. Level 3 assessments are conducted on pumping systems where conditions vary substantially over time. In such systems, the assessment team shall measure system performance over a period long enough to capture all operating conditions

For the situation described in task 1, a Level 2 assessment could be appropriate because the pumps are positive displacement type with fixed speed motors. This means they will deliver a near constant flow rate. However, since there are multiple failures, in addition to gathering a single operating point for the pump system in question, additional more detailed failure analysis should take place to come to a firm conclusion on the failure modes. The more detailed failure analysis could require monitoring system conditions over a period, to understand how pressures and demand change, so a Level 3 assessment is most likely the best approach.

3. **Task:** Assemble a pump system assessment team and define roles and responsibilities.

   Exercise: The assessment team should be comprised of personnel from cross-functional backgrounds, define backgrounds.

Answer:

- An assessor who has the pump system analysis competencies
- The host organization representative who has overall responsibility and ownership for the assessment
- Specialist on the processes, system components, and the function of the system
- Specialist on the maintenance practices of the pumping system
- Specialist who can provide the team with cost data

The assessment team may be from the host organization or enhanced by using outsourced specialists, particularly considering the competence of the assessor, or to provide specialized knowledge on the system components such as the pump(s), driver(s), or control(s).

The host organization should appoint the assessment team leader. The leader may be from the host organization or a contracted assessment specialist. If the leader is not from the host organization, the host organization should have a sponsor/point person to help facilitate.

4. **Task:** Obtain and analyze initial information about the pump system (i.e., perform prescreening).

Make a visual assessment of the pump system, or have the plant verify the accuracy of the information provided, to confirm initial information, obtain additional information, and make a final determination of the project scope.

Conduct a pump systems operation discussion with appropriate personnel to answer questions, verify information previously obtained, and provide additional information.

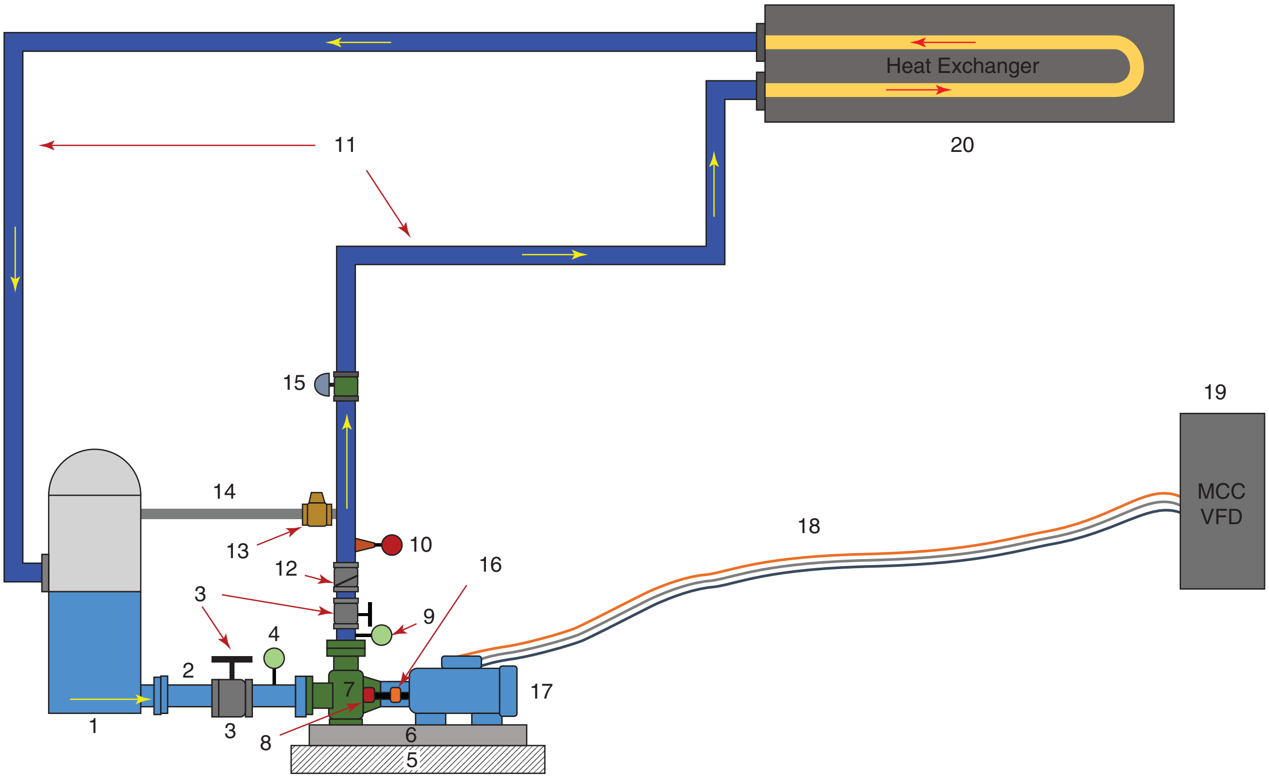
Exercise: Define the steps/actions necessary to complete Tasks 2, 4, and 5.

Answer:

- Walk down the pumping system with an individual who understands the process.
- Interview maintenance, operations, engineering, and purchasing specialists to understand issues and concerns from all parties with vested interest in the system. Ask the right questions. (Note: Refer to answers from Question 1.)
- Using the Preassessment Screening checklist to obtain initial data, review content for accuracy.
- Prepare a diagram of the system boundary and submit it to the equipment owner for review and validation to confirm you have a sound understanding of the system and its operating envelope.
- Agree to the scope and boundary of the assessment so that additional data can be obtained.

5. **Task:** Obtain real-time pump system operation data.

Exercise: Identify the numbered pump system components, then explain what data you would acquire from each component and why.



Answer: Note: The answer to this exercise is lengthy. The intention is to provide the candidate with a complete picture of pumping system components and how they impact an assessment.

1. **Suction source –** Suction fluid level, pressure, and temperature must provide adequate NPSH margin to ensure the pump can reliably meet design conditions. The NPSHA is a function of the following attributes of the pump and piping system.
   a) Elevation difference between the liquid level and the eye of the impeller
   b) Pressure on the surface of the liquid
   c) Head loss in the pumps suction pipelines
   d) Flow velocity of the pump suction nozzle
   e) Vapor pressure and density (as function of temperature) of the liquid being pumped
   f) Barometric pressure at the pump site

2. **Suction Piping –** Many of the hydraulic problems encountered in pumping systems originate in the suction piping. It is important to provide the best possible suction piping layout. Piping must be large enough to carry the volume without excessive head loss. Piping configuration must be such that the liquid enters the pump in a uniform manner. Industry standards for straight run of pipe entering the pump should be followed based on the flow obstructions in the suction piping.
   - The head loss component of the NPSHA is based on the losses in the pump suction piping. These losses can be significant and increase with the square of the increased ratio of flow rate. Sometimes pump performance is limited by the NPSHA. It may be possible to reduce the piping head losses by increasing the diameter of the suction piping or reconfiguring so that obstructions are minimized.

3. **Block valve –** Block valves are used to isolate the pump for repair and service without having to evacuate the system. Block valves should be installed at the suction and discharge side of the pump. Block valves should never be used for process control.

4. **Suction pressure gauge or transducer –** The suction gauge should be liquid filled and sized according to the suction pressure felt by the pump. If the pump experiences a vacuum condition, a gauge that reads vacuum as well as pressure should be selected.

5. **Foundation/subbase –** The success of a reliable pumping system begins with the subbase. The subbase is the foundation on which the primary base plate is installed. The subbase must be of appropriate size and mass to support the primary base plate as well as the components installed on the base plate. An inadequate foundation can be the source of many mechanical reliability issues.

6. **Primary base plate –** Torsional stiffness, rigidity, and flatness are the most important considerations with respect to the primary base plate. Refer to the manufacturer's installation, operation, and maintenance manual for requirements on levelness, grouting, etc.

7. **Pump –** Selecting a pump for an application is governed by the system head versus flow requirements, suction head available, the pump performance characteristics, the pumping application/liquid properties, the footprint required for the pump and driver, application specifications, codes, regulations, reliability and maintainability considerations, and energy cost considerations. The specifying engineer may need to work closely with the pump manufacturer to select the pump, its size, speed, power requirements and type of drive, mechanical seals, and any ancillary components. It should be noted that pump selection is a multistep, multidisciplinary process requiring a clear picture of the process system and piping, a clear understanding of system operation and energy requirements, and the economics over the life cycle of the system.

8. **Mechanical seal –** The mechanical seal is a precision component with flat stationary and rotating face that is lubricated and cooled by a flush. Both the mechanical seal and support system must be selected to meet the system requirements. Some important aspects to consider are liquid properties, solids content, liquid vapor pressure, temperature, speed and face loading, material compatibility with liquid, and emissions requirements.

9. **Discharge pressure gauge/transducer –** As with the suction gauge, the discharge gauge should be liquid filled and sized appropriately to meet the maximum discharge pressure of the system with a slight margin.

10. **Flow meter –** There are various types of flow meters available for pumping systems, including intrusive and nonintrusive design. Intrusive designs consist of orifices, venturies, nozzles, rotameters, pitot tubes, turbine, vortex, and calorimetric devices. Nonintrusive designs include ultrasonic Doppler or transit time. Ultrasonic designs can be permanently installed, but one advantage is that they can be installed externally on the piping and read flow through motion of sound. Flow meters should be selected based on type of pumpage, temperature, and accuracy of flow readings.

11. **Discharge piping –** A piping system is composed primarily of individual pipelines connecting the other system components together. A pipeline is the basic building

block of a pump system. They are one of the major sources of friction losses in a pump system, so it's important to examine the losses associated with piping to understand the total frictional head loss in the system.

12. **Check valve –** An essential element in the design of a pumping system is the proper selection of the check valve, whose purpose is to automatically open to allow forward flow and automatically return to the closed position to prevent reverse flow when the pump is shut down.

13. **Bypass valve –** When considering what types of valves are suitable for installation in bypass piping, it is necessary to think about the role of the bypass line. What was the purpose for the installation of that bypass line? For example, is the bypass line used to control the pressure in the main system by continually leaking flow back to the suction source? Or is it there to only provide protection to the pump during start-up, shut-down, or reduced load periods? These different objectives require valves with different features. Therefore, the optimal valve models will be different.

14. **Bypass line –** Sizing of the bypass line depends on its intended purpose. As noted with the bypass valve, the intended purpose must be known to evaluate the suitability of the bypass line. If the bypass line is for providing minimum flow protection for the pump, proper sizing will minimize the risk of premature pump failure should the system requirements force the pump to operate back on the curve.

15. **Control valve –** Control valves are used to control conditions such as flow, pressure, temperature, and liquid level by fully or partially opening or closing in response to signals received from controllers. As with other pump system components, the control valve should be selected based on the type of pumpage, temperature, pressure, and volumetric flow rate. Control valves are a relatively straightforward and effective way to control a rotodynamic pump system. However, control valves increase the friction head loss in the system, resulting in wasted energy and potentially off-design operating condition and should be evaluated during an assessment.

16. **Coupling –** The basic functions of the coupling are to transmit power, accommodate misalignment, and compensate for axial movement (end movement of shafts). Factors in coupling selection include torque, chemical compatibility, temperature, speed, starts and stops, physical dimension, starting method, and system alignment.

17. **Motor –** When selecting an AC motor and associated equipment for an application, the following points should be considered:

    - **Environment –** The environment in which the motor operates is a prime concern. Conditions such as ambient temperature, air supply, the presence of gas, moisture, or dust should all be considered when choosing a motor.
    - **Speed range –** The minimum and maximum speeds for the application will determine the motor base speed.
    - **Speed variation –** The allowable amount of speed variation should be considered. Does it require constant speed at all torque values, or will variations be tolerated?
    - **Torque requirements –** The starting torque and running torque should both be considered when selecting a motor. Starting torque requirements can vary from a small percentage of the full load to a value several times full-load torque. The

starting torque can vary because of a change in load conditions or mechanical nature of the machine. The motor torque supplied to the driven machine must be more than that required from start to full speed. The greater the excess torque, the more rapid the acceleration.

- **Acceleration –** The necessary acceleration time should be considered. Acceleration time is directly proportional to the total inertia and inversely proportional to the torque.
- **Duty cycle (RMS calculation) –** Selecting the proper motor depends on whether the load is steady, varies, follows a repetitive cycle of variation, or has pulsating torques. The duty cycle, which is defined as a fixed, repetitive load pattern over a given period, is expressed as the ratio of on-time to the cycle period. When the operating cycle is such that the motor operates at idle or reduced load for more than 25% of the time, the duty cycle becomes a factor in selecting the proper motor.
- **Heating –** The temperature of an AC motor is a function of ventilation and losses in the motor. Losses, such as operating self-ventilated motors at reduced speeds, may cause above normal temperature rises. De-rating or forced ventilation may be necessary to achieve the rated torque output at reduced speeds.

18. **Input power/Power cable –** Input power cable selection depends on whether or not a variable frequency drive is used. Using the proper (shielded) cable when connecting the VFD drive to the motor can significantly influence the reliability of a system. Refer to the motor and drive manuals to make sure the correct cable is being used and there is proper grounding, per the VFD and motor manufacturer's instructions.

    Every VFD has a maximum motor cable length. Before installing, you should know the maximum distance from the motor to the drive. The reason for maximum cable distance is that the firing/gating of the insulated gate bipolar transistors (IGBTs) can be adversely affected by the capacitance of the cable. Conductors have a very small capacitance, but the longer the wire, the more capacitance is introduced into the system.

19. **Variable frequency drive –** Selection criteria for applying a VFD to a centrifugal pumping system:

    Voltage considerations:

    - What is the voltage available on site?
    - Does the VFD-rated output voltage = motor voltage?
    - Single-phase input?

    Amperage considerations:

    - Motor full load Amps: Is the VFD output rating sufficient?
    - Motor service factor Amps: Will the motor run into the SF?
    - Load type: Variable Torque or Constant Torque?

    Environmental considerations:

    - Temperature: Is enclosure cooling or heating needed?
    - Ingress protection: Dust, moisture, corrosive gas?
    - Elevation: More than 3300 ft above sea level?
    - Hazardous location: Explosion proof?

Motor cable length:

- VFD output filters – to protect motors or to avoid nuisance tripping issues
- Output sine wave filters
- $\frac{dv}{dt}$ filters
- Common mode filters

Harmonic level: IEEE 519:

- Line reactor
- DC choke
- Active/passive filter
- 12, 18, or 24 pulse rectifier VFD
- Active front end VFD

20. **Process (Heat exchanger) –** The system depicted is a closed-loop system with one pump feeding a heat exchanger. To size the pump to the system, we must establish a system curve. The system curve represents the head required to move fluid through the system at various flow rates. It has two components: friction head and static head. The system will operate where the pump and system curve intersect. The process (heat exchanger) creates resistance to flow (friction) and therefore is a critical factor when determining the required head and flow for pump selection. The heat exchanger is designed to reject a certain amount of heat, and this is dependent on the flow rate and velocity of the liquid passing through it. The purpose of this system is to exchange heat; therefore, the requirements of the heat exchanger need to be met by the pump.

Domain II

Data Analysis **46%**

- Task 7: Cross-validate the pump system data previously collected or obtained in order to ensure accuracy.
- Task 8: Analyze the data based on the project scope and established boundary conditions.
- Task 9: Interpret the results of the analyses to establish initial findings and possible options (e.g., equipment, control, etc.) for pump system optimization.
- Task 10: Evaluate the identified options to formulate specific recommendations for optimizing pump system efficiency and reliability.
- Task 11: Document findings and prepare a pump system assessment report that includes recommendations with costs and benefits.

○ Be able to read and understand pump and motor performance curves, as well as system curves.
○ Understand parameter estimation methods and when they should be used.
○ Understand the various types of data gathered during an assessment and its relationship to reliability.
○ Understand and apply reliability metrics.
○ Be able to identify currently available equipment and technology.
○ Understand industry best practices.
○ Understand and perform basic financial analyses.
○ Understand utility rate structures and incentives.
○ Identify and apply principles and techniques of prioritizing solutions.
○ Understand the elements and layout of a pump system assessment report.

Pump and Motor Performance Curves

14

A pump curve, or performance curve, shows the total head, power, efficiency and NPSHR curves plotted against the flow rate.

There are three basic pump curves:

- Selection chart
- Published curve
- Certified curve

Pump Selection Chart

A selection chart shows the typical operating region for the various pump sizes and speeds for a given manufacturer's pump type. Shown in Figure 14.1 is an example of a selection chart for a line of general-purpose, end-suction pumps.

The selection chart shows the various pump sizes available for a given manufacturer's pump type and speed. The desired head and flow rates are entered on the curve, and the pumps that overlap the area are valid choices to consider for selection.

TIP

The selection chart is very useful in developing a short list of pumps for consideration. For example, if the application called for a pump running at a nominal 1800 rpm that could provide 1000 gpm at 100 ft of total head, the chart shows that 5 × 6 × 11 and 6 × 8 × 11 size pumps overlap on the selection chart and will likely be the two best sizes to evaluate further.

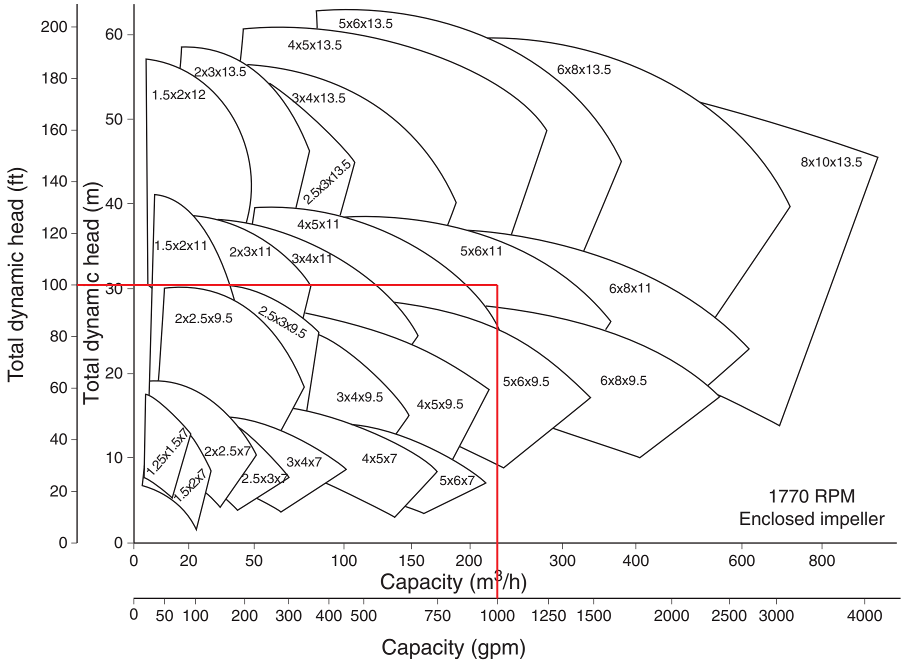


Figure 14.1: Pump Selection Chart

Pump Manufacturer's Published Curve

After narrowing down the appropriate pump's size for the duty point of 1000 gpm and 100 ft of head, the manufacturer's published curves can be referenced to help determine the best pump for an application. Figure 14.2 shows an example of a published curve for a 5 × 6 × 11 pump running at 1770 rpm. A significant amount of information can be derived from the manufacturer's pump curve for this application, including the following:

- The impeller diameter that meets the duty point falls between 10 and 10.5 in.
- Pump is 85% efficient at the duty point and 86% efficient at BEP.
- At the duty point, the shaft power will be between 25 hp and 30 hp; however to ensure a non-overloading condition at the end of curve, a 40 hp motor may be required.
- NPSH3 is between 9 and 10 ft at the duty point.

Note that data displayed on manufacturer's pump curves are based on 68 °F or 20 °C water. If a liquid other than water will be pumped, information on the manufacturer's published curve must be adjusted for the liquid density and viscosity, which affects the head, flow, efficiency and pump input power.

Density affects the pump input power with a linear relationship. Fluid viscosity affects the flow, head and efficiency. If the viscosity of the fluid to be pumped is greater than that of water at 68 °F, ANSI/HI 9.6.7 *Rotodynamic Pumps – Guidelines for Effects of Liquid Viscosity on Performance* should be consulted, to adjust the performance for liquid viscosity.

The pump operating data and landmarks found on a typical manufacturer's published pump curve can be examined. These include the following:

- total head versus rate of flow (capacity), or head versus flow (pump head curve)
- pump efficiency
- shut-off head
- (optional) minimum flow
  - continuous
  - intermittent
  - thermal (temperature rise limitation)
- (optional) allowable operating region (AOR)
- best efficiency point (BEP)
- (optional) preferred operating region (POR)
- maximum flow, or end of curve
- NPSH3

The head versus flow data show the total head developed by the pump at a specific rate of flow. Head is the energy content of the liquid referred to a datum, and is expressed in energy per unit weight of liquid. The units for head are meters (or feet) of liquid being pumped. Rate of flow or capacity is the total volume of throughput per unit time at suction conditions, assuming no entrained gases.

The pump head curve is developed by plotting the pump total head as a function of the rate of flow through the pump. The pump head curve data are based on water at 20 °C (68 °F) as the test liquid. Other variables that affect the pump curve are rotational speed and impeller diameter. The manufacturer provides head versus flow values for the allowable operating region of that pump.

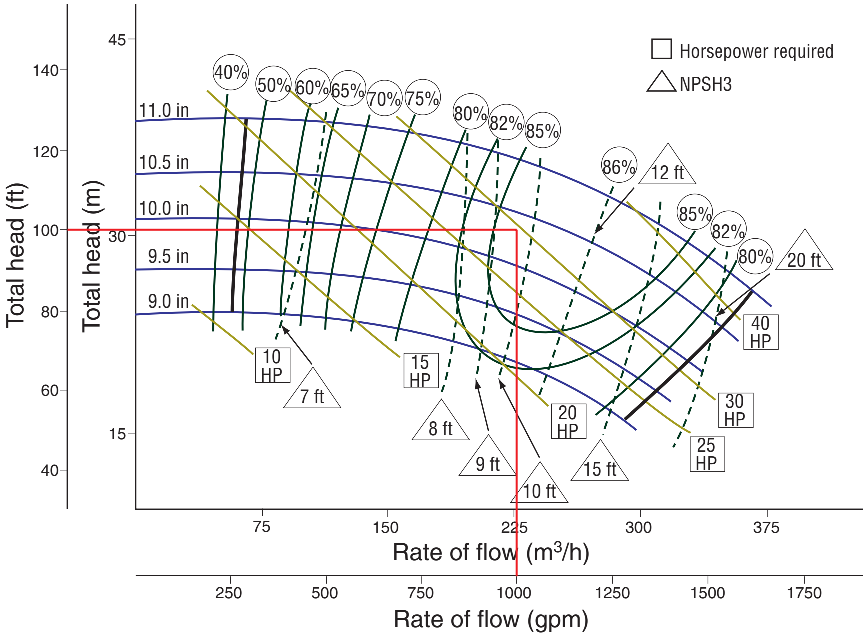


Figure 14.2: Pump Manufacturer's Published Curve

Certified Performance Curve

Once a pump is specified for a project, the manufacturer builds it and, if specified by the purchaser, a certified performance curve (Figure 14.3) is supplied.

The certified performance curve is based on measurements taken at flow rates at or around the rated point. Unlike the published curve, which may be applied generally for a given pump model type and size, the certified pump curve is developed for the particular pump being supplied under the purchase order. The test is performed by the manufacturer in accordance with ANSI/HI 14.6 *Rotodynamic Pumps for Hydraulic Performance Acceptance Tests*. This standard also specifies acceptance test methods for hydrostatic tests and NPSH tests.

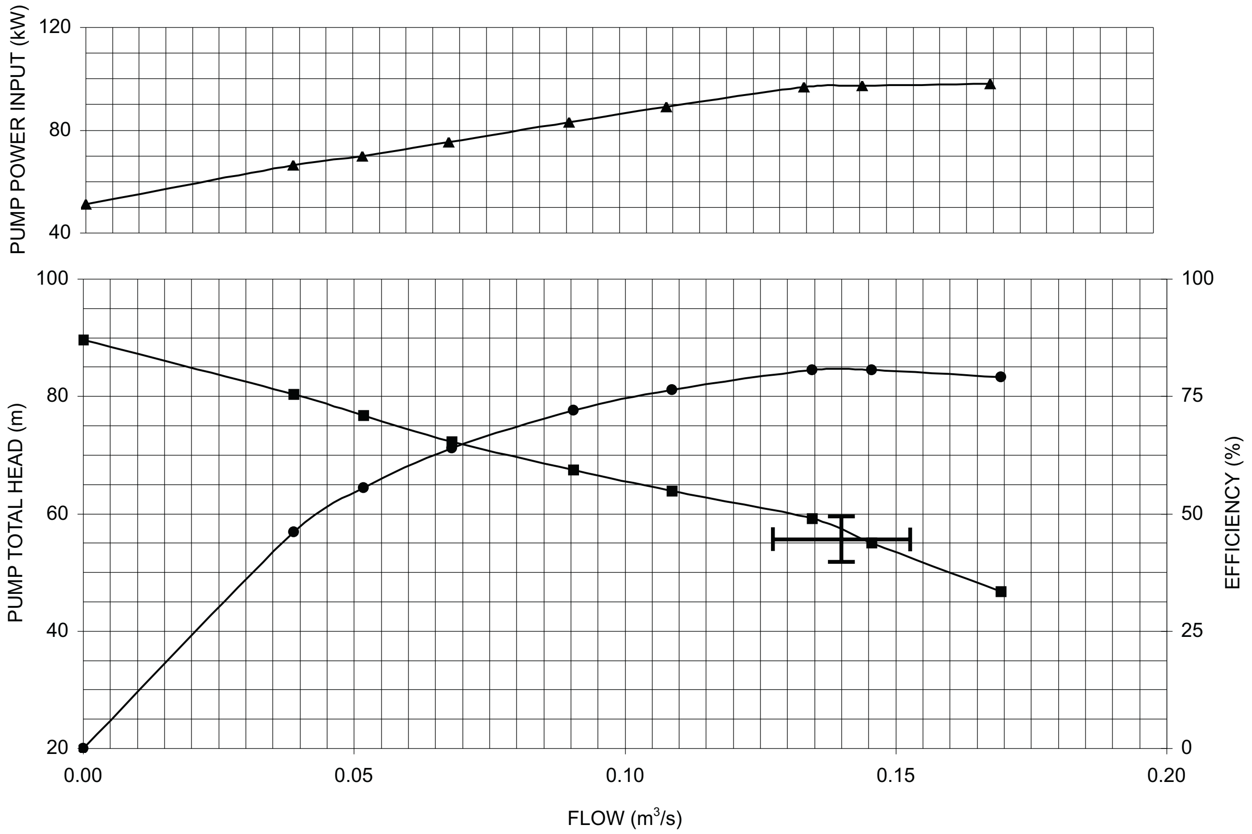
Figure 14.3 Certified Performance Curve

MANUFACTURER		PUMP SERIAL NUMBER:		TEST CURVE NUMBER:		CUSTOMER / ORDER INFORMATION:	
SPEED n (rpm)	POWER P (kW)	IMPELLER (IDENTIFICATION)	DIAMETER D (m)	PUMP MODEL NUMBER:			
TEST DATE:		TESTER:		ACCEPTANCE CLASS: 3B			

DATA POINT	RATE OF FLOW Q (m^3/s)	HEAD GAUGE p (kPa)	VELOCITY h_v (m)	ELEVATION z (m)	PUMP TOTAL H (m)	PUMP POWER INPUT P (kW)	PUMP EFFICIENCY η %
1	0.0000	871.4	0.00	0.70	89.58	51.2	00.0
2	0.0389	778.3	0.24	0.70	80.32	66.4	46.1
3	0.0518	741.0	0.43	0.70	76.71	70.0	55.6
4	0.0680	695.0	0.70	0.70	72.29	75.3	63.9
5	0.0905	642.9	1.25	0.70	67.52	83.0	72.1
6	0.1087	601.5	1.83	0.70	63.88	89.0	76.4
7	0.1345	547.9	2.65	0.70	59.23	96.7	80.7
8	0.1455	501.2	3.26	0.70	55.08	97.4	80.6
9	0.1694	408.5	4.42	0.70	46.79	98.0	79.2

GUARANTEE POINT		
FLOW	0.1400	m^3/s
HEAD	55.6	m
EFFICIENCY		%

CERTIFICATION: TEST WAS PERFORMED WITH CLEAR WATER AT 21 °C AMBIENT TEMPERATURE. HEAD, FLOW, AND POWER DATA ACQUIRED BY ELECTRONIC METERING EQUIPMENT. ACCURACY OF TEST EQUIPMENT IS VERIFIED BY PERIODIC CALIBRATIONS.



Total Head versus Rate of Flow (Head vs. Flow)

The total head versus rate of flow data show the total head developed by the pump at a specific flow rate. Head is the energy content of the liquid and is expressed in energy per unit weight of liquid. The units for head are meters or feet of pumped liquid. Rate of flow or capacity is the total volume of throughput per unit time at suction conditions, assuming no entrained gases.

The pump head curve is developed by plotting the pump total head as a function of flow rate through the pump. The pump head curve data are based on water at 20 °C or 68 °F as the test liquid. Other variables that affect the pump curve are rotational speed and impeller diameter.

To extend pump operating range, the pump manufacturer typically makes available various rotational speeds and impeller diameters. Because the majority of pumps are driven with AC induction motors, manufacturers provide curves for the various motor speeds such as nominal 3600, 1800, 1200, and 900 rpm for 60 Hz power. Larger pumps might be limited to a maximum speed.

Manufacturers provide pump curves for various impeller diameters that can be used in the pump casing. The pump curve you are viewing shows the pump performance curves for the impeller diameters of 9.0, 9.5, 10.0, 10.5, and 11.0 in. Some pumps are only available with specific impeller diameters and others can be trimmed incrementally to achieve a specific operating point of head and flow.

Pump Efficiency

Pump efficiency is another performance parameter provided by the manufacturer. Pump efficiency is the ratio of the hydraulic output energy of the pumped liquid (Hydraulic Power, P_u) to the mechanical shaft input energy (Pump Input Power, P). It is usually expressed as a percentage. Pump efficiency varies considerably over the allowable range of flow.

Even though a pump may be capable of operating throughout the published flow range, it is always best to operate a pump close to BEP as it saves energy and has less wear on bearings and seals. This leads to improved reliability.

Unfortunately, no efficiency standard can be applied generally to all rotodynamic pumps. Pumps designed for smaller volumetric rates of flow are typically less efficient than larger-capacity pumps. Pump efficiency is also affected by the required application-specific features. For example, grinder pumps or non-clog, solids-handling pumps used in wastewater collection and treatment systems are less efficient than an end-suction pump designed to pass clear, clean liquids.

Net Positive Suction Head

Manufacturers also typically provide a published curve of NPSH3 as a function of the flow rate through the pump.

But, owners/operators deal with NPSH available or NPSHA, which is a function of the following attributes of the pump and piping system:

- elevation difference between the liquid level and the eye of the impeller
- pressure on the surface of the liquid
- head loss in the pump's suction pipelines

TIP

It is very important to be aware that if a manufacturer does not show data for a specific area for the pump curve, do not assume the pump can safely be operated in that region.

- flow velocity at the pump suction nozzle
- vapor pressure and density (as function of temperature) of the liquid being pumped
- barometric pressure at the pump site

The NPSH3 data are displayed as the vertical lines with triangle annotation on the manufacturers curve. The NPSH3 typically increases with increasing rate of flow. While the NPSH3 values decrease as flow is reduced, the NPSH3 curve may increase sharply as flow is reduced, even further toward shutoff.

Best Efficiency Point (BEP)

Best efficiency point, as previously defined, is the flow rate on the pump head-capacity curve in which the efficiency of the pump is at a maximum.

At BEP, the hydraulic efficiency is maximized and internal losses are at a minimum. Flow enters and leaves the pump with a minimum of flow separation, turbulence, and “shock” losses relative to useful hydraulic energy conversion.

Preferred Operating Region

POR is the area on the pump curve around the BEP in which the internal flow is well matched to the hydraulic geometry. As long as the pump remains in the POR, the service life of the pump will not be significantly affected by adverse hydraulic loads, vibration, and impeller flow recirculation.

For centrifugal pumps the POR is typically between 70% and 120% of BEP flow, but the range will narrow for mixed and axial flow pumps. Refer to ANSI/HI 9.6.3. For pumps of 5 horsepower or less, the manufacturer may recommend a wider POR.

Allowable Operating Region

As previously defined, the AOR is a wider range of rates of flow, outside the POR, over which the service life of a pump is acceptable. It is based on the pumped liquid and specific application such as NPSHA.

Shut-off Head

Shut-off head is the condition of zero flow where no liquid is flowing through the pump, but the pump is primed and running. This is an important landmark used in determining the pump condition or slope of the pump curve.

Remember, that operating a pump at shutoff can be mechanically severe and must be limited to the few seconds needed to collect the suction and discharge pressure readings. Certain pumps with power characteristics that rise toward shutoff flow should never be operated at shut-off flow, such as mixed and axial flow pumps. Also, positive displacement pumps do not vary flow rate based on system pressure so they should never be operated with a closed valve as the system pressure will continue to rise and the same flow rate will be delivered and damage may occur.

Minimum Flow

Another important aspect of reading a pump curves is to understand minimum flow. Various minimum flow values may be calculated by the pump manufacturer in the design process and are used to determine the published minimum flow rate through a specific pump. Various designations of minimum flow are based on the length of time a pump operates at reduced flow conditions.

More recently, reliability engineers and pump manufacturers have worked together to set what is called Minimum Continuous Stable Flow (MCSF), which is typically tied to the onset of suction recirculation, and in many cases is near 50% of BEP. However, there are many factors that affect the Allowable Operating Region and they must be considered on a case-by-case basis to set the minimum continuous flow rate for a pump. Refer to ANSI/HI 9.6.3 for a comprehensive list of factors that affect the AOR. At flows not less than the minimum continuous stable flow threshold, which may be the same at the lower limit of the AOR, the pump has no operating time limitations.

Some pump types may be permitted to or the AOR may be limited to a thermal minimum flow established by an allowable liquid temperature rise. Temperature rise through the pump may be calculated as follows:

$$\Delta t = \frac{H}{778 \times C_p}\left(\frac{1}{\eta} - 1\right) \quad \text{(US customary units)}$$

$$\Delta t = \frac{H}{102 \times C_p}\left(\frac{1}{\eta} - 1\right) \quad \text{(metric units)}$$

Where

Δt = temperature rise through the pump, °F (°C)

H = total head at flow being considered, ft (m)

778 = constant

102 = constant

C_p = specific heat of the liquid at pumping temperature, Btu/(lbm °F) [kJ/(kg °K)]

η = efficiency of the pump at flow being considered, expressed as a decimal

Maximum Flow Rate (Pump Runout)

The end of the manufacturer's pump curve is the maximum flow rate, beyond which the pump may experience excessive cavitation and vibration. Centrifugal pumps that have a rising power characteristic may overload or overheat the driver if operated beyond the end of the curve.

Special pump or driver design considerations may apply if the user intends to operate the pump at a runout condition beyond the published end of curve flow. In this case, it is always advisable to consult the pump manufacturer.

Motor Performance Curve

A typical motor performance characteristics curve (Figure 14.4) shows torque, power factor, efficiency, current and power relationships. This curve can be used by the assessment professional to determine output power based on other measured parameters, such as motor current measured at the rated voltage. The motor input power can then be calculated based on the output power and efficiency at the measured motor current. Additionally, the power factor from this chart should be used in Equation 1 (Chapter 11) to determine motor input power.

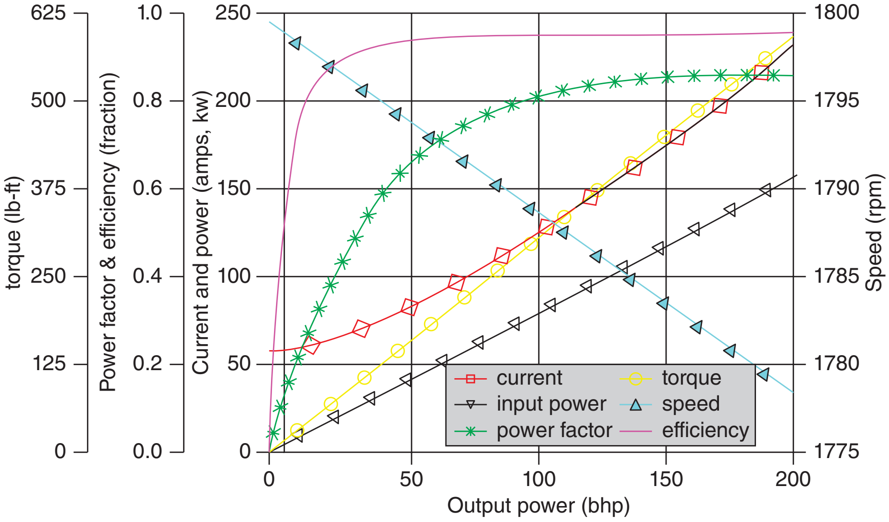


Figure 14.4: Motor Performance Characteristics

15

System Curves

In a pumping system, the objective in most cases is to either transfer a liquid from a source to a desired destination, such as filing a tank or reservoir, or to circulate a liquid around a system, such as heating system. Energy is required for this and can be provided by a pump. For example, energy must be provided to overcome friction losses within the system (dissipation), to lift fluid to a higher elevation, or to supply higher pressure that can be used in a process or supply. For steady-state flow, the pressure produced by the pump must equal the sum of the friction loss, elevation change, and pressure change between the suction and discharge vessels, as shown in Figure 15.1.

This can be demonstrated by applying the equation for steady flow in a piping system. The energy state at one point in a system is equal to the energy state at a second point plus the energy added by pumping minus energy losses due to pipe friction. The equation accounts for changes in energy due to changes in pressure, kinetic energy, and potential energy. The kinetic energy term, $\frac{\rho v_1^2}{2}$ is also referred to as the dynamic pressure.

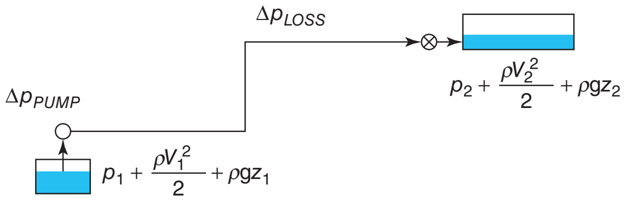


Figure 15.1: Equation for Pipeline Flow

The pipe flow equation (Bernoulli's equation) is as follows:

$$\Delta p_{PUMP} + p_1 + \frac{\rho v_1^2}{2} + \rho g z_1 = p_2 + \frac{\rho v_2^2}{2} + \rho g z_2 + \Delta p_{LOSS}$$

Where

Δp_{PUMP} = pressure added by the pump, psi (bar)

p = static pressure, psi (bar)

ρ = fluid density, lbm/ft^3 (kg/m^3)

v = flow velocity, ft/s (m/s)

z = elevation, ft (m)

g = acceleration due to gravity, 32.2 ft/s^2 (9.81 m/s^2)

Δp_{LOSS} = friction losses in the pipe, fitting, valves, heat exchangers, etc.

The subscripts 1 and 2 refer to the upstream and downstream locations within the system, respectively.

This equation can be rewritten in terms of head, which is more convenient for pumping systems in that everything is referenced to an equivalent height of pumped liquid, as follows:

$$\Delta h_{PUMP} + h_1 + \frac{v_1^2}{2g} + z_1 = h_2 + \frac{v_2^2}{2g} + z_2 + \Delta h_{LOSS}$$

This equation can be used to determine how much pressure, or total head (H or Δh_{PUMP}), that the pump must generate so the desired flow will be produced within the system. The system curve is the relationship between pressure (head) and flow for the connected system as seen by the pump.

The Δh_{LOSS} or frictional resistance in head (h_f) can be calculated based on the Darcy–Weisbach equation for piping and pipe fittings/valves/end-use equipment, respectively, as follows:

Frictional resistance in head for piping:

$$h_f = f \times \frac{l}{d} \times \frac{v^2}{2g}$$

Where

h_f = frictional resistance in head

f = piping frictionfactor

L = length of pipe ft (m)

d = average ID of piping, ft (m)

v = average velcoity, ft/s (m/s)

g = acceleration due to gravity 32.2 ft/s² (9.81 m/s²)

Frictional resistance in head for fittings, valves, and end-use equipment:

$$h_f = k \times \frac{v^2}{2g}$$

Where

h_f = frictional resistance in head

k = resistance coefficient for value or fitting

v = average velocity ft/s (m/s)

g = acceleration due to gravity 32.2 ft/s² (9.81 m/s²)

The system curve provides a graphical representation of flow, static lift, and pressure requirements, and frictional head losses in a pumping system. The system head curve can be calculated by the equations provided above and can be verified through system measurements by measuring two points: (1) the static lift and pressure head, and (2) the operating point (flow and head). By subtracting the static head components from the total head, you determine the friction head (h_f). When the assessment professional is measuring pressure in two locations to determine the pressure differential and friction head loss, the velocity at each location should be considered to see if the velocity head difference is negligible or should be considered.

For the example system shown in Figure 15.2 that contains static lift (head), pressure difference between the sources and load and frictional head losses, a system curve is shown in Figure 15.3. Note that the shape of the system curve follows a squared relationship with flow rate and that there is an “offset” where the curve intersects the vertical axis. The offset is the sum of the static lift and the pressure difference between the source and load. These do not vary with flow rate; however, the frictional losses vary with the proportional to square of velocity (flow rate).

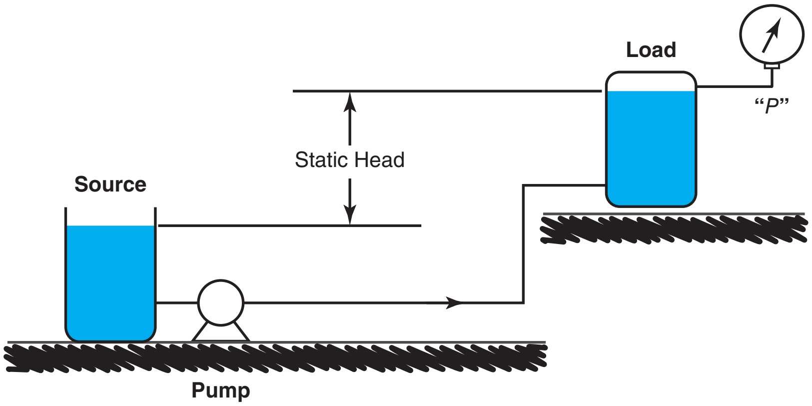


Figure 15.2: Example System with Friction Loss, Static Head, and Pressure Head

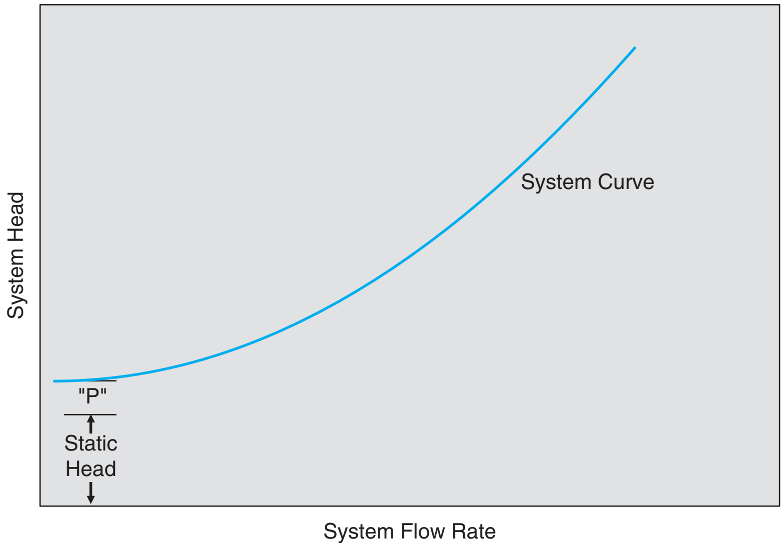


Figure 15.3: System Curve with Friction Loss, Static Head, and Pressure Head

The pump system curve depicts the relationship between head and flow at a single point in time, based on both static and dynamic head. In systems with variable flow and/or level, the system curve can change as shown in Figure 15.4. In these systems, historical flow and system pressures determined from the plant’s distributed control center, or through data logging, can be used to determine the maximum, minimum, and normal system curves.

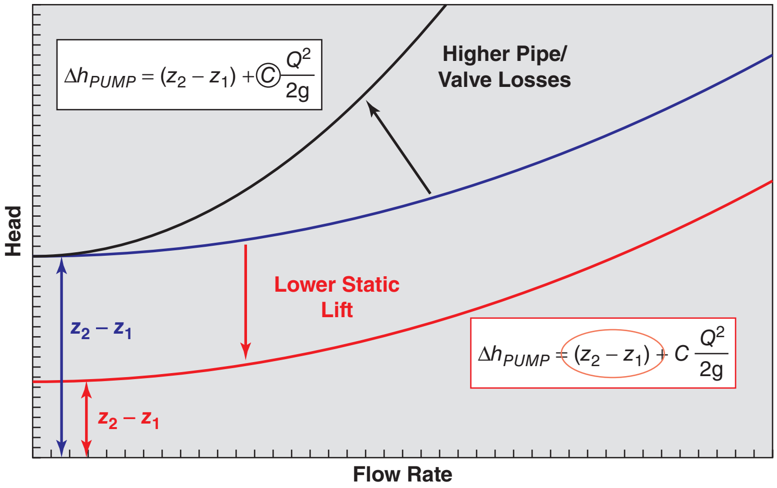


Figure 15.4: Varying System Curves

By overlaying the pump curve and the system curve(s), the pumps operating region can be determined as shown in Figure 15.5.

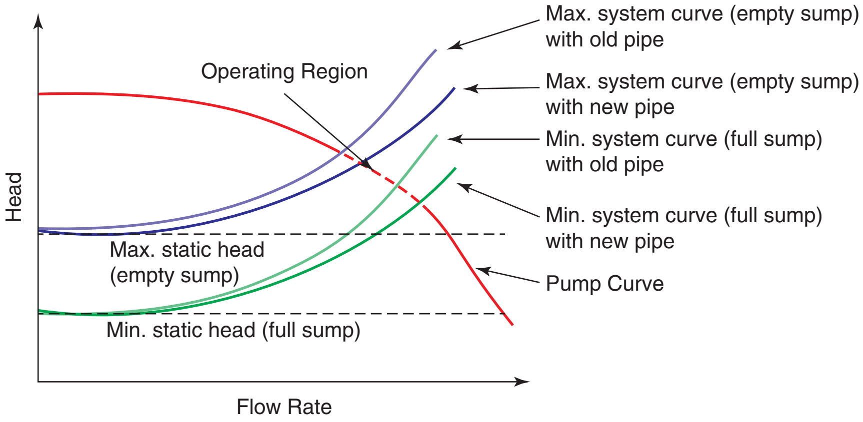


Figure 15.5: Pump Operating Region due to Varying Static and Friction Head

Operating Duty Point

When connected to a piping system, a rotodynamic pump will operate at a duty point with equilibrium between the pump and the piping system. At the point of equilibrium, the delivery head of the pump equals the required static head plus head loss in the piping system. The performance of the pump in this respect is usually represented in a diagram format by the so-called *pump head-capacity (H-Q) curve*. The corresponding curve for the piping system is called the *system curve*.

The volume flow at which the pump and system curves intersect each other is the flow that will pass through the piping system. To correctly determine the sizes of the pump and piping system, knowledge of the characteristics of their respective curves is necessary.

Figure 15.6 shows a typical curve for a rotodynamic pump. Whatever the shape of the curve, the duty point is determined by the point at which the pump and the system are in balance.

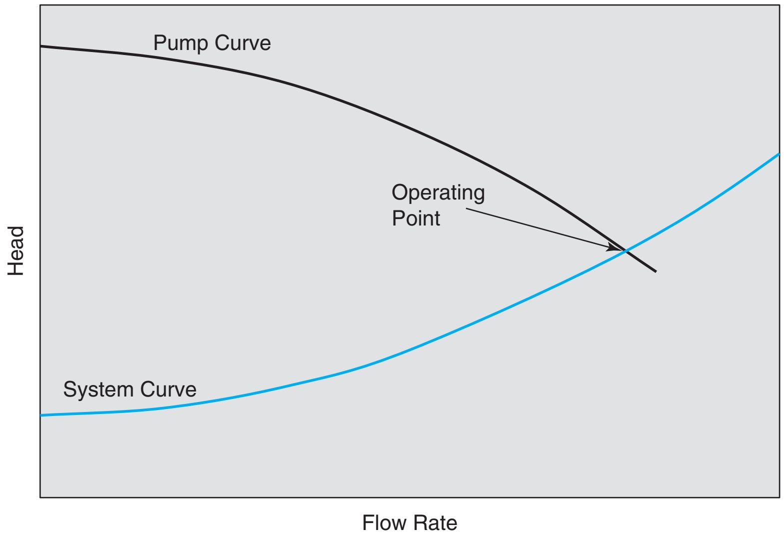


Figure 15.6: Operating Duty Point at $H_{pump} = H_{syst}$ for a Rotodynamic Pump

For positive displacement pumps, the *Q*-*H* curve has a different shape (see Figure 15.7). However, the same equilibrium relation between H_{pump} and H_{syst} determines the operating duty point. As shown in the figure, PD pumps deliver a relatively constant rate of flow regardless of pressure. Therefore, if the system restricts the flow, a relatively constant flow will be maintained, but the system pressure can increase substantially, resulting in motor overloading and system damage. Removing system head in PD pump systems always results in lower energy usage.

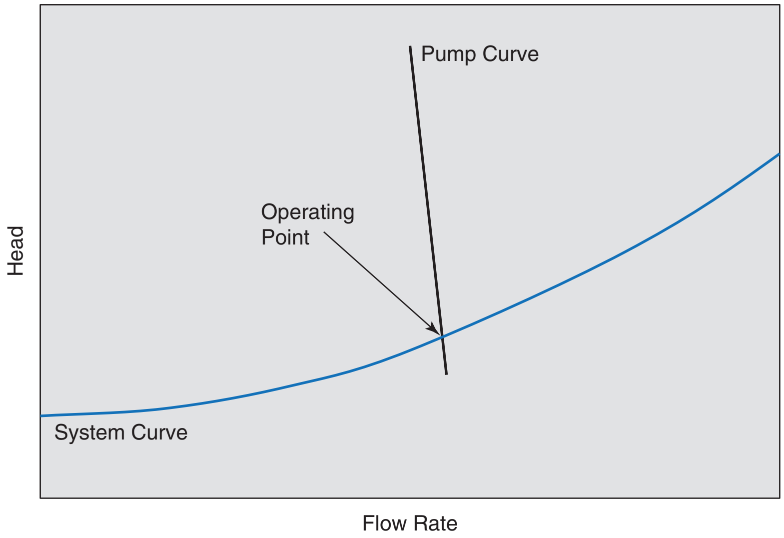


Figure 15.7: Operating Duty Point at $H_{pump} = H_{syst}$ for a Positive Displacement Pump

16

Parameter Estimation, Data (Electrical, Vibration, Thermography, Etc.), and its Relationship to Reliability

To ensure that proper conclusions are made during the assessment, it is imperative that the data collection is done accurately and covers the full scope of operation.

When determining the field measurement parameters, it is important to cross validate these parameters. Cross validation of operating parameters is another method to estimate or calculate flow rates. It includes a three-step process:

1. Compare measured pump head to head-capacity curve to estimate flow rate.
2. Compare power consumption (in horsepower or kilowatts) with the head-capacity curve to estimate flow rate.
3. Measure or calculate flow rate (tank drawdown over time) and compare to the head-capacity curve to determine the expected head and power.

If system demands change over time, the operating parameters must be monitored over time as well.

Measurement points should include flow rate(s), pressures, temperature(s), power, vibration, and any other important system parameters.

When collecting data, calibrated instruments must be used, or the data must be validated through other means. It is important that instrumentation is used per the manufacturer's specifications and that the installed uncertainty is understood.

The data measured will inform the assessment professional on certain points that impact efficiency and reliability, such as

- Operating point of the pump and system (cavitation, bearing loading, etc.)
- Bearing temperature (loading on the bearing, damaged bearing, improper lubrication, etc.)
- Differential pressure (operating point of the pump, system conditions, etc.)
- Motor input power (overloading or loading of the motor)

Reliability Metrics

17

The assessment professional can use reliability metrics to make the business case for improvements when the LCC is considered.

Mean Time between Repair

MTBR may be calculated for individual units of equipment, but it is more commonly applied to a specific population. The general form for calculating MTBR is to take the total number of units of equipment, multiplied by the total number of time units, divided by the total number of repairs. The time value (*t*) may be expressed in any unit of time, so long as the same unit is used for all calculations. Months are often used to measure MTBR, but the measurement unit can be years, weeks, or days. The unit of time will depend on the process and the level of details that are required.

In the following example, hours will be used for a population of pumps. The hour unit may be most useful for equipment connected to hour meters.

$$MTBR = (\text{Number of pumps/Total number of repairs}) \times \text{time}$$

A total of 670 failures were observed in a population of 3000 pumps over a period of 1 year (8766 hours). What is the MTBR?

$$MTBR = \frac{3000}{670} \times 8766 = 39{,}250 \ pump \bullet hours$$

Note that the unit of measure is pump • hours, not just simply hours.

Expected Life

A common misconception in regard to MTBR data is that the number of 39,250 pump • hours represents the expected life of any pump in the population being studied. That is incorrect. There may be some pumps in the population that have not failed at all during the time of study, and in fact, may have a serviceable life of many years. For MTBR data to give a true prediction of actual expected life, we would need to wait for the entire population of pumps to fail. As it is, the pumps that have not yet failed will distort the data, as they appear to have an infinite life. MTBR does, however, provide a very effective comparative metric.

The repair rate (λ) is defined as

$$Repair\ rate\ (\lambda) = 1/MTBR$$

Repair rate is simply another way to express the MTBR data. It is useful to use repair rate when calculating reliability or exponentially distributed repair rates.

The overall goal is to improve the general reliability of pumping equipment. Reliability, however, also can be defined in a narrow sense. One of the reasons for calculating MTBR for a population is to determine or predict reliability in a strict technical sense.

Though often misused in common language, for our purposes, reliability (R_e) is simply the probability of an individual unit within a population with a known MTBR of achieving a given time (t) length of service. Though variations do exist, a simplified formula for reliability based on the Poisson distribution is defined as

$$R_e(t) = e^{-\lambda(t)}$$

Reliability example: Given the MTBR above of 39,250 pump·hours ($\lambda = 1/39{,}250 = 0.000025478$), what is the probability a pump will still be have a useful run life of 10,000 hours?

$$R_e = e^{-0.0000255 \times 10{,}000} = 0.775$$

So the odds are 77.5% that any member of the subject population of 3000 pumps would still be running after 10,000 hours. Reliability is most often calculated with MTBF, not with MTBR metrics, but given relatively long service run times compared to repair times, the difference is relatively small. In evaluating the reliability of individual units of equipment, the total reliability is the sum of the reliability of each individual component. For example, if each bearing supporting a shaft has a reliability for any given time $R_e(t)$ of 0.95, the reliability of the total bearing system is (0.95 × 0.95 = 0.90).

Availability

One metric used to account for the effects of mean time to repair (MTTR) is system availability. Availability is defined as

$$Availability = \frac{MTBF}{MTBF + MTTR}$$

As repair times (MTTR) become smaller, the difference between MTBF and availability becomes smaller. In theory, if the time to repair was zero, MTBF would equal availability.

$$Availability\ (\%) = \frac{Number\ of\ Days\ Machinery\ Train\ Available\ x\ 100\%}{Number\ of\ Unit\ Operating\ Days\ for\ the\ Year}$$

Average Cost per Repair

$$Average\ Cost\ per\ Repair = \frac{Total\ Repair\ Costs}{Total\ Number\ of\ Repairs}$$

Annual Repair Cost per Installed Horsepower

$$Annual\ Repair\ Cost\ per\ Installed\ Horsepower = \frac{Annual\ Repair\ Cost}{Nameplate\ Horsepower}$$

Installed Cost per Horsepower per Machinery Type

$$Installed\ Cost\ per\ Horsepower\ per\ Machinery\ Type = \frac{Installed\ Cost}{Nameplate\ Horsepower}$$

Material Multiplier

$$Material\ Multiplier = \frac{Total\ Installed\ Cost}{Actual\ Material\ Cost}$$

Currently Available Equipment and Technology

18

The technology available for assessing pumping systems is constantly being updated, with great advancements in data acquisition due to wireless data monitoring. Wireless technologies enable instrumenting systems and monitoring for short or extended periods of time, giving the assessment professional a method to gain valuable system data and to understand system interactions.

Flow modeling software can be used either as an initial tool or after data is gathered to understand the best way to optimize a system. It is important for the assessment professional to know what is technologically feasible so that proper upgrade opportunities can be recommended. For motors, it is important to know the latest premium efficiency standards and how the current motor compares to those standards. For pumps, in addition to company/industry knowledge, there are two resources to help the assessment professional understand what is technically feasible.

- HI 20.3, Pump Efficiency Prediction, provides an overview of what efficiency is attainable for rotodynamic pump designs for different applications, as well as the impact that design, manufacturing, and wear have on efficiency.
- US Department of Energy, Energy Conservation Standard, which is specific to clean water pumps up to 200 hp, is the first ever energy conservation standard for pumps, published in January of 2016. This standard sets minimum efficiency requirements for certain pumps and must be complied with in January of 2020. Information on the DOE standards and links to the published standards can be found at http://www.pumps.org/doerulemaking.

Additionally, HI has developed the HI Energy Rating Program, which builds on the DOE regulation by creating a comparison label for pumps within the scope of the DOE regulation. Details on the HI Energy Rating Program and Label can be found at http://www.pumps.org/40.5.

Other tools include

- Hydraulic Institute P*SMART
- Hydraulic Institute PSIM
- Hydraulic Institute PSAT

19

Basic Financial Analysis

Financial analysis should include the time value of money, represented in one of the following ways:

- Net present value (NPV)
- Internal rate of return (IRR)
- lifecycle costs (LCC)
- True cost of energy

There are systems optimization benefits, other than energy, that affect total cost of ownership. Each component should be added to the analysis with the appropriate savings.

System optimization benefits beyond energy savings include

- Increased productivity
- Reduced costs of environmental compliance
- Reduced production costs
- Reduced waste disposal costs
- Improved product quality
- Improved capacity utilization
- Improved reliability
- Improved worker safety

Lifecycle Costing

The elements of lifecycle costing are presented in Chapter 6. This section builds on the LCC and how it should be reviewed related to the investment required. A simple (and widely used) measure of project economics is the payback period. This is the period required for a project to break even in terms of costs, or the time needed for the net benefits of an investment to accrue to the point where they equal the cost of the initial outlay. For a project that returns benefits in consistent, annual increments, the simple payback equals the initial investment divided by the annual benefit.

The simple payback does not take into account the time value of money; in other words, it makes no distinction between a dollar earned today and a dollar of future (and thus uncertain) earnings. Still, the measure is easy to use and understand, and many companies use simple payback in making a quick "go/no-go" decision on a project. Here are five important factors to remember when calculating a simple payback:

1. It is an approximation, not an exact economic analysis.
2. All benefits are measured without considering their timing.

3. All economic consequences beyond the payback are ignored.

4. Payback calculations will not always identify the best solution (because of the two factors listed above) among several project options.

5. Paybacks do not take into consideration the time value of money or tax consequences.

More sophisticated analyses take into account factors such as discount rates, tax impacts, and the cost of capital. One approach involves calculating the NPV of a project, which is defined in this equation:

Net present value (NPV) = present worth of benefits – present worth of costs

NPV is the value of an investment project found by adding the present value of expected future cash flows and the cost of the initial investment.

Another commonly used calculation for determining the economic feasibility of a project is IRR. This is defined as the discount rate that equates future net benefits (cash) to an initial investment outlay. This discount rate can be compared to the interest rate at which a corporation borrows capital

Many companies set a threshold, or “hurdle,” rate for projects, which is the minimum required IRR needed for a project to be considered viable. Future benefits are discounted at the threshold rate, and the net present worth of the project must be positive for the project to be approved.

Many organizations consider only the initial purchase and installation costs of a system. However, plant designers and managers will benefit from evaluating the LCC of different solutions before installing major new equipment or carrying out a major overhaul, to identify the most financially attractive alternative.

TIP

Plant operations can be a significant source of savings, especially because energy-efficient equipment can minimize energy consumption and plant downtime.

20

Utility Rate Structures and Incentives

Electricity rates are usually stated in terms of dollars per kilowatt-hour ($/kWh). However, electric utilities bill industrial customers using more complicated rate structures. These typically include both energy ($/kWh) and demand charges ($/kW real power or $/kVA apparent power) and have different rates depending on the level of consumption and time of year.

Commercial and industrial customers' demand charges may include a penalty for a poor power factor (i.e., below 0.9,) or they may be billed for apparent power (kVA) instead of kW. Power factor is the ratio of real power to apparent power, meaning that if there is a power factor of 0.9, 10% of the power supplied is not converted into real power.

Demand charges are based on the peak demand for a given month or season and can have significant impacts on electricity costs for some customers. When the economic impacts of efficiency measures are calculated, the marginal cost of the electricity needs to be considered, taking into account energy and demand charges, seasonal rates, and different rates for different levels of consumption.

Most utilities offer incentives to reduce the amount of kWh consumed by a customer. Incentives received for pumping upgrades should be considered into the payback calculations presented in Chapter 19.

Incentive programs can take two forms – a custom program or a prescriptive program.

Since the incentives will be paid with rate-payer funds, the utility needs to conduct measurement and verification to ensure power demands are actually reduced by the upgrade.

In the custom program option, this is routinely done by measuring and documenting the power consumption over time for an existing system, and then again after an upgrade has been completed. The results are then submitted for incentive dollars. However, this takes a lot of time and money to manage. With the advent of energy standards for equipment that define a market baseline, and with some additional market research, the measurement and verification can be done upfront. Once approved by the utility, it can offer prescriptive rebates (i.e., $50 per unit or $50 per rated hp). This results in an easier way to distribute the incentive dollars and move more efficient products into the market place.

Principles and Techniques of Prioritizing Solutions

21

When screening equipment for assessmenht and optimization, the following initial questions can be used to identify the best potential energy efficiency and MTBR improvement paybacks:

- What improvements in energy efficiency and MTBR are technically feasible to achieve?
- What will it cost?
- What is the projected payback?

Evaluation criteria can be divided into four categories, or groups, depending on their potential importance or paybacks.

Group A

- Single pieces or populations of equipment with an MTBR of 2 years or less
- Criticality of equipment to process output is high
- Safety risk if equipment fails is high
- Single pieces or populations of equipment with an average annual cost of repair and/or cost of being out of service of $100,000 or greater
- Equipment with highest power – for example, 200+ hp
- Equipment with highest operating hours – for example, 6000+ h/year

Group B

- Single pieces or populations of equipment with an MTBR of 3–5 years
- Criticality of equipment to process output is moderate
- Safety risk if equipment fails is moderate
- Single pieces or populations of equipment with an average annual cost of repair and/or cost of being out of service of $75,000–$100,000
- Equipment with high power – for example, 100–200 hp
- Equipment with high operating hours – for example, 4000–6000 h/year

Group C

- Single pieces or populations of equipment with an MTBR of 5–7 years
- Criticality of equipment to process output is low
- Safety risk if equipment fails is low
- Single pieces or populations of equipment with an average annual cost of repair and/or cost of being out of service of $50,000–$75,000

- Equipment with moderate power – for example, 10–100 hp
- Equipment with moderate operating hours – for example, 2000–4000 h/year

Group D

- Single pieces or populations of equipment with an MTBR of 7–10 years
- Criticality of equipment to process output is zero
- Safety risk if equipment fails is very close to zero
- Single pieces or populations of equipment with an average annual cost of repair and/or cost of being out of service of $25,000–$50,0000
- Equipment with low power – for example, 10 hp and below
- Equipment with low operating hours – for example, less than 2000 h/year

In most cases, individual pieces or defined populations of equipment will have a mix of the above characteristics, so it is helpful to place them in a matrix format, such as the one shown in Figure 21.1.

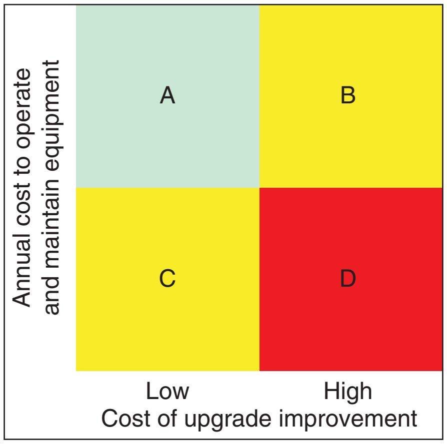


Figure 21.1: Best Potential MTBR Improvement Paybacks

Figure 21.1 shows the relationship between the current annual costs to operate and maintain the equipment, versus the cost to upgrade the equipment to improve MTBR. It is likely that the best paybacks will be achievable with equipment or defined populations of equipment in box A with relatively high opportunities for improvement due to their high annual cost of repair, high criticality, and/or high safety risk with relatively low cost of upgrading and improving MTBR.

Conversely, those pieces of equipment or defined populations of equipment with annual cost of repair, criticality, and/or safety risk contrasted with relatively high cost of upgrading and improving MTBR (box D) are projects that are not likely to be worthwhile from the standpoint of a financial payback.

Elements and Layout of a Pump Systems Assessment Report

22

Once the assessment is completed, the pump systems assessment results must be documented and reported to the management team.

The final assessment report should include the following factors:

1. Executive summary
2. Introduction including facility information
3. Assessment objectives and scope
4. Description of systems studied and system deficiencies
5. Assessment data collected
6. Data analysis
7. Annual baseline costs of operation, maintenance, downtime, and production loss
8. Performance improvement opportunities and prioritization
9. Implementation steps
10. Data appendices

When creating an executive summary, the following key points should be included:

- Facility review, background, and products
- Goals and scope of the pump systems assessment
- System(s) assessed and boundaries used
- Annual energy usage
- Performance opportunities, with associated improvements in energy usage, cost savings, and reliability

A background of the assessment should be included in the general discussion.

Following implementation of upgrades outlined in the initial assessment report, it is highly recommend that the system owner verify the performance with a supplemental measurement and verification report, documenting the actual performance improvements.

If the assessment personnel performed the initial assessment under contract, the system owner may not have purchased the postimplementation measurement and verification, which can be a missed step in the process.

Monitoring maintenance improvements from implemented upgrades is a long-term process and should be monitored by the system owner and documented in a supplemental report.

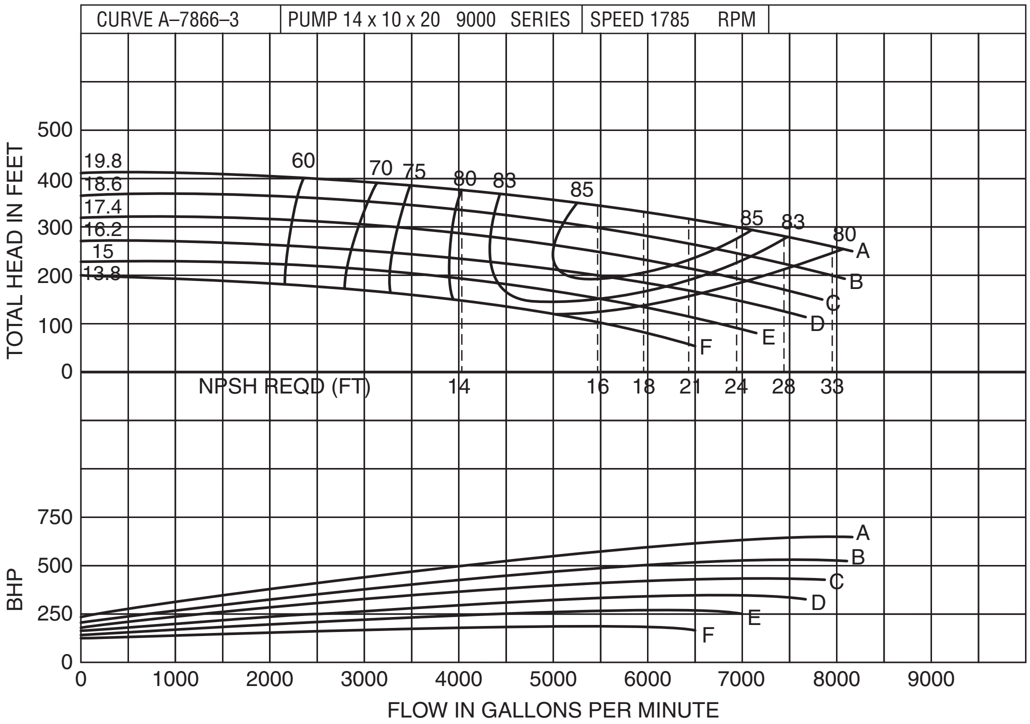
- ○ There are three basic pump curves – selection chart, published curve, and certified curve. Understand how to use these, as well as the motor performance curve, to determine pump performance.
- ○ Understand how to read and use the system curve and the pump head-capacity (*H*-*Q*) curve.
- ○ Data collection should include flow rate(s), pressures, temperature(s), power, vibration, and any other important system parameters.
- ○ Reliability is the probability of an individual unit within a population with a known MTBR of achieving a given time length of service. Be familiar with the reliability equation.
- ○ Be familiar with the available tools and technology for assessing pumping systems.
- ○ Be able to apply the methods for determining the economic feasibility of a project, including simple payback, net present value (NPV), and internal rate of return (IRR).
- ○ Utility companies use complicated rate structures to charge industrial customers, including demand charges.
- ○ There are four evaluation groups for identifying energy efficiency and MTBR improvement projects with the best potential paybacks.
- ○ The executive summary is a key part of the pump system assessment report when reporting to management.

Domain II – Knowledge Check

1. **Task:** Cross-validate the pump system data previously collected or obtained to ensure accuracy.

   Exercise: Field data collected indicates referenced pump (below) is configured with a 19.8 in. impeller. The unit is pumping 70 °F water at 300 ft of head, and flow was recorded at approximately 7000 gpm. What steps would you take to cross-validate the head and flow data? Show the math.

   Answer: The pump has a steady rising power curve; therefore, the pump input power can be used to cross-validate the pump data. (1) Calculate the pump input power for the flow and head measured using the pump efficiency from the curve provided and (2) measure the motor input power and calculate the corresponding pump input power by using the motor efficiency to cross-validate the data.



$$P(hp) = \frac{H \times Q \times s}{3960 \times \eta} = \frac{300\ ft \times 7000\ gpm \times 1.0}{3960 \times 0.85} = 624\ hp$$

Calculate the motor horsepower based on actual field measurements using calibrated instruments:

Motor performance data: measured voltage 4160, measured amperage 78, motor curve at amperage 0.88, motor curve efficiency at amperage 94%

$$Motor\ Output\ power\ (hp) = \frac{I \times V \times PF \times C \times \eta_r}{1000 \times 0.746} = \frac{78 \times 4160 \times 0.88 \times 1.73 \times 0.94}{1000 \times 0.746} = 622\ hp$$

Where

I = RMS current in amperes (A) (meter reading)

V = RMS volts (meter reading)

PF = power factor (motor curve or measured)

η_r = motor efficiency (motor curve or measured)

C = 1 for single-phase current

= 2 for two-phase four-wire control

= 1.73 for three-phase current

2. **Task:** Analyze the data based on the project scope and established boundary conditions.

   Exercise: Calculate the horsepower and efficiency of a fixed speed pump based on the following data collected by the assessor. What questions would you ask to establish boundary conditions for an additional assessment?

- Flow required: 2500 gpm
- Head required: 250 ft
- Speed: 3550 rpm
- Specific gravity: 1.0
- Motor efficiency: 94%
- Motor measured data: 460 V, 285 A, 0.88 PF, 94% efficiency
- Pump efficiency at BEP: 88%
- Energy cost: $0.07 kW·h
- The pump is being throttled with a 50 ft head drop across the control valve.
- Customer indicated the pump operates at this load point 3500 hours a year.

Answer:

$$hydraulic\ power\ \left(P_u\right) = \frac{Q \times H \times s}{3960} = \frac{250 \times 2500 \times 1.0}{3960} = 158\ hp$$

$$Pump\ Input\ Power\ (P) = \frac{I \times V \times PF \times C \times \eta_r}{1000 \times 0.746} = \frac{285 \times 460 \times 0.88 \times 1.73 \times 0.94}{1000 \times 0.746} = 252$$

$$Pump\ Efficiency\ (\eta) = \frac{P_u}{P} = \frac{158}{252} = 63\%$$

Questions to establish boundary conditions:

1. Is the system operating satisfactorily?
   a) Unexpected downtime?
   b) Lost production?
   c) High maintenance?
2. What is the required head and flow to the system?
3. Has a system curve been developed?
   a) Is it predominantly friction head?
   b) Is it predominantly static head
   c) Is it a combination?
4. How is the head loss across the valve being controlled?
5. What is the actual operating envelop of the system?
6. Is there any variability to the system flow conditions?
7. Has the system demand ever not been met?
8. Has variable speed pumping ever been considered
9. Is the existing motor inverter duty?
10. Is pump replacement an acceptable solution?

11. What is the cost of downtime?

12. Is there an energy demand charge?

13. When can improvements be implemented – what is the window of opportunity?

3. Task: Interpret the results of the analyses to establish initial findings and possible options (e.g., equipment, control, etc.) for pump system optimization.

Exercise: Using the system in the previous exercise, interpret the results.

Answer:

Calculate power consumed by the motor in kW:

$$Motor\ input\ power\ (kW) = \frac{252 \times 0.746}{0.94} = 200\ kW$$

Energy consumption operating under documented conditions:

$$Annual\ Energy\ Cost\ (\$) = 200 \times 3500 \times 0.07 = \$49{,}000$$

Calculate wasted energy across the control valve:

$$Valve\ loss\ hydraulic\ power\ \left(P_u\right) = \frac{Q \times H \times s}{3960} = \frac{50 \times 2500 \times 1.0}{3960} \times 0.746 = 24\ kW$$

$$Valve\ head\ loss\ cost\ (\$) = 24 \times 3500 \times 0.07 = \$5900$$

Potential energy savings with properly sized pump:

Calculate specific speed for properly sized pump without the 50-ft head loss across the valve (2500 gpm and 200 ft) and determine generally attainable efficiency:

$$N_s = \frac{n \times Q^{1/2}}{H^{3/4}} = \frac{3550 \times 2500^{0.5}}{200^{0.75}} = 3338$$

Where

N_s = specific speed (US units)

n = rotational speed (rpm)

Q = flow rate at best efficiency, with maximum diameter impeller (gpm)

H = head at best efficiency, with maximum diameter impeller (ft)

Based on the generally attainable efficiency chart presented in chapter 5, a pump with a specific speed of 3338 and 2500 gpm BEP should have a generally attainable efficiency of 88%. By sizing the optimal pump for the application, the wasted energy across the valve can be eliminated and the efficiency of the pump can be increased from the measured 63%–88%.

The pump input power for the optimal solution (2500 gpm, 200 ft, 88% efficiency) is as follows:

$$Pump\ input\ power\ (P) = \frac{Q \times H \times s}{3960 \times \eta} = \frac{2500 \times 200 \times 1.0}{3960 \times 0.88} = 143\ hp$$

Assuming an equivalent motor efficiency, the power savings and annual energy savings for optimal solutions over the existing system is

Power Savings (kW) = (252 hp – 143 hp) x 0.746 = 81 kW

Annual energy cost savings: 81 x 3500 x 0.07 = **$20,000 in potential annual energy savings with optimal pump**

4. **Task:** Evaluate the identified options to formulate specific recommendations for optimizing pump system efficiency and reliability.

   Exercise: Make a business case – show dollars along with potential solutions.

   Potential energy savings of $20,000 annually

   Options to achieve the energy savings:

   - Option 1 – Replace the existing pump with a new one that can deliver the system required head of 200 ft at 2500 gpm and 88% efficiency. Install a premium efficiency (94.5%) 150 hp motor.
     - This option has the potential to save $20,000 annually.
     - Cost would include the new pump and motor as well as installation of the new equipment and disposal of the old equipment.
     - Maintenance issues were not defined in the question, but reduced valve maintenance and pump maintenance would be a benefit of this solution.
   - Option 2 – Trim impeller of existing pump.
     - This option has the potential to save 24 kW hydraulic power loss across the valve and the associated $5900 wasted electrical costs.
     - The system curve was not defined in the question so it is not understood if the trimmed impeller pump would operate at a better or worse efficiency than 63%.
     - The cost for this option would include labor to remove the impeller, trim the impeller, and reinstall it.
     - Maintenance issues were not defined in the question, but reduced valve maintenance would be a benefit of this solution.
   - Option 3 – Install a VFD to reduce the speed of the pump to meet the design conditions.
     - This option has the potential to save 24 kW hydraulic power loss across the valve and the associated $5900 wasted electrical costs.
     - The system curve was not defined in the question so it is not understood if the trimmed impeller pump would operate at a better or worse efficiency than 63%. The VFD will add about 3% efficiency loss to the system that would need to be accounted for.
     - The variability of the system is not defined. If the system varies and requires less than 200 ft of head, additional energy savings could be achieved. An additional benefit would be soft starting and stopping of the equipment.
     - The cost for this option would include purchasing and installing a new VFD. Additionally, the existing motor would need to be evaluated to see if it is inverter duty. If it is not, a new motor may need to be purchased and installed.
     - Maintenance issues were not defined in the question, but reduced valve maintenance would be a benefit of this solution.

5. **Task:** Document findings and prepare a pump system assessment report that includes recommendations with costs and benefits.

   Exercise: Describe how you would document savings and what you would include in your assessment report

   Answer: The report should include the following factors: an executive summary, a process flow diagram with flow rates, equipment excluded from the study, boundary conditions for the analyzed systems, site performance data, analysis of each pump system, baseline operating and maintenance costs, and prioritized optimization opportunities with cost benefits and implementation strategy.

   - Develop more than one option for operating cost savings.
   - Existing and postpump optimization flow rates are to be the same.
   - Electrical energy costs were reported at $.0.07/kWh. Savings calculations are based on this rate.
   - Work within the boundaries for which we have data.
     - Internal piping condition is not assumed to affect the slope of the system curve (corrosion/buildup).
     - Pump performance is not degraded from existing impeller trims.
   - Substantiate all sources of reference (efficiencies, calculation methodologies).

Example of Documented Savings

Pump Name	**Number**	**Existing Annual Cost of Operation**	**Calculated Annual Operating Cost by Optimization Method**	
			New Pump and New Motor	**VFD and New Motor on Existing Pump**
D0 Washer Feed Pump	431-0402	$180,900	$92,800	$75,700
D0 Mining Water Pump	431-0403	$95,900	$47,200	$63,400
E0P Washer Feed Pump	431-0410	$179,000	$107,900	$75,200
E0P Mining Water Pump	431-0411	$100,000	$77,400	$75,200
D1 Washer Feed Pump	431-0414	$179,800	$120,300	$79,600
D1 Mining Water Pump	431-0415	$155,100	$103,300	$96,300
E2 Washer Feed Pump	431-0418	$170,500	$82,000	$72,000
E2 Mining Water Pump	431-0419	$97,300	$79,300	$68,600
D2 Mining Water pump	431-0423	$157,000	$130,700	$105,200
D2 Washer Feed Pump	431-0422	$175,600	$108,000	$73,200
	Total	$1,491,100	$948,900	$784,400

Domain III

Post-Assessment **18%**

- ➢ Task 12: Present the report to the client/customer and assist in the transition from assessment to implementation.
- ➢ Task 13: Perform postimplementation measurement and verification and generate a report.

- ○ Understand and apply presentation techniques
- ○ Understand and apply techniques for assisting clients/customers in aligning goals and strategies with assessment recommendations
- ○ Understand strategies for implementation of recommendations

Presentation Techniques

23

Almost any presentation of a system assessment with proposed upgrades should incorporate the concepts of an LCC analysis. Some companies will set a simple payback period requirement, while others require more detailed NPV calculations in order to make decisions.

It is important for the assessment professional to understand the purpose of the assessment and who will be making the decision regarding implementation of the recommendations. For example, is the purpose of the assessment to evaluate a reliability issue or failures and propose ways to improve reliability? Or is the purpose to determine the energy consumption of a system and propose ways to reduce energy usage? Or both?

The presentation of these results for the engineering and reliability community will be technical in nature and include the detailed results of the assessment. However, the personnel making the decision regarding implementation of upgrades may not be the team who was directly involved in the assessment. If the upgrades are a significant capital investment, the decision-making process will likely involve different sets of individuals who control budgets and capital expenditures. Presentations to these personnel may need to be less technical in nature related to the actual assessment, but will need to include more content on the LCC and financial analysis.

In either case, the presentation of the report should be tailored to the purpose of the assessment, which may take different forms depending on the reason for the assessment and the personnel being presented to.

24

Techniques for Assisting Clients in Aligning Goals and Strategies with Assessment Recommendations

Saving money, in and of itself, should be a strong incentive for implementing a pumping system project. Still, that may not be enough for some corporate observers. The facility manager's case can be strengthened by relating a positive LCC outcome to specific corporate needs. Some suggestions for interpreting the benefits of energy cost savings include the following:

- A new source of permanent capital. Reduced energy expenditures – the direct benefit of pumping system efficiency, can be thought of as a new source of capital to the corporation. The investment that makes this efficiency possible will yield annual savings each year over the economic life of the improved pumping system
- Added shareholder value. Publicly held corporations usually embrace opportunities to enhance shareholder value. Pumping system efficiency can be an effective way to capture new value. Shareholder value is the product of two variables: annual earnings and the price-to-earnings (or "P/E") ratio. The P/E ratio describes the corporation's stock value as the current stock price divided by the most recent annual earnings per share. To take advantage of this measure, the pumping system efficiency proposal should first identify annual savings (or rather, addition to earnings) that the proposal will generate. Multiplying that earnings increment by the P/E ratio yields the total new shareholder value attributable to the pumping system efficiency implementation.
- Improved reliability and capacity utilization. Another benefit to be derived from a pumping system improvement project is the more productive use of pumping system assets. By improving pumping system performance, the facility manager can improve the reliability of plant operations and generate more reliable production. The flip side, from the corporate perspective, is a greater rate of return on assets employed in the plant.

Implementation Strategies 25

A key element to achieving real results from an energy assessment – savings on the ground – is to view the assessment as an initial step to implementation. This can be achieved by applying the 11 "implementation principles" presented below prior to, during, and after an assessment.

Throughout the Entire Assessment Process

1. Integrate the process of identifying operating and maintenance savings opportunities with the process of implementing opportunities.
    - Integrate key processes to promote the implementation of identified savings opportunities.
2. Assign clear accountability to those participating in an assessment.
    - Assign the completion of specific activities and projects to specific individuals.
3. Explain and communicate the implications of performing an assessment.
    - Understand the value of an assessment.
    - Recognize that no assessment is free.
    - Understand management expectations in relation to identified implementation opportunities.
4. Know the company conducting the assessment.
    - Verify the company's credibility.
    - Ensure that the assessment contract clearly defines all components of the assessment.
    - Ensure that the assessor fully understands what motivates company decisions.
    - Review the assessor's history of follow-up and partnership with its clients.
5. Undergo an assessment only if the plant welcomes it and demonstrates its commitment to implementation.
    - Make sure the plant welcomes the assessment and shows its commitment to implementation.
    - Ensure that management provides resources for the assessment and the implementation recommendations.

6. Organize assessment logistics to promote a successful identification process for opportunities.
    - Ensure that the assessment experts are provided with “need-to-know” information before the assessment.
    - Conduct safety briefings and address confidentiality issues.
    - Make certain that diagnostic measurement processes are in place before an assessment starts.
    - Obtain management participation in a kick-off meeting and closeout meeting.
    - Request potential participation and support from utilities and key plant service providers.
    - Ensure key plant team members are available to assist.
    - Conduct assessments primarily when the targeted systems are operating.

During the Assessment

7. Employ an assessment process that moves smoothly from identifying opportunities to implementing them.
    - Ensure that identified opportunities meet the facility and/or organizational hurdle rates.
    - Discuss next-step activities to increase implementation.
    - Have the team lead sign off on all pursuable opportunities identified during the assessment.
    - Assign ownership for all identified assessment opportunities to ensure accountability.
    - Obtain management participation in a closeout meeting.

After the Assessment

8. Ensure continued momentum from the assessment to the implementation of approved energy savings projects.
    - Ensure that “risk” issues are evaluated and understood.
    - Ensure that funding is available for identified opportunities.

9. Quantify operating and maintenance savings benefits.
    - Track the status of approved optimization projects after the assessment.
    - Report implementation progress to senior management on a periodic basis and demonstrate the resultant savings in company language.
    - Implement the measurement and verification (M&V) plan based on company expectations.

10. Publicize successful implementation results and recognize employee contributions.
    - Inform key stakeholders of accomplishments.
    - Have communications and public relations staff continually announce progress.
    - Celebrate company and individual achievements through recognition programs.

11. Identify “lessons learned” to ensure future success.
   - Have plant personnel review assessment and implementation efforts.
   - Identify and implement key process improvements.

Implementation

After sign-off on all identified implementation opportunities and which of those will be implemented, the next activity is for the system owner to create an implementation team and assign team members to this project. The implementation team could be different from the initial assessment team. The system owner may choose to work directly with the equipment suppliers and may implement the upgrades without any other contract resources. Or, they may retain contract resources, particularly if those resources were involved in the initial assessment, to support a successful implementation.

It is important that the implementation plan includes a supplemental measurement and verification report to ensure that performance improvements are realized.

As with the assessment team, the implementation lead should provide project management functions, to ensure successful implementation. Proper communication and project management tools should be used to ensure each team member understands their role and responsibilities and how they will be held accountable. The scope of the implementation and progress related to the implementation should be shared with the entire team periodically so that all team members are aware of any deviations to the original schedule and how those deviations impact their deliverables.

Summary

- ○ The assessment professional should understand the purpose of the assessment and who will be making the decision regarding implementation of the recommendations.
- ○ The presentation of the assessment report should be tailored to the purpose of the assessment and to the personnel being presented to.
- ○ In some cases, the specific benefits of energy cost savings – such as improved reliability and capacity utilization – need to be included in the presentation.
- ○ There are 11 implementation principles that should applied prior to, during, and after an assessment.
- ○ After agreement on all identified implementation opportunities and which will be implemented, the system owner should create an implementation team.
- ○ The implementation plan should include a measurement and verification report to ensure performance improvements are realized.

Domain III – Knowledge Check

1. **Task:** Present the report to the client/customer and assist in the transition from assessment to implementation.

Exercise: Using questions 2, 3, and 4 from the Domain II Knowledge Check, formulate a "conceptual" justification for the two options identified in the previous four exercises. Describe how you would move forward with this project.

Answer: Based on the boundary conditions that you and the client agreed upon, take an LCC approach. In other words, look beyond energy savings, for

- Higher reliability
- Increased productivity
- Less equipment wear and tear
- Reduced maintenance cost
- Reduced production losses
- Increased capacity utilization
- Reduced environmental impact

The above information should have been identified early in the assessment process. Using this information, bundle the benefits along with the energy savings to make the business case.

Early in the assessment process, the assessor should have determined the client's level of commitment to implement solutions (based on findings) and determined plant availability for implementation (again, based on findings).

In many cases, the cost of downtime, lost production, and maintenance far exceeds the potential energy savings.

Appendix A: Pump Systems Assessment Professional Job Task Analysis (JTA)

This document represents a delineation of common or typical tasks (T) performed and knowledge (K) applied by Pump System Assessment Professionals. In the course of pump system assessments, some tasks may be performed simultaneously or multiple times with modifications made based on data, findings, and results as part of ongoing feedback loops. (For clarity and simplicity, the feedback loops are not presented in this document. However, it is assumed and understood that they may be a routine part of the process.)

(36%) Domain I Information/Data Gathering

T-1 Assess the presenting situation and determine if it is amenable to a pump system assessment (i.e., jointly determine the value proposition/objectives).

The successful performance of this task requires knowledge of

K-1 Pump types (e.g., centrifugal, positive displacement, vertical turbine, etc.)

K-2 Pump system components (e.g., tanks, valves, pipes, sealing, heat exchangers, couplings, etc.)

K-3 Pump system component interactions

K-4 Standard pump system operating procedures

K-5 Benefits of pump system optimization

K-6 Factors that impact pump efficiency and reliability (e.g., size, age, installation, process change, fluid properties, pressure head flow, etc.)

K-7 Factors that affect pump system reliability and efficiency (e.g., age, installation, piping modifications, system controls, hydraulic design modifications, instrumentation, operational parameters, etc.)

K-8 Elements of lifecycle costing

T-2 Obtain and analyze initial information about the pump system (i.e., perform pre screening).

The successful performance of this task requires knowledge of

K-1 Pump types (e.g., centrifugal, positive displacement, vertical turbine, etc.)

K-2 Pump system components (e.g., tanks, valves, pipes, sealing, heat exchangers, couplings, etc.)

K-3 Pump system component interactions

K-4 Standard pump system operating procedures

K-5 Benefits of pump system optimization

K-6 Factors that impact pump efficiency and reliability (e.g., size, age, installation, process change, fluid properties, pressure head flow, etc.)

K-7 Factors that affect pump system reliability and efficiency (e.g., age, installation, piping modifications, system controls, hydraulic design modifications, instrumentation, operational parameters, etc.)

K-8 Elements of lifecycle costing

K-9 Basic pump maintenance practices

K-10 Piping and instrumentation diagrams

K-11 Isometrics

K-12 Process flow diagrams

K-13 Blueprints

T-3 Assemble a pump system assessment team and define roles and responsibilities.

The successful performance of this task requires knowledge of

K-14 Key plant personnel (positions) needed on assessment team

K-15 Roles and responsibilities of an assessment team

K-16 Field measurement parameters and their acceptable ranges

T-4 Make a visual assessment of the pump system or have the plant verify the accuracy of the information provided in order to confirm initial information, obtain additional information, and make a final determination of the project scope.

The successful performance of this task requires knowledge of

K-1 Pump types (e.g., centrifugal, positive displacement, vertical turbine, etc.)

K-2 Pump system components (e.g., tanks, valves, pipes, sealing, heat exchangers, couplings, etc.)

K-3 Pump system component interactions

K-4 Standard pump system operating procedures

K-5 Benefits of pump system optimization

K-6 Factors that impact pump efficiency and reliability (e.g., size, age, installation, process change, fluid properties, pressure head flow, etc.)

K-7 Factors that affect pump system reliability and efficiency (e.g., age, installation, piping modifications, system controls, hydraulic design modifications, instrumentation, operational parameters, etc.)

K-8 Elements of lifecycle costing

K-9 Basic pump maintenance practices

K-10 Piping and instrumentation diagrams

K-11 Isometrics

K-12 Process flow diagrams

K-13 Blueprints

K-14 Typical plant organizational structures

K-15 Roles and responsibilities of an assessment team

K-16 Field measurement parameters and their acceptable ranges

K-17 Hydraulic and electrical formulae

K-18 Measuring devices and their requirements and proper applications

T-5 Conduct a pump systems operations discussion with personnel in a position to answer questions, verify information previously obtained, and provide additional information.

The successful performance of this task requires knowledge of:

K-1 Pump types (e.g., centrifugal, positive displacement, vertical turbine, etc.)

K-2 Pump system components (e.g., tanks, valves, pipes, sealing, heat exchangers, couplings, etc.)

K-3 Pump system component interactions

K-4 Standard pump system operating procedures

K-5 Benefits of pump system optimization

K-6 Factors that impact pump efficiency and reliability (e.g., size, age, installation, process change, fluid properties, pressure head flow, etc.)

K-7 Factors that affect pump system reliability and efficiency (e.g., age, installation, piping modifications, system controls, hydraulic design modifications, instrumentation, operational parameters, etc.)

K-8 Elements of lifecycle costing

K-9 Basic pump maintenance practices

K-10 Piping and instrumentation diagrams

K-11 Isometrics

K-12 Process flow diagrams

K-13 Blueprints

K-14 Typical plant organizational structures

K-15 Roles and responsibilities of an assessment team

K-16 Field measurement parameters and their acceptable ranges

K-17 Hydraulic and electrical formulae

K-18 Measuring devices and their requirements and proper applications

K-19 Common operating problems and errors

T-6 Obtain real-time pump system operation data.

The successful performance of this task requires knowledge of:

K-2 Pump system components (e.g., tanks, valves, pipes, sealing, heat exchangers, couplings, etc.)

K-3 Pump system component interactions

K-6 Factors that impact pump efficiency and reliability (e.g., size, age, installation, process change, fluid properties, pressure head flow, etc.)

K-7 Factors that affect pump system reliability and efficiency (e.g., age, installation, piping modifications, system controls, hydraulic design modifications, instrumentation, operational parameters, etc.)

K-16 Field measurement parameters and their acceptable ranges

K-18 Measuring devices and their requirements and proper applications

(46%) Domain II Data Analysis

T-7 Cross-validate the pump system data previously collected or obtained in order to ensure accuracy.

The successful performance of this task requires knowledge of

K-2 Pump system components (e.g., tanks, valves, pipes, sealing, heat exchangers, couplings, etc.)

K-3 Pump system component interactions

K-6 Factors that impact pump efficiency and reliability (e.g., size, age, installation, process change, fluid properties, pressure head flow, etc.)

K-7 Factors that affect pump system reliability and efficiency (e.g., age, installation, piping modifications, system controls, hydraulic design modifications, instrumentation, operational parameters, etc.)

K-16 Field measurement parameters and their acceptable ranges

K-17 Hydraulic and electrical formulae

K-18 Measuring devices and their requirements and proper applications

K-20 Pump and motor performance curves

K-21 System curves

K-22 Parameter estimation methods

T-8 Analyze the data based on the project scope and established boundary conditions.

The successful performance of this task requires knowledge of:

K-1 Pump types (e.g., centrifugal, positive displacement, vertical turbine, etc.)

K-2 Pump system components (e.g., tanks, valves, pipes, sealing, heat exchangers, couplings, etc.)

K-3 Pump system component interactions

K-4 Standard pump system operating procedures

K-5 Benefits of pump system optimization

K-6 Factors that impact pump efficiency and reliability (e.g., size, age, installation, process change, fluid properties, pressure head flow, etc.)

K-7 Factors that affect pump system reliability and efficiency (e.g., age, installation, piping modifications, system controls, hydraulic design modifications, instrumentation, operational parameters, etc.)

K-8 Elements of lifecycle costing

K-9 Basic pump maintenance practices

K-10 Piping and instrumentation diagrams

K-11 Isometrics

K-12 Process flow diagrams

K-13 Blueprints

K-16 Field measurement parameters and their acceptable ranges

K-17 Hydraulic and electrical formulae

K-18 Measuring devices and their requirements and proper applications

K-19 Common operating problems and errors

K-20 Pump and motor performance curves

- K-21 System curves
- K-22 Parameter estimation methods
- K-23 Data (electrical, vibration, thermography, etc.) and its relationship to reliability
- K-24 Reliability metrics

T-9 Interpret the results of the analyses to establish initial findings and possible options (e.g., equipment, controls, etc.) for pump system optimization.

The successful performance of this task requires knowledge of

- K-1 Pump types (e.g., centrifugal, positive displacement, vertical turbine, etc.)
- K-2 Pump system components (e.g., tanks, valves, pipes, sealing, heat exchangers, couplings, etc.)
- K-3 Pump system component interactions
- K-4 Standard pump system operating procedures
- K-5 Benefits of pump system optimization
- K-6 Factors that impact pump efficiency and reliability (e.g., size, age, installation, process change, fluid properties, pressure head flow, etc.)
- K-7 Factors that affect pump system reliability and efficiency (e.g., age, installation, piping modifications, system controls, hydraulic design modifications, instrumentation, operational parameters, etc.)
- K-8 Elements of lifecycle costing
- K-9 Basic pump maintenance practices
- K-10 Piping and instrumentation diagrams
- K-11 Isometrics
- K-12 Process flow diagrams
- K-13 Blueprints
- K-16 Field measurement parameters and their acceptable ranges
- K-17 Hydraulic and electrical formulae
- K-18 Measuring devices and their requirements and proper applications
- K-19 Common operating problems and errors
- K-20 Pump and motor performance curves
- K-21 System curves

K-22 Parameter estimation methods

K-23 Data (electrical, vibration, thermography, etc.) and its relationship to reliability

K-24 Reliability metrics

K-25 Currently available equipment and technology

K-26 Industry best practices

T-10 Evaluate the identified options to formulate specific recommendations for optimizing pump system efficiency and reliability

The successful performance of this task requires knowledge of

K-27 Basic financial analysis

K-28 Utility rate structures and incentives

K-29 Principles and techniques of prioritizing solutions

T-11 Document findings and prepare a pump system assessment report that includes recommendations with costs and benefits.

The successful performance of this task requires knowledge of

K-30 Elements and layout of a pump system assessment report

(18%) Domain III Postassessment

T-12 Present the report to the client/customer and assist in the transition from assessment to implementation.

The successful performance of this task requires knowledge of

K-14 Typical plant organizational structures

K-31 Presentation techniques

K-32 Techniques for assisting clients/customers in aligning goals and strategies with assessment recommendations

K-33 Implementation strategies

T-13 Perform postimplementation measurement and verification and generate a report.

The successful performance of this task requires knowledge of

K-1 Pump types (e.g., centrifugal, positive displacement, vertical turbine, etc.)

K-2 Pump system components (e.g., tanks, valves, pipes, sealing, heat exchangers, couplings, etc.)

K-3 Pump system component interactions

K-4 Standard pump system operating procedures

K-5 Benefits of pump system optimization

K-6 Factors that impact pump efficiency and reliability (e.g., size, age, installation, process change, fluid properties, pressure head flow, etc.)

K-7 Factors that affect pump system reliability and efficiency (e.g., age, installation, piping modifications, system controls, hydraulic design modifications, instrumentation, operational parameters, etc.)

K-8 Elements of lifecycle costing

K-9 Basic pump maintenance practices

K-10 Piping and instrumentation diagrams

K-11 Isometrics

K-12 Process flow diagrams

K-13 Blueprints

K-16 Field measurement parameters and their acceptable ranges

K-17 Hydraulic and electrical formulae

K-18 Measuring devices and their requirements and proper applications

K-19 Common operating problems and errors

K-20 Pump and motor performance curves

K-21 System curves

K-22 Parameter estimation methods

K-23 Data (electrical, vibration, thermography, etc.) and its relationship to reliability

K-24 Reliability metrics

K-34 Commissioning

Knowledge Summary

K-1 Pump types (e.g., centrifugal, positive displacement, vertical turbine, etc.)

K-2 Pump system components (e.g., tanks, valves, pipes, sealing, heat exchangers, couplings, etc.)

K-3 Pump system component interactions

K-4 Standard pump system operating procedures

K-5 Benefits of pump system optimization

K-6 Factors that impact pump efficiency and reliability (e.g., size, age, installation, process change, fluid properties, pressure head flow, etc.)

K-7 Factors that affect pump system reliability and efficiency (e.g., age, installation, piping modifications, system controls, hydraulic design modifications, instrumentation, operational parameters, etc.)

K-8 Elements of lifecycle costing

K-9 Basic pump maintenance practices

K-10 Piping and instrumentation diagrams

K-11 Isometrics

K-12 Process flow diagrams

K-13 Blueprints

K-14 Typical plant organizational structures

K-15 Roles and responsibilities of an assessment team

K-16 Field measurement parameters and their acceptable ranges

K-17 Hydraulic and electrical formulae

K-18 Measuring devices and their requirements and proper applications

K-19 Common operating problems and errors

K-20 Pump and motor performance curves

K-21 System curves

K-22 Parameter estimation methods

K-23 Data (electrical, vibration, thermography, etc.) and its relationship to reliability

K-24 Reliability metrics

K-25 Currently available equipment and technology

K-26 Industry best practices

K-27 Basic financial analysis

K-28 Utility rate structures and incentives

K-29 Principles and techniques of prioritizing solutions

K-30 Elements and layout of a pump system assessment report

K-31 Presentation techniques

K-32 Techniques for assisting clients/customers in aligning goals and strategies with assessment recommendations

K-33 Implementation strategies

K-34 Commissioning

Appendix B: Useful Formulas and Conversions

Convert pressure (psi) to head in feet

$$h\ (\text{ft}) = \frac{p(\text{psi}) * 2.31}{\textit{Specific Gravity}}$$

1 meter (m) = 3.281 feet (ft)

Calculation of velocity head

$$h_v = \frac{v^2}{2g}$$

Where

h_v = velocity head, ft (m)

v = flow velocity, ft/s (m/s)

g = acceleration constant due to gravity

Gravity acceleration constants

$$g = 32.2\frac{\text{ft}}{\text{s}^2} = 9.81\frac{\text{m}}{\text{s}^2}$$

Pump affinity rules with respect to impeller diameter

$$Q_2 = Q_1\frac{D_2}{D_1} \quad H_2 = H_1\frac{D_2^2}{D_1^2} \quad P_2 = P_1\frac{D_2^3}{D_1^3}$$

Pump affinity rules with respect to pump speed

$$Q_2 = Q_1\frac{n_2}{n_1} \quad H_2 = H_1\frac{n_2^2}{n_1^2} \quad P_2 = P_1\frac{n_2^3}{n_1^3}$$

Calculation of NPSHA

$$\text{NPSHA} = h_{atm} + h_{gs} + h_{vs} + z_s - h_{vp}$$

Where

h_{atm} = atmospheric pressure head, ft (m)

h_{gs} = suction gauge head, ft (m)

h_{vs} = suction velocity head, ft (m)

z_s = *elevation from the suction gauge centerline to datum, ft (m)*

h_{vp} = liquid vapor pressure head, ft (m)

Calculation of electrical input power

$$Input\ \ power\ (kW) = \frac{I \times V \times PF \times C}{1000}$$

Where

I = current in amperes (A) (meter reading)

V = volts (meter reading)

PF = power factor (motor curve or measured)

C = 1 for single-phase current

= 2 for two-phase four-wire control

= 1.73 for three-phase current

Calculation of power

$hydraulic\ \ power\ (P_u) = \dfrac{Q \times H \times s}{3960}\ (hp)$, also known as Water Horsepower (WHP) when water is the pumped fluid

Hydraulic power (P_u)	hp (horsepower)
Head (H)	feet
Flow (Q)	gpm
Specific gravity (s)	dimensionless

3960 is a constant that incorporates two conversions: (1) convert flow (gpm) to pounds/minute, and (2) convert the product of mass flow × head (pound-foot/minute) to horsepower

$$\text{Hydraulic power } (P_u) = \frac{Q \times H \times s}{0.1022}\ (kW)$$

ad (H)	meters (m)
Flow (Q)	m^3/s
Specific gravity (s)	dimensionless

0.1022 is metric units conversion to provide power in kilowatt (kW)

$Pump\ \ Power\ \ Input\ (P) = \dfrac{P_u}{\eta}$, also known as shaft power or Brake Horsepower (BHP)

- Pump Efficinecy (η)

$$Power\ \ (kW) = 0.746 \times Horsepower$$

Velocity (v) in pipe

$$v = \frac{Volume\ \ rate\ \ of\ \ flow}{Pipe\ \ inside\ diameter\ \ area}$$

$$v = \frac{0.4085 \times Q}{d^2}$$

Where

v = velocity in feet per second (ft/s)

Q =flow rate in gallons per minute (gpm)

d =pipe inside diameter in inches (in)

Resistance to flow in pipes and fittings

$$h_f = f \times \frac{l}{d} \times \frac{v^2}{2g}$$

Where

h_f = frictional resistance in head

f = piping frictionfactor

l = length of pipe, ft (m)

d = average ID of piping, ft (m)

v = average velocity, ft/s (m/s)

g = acceleration due to gravity

$$h = k \times \frac{v^2}{2g}$$

Where

h = frictional resistance in head

k = resistance coefficient for valve or fitting

v = average velcoity, ft/s (m/s)

g = acceleration due to gravity

Appendix C: References

Hydraulic Institute and Europump, *Pump Life Cycle Costs – A Guide to LCC Analysis for Pumping Systems* – Hydraulic Institute Europump, 2001

US Department of Energy's Industrial Technologies Program and Hydraulic Institute – *Improving Pumping System Performance – A Sourcebook for Industry, Second Edition* – US Department of Energy, 2006

Hydraulic Institute and Pump Systems Matter– *Optimizing Pumping Systems, A Guide to Improved Energy Efficiency, Reliability, and Profitability, First Edition* – Hydraulic Institute, Pump Systems Matter, 2008

US Department of Energy's Industrial Technologies Program – *Guiding Principles for Successfully Implementing Industrial Energy Assessment Recommendations* – US Department of Energy, 2011

ISO/ASME 14414:2015, Pump System Energy Assessment

ANSI/HI 3.1–3.5, American National Standard for Rotary Pumps, for Nomenclature, Definitions, Application and Operation

ANSI/HI 6.1–6.5, American National Standard for Reciprocating Power pumps, for Nomenclature, Definitions, Application and Operation

ANSI/HI 1.3, American National Standard for Rotodynamic Centrifugal Pumps, for Design & Application

ANSI/HI 1.4, American National Standard for Rotodynamic Centrifugal Pumps, for Manuals Describing Installation, Operation, and Maintenance

ANSI/HI 14.6, American National Standard, Rotodynamic Pumps, for Hydraulic Performance Acceptance Tests

Hydraulic Institute Reliability of Pumping Equipment Committee – *Reliability of Pumping Equipment: Guidelines for Maximizing Uptime, Availability, and Reliability, First Edition* – Hydraulic Institute, 2015

Index