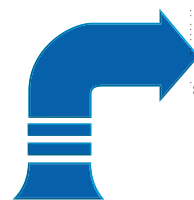
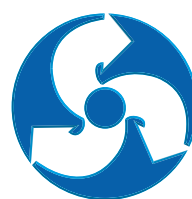


Hydraulic Institute Standard for

Methods for Rotodynamic Pump Efficiency Testing



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Hydraulic Institute Standard for Methods for Rotodynamic Pump Efficiency Testing

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Approved by Hydraulic Institute
October 27, 2016

Hydraulic Institute Standard

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Foreword (Not part of Standard)

Purpose and aims of the Hydraulic Institute

The purpose and aims of the Hydraulic Institute are to promote the advancement of the pump manufacturing industry and further the interests of the public and to this end, among other things:

- a) Develop and publish standards.
- b) Address pump systems.
- c) Expand knowledge and resources.
- d) Educate the marketplace.
- e) Advocate for the industry.

Purpose of Standards and Guidelines

- a) Hydraulic Institute Standards and Guidelines are adopted in the public interest and are designed to help eliminate misunderstandings between the manufacturer, the purchaser, and/or the user and to assist the purchaser in selecting and obtaining the proper product for a particular need.
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Quoting from Article XV, Standards, of the By-Laws of the Institute, Section B:

“An Institute Standard defines the product, material, process or procedure with reference to one or more of the following: nomenclature, composition, construction, dimensions, tolerances, safety, operating characteristics, performance, quality, rating, testing and service for which designed.”

Definition of a Hydraulic Institute Guideline

A Hydraulic Institute Guideline is not normative. The guideline is tutorial in nature, to help the reader better understand the subject matter.

Comments from users

Comments from users of this standard will be appreciated, to help the Hydraulic Institute prepare even more useful future editions. Questions arising from the content of this standard may be directed to the Technical Director of the Hydraulic Institute. If appropriate, the inquiry will then be directed to the appropriate technical committee for provision of a suitable answer.

Revisions

Standards and Guidelines of the Hydraulic Institute are subject to constant review, and revisions are undertaken whenever it is found necessary because of new developments and progress in the art. If no revisions are made for five years, the standards are reaffirmed using the HI balloting procedures.

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This document does not contain a complete statement of all requirements, analyses, and procedures necessary to ensure safe or appropriate selection, installation, testing, inspection, and operation of any pump or associated products. Each application, service, and selection is unique with process requirements that shall be determined by the owner, operator, or its designated representative.

Units of measurement

Metric units of measurement are used, and corresponding US customary units appear in parentheses. Charts, graphs, and sample calculations are also shown in both metric and US customary units. Because values given in metric units are not exact equivalents to values given in US customary units, it is important that the selected units of measure to be applied be stated in reference to this standard. If no such statement is provided, metric units shall govern.

Committee list

A working committee met many times to facilitate the development of this document. At the time it was developed, the committee had the following members:

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Special acknowledgement – peer review

Several independent experts in the industry provided their time to review and evaluate the committee draft. They conducted a thorough review of the material, ensuring the document met the intended goal established by the committee chairs, and provided accurate, coordinated, and relevant information to the reader. Their work was extremely valuable, and the committee thanks all of them for their time and efforts.

Sarah Widder
Pacific Northwest National Laboratory

40.6 Methods for rotodynamic pump efficiency testing

40.6.1 Scope

This standard covers efficiency testing of rotodynamic pumps that are included in DOE regulations for energy conservation.¹

HI 40.6 is intended to be used for efficiency testing at pump test facilities or laboratories only. Industry experience shows that it is very difficult to perform measurements accurate enough to satisfy the requirements in this standard when testing is performed in the field. Therefore field-testing is not permitted as a method of efficiency testing per this standard.

In general, a pump consists of a bare pump alone or a bare pump with driver, mechanical equipment, and/or controls.

This standard applies to a pump without any fittings. In the case where fittings are an integral part of the pump, the losses for these components must be included with the performance of the pump.

This standard is not intended for production pump testing. Refer to ANSI/HI 14.6 *Rotodynamic Pumps for Hydraulic Performance Acceptance Tests* and ANSI/HI 11.6 *Rotodynamic Submersible Pumps for Hydraulic Performance, Hydrostatic Pressure, Mechanical, and Electrical Acceptance Tests* for production pump testing.

40.6.1.1 Introduction

HI 40.6-2014 *Methods for Rotodynamic Pump Efficiency Testing* was developed as a normative standard for the testing of rotodynamic pump efficiency. HI 40.6 is derived from ANSI/HI 14.6, extracting that material that pertains specifically to the determination of the efficiency of a rotodynamic pump with no criteria for acceptance.

While the DOE has drafted and published pump efficiency testing regulations fundamentally based on HI 40.6-2014, there are some differences between HI 40.6-2014 to the test procedure (TP) final rule, as published by the DOE in the US *Federal Register* (DOE TP final rule). (81 FR 4085 [Jan. 25, 2016].) The HI 40.6 committee has identified these differences and has produced an updated version of the standard, HI 40.6-2016, that is believed to be in conformance with the DOE TP final rule.

This updated standard provided to the public is not considered an alternative efficiency determination method (AEDM) by the DOE. The Hydraulic Institute is providing this standard as a convenience at the request of interested parties. Manufacturers should consult the adopted regulatory text of 10 CFR 431 subpart Y to determine compliance.

40.6.2 Terms and definitions

For the purposes of this standard, the quantities, definitions, symbols, and units given here apply.

Table 40.6.2 gives definitions of quantities used in this standard.

Table 40.6.2.1a gives an alphabetical list of symbols used, and Table 40.6.2.1b gives a list of subscripts.

In this standard all formulae are given in coherent metric units. For conversion of other units to metric units, see Appendix E.

¹ This document contains the test protocol for determining measured pump performance characteristics. The DOE test procedure for pumps (10 CFR 431.464) contains additional analysis and calculations necessary to determine the constant load or variable load pump energy index (PEI_{CL} or PEI_{VL}).

Table 40.6.2 — List of quantities, terms, and definitions

Row	Quantity	Definition	Symbol	Dimension	Unit ^a
1	Mass	The inertial resistance of a body to acceleration. A quantitative measure of inertia.	m	M	kg (lbm)
2	Length	The measurement of something from end to end.	L	L	m (ft)
3	Acceleration due to gravity	The acceleration of a body due to the influence of the pull of gravity alone. It is sufficient to use a value of 9.81 m/s ² .	g	LT ⁻²	m/s ² (ft/s ²)
4	Speed of rotation	Number of rotations per unit time. (Commonly referred to as <i>revolutions per minute, rpm</i> .)	n	T ⁻¹	s ⁻¹ min ⁻¹ rpm
5	Density	Mass per unit volume.	ρ	ML ⁻³	kg/m ³ (lbm/ft ³)
6	Pressure	Force per unit area. In this standard, all pressures are gauge pressures, i.e., measured with respect to the atmospheric pressure, except the atmospheric pressure and the vapor pressure, which are absolute pressures.	p	ML ⁻¹ T ⁻²	Pa (psi)
7	Kinematic viscosity	A coefficient defined as the ratio of the dynamic viscosity of a fluid to its density.	ν	L ² T ⁻¹	m ² /s (ft ² /s)
8	Power (general term)	Energy transferred per unit time.	P	ML ² T ⁻³	W (hp)
9	Reynolds number	Defined, especially for this standard, by the relation: $Re = \frac{UD}{\nu}$	Re	pure number	
10	Diameter	The measure of a straight line passing through the center of a circular shape that intersects the circular shape at both of its ends.	D	L	m (ft)
11	Volume per unit time ^b	In this standard this symbol designates the volume rate of flow in any given section. (The section may be designated by subscripts.) Typical US customary units used are gallons per minute (gpm). Also referred to as <i>flow</i> , <i>flow rate</i> , and <i>rate of flow</i> .	Q	L ³ T ⁻¹	m ³ /s (ft ³ /s) (gpm)
12	Mean velocity	The mean axial velocity of flow equal to the volume rate of flow divided by the pipe cross-section area. $U = \frac{Q}{A}$	U	LT ⁻¹	m/s (ft/s)
13	Head (general term)	The energy per unit mass of fluid, divided by acceleration due to gravity, g .	h	L	m (ft)

Table 40.6.2 — List of quantities, terms, and definitions (*continued*)

Row	Quantity	Definition	Symbol	Dimension	Unit ^a
14	Height above reference plane	The height of the considered point above the reference plane. Its value is: • positive, if the considered point is above the reference plane; • negative, if the considered point is below the reference plane. Reference plane: Any horizontal plane used as a datum for height measurement. For practical reasons it is preferable not to specify an imaginary reference plane.	z	L	m (ft)
15	Gauge pressure	The pressure relative to atmospheric pressure. Its value is: • positive, if this pressure is greater than the atmospheric pressure; • negative, if this pressure is less than the atmospheric pressure. NOTE: All pressures in this standard are gauge pressures read from a manometer or similar pressure-sensing instrument, except atmospheric pressure and the vapor pressure of the liquid, which are expressed as absolute pressures.	p	$ML^{-1}T^{-2}$	Pa (psi)
16	Atmospheric pressure (absolute)	The pressure exerted by the weight of the air above it at any point on the earth's surface.	p_{atm}	$ML^{-1}T^{-2}$	Pa (psi)
17	Inlet total head	Total head in the inlet section of the pump: $h_1 = z_1 + \frac{p_1}{\rho g} + \frac{U_1^2}{2g}$	h_1	L	m (ft)
18	Outlet total head	Total head in the outlet section of the pump: $h_2 = z_2 + \frac{p_2}{\rho g} + \frac{U_2^2}{2g}$	h_2	L	m (ft)
19	Pump total head ^b	Algebraic difference between the outlet total head h_2 and the inlet total head h_1: $H = h_2 - h_1$ and the pump total head shall be calculated by the formula: $H = z_2 - z_1 + \frac{p_2 - p_1}{\rho \cdot g} + \frac{U_2^2 - U_1^2}{2g}$ For vertical turbine pumps, the pump total head includes the bowl assembly head minus all the pump internal hydraulic friction losses.	H	L	m (ft)

Table 40.6.2 — List of quantities, terms, and definitions (*continued*)

Row	Quantity	Definition	Symbol	Dimension	Unit ^a
20	Bowl assembly total head ^b	The bowl assembly total head is the gauge head measured at the gauge connection located on the column pipe downstream from the bowl assembly, plus the velocity head at the point of the gauge connection, plus any losses between top of bowl assembly to tap location, plus datum from gauge plus liquid level. Friction losses of suction piping, can (barrel), and strainers must also be added. (h_J includes all losses before and after the bowl assembly.) Refer to Section 40.6.4.1 and Figure A.5. In essence the bowl assembly total head is equal to the pump total head adjusted for the losses external to the bowl.	H_{ba}	L	m (ft)
21	Loss of head at inlet	The difference between the total head of the liquid at the measuring point and the total head of the liquid in the inlet section of the pump.	h_{J1}	L	m (ft)
22	Loss of head at outlet	The difference between the total head of the liquid in the outlet section of the pump and the total head of the liquid at the measuring point.	h_{J2}	L	m (ft)
23	Pipe friction loss coefficient	Coefficient for the head loss by friction in the pipe according to the Darcy-Weisbach method.	λ	pure number	
24	Pump power input ^b	The power transmitted to the pump by its driver.	P	ML^2T^{-3}	W (hp)
25	Bowl assembly power input ^b	Power delivered to the bowl assembly. This is the pump power input minus any losses external to the bowl assembly. This power excludes line-shaft bearing power loss, stuffing-box losses, and thrust bearing losses.	P_{ba}	ML^2T^{-3}	W (hp)
26	Pump power output ^b	The mechanical power transferred to the liquid as it passes through the pump, also known as <i>pump hydraulic power</i> . $P_u = \rho QgH$	P_u	ML^2T^{-3}	W (hp)
27	Driver or control power input ^b	The power input to the driver or control.	P_{gr}	ML^2T^{-3}	W (hp)
28	Pump efficiency ^b	$\eta = \frac{P_u}{P} = \frac{\text{Pump power output}}{\text{Pump power input}}$	η	pure number	
29	Bowl efficiency ^b	$\eta_{ba} = \frac{P_{uba}}{P_{ba}} = \frac{\text{Bowl power output}}{\text{Bowl power input}}$	η_{ba}	pure number	

Table 40.6.2 — List of quantities, terms, and definitions (*continued*)

Row	Quantity	Definition	Symbol	Dimension	Unit ^a
30	Overall efficiency ^b	$\eta_{gr} = \frac{P_u}{P_{gr}} = \frac{\text{Pump power output}}{\text{Driver or control power input}}$	η_{gr}	pure number	

^a Refer to Appendix E for unit conversions.

^b Refer to Appendix F for DOE equivalent nomenclature.

40.6.2.1 Lists of symbols and subscripts

Table 40.6.2.1a — List of symbols

Symbol	Quantity	Unit ^a
D	Diameter	m (ft)
e	Overall uncertainty of the measurement, expressed as a percent	
f	Frequency	s ⁻¹ , Hz
g	Acceleration due to gravity	m/s ² (ft/s ²)
H	Pump total head	m (ft)
h _j	Losses in terms of head of liquid	m (ft)
k	Equivalent uniform roughness	m (ft)
L	Length	m (ft)
n	Speed of rotation	s ⁻¹ , min ⁻¹ , rpm
p	Pressure	Pa (psi)
P	Power	W (hp)
Q	Volume per unit time	m ³ /s (ft ³ /s) (gpm)
r	Radius	mm (in)
R ²	Measurement of how successful the curve fit represents the data. It is the sum of squares of regression and the total sum of the squares. It has a value from 0 to 1, with 1 being an ideal fit.	
S	Measuring section for the determination of head	
u	The value of the quantity measured	
U	Mean velocity	m/s (ft/s)
u _x	Probability of uncertainty of the quantity measurement, the potential error divided by the distribution of probability (see G.2)	

Table 40.6.2.1a — List of symbols (*continued*)

Symbol	Quantity	Unit ^a
z	Height above reference plane	m (ft)
η	Efficiency	
λ	Pipe friction loss coefficient	
ρ	Density	kg/m ³ (lbm/ft ³)

^a Refer to Appendix E for unit conversions.

Table 40.6.2.1b — List of subscripts

Subscript	Meaning
1	Inlet
1'	Inlet measuring section
2	Outlet
2'	Outlet measuring section
atm	Atmospheric pressure
ba	Bowl assembly
J1	Pipe losses at the inlet
J2	Pipe losses at the outlet
L	Liquid level
M	Measurement
M1	Measurement at the inlet
M2	Measurement at the outlet
sp	Specified (nominal)
T	Speed translated value
u	Output
vd	Velocity head

40.6.3 Pump efficiency testing

Pump efficiency tests are performed to verify the efficiency of pumps and their conformance to any standards as applicable. A typical pump efficiency test consists of measurement of flow, head, and pump power input. Pump efficiency is a dependent variable that is calculated from measured independent variables.

40.6.3.1 General

Testing shall be performed with clear water as described in Section 40.6.5.5.

40.6.3.2 Measurement uncertainty

40.6.3.2.1 General

The following are causes and acceptable limits of measurement uncertainties when testing to this standard. Every measurement is subject to some uncertainty, even if the measuring procedures, instruments used, and methods of analysis fully comply with good practice and with the requirements of this standard.

40.6.3.2.2 Permissible fluctuations (random fluctuations)

Table 40.6.3.2.2 gives the permissible amplitude of fluctuations for each quantity to be measured.

Where the construction or operation of a pump is such that fluctuations of amplitude greater than those specified in Table 40.6.3.2.2 are present, measurements shall be carried out by providing a damping device in the measuring instruments, their connecting lines, or by electronic data averaging. This must reduce the amplitude of the fluctuations to within the values given in Table 40.6.3.2.2.

Since it is possible that damping will affect the accuracy of the readings, use shall be made of symmetrical and linear damping devices, e.g., a capillary tube, which must provide an integration over at least one complete cycle (peak-to-peak) of fluctuations.

Table 40.6.3.2.2 — Permissible amplitude of fluctuation as a percentage of mean value of quantity being measured at any test point

Measured quantity	Permissible amplitude of fluctuations
Rate of flow	$\pm 3\%$
Differential head	$\pm 4\%$
Discharge head	$\pm 3\%$
Suction head	$\pm 3\%$
Driver or control input power	$\pm 3\%$
Speed of rotation	$\pm 1\%$
Torque	$\pm 3\%$
Temperature	$\pm 0.3\text{ }^{\circ}\text{C}$ ($0.5\text{ }^{\circ}\text{F}$)

40.6.3.2.3 Maximum permissible measurement device uncertainty (systematic)

The uncertainty of a measurement depends on the residual uncertainty of the measurement device and on the method of measurement used. After all known errors have been removed by zero adjustment, calibration, careful measurement of dimensions, proper installation, etc., there remains a value of uncertainty that never disappears.

This uncertainty cannot be reduced by repeating the measurements if the same instrument and the same method of measurement is used.

Table 40.6.3.2.3 shows the maximum permissible measurement device uncertainty. It is important to note that these maximum uncertainty values pertain to the measurements taken over a range of flows from 40% to 120% of the best efficiency point (BEP). When more than one instrument is used to measure a given parameter, the combined certainty calculated as the root sum of squares of individual instrument accuracies, must meet the specified uncertainty requirements. Refer to Appendix G Determination, application, and calculation of instrument (systematic) uncertainty.

$$e = \sqrt{\sum \left(\frac{u_x}{u} \right)^2}$$

Where:

e = overall uncertainty of the measurement, expressed as a percent

u_x = probability of uncertainty of the quantity measurement, the potential error divided by the distribution of probability

u = the value of the quantity measured

Appendix C describes different methods of measurement and devices typically used to determine rate of flow, pump total head, speed of rotation, and power input in the range of accuracy required for tests according to this standard.

After having selected an appropriate measurement device and setup, the best assurance of an accurate measurement is obtained by ensuring that a zero adjustment is performed regularly and that device calibration is performed at proper intervals per Appendix D.

Table 40.6.3.2.3 — Maximum permissible measurement device uncertainty

Measured quantity	Maximum permissible measurement device uncertainty
Rate of flow	± 2.5%
Differential head ^a	± 2.5%
Discharge head ^a	± 2.5%
Suction head ^a	± 2.5%
Pump power input	± 2.5%
Driver power input	± 2.0%
Speed of rotation	± 1.4%
Torque	± 2.0%
Temperature	± 0.3 °C (0.5 °F)

^a Permissible device uncertainty for head-measuring devices includes instruments for measuring distance.

40.6.4 Considerations when determining the efficiency of certain pumps

There are unique losses attributed to specific pump types and constructions. The following sections describe the impact on the calculation of efficiency for specific pump types.

40.6.4.1 Vertically suspended pumps

For vertically suspended pump types VS1 and VS3 (see ANSI/HI 2.1-2.2 *Rotodynamic Vertical Pumps of Radial, Mixed, and Axial Flow Types for Nomenclature and Definitions*) only the losses that are internal to the bowl assembly are to be considered. Only the bowl assembly power input, bowl assembly total head, and rate of flow are to be considered. Any mechanical losses for line shaft and bearings, discharge head (elbow), motor bearings and seals, including thrust bearing losses are not included in the bowl assembly power input. Any hydraulic losses external to the bowl assembly, i.e., seal flush or venting, friction losses from the column pipe and shaft, expansion, head losses, and any pipe friction loss must be credited back to the bowl assembly in the determination of bowl efficiency. Calculation of these losses shall be made using data from the *Hydraulic Institute Engineering Data Book* and ANSI/AWWA E103 *Horizontal and Vertical Line-Shaft Pumps Standard*.

All other vertically suspended pump types are to include all internal losses due to the construction of the pump. This includes all mechanical losses from shafting and bearings from thrust loads applied by the pump, all hydraulic losses from flush/lubricating flow and head loss discharge fittings intended to be the final customer connection to the pump. Any head loss between the measurement sections of the pump suction (if piped) and discharge pump connections must be credited when determining the pump efficiency. Calculation of these losses can be made using the data from the *Hydraulic Institute Engineering Data Book*.

A variation to this is pump type VS0. The motor is a separate item and can be the product of any manufacturer with varying performance and efficiency. Therefore, the VS0 is evaluated as a pump end only similar to the bowl performance and efficiency described for line-shafted VS product.

40.6.4.2 Submersible pumps

A *submersible pump* is defined as a close-coupled pump/motor unit designed to operate submerged in the pumped liquid. Because of the construction of the pump, there may not be access to the pump shaft to allow the use of torque and speed to measure pump power input to the pump shaft. However, the pump efficiency may be calculated from driver power input to a calibrated motor to determine pump power input (to the pump shaft). The motor efficiency is to be determined by calibration testing of the motor and will include the power to drive any shaft seals and viscous losses internal to the motor. See Appendix C.4.3.1 for the requirements for measurement of driver power input and the overall uncertainty when using a calibrated motor to measure pump input power. Variable-speed drives or nonsinusoidal power supplies are not to be used for powering the pump when testing to determine the pump efficiency when using a calibrated motor. Power used by external cooling devices is not included in the driver or pump power input, depending on the configuration in which the pump is being tested. Mechanical power losses due to pump thrust loads applied to the motor bearings and any electrical losses from power cable integral to the pump/motor necessary to power the unit will not be removed when calculating pump efficiency. Any additional cable losses are to be removed from the driver or pump power input. Internal losses within the pump up to the point of the discharge connection are to be included in determining the pump efficiency when using a calibrated motor. Any head losses between the measurement section of the pump suction (if dry pit) and discharge pump connection must be credited when determining the pump efficiency. Calculation of these losses can be made using the data from the *Hydraulic Institute Engineering Data Book*.

40.6.4.3 All other pump types

For all other pump types identified by ANSI/HI 1.1-1.2 *Rotodynamic Centrifugal Pumps for Nomenclature and Definitions*, all internal mechanical and hydraulic losses due to the construction of the pump are to be included in the measurement of pump efficiency. For these pump types, the pump power input includes mechanical losses from bearings and seals, and losses due to thrust loads applied to the bearings. All hydraulic losses that are internal to the pump from running clearances, cooling, and flush flows are attributed to the pump. Any head losses between

the measurement section of the pump suction and discharge connection must be credited when determining the pump efficiency. Calculation of these losses can be made using the data from the *Hydraulic Institute Engineering Data Book*.

40.6.4.4 Determination of pump overall efficiency

To determine the overall (wire-to-water) efficiency of a motor pump unit or a complete pump (i.e., bare pump, drive mechanical, driver and drive coupled together and treated as an integral unit), the driver or control power input and the pump power output are measured with the drive working under test conditions.

The ratio between pump power output and driver or control power input yields the overall efficiency. The driver or control power input shall be measured at the input terminals of the motor or control, if present on the pump under test. If the tested pump efficiency is known, and the efficiency of all pump components are known, the product of the pump and all component efficiencies may be used to calculate overall efficiency.

40.6.5 Test procedures

40.6.5.1 General

This standard is intended for tests conducted at test facilities, such as pump manufacturers' test facilities or independent laboratories.

40.6.5.2 Testing equipment

Only calibrated instruments shall be used for pump efficiency testing. See calibration requirements given in Appendix D.

40.6.5.3 Test report

The test results shall be summarized in a report. DOE has developed test reporting requirements for compliance with the energy conservation standards specified in 10 CFR Parts 429 and 431 for Pumps. Refer to Appendix B for more details.

40.6.5.4 Test arrangements

The test arrangements must be appropriate for the style of pump being tested. Recommendations and general guidance about suitable test setup and pipe arrangements to ensure satisfactory measurements for rate of flow and head are given in Appendix A.

40.6.5.5 Test conditions

Tests shall be made with clear water at a temperature between 10 and 30 °C (50 and 86 °F).

Clear water means water to be used for pump testing, with a maximum kinematic viscosity of $1.5 \times 10^{-6} \text{ m}^2/\text{s}$ ($1.6 \times 10^{-5} \text{ ft}^2/\text{s}$) and a maximum density of 1000 kg/m^3 (62.4 lb/ft^3).

40.6.5.5.1 Test procedure

Allow the pump to operate at the expected BEP rate of flow for a minimum of 20 minutes (to allow for warm up and break-in for the driver and other mechanical components).

All measurements shall be made under steady state conditions (no vortexing, margins as specified in ANSI/HI 9.6.1 *Rotodynamic Pumps Guideline for NPSH Margin*, and with stabilized readings after any change in flow setting; see Appendix A). At least two unique measurements shall be recorded more than 5 seconds apart, and their